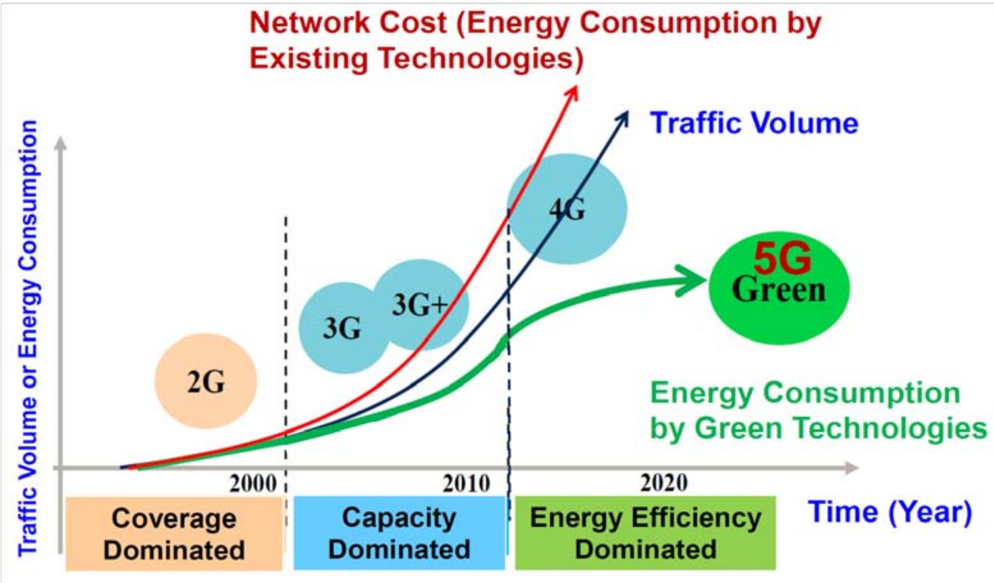
Radio Science Bulletin

ISSN 1024-4530

INTERNATIONAL
UNION OF
RADIO SCIENCE

UNION
RADIO-SCIENTIFIQUE
INTERNATIONALE



No 347
December 2013

URSI, c/o Ghent University (INTEC)
St.-Pietersnieuwstraat 41, B-9000 Gent (Belgium)

Contents

Front cover. The evolution from coverage- and capacity-driven telecommunications to energy-efficient green radio communications. See the paper by Jacques Palicot et al. pp. 40-56.

For information, please contact :
The URSI Secretariat
c/o Ghent University (INTEC)
Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium
Tel.: (32) 9-264 33 20, Fax: (32) 9-264 42 88
E-mail: info@ursi.org
http://www.ursi.org

The International Union of Radio Science (URSI) is a foundation Union (1919) of the International Council of Scientific Unions as direct and immediate successor of the Commission Internationale de Télégraphie Sans Fil which dates from 1913.

Editorial

Submit a Paper to the GASS!

The URSI XXXIth General Assembly and Scientific Symposium will be held August 17-23, 2014, in Beijing, China (CIE). The call for papers appears in this issue, and everyone is welcome to submit a paper. The deadline for submission is **February 15, 2014**, and the Web site (http://www.chinaursigass.com) is open for submissions *now*. There are also opportunities for support for Young Scientists. The US National Committee of URSI is again sponsoring a Student Paper Competition. This is going to be a historic meeting. I urge you to submit a paper, and to plan on attending.

Our Papers

MIMO (multiple-input multiple-output) radio systems have opened a new era in increased data communications throughput and in the ability to overcome propagation limitations. In his paper, Rodrigo de Lamare looks at the next major evolution of MIMO systems: massive MIMO systems, in which one or both ends of the communication link have very large numbers of antennas. The paper begins with an overview of MIMO networks, and explains the advantages of such architectures. The major ingredients for a massive MIMO network are then introduced, along with the signal-processing challenges involved in such networks. Several scenarios in which massive MIMO networks could be used are identified, including multibeam-satellite, cellular, and wireless local-area networks. The downlink and uplink signal-processing models for massive MIMO networks are presented and discussed. This leads to an in-depth look at a number of signal-processing considerations for massive MIMO networks, for both the transmitting and receiving parts of a network. Two simulations of massive MIMO networks are described. The results demonstrated the relative performance of the various signal-processing techniques that were described. The paper concludes with a look at future trends in this area, and emerging topics for future research.

The efforts of Sana Salous in bringing us the contribution from Commission C are gratefully acknowledged.

The Spanish Symposium of URSI was held in Santiago de Compostela, Spain, September 11-13, 2013. The paper by Mitra Gilasgar, Antoni Barlabé, and Lluís Pradell won second place in the Young Scientist best paper contest held as part of the symposium, and we are fortunate to have this paper in this issue. Power amplifiers play a critical role in determining both the transmission performance and the battery lifetime of mobile devices. Achieving low distortion with high efficiency, while at the same time reducing the circuit complexity, is a challenge. The authors describe a new class-F power-amplifier design that achieves these goals over significant bandwidths for both the 900 MHz and 1800 MHz bands. The paper begins with a review of the challenges associated with power amplifiers, and the advantages and challenges associated with class-F designs. The design of the amplifiers for the two frequency bands is introduced. The design uses a harmonic tuning structure that eliminates the need for an extra filtering section. This tuning structure also results in very low harmonic distortion. The fabrication of the amplifiers, and the measurements performed to verify their performance, are described. As an example, efficiencies higher than 60% over a bandwidth of 225 MHz, and higher than 70% over a bandwidth of 105 MHz, were obtained for the 900 MHz amplifier. The total harmonic distortion was around 1.2%.

The efforts of Francisco Ares in bringing us this paper are gratefully acknowledged.

Satellite radiometers measure the brightness temperature of the sea surface at multiple frequencies and with different polarizations. Simultaneously obtaining useful geophysical parameters, such as the sea-surface wind speed and the sea-surface temperature, from such data is a challenge. This is the topic of the paper by Debadatta Swain. The focus is on the use of a model based on an artificial neural network to simultaneously retrieve both these parameters from data from the radiometer on the IRS-P4 satellite, over the North Indian Ocean. The paper begins with a discussion of the challenges of doing this. The available data is described. For the case of the data used in this study, brightness-temperature measurements at four frequencies and two polarizations over a one-year period were used. Two methods for recovering the parameters were used, and compared with each other and with data obtained from sea buoys. One method was the artificial neural network, which is described. The second method, a multiple regression technique, is also explained. The training of the artificial neural network is described, along with the methods used to process and compare the data. The results are presented, compared, and discussed in detail. The artificial-neural-network approach was found to give better results than the more-commonly used multiple-regression technique. Methods for further improvement are discussed.

The invited Commission C paper by Jacques Palicot, Honggang Zhang, and Christophe Moy looks at "green" radio: an approach to wireless communication networks in which at least the same importance as other performance measures is given to energy efficiency at the network and at the component levels, as well as to considerations of electromagnetic pollution. The reasons for considering green radio are explained, with an emphasis on the growth rates of wireless communications and the attendant issues caused by the associated energy consumption. Metrics for characterizing the energy-consumption aspects of radio networks are introduced and evaluated. These include such measures as the bit rate per Joule consumed, or the bit rate per unit of bandwidth per Joule consumed. A variety of tradeoffs among various aspects of communications efficiency, quality-of-service, and energy efficiency and power consumption are analyzed. Solutions to increase energy efficiency are explored, both at the network level and at the level of the components making up the network. The role of cognitive radio in making radio "green" is explained. This leads to the concept of cognitive green radio, which is explored in depth. The many open problems and technical challenges for cognitive green radio are analyzed, and approaches for possible solutions are presented. The issues of electromagnetic pollution and the reduction of electromagnetic radiation hazards are examined. The paper concludes with a look at the future of green radio.

The efforts of Sana Salous in bringing us this paper are gratefully acknowledged.

Our Other Contributions

Kristian Schlegel has brought us a review of a new book on electromagnetics. Guy Vandenbosch, who wrote the review, feels it is one of the best books on electrodynamics he has read. We have reports on the AFRICON 2013 conference and the OCOSS 2013 (Ocean and Coastal Observation Sensors and Observing Systems 2013) conference. We also have a report on a symposium in honor of the 100th birthday of an ionospheric research pioneer, Karl Rawer. Finally, we have the usual year-end information on the organization of URSI, and how to contact those who play such important roles in the organization. You'll want to keep this issue available for reference.

Plan to Attend the GASS

I started this column by urging you to submit one or more papers to the URSI XXXIth General Assembly and Scientific Symposium to be held next August in Beijing. Please do consider submitting a paper, and definitely plan on attending. I have recently visited the venue, the Beijing Convention Center, and it is a very nice setting for the meeting. All of the sessions will be in a single building, and arranged in such a manner that it will be very easy to move between sessions. There are quite nice hotels immediately adjacent to where the sessions will be held. The whole convention center is in a park-like setting in the middle of one of the most rapidly growing and yet historically significant cities in the world. Plan some extra time for your visit: books have been written on all there is to see and do in this city! This will be the first time URSI has held a General Assembly in China (CIE). I'm sure you will find it to be a most outstanding and memorable experience. Please do start making your plans now. You won't want to miss this!

As the year comes to an end, my very best wishes for most joyous holidays, and for a very happy, healthy, safe, and prosperous New Year.

August 17-23, 2014
Beijing, China (CIE)
http://www.chinaursigass.com

XXXI General Assembly and Scientific Symposium of the International Union of Radio Science

Union Radio Scientifique Internationale

The XXXIst General Assembly and Scientific Symposium (GASS) of the International Union of Radio Science (Union Radio Scientifique Internationale: URSI) will be in Beijing. The XXXIst GASS will have a scientific program organized around the ten Commissions of URSI, including oral sessions, poster sessions, plenary and public lectures, and tutorials, with both invited and contributed papers. In addition, there will be workshops, short courses, special programs for Young Scientists, a student paper competition, programs for accompanying persons, and industrial exhibits. More than 1,500 scientists from more than 50 countries are expected to participate. The detailed program, the link to the electronic submission site for papers, the registration form, the application for the Young Scientists program, and hotel information are available on the GASS Web site: http://www.chinaursigass.com. **Submission deadline: February 15, 2014.**

Suggested Topics

Commission A Electromagnetic Metrology

Universal Coordinated Time: The International Reference Time Scale & Possible Redefinition / Time Scale / Time & Frequency Transfer / Quantum-Based Metrology / Education & Training in Metrology / Advances in Sensor Development & Applications / Global Navigation Systems (Overview of Timing Techniques in Various Satellite Systems) / Nonlinear Measurements & Characterization / Mode-Stir Chambers / Bioeffects and Medical Applications / EMC and EM Metrology/Pollution / Interconnect and Packaging Evaluation / Material Measurement and Characterization / Microwave to Sub-Millimeter Measurements/Standards Noise Measurements and Standards / Time-Domain Metrology / Techniques for Remote Sensing / Measurements and Calibration in Propagation / RFID / Signal Enhancement for EM Metrology / Scattering Calibration, References (bistatic) / Other Topics

Topics joint with:

Com. B: Recent Advances in Antenna Measurement Techniques
Com. D: Quantum Metrology
Com. D: Metrology of Optical Frequencies and Optical-Dimensional Measuring Techniques
Com. J: Pulsars and the Application to Time Scales
Com. E & K: Dosimetry and Safety of EM wave

Commission B: Fields and Waves

Inverse Scattering and Imaging / Scattering and Diffraction / Electromagnetic Theory / Recent Advances in Metamaterials / Analytical, Numerical and Hybrid Methods in Electromagnetics / Beam & High-Frequency Methods / Ultra-Wideband Antennas and Arrays / Nano-Electromagnetics / Antennas: Recent Advances and Future Outlooks / Electromagnetic Field Transformations for Measurements and Numerical Methods / Time-Domain Electromagnetics and Transient Phenomena / Novel Mathematical Methods in Electromagnetics / Other Topics

Topics joint with:

Com. A: Recent Advances in Antenna Measurement Techniques
Com. C: Radio Channel Measurements and Modeling: MIMO, Indoor, Outdoor
Com. D: Advanced Computational Techniques for Multi-Scale and Multi-Physics Electromagnetics
Com. D: Plasmonics
Com. D: RF MEMs and NEMS
Com. D: Multi-Physics Modeling in Radio Frequency Nanoelectronics
Com. E: Modeling
Com. F: EM Modeling & Applications of Underground Imaging
Com. K: Electromagnetic Modeling of the Human Body
Com. K: Non-Ionizing Electromagnetic Medical Imaging
Com. K: Antennas for Wireless Medical Telemetry
Com. C & D: Reconfigurable Antennas for Cognitive Radio
Com. C & D: Emerging Wireless Technologies
Com. C & D: Signal Processing Antennas
Com. C & D: Energy Harvesting in Wireless Systems
Com. E & K: Uncertainty Management
Com. C, D & K: Body-Area Networks

Commission C: Radiocommunication Systems and Signal Processing

Advances in Signal Processing for Cognitive Radio / Radio Localization Techniques: Satellite, Indoor, In Tunnels, Autonomous / Advances in Channel Coding for Reliable Communications / Emerging Technologies for 5G Cellular Communications / Cooperative Communications and Network Coding / Wireless Physical Layer Security / Urban Scenarios: Small Cells, Indoor to Outdoor, Vegetation / Resource Allocation in Wireless Networks / Advanced Technologies for WLANs and WSNs / Communications Technologies for (High-Speed) Transportation Systems

Topics joint with:

Com. B: Radio Channel Measurements & Modeling: MIMO, In-& Outdoor
Com. D: Circuit Technologies for Mobile Communications
Com. D: Ultra-High-Bit-Rate Radio Communications (THz and 60 GHz)
Com. D: Broadband Ubiquitous Network with Wired & Wireless Convergence
Com. F: Communications and Remote Sensing in Disaster Scenarios
Com. B & D: Reconfigurable Antennas for Cognitive Radio
Com. B & D: Emerging Wireless Technologies
Com. B & D: Signal Processing Antennas
Com. B & D: Energy Harvesting in Wireless Systems
Com. D & F: Trends in THz Communications
Com. B, D & K: Body-Area Networks

Commission D: Electronics and Photonics

Micro and Nanophotonics / New Frontiers and Applications of Optical Fibers / Graphene Nanoelectronics for THz Applications / Trends in RFID, from Identification to Sensing / Nonlinear Optics and Guided Wave Devices / Hybrid and Monolithic Digital-RF Integrated Circuits / Quantum Optics, Quantum Information, Quantum Precise Measurement and THz systems and Applications / 60 GHz Electronics / Other Topics

Topics joint with:

Com. A: Quantum Metrology
Com. A: Metrology of Optical Frequencies and Optical-Dimensional Measuring Techniques
Com. B: Plasmonics
Com. B: RF MEMs and NEMS
Com. B: Multi-Physics Modeling in Radio Frequency Nanoelectronics
Com. B: Advanced Computational Techniques for Multi-Scale and Multi-Physics Electromagnetics

Com. C: Broadband Ubiquitous Network with Wired & Wireless Convergence
Com. C: Circuit Technologies for Mobile Communications
Com. C: Ultra-High-Bit-Rate Radio Communications (THz and 60 GHz)
Com. B & C: Signal Processing Antennas
Com. B & C: Energy Harvesting in Wireless Systems
Com. B & C: Reconfigurable Antennas for Cognitive Radio
Com. B & C: Emerging Wireless Technologies
Com. C & F: Trends in THz Communications
Com. B, C & K: Body-Area Networks

Commission E: Electromagnetic Environment and Interference

EMC in Complex Systems / High Power Electromagnetics and Intentional EMI / Stochastic Techniques in EMC / EMC in Wired and Wireless Systems / Lightning & Related Phenomena / EMC of Power Electronics / EMC for IC, PCB, and Package / Recent Developments / EMC in Power Engineering / Measuring Techniques / Other Topics

Topics joint with:
Com. B: Modeling
Com. J: Spectrum Management and Utilization
Com. K: EMC of Wireless Power Transfer
Com. A & K: Dosimetry and Safety of EM wave
Com. B & K: Uncertainty Management
Com. G & H: Terrestrial and Planetary Electromagnetics
Com. G & H: Electromagnetic Effects in Lithosphere-Atmosphere-Ionosphere Coupling
Com. G & H: Ionospheric, Magnetospheric and High Energy Effects of Lightning

Commission F: Wave Propagation and Remote Sensing

Remote Sensing of Snow and Ice / Millimeter Propagation and Remote Sensing / Advances in Spaceborne SAR Imaging and Applications / Fixed Terrestrial Links: Measurements, Models & Planning-Procedures / Remote Measurement of Precipitation at Local, Regional, and Global Scales / Mobile Propagation Models and Measurements / Microwave Radiometry of Vegetation and Terrestrial Snow / Radio-Frequency Interference (RFI) / Remote Sensing of Biomass / Remote Sensing of Land and Sea at L band / Other Topics

Topics joint with:
Com. B: EM Modeling and Applications of Underground Imaging
Com. C: Communications and Remote Sensing in Disaster Scenarios
Com. C & D: Trends in THz Communications

Commission G: Ionospheric Radio and Propagation

Impacts of the Ionosphere on Radio Systems / Advances in Incoherent Scatter Radar / Studies of Irregularities and Scintillation / Radio Studies of Equatorial and Low-Latitude Aeronomy / Radio Studies of Polar Aeronomy / Modeling the Geospace Environment / Ionosphere and Plasmasphere Density Profiles / Other Topics

Topics joint with:
Com. H: Plasma Waves
Com. H: Radio Sounding in Magnetospheres and Ionospheres
Com. H: The Geospace Environment and Meteors
Com. H: Active Experiments
Com. H: Drivers, Detection, and Ionospheric Impacts of Precipitation from the Radiation Belts
Com. E & H: Terrestrial and Planetary Electromagnetics
Com. E & H: E Effects in Lithosphere-Atmosphere-Ionosphere Coupling
Com. E & H: Ionospheric, Magnetospheric and High Energy Effects of Lightning

Commission H: Waves in Plasmas

Wave-Particle Interactions & Their Effects on Planetary Radiation Belts / Laboratory Simulations of Space Plasma Waves / Boundary Layers in Terrestrial and Planetary Environments: Macro/Micro-Scale Kinetic Processes / Plasma Interactions with Solar System Bodies / Remote Sensing of the Plasmasphere / Other Topics

Topics joint with:
Com. G: Active Experiments
Com. G: Drivers, Detection, and Ionospheric Impacts of Precipitation from the Radiation Belts
Com. G: Plasma Waves
Com. G: Radio Sounding in Magnetospheres and Ionospheres
Com. G: The Geospace Environment and Meteors
Com. E & G: Terrestrial and Planetary Electromagnetics
Com. E & G: Electromagnetic Effects in Lithosphere-Atmosphere-Ionosphere Coupling
Com. E & G: Ionospheric, Magnetospheric and High Energy Effects of Lightning

Commission J: Radio Astronomy

Radio Astronomy in China / Observatory Reports / New Generation Radio Telescopes / Polarization and Magnetic Fields from the Solar System to the CMBR / Observing the mm and Sub-mm Universe: From the CMBR to Local Molecules / Probing the Hydrogen Universe / Correlation, Calibration, and Imaging Across all Wavelengths / Solar Radio Emission: Astrophysics and Space Weather Applications / Time Domain Radio Astronomy: An Example of Big Data in Astronomy / Antennas, Detectors & Receivers for New Generation Radio Telescopes

Topics joint with:
Com. A: Pulsars and the Application to Time Scales
Com. E: Spectrum Management and Utilization

Commission K: Electromagnetics in Biology and Medicine

Interaction Between EMF and Biosystems / Biological Effects of EMF / Millimeter and THz Waves in Medicine and Biology / Therapeutic Applications of High-Frequency EM / EMF Exposure Assessment / Interactions Between Human Body and Implanted Systems Field Applications / Biomedical Applications: Static, ELF and Pulsed Field Applications / Other Topics

Topics joint with:
Com. B: Electromagnetic Modeling of the Human Body
Com. B: Non-Ionizing Electromagnetic Medical Imaging
Com. B: Antennas for Wireless Medical Telemetry
Com. E: EMC of Wireless Power Transfer
Com. A & E: Dosimetry and Safety of EM wave
Com. B & E: Uncertainty Management
Com. B, C & D: Body-Area Networks

All papers (a maximum of four pages) should be submitted electronically via the link provided on the GASS Web site: http://www.chinaursigass.com. Please consult the symposium Web site for the latest instructions, templates, and sample formats. Accepted papers that are presented at the GASS will be submitted for posting to IEEE Xplore.

Young Scientists Program and Student Paper Competition

A limited number of awards are available to assist Young Scientists from both developed and developing countries to attend the GASS. Information on this program and on the Student Paper Competition is available on the Web site. Application for Young Scientists Awards and Student Paper Competitions should be done during paper submission.

Important Deadlines

Paper submission: **February 15, 2014** Acceptance Notification: **April 15, 2014**

Contact

For all questions related to the GASS, please contact the GASS Secretariat:
Cynthia Lian, e-mail: cynthia_nano@hotmail.com Lucy Zhang, e-mail: yzha0943@gmail.com Yihua Yan, e-mail: yyh@nao.cas.cn
Tel: +86 10-68278214

URSIGASS 2014

http://www.chinaursigass.com

U.R.S.I.

AWARDS FOR YOUNG SCIENTISTS CONDITIONS

A limited number of awards are available to assist young scientists from both developed and developing countries to attend the General Assembly and Scientific Symposium of URSI.

To qualify for an award the applicant:

1. must be less than 35 years old on September 1 of the year of the URSI General Assembly and Scientific Symposium;
2. should have a paper, of which he or she is the principal author, submitted and accepted for oral or poster presentation at a regular session of the General Assembly and Scientific Symposium.

Applicants should also be interested in promoting contacts between developed and developing countries. Applicants from all over the world are welcome, also from regions that do not (yet) belong to URSI. All successful applicants are expected to participate fully in the scientific activities of the General Assembly and Scientific Symposium. They will receive free registration, and financial support for board and lodging at the General Assembly and Scientific Symposium. Limited funds will also be available as a contribution to the travel costs of young scientists from developing countries.

The application needs to be done electronically by going to the same website used for the submission of abstracts/papers via http://www.chinaursigass.com/. The deadline for paper submission for the URSI GASS2014 in Beijing is 15 February 2014.

A web-based form will appear when applicants check “Young Scientist paper” at the time they submit their paper. All Young Scientists must submit their paper(s) and this application together with a CV and a list of publications in PDF format to the GA submission Web site.

Applications will be assessed by the URSI Young Scientist Committee taking account of the national ranking of the application and the technical evaluation of the abstract by the relevant URSI Commission. Awards will be announced on the URSI Web site in April 2014.

For more information about URSI, the General Assembly and Scientific Symposium and the activities of URSI Commissions, please look at the URSI Web site at: http://www.ursi.org or the GASS 2014 website at http://www.chinaursigass.com/

If you need more information concerning the Young Scientist Program, please contact:

The URSI Secretariat
c/o Ghent University / INTEC
Sint-Pietersnieuwstraat 41
B-9000 GENT
BELGIUM
fax: +32 9 264 42 88
E-mail: ingeursi@intec.ugent.be

Massive MIMO Systems: Signal Processing Challenges and Future Trends

Rodrigo C. de Lamare

Centre for Telecommunications Studies (CETUC)
Pontifical Catholic University of Rio de Janeiro Gávea
22453-900, Rio de Janeiro, Brazil
Communications Research Group, Department of Electronics,
University of York,
York Y010 5DD, United Kingdom
E-mail: delamare@cetuc.puc-rio.br

Abstract

This article presents a tutorial on multi-user multiple-antenna wireless systems with a very large number of antennas, known as massive multi-input multi-output (MIMO) systems. Signal-processing challenges and future trends in the area of massive MIMO systems are presented, and key application scenarios are detailed. A linear-algebra approach is considered for the description of the system and data models of massive MIMO architectures. The operational requirements of massive MIMO systems are discussed, along with their operation in time-division duplexing mode, resource allocation, and calibration requirements. In particular, transmitter and receiver processing algorithms are examined in light of the specific needs of massive MIMO systems. Simulation results illustrate the performance of transmitter and receiver processing algorithms under scenarios of interest. Key problems are discussed, and future trends in the area of massive MIMO systems are pointed out.

1. Introduction

Wireless networks are experiencing a very substantial increase in the amount of data delivered due to a number of emerging applications, which include machine-to-machine communications and video streaming [1-3]. This very large amount of data exchange is expected to continue and rise in the next decade or so, presenting a very significant challenge to designers of wireless communications systems. This constitutes a major problem, not only in terms of exploitation of available spectrum resources, but also regarding the energy efficiency in the transmission and processing of each information unit (bit), which has to substantially improve. The wireless Internet of the future (WIoF) will therefore have to rely on technologies that can offer a substantial increase in transmission capacity as measured in bits/Hz, but that do not require increased spectrum bandwidth or energy consumption.

Multiple-antenna or multi-input multi-output (MIMO) wireless communication devices that employ antenna arrays with a very large number of antenna elements are known as massive MIMO systems. They have the potential to overcome those challenges and deliver the required data rates, representing a key enabling technology for the wireless Internet of the future [4-6]. Among the devices of massive MIMO networks are user terminals, tablets, and base stations, which could be equipped with numbers of antenna elements that are orders of magnitude higher than current devices. Massive MIMO networks will be structured from the following key elements: antennas, electronic components, network architectures, protocols, and signal processing.

The first important ingredient of massive MIMO networks is antenna technology. This allows designers to assemble large antenna arrays with various requirements in terms of spacing of elements and geometries, reducing the number of required radio-frequency (RF) chains at the transmitting and the receiving ends, and their implementation costs [7-9]. In certain scenarios and deployments, the use of compact antennas with closely-spaced elements will be of great importance in equipping devices with a large number of antennas, but this will require techniques to mitigate the coupling effects, especially at the user terminals [10]. The second key area for innovation is that of electronic components and RF chains, where the use of low-cost amplifiers with output power in the milliwatt range will play an important role. Architectures such as the direct-conversion radio (DCR) [11] are very attractive, due to their flexibility and ability to operate with several different

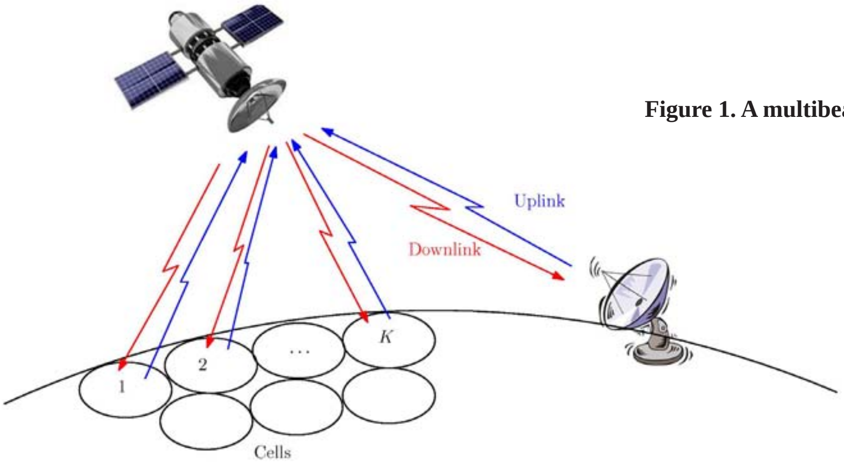


Figure 1. A multibeam satellite network.

air interfaces, frequency bands, and waveforms. Existing peripherals, such as large coaxial cables and power-hungry circuits, will have to be replaced with low-energy solutions.

Another key element of massive MIMO networks is the network architecture. This will evolve from homogeneous cellular layouts to heterogeneous architectures that include small cells and the use of coordination between cells [12]. Since massive MIMO technology is likely to be incorporated into cellular and local-area networks in the future, the network architecture will necessitate special attention to how to manage the interference that is created [13], and measurement campaigns will be of fundamental importance [14-16]. The coordination of adjacent cells will be necessary, due to the current trend towards aggressive reuse factors for capacity reasons, which inevitably leads to increased levels of inter-cell interference and signaling. The need to accommodate multiple users while keeping the interference at an acceptable level will require significant work in scheduling and medium-access protocols.

The last ingredient of massive MIMO networks, and the main focus of this article, is signal processing. In particular, MIMO signal processing will play a crucial role in dealing with the impairments of the physical medium, and in providing cost-effective tools for processing information. Current state-of-the-art in MIMO signal processing requires a computational cost for transmitting and receiving processing that grows as a cubic or super-cubic function of the number of antennas, which is clearly not scalable with a large number of antenna elements. We advocate the need for simpler solutions for both transmitting and receiving processing tasks, which will require significant research efforts in the next years. Novel signal-processing strategies will have to be developed to deal with the problems associated with massive MIMO networks, such as computational complexity and its scalability, pilot contamination effects, RF impairments, coupling effects, and delay and calibration issues. Other key points for future massive MIMO technology are the application scenarios, which will become the main object of investigation in the coming years. Amongst the most important scenarios are multi-beam satellite networks, cellular systems beyond LTE-A [2], and local-area [3] networks.

This article is structured as follows. Section 2 reviews the system model, including both uplink and downlink, and discusses the application scenarios. Section 3 is dedicated to transmitting processing techniques, whereas Section 4 concentrates on receiving processing. Section 5 discusses the results of some simulations, and Section 6 presents some open problems and suggestions for further work. The conclusions of this article are given in Section 7.

2. Application Scenarios and Signal Models

In this section, we discuss several application scenarios for multi-user massive MIMO systems, which include multibeam satellite systems, cellular, and local-area networks. Signal models based on elementary linear algebra are then presented to describe the information

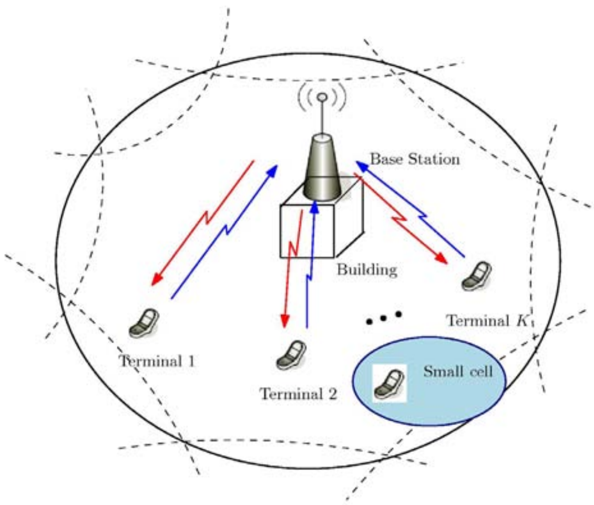


Figure 2. A mobile cellular network.

processing in both uplink and downlink transmissions. These models are based on the assumption of a narrowband signal transmission over flat fading channels, which can be easily generalized to broadband signal transmission with the use of multi-carrier systems.

2.1 Application Scenarios

Amongst the most promising application scenarios of multi-user massive MIMO techniques are multibeam satellite [17], cellular, and local-area networks. Multibeam satellite systems are perhaps the most natural scenario for massive MIMO because the number of antenna elements is above one hundred. The major benefit of satellite communications is that all users can be served within the coverage region at the same cost. In this context, the next generation of broadband satellite networks will employ multibeam techniques in which the coverage region is served by multiple spot beams intended for the users, which are shaped by the antenna feeds forming part of the payload [17], as depicted in Figure 1. A fundamental problem with the multibeam approach is the interference caused by multiple adjacent spot beams that share the same frequency band. This interference between spot beams must be mitigated by suitable signal-processing algorithms. Specifically, multi-user interference mitigation schemes, such as pre-coding or multi-user detection, can be jointly designed with the beamforming process at the gateway station. The interference mitigation must be applied to all the radiating signals, instead of directly to the user beams. In the downlink (also known as the forward link in the satellite-communications literature), the interference-mitigation problem corresponds to designing transmitting processing or pre-coding strategies that require the channel-state information (CSI). For the uplink (also known as the reverse link), the interference-mitigation problem can be addressed by the design of multi-user detectors.

The second highly-relevant scenario is that of mobile cellular networks beyond LTE-A [2], which is illustrated in Figure 2. In such networks, massive MIMO would play a key role with the deployment of hundreds of antenna elements at the base station, coordination among cells, and a more modest number of antenna elements at the user terminals. At the base station, very large antenna arrays could be deployed on the roof or on the façade of buildings. With further development in the area of compact antennas and techniques to mitigate mutual-coupling effects, it is likely that the number of antenna elements at the user terminals (mobile phones, tablets, and other gadgets) might also be significantly increased, from one to four elements in current terminals to 10 to 20 in future devices. In these networks, it is preferable to employ time-division-duplexing (TDD) mode to perform uplink channel estimation, and to obtain downlink channel-state information by reciprocity for signal processing at the transmitting side. This operational mode will require cost-effective calibration algorithms. Another critical requirement is the uplink channel estimation, which employs non-orthogonal pilots. Due to the existence of adjacent cells and the coherence time of the channel, this needs to reuse the pilots [18]. Pilot contamination occurs when channel-state information at the base station in one cell is affected by users from other cells. In particular, the uplink (or multiple-access channel) will need channel-state information obtained by uplink channel estimation, efficient multi-user detection, and decoding algorithms. The downlink (also known as the broadcast channel) will require channel-state information obtained by reciprocity for transmitting processing, and the development of cost-effective scheduling and pre-coding algorithms.

The third and last highly relevant scenario is represented by wireless local-area networks (WLANs) [3], which are shown in Figure 3. The deployment of WLANs has increased tremendously in the last few years, with the proliferation of hot spots and home users. These systems have adopted orthogonal frequency-division multiplexing (OFDM) for their air interface. They are equipped with numbers of antennas of up to eight at the access point, and up to four antennas at the user terminals [3]. Massive MIMO could play an important role in the incorporation of a substantial number of antenna elements at the access point, using compact antennas and planar array geometries to keep the size of the access point down to reasonable physical dimensions. The user terminals (laptops, tablets, and smart phones) could also rely on compact antennas to accommodate a substantial number of radiating elements. In the future, it is possible that the number of antenna elements at the user terminals will be significantly increased, from eight to over 100 elements at the access-point terminals, and from four to over 40 in future devices.

A key challenge in all the three scenarios is how to deal with a very large number of antenna elements and to develop cost-effective algorithms, resulting in excellent performance in terms of the metrics of interest, namely, bit-error rate (BER), sum-rate, and throughput. In what follows, signal models that can describe the processing and transmission will be detailed.

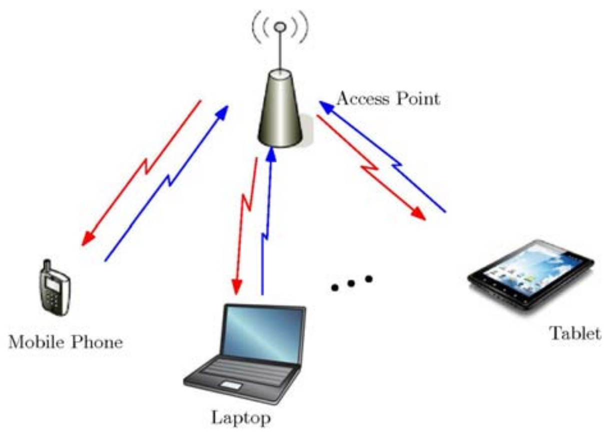


Figure 3. A wireless local-area network.

2.2 Downlink Model

In our description, we consider a multi-user massive MIMO system with a number of antenna elements equal to N_A at the transmitter, which could be a satellite gateway, a base station of a cellular network, or an access point of a WLAN. The transmitter communicates with K users in the system, where each user is equipped with N_U antenna elements, and $N_A > KN_U$. It should be noted that in massive MIMO systems, it is desirable to have an excess of degrees of freedom [4], which means that N_A should exceed KN_U by a significant margin, in order to leverage the array's gain. At each time instant [i], the transmitter applies a pre-coder to the KN_U data vector $\boldsymbol{s}[i]$ intended for the K users. The KN_U data vector $\boldsymbol{s}[i]$ consists of the stacking of the $N_U \times 1$ vectors $\mathbf{s}_k[i] = \left\{s_{k,1}[i], s_{k,2}[i], \ldots, s_{k,N_U}[i]\right\}^T$ of the K users. Each entry is a data symbol taken from a modulation constellation $A = \{a_1, a_2, \ldots, a_N\}$, with zero mean and variance σ_s^2, where $(\bullet)^T$ denotes transpose. The $N_A \times 1$ pre-coded data vector for user k is given by $\boldsymbol{x}_k[i] = \mathcal{P}(\mathbf{s}_k[i])$, where $\mathcal{P}(\bullet)$ is the mathematical mapping applied by the pre-coder, and this is then transmitted over flat-fading channels.

The received signal at each user after demodulation, matched filtering, and sampling is collected in an $N_U \times 1$ vector $\boldsymbol{r}_k[i] = \left\{r_{k,1}[i], r_{k,2}[i], \ldots, r_{k,N_U}[i]\right\}^T$ with sufficient statistics for processing, and given by

$$\boldsymbol{r}_k[i] = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{x}_k[i] + \boldsymbol{n}_k[i], \qquad (1)$$

where the $N_U \times 1$ vector $\boldsymbol{n}_k[i]$ is a zero-mean complex circularly symmetric Gaussian noise with covariance matrix $E\left\{\boldsymbol{n}_k[i]\boldsymbol{n}_k^H[i]\right\} = \sigma_n^2 \boldsymbol{I}$, where $E[\bullet]$ stands for expected value, $(\bullet)^H$ denotes the Hermitian operator, σ_n^2 is the noise variance, and $\boldsymbol{I}$ is the identity matrix. The $N_A \times 1$ pre-coded data vectors $\boldsymbol{x}_k[i]$ have covariance matrices $E\left\{\boldsymbol{x}_k[i]\boldsymbol{x}_k^H[i]\right\} = \sigma_{x_k}^2 \boldsymbol{I}$, where $\sigma_{x_k}^2$ is the signal power. The elements h_{n_U,n_A} of the $N_U \times N_A$ channel matrices $\boldsymbol{H}_k$ are the complex channel gains from the n_A th transmitting antenna to the n_U th receiving antenna.

2.3 Uplink Model

Let us now consider the uplink of a multi-user massive MIMO system with K users that are equipped with N_U antenna elements and communicate with a receiver with N_A antenna elements, where $N_A > KN_U$. At each time instant, the K users transmit N_U symbols, which are organized into a $N_U \times 1$ vector $\mathbf{s}_k[i] = \left\{s_{k,1}[i], s_{k,2}[i], \ldots, s_{k,N_U}[i]\right\}^T$, taken from a modulation constellation $A = \{a_1, a_2, \ldots, a_N\}$. The data vectors $\boldsymbol{s}_k[i]$ are then transmitted over flat-fading channels. The received signal after demodulation, matched filtering, and sampling is collected in an $N_A \times 1$ vector $\mathbf{r}[i] = \left\{r_1[i], r_2[i], \ldots, r_{N_R}[i]\right\}^T$, with sufficient statistics for processing as described by

$$\boldsymbol{r}[i] = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{s}_k[i] + \boldsymbol{n}[i], \qquad (2)$$

where the $N_A \times 1$ vector $\boldsymbol{n}[i]$ is a zero-mean complex circularly symmetric Gaussian noise with covariance matrix $E\left\{\boldsymbol{n}[i]\boldsymbol{n}^H[i]\right\} = \sigma_n^2 \boldsymbol{I}$. The data vectors $\boldsymbol{s}_k[i]$ have zero mean and covariance matrices $E\left\{\boldsymbol{s}_k[i]\boldsymbol{s}_k^H[i]\right\} = \sigma_{s_k}^2 \boldsymbol{I}$, where $\sigma_{s_k}^2$ is the signal power. The elements h_{n_A,n_U} of the $N_A \times N_U$ channel matrices $\boldsymbol{H}_k$ are the complex channel gains from the n_U th transmitting antenna to the n_A th receiving antenna.

3. Transmitting Processing

In this section, we discuss several aspects related to transmitting processing in massive MIMO systems. Fundamental results in information theory have shown that the optimum transmitting strategy for the multi-user massive MIMO downlink channel involves a theoretical dirty-paper coding (DPC) technique that performs interference cancellation, combined with an implicit user-scheduling and power-loading algorithm [37]. However, this optimal approach is extremely costly, and unlikely to be used in any practical deployment. In what follows, we consider several aspects of transmitting processing in massive MIMO systems, which include TDD operation, pilot contamination, resource allocation and pre-coding, and related signal-processing tasks.

3.1 TDD Operation

One of the key problems in modern wireless systems is the acquisition of channel-state information in a timely way. In time-varying channels, TDD offers the most suitable alternative for obtaining channel-state information, because the training requirements in a TDD system are independent of the number of antennas at the base station (or access point) [18], and there is no need for channel-state information feedback. In particular, TDD systems rely on reciprocity, by which the uplink channel is used as an estimate of the downlink channel. An issue in this operational mode is the difference in the transfer characteristics of the amplifiers and the filters in the two directions. This can be addressed through measurements and appropriate calibration [5]. In contrast, in a frequency-division duplexing (FDD) system, the training requirements are proportional to the number of antennas, and channel-state information feedback is essential. For this reason, massive MIMO systems will most likely operate in TDD mode, and will require further investigation in calibration methods.

3.2 Pilot Contamination

The adoption of TDD mode and uplink training in massive MIMO systems with multiple cells results in a phenomenon called pilot contamination. In multi-cell scenarios, it is difficult to employ orthogonal pilot sequences. This is because the duration of the pilot sequences depends on the number of cells, and this duration is severely limited by the channel-coherence time, due to mobility. Therefore, non-orthogonal pilot sequences must be employed, and this affects the channel-state information employed at the transmitter. Specifically, the channel estimate is contaminated by a linear combination of channels of other users that share the same pilot [18]. Consequently, the pre-coders and resource-allocation algorithms will be highly affected by the contaminated channel-state information. Strategies to control or mitigate pilot contamination and its effects are very important for massive MIMO networks. Possible approaches include work on optimization of waveforms, blind channel-estimation techniques, implicit training approaches, and pre-coding and resource-allocation techniques that take into account pilot contamination to mitigate its effects.

3.3 Resource Allocation

Prior work on multi-user MIMO [32-34] has shown that resource-allocation techniques are fundamental to obtaining further capacity gains. In massive MIMO, this will be equally important, and will have the extra benefit of more-accurate channel-state information. From a multi-user information-theoretic perspective, the capacity-region boundary is achieved by simultaneously serving all K active users. The resources (antennas, users, and power) that should be allocated to each user depend on the instantaneous channel-state information, which may vary amongst users. Since the total number of users, Q, that could be served is often much higher than the number of transmitting antennas, N_A, the system needs a resource-allocation algorithm to select the best set of users according to a chosen criterion, such as the sum rate or a user target rate. The resource-allocation task is then to choose a set of users and their respective powers in order to satisfy a given performance metric. In massive MIMO systems, the spatial signatures of the users to be scheduled might play a fundamental role, thanks to the very large number of antennas and an excess of degrees of freedom [4, 5]. The multi-user diversity [32], along with high array gains, might be exploited by the resource-allocation algorithm, along with timely channel-state information. In particular, the problem of user selection, i.e., scheduling, corresponds to a combinatorial problem equivalent to the combination of K choosing Q. It is hence clear that the exhaustive search over all possible combinations is computationally prohibitive when the K in the system is reasonably large, and thus cost-effective user-selection algorithms will be required. Strategies based on greedy, low-cost, and discrete optimization methods [33, 34, 36] are very promising for massive MIMO networks, because they could reduce the cost of resource-allocation algorithms.

3.4 Pre-Coding and Related Techniques

Strategies for mitigating the multi-user interference at the transmitting side include transmitting beamforming [5] and pre-coding based on linear minimum-mean-square error (MMSE) [38] or zero-forcing (ZF) [39] techniques, and nonlinear approaches, such as dirty-paper coding, Tomlinson-Harashima pre-coding (THP) [58], and vector perturbation [43]. Transmitting matched filtering (TMF) is the simplest method for processing data at the transmitter side, and has been recently advocated by several works for massive MIMO systems [4, 5]. The basic idea is to apply the conjugate of the channel matrix to the data symbol vector $\boldsymbol{s}[i]$ prior to transmission, as described by

$$\boldsymbol{x}[i] = \boldsymbol{H}^H \boldsymbol{s}[i], \tag{3}$$

where the $N_A \times KN_U$ matrix $\boldsymbol{H}$ contains the parameters of all the channels, and the $N_A \times 1$ vector $\boldsymbol{x}[i]$ represents the data processed by transmitting matched filtering.

Linear pre-coding techniques, such as zero-forcing and minimum-mean-square error pre-coding, are based on channel-inversion operations. They are attractive due to their relative simplicity for MIMO systems with a small to moderate number of antennas. However, channel-inversion based pre-coding requires a higher average transmitted power than other pre-coding algorithms, especially for ill-conditioned channel matrices, which could result in poor performance. A linear pre-coder applies linear transformations to the data-symbol vector, $\boldsymbol{s}[i]$, prior to transmission, as described by

$$\boldsymbol{x}[i] = \boldsymbol{W}_k \boldsymbol{s}_k[i] + \sum_{l=1, l \neq k}^{K} \boldsymbol{W}_l \boldsymbol{s}_l[i], \tag{4}$$

where the $N_A \times N_U$ matrix $\boldsymbol{W}_l$ contains the parameters of the channels, and the $N_U \times 1$ data-symbol vectors $\boldsymbol{s}_k[i]$ represent the data processed by the linear pre-coder. The linear minimum-mean-square error pre-coder is described by $\boldsymbol{W}_{\text{MMSE}} = \boldsymbol{H}^H \left(\boldsymbol{H}\boldsymbol{H}^H + \gamma \boldsymbol{I}\right)^{-1}$, where γ is a gain factor, and the linear zero-forcing pre-coder is expressed by $\boldsymbol{W}_{\text{ZF}} = \boldsymbol{H}^H \left(\boldsymbol{H}\boldsymbol{H}^H\right)^{-1}$.

Block-diagonalization (BD)-type pre-coding algorithms were proposed in [39-41] for MU-MIMO (multi-user MIMO) systems. The main advantage of block-diagonalization type algorithms is that the sum-rate performance is not far from that obtained by dirty-paper-coding techniques, and the relative simplicity for implementation in systems with a modest number of antennas. However, existing block-diagonalization solutions are unlikely to be used in massive MIMO systems, due to the cost associated with their implementation in antenna arrays with hundreds of elements. This suggests that there is need for cost-effective block-diagonalization-type strategies for very large antenna arrays. Tomlinson-Harashima pre-coding [58] is a nonlinear pre-coding technique that employs feed-forward and feedback matrices, along with a modulo operation, to cancel the multi-user interference in a more effective way than a standard linear pre-coder. With Tomlinson-Harashima pre-coding, the $N_A \times 1$ pre-coded data vector is given by

$$\mathbf{x}[i] = \boldsymbol{F}\tilde{\mathbf{x}}[i], \qquad (5)$$

where $\boldsymbol{F}$ is the $N_A \times KN_U$ feed-forward pre-coding matrix, which can be obtained by an LQ decomposition of the channel matrix, $\boldsymbol{H}$. The input data, $\tilde{\mathbf{x}}[i]$ is computed element-by-element by

$$\tilde{x}_l[i] = \text{mod}\left\{ s_l[i] - \sum_{q=1}^{l-1} b_{lq} x_q[i] \right\}, \; l = 1, \ldots, KN_U \qquad (6)$$

where the b_{lq} are the elements of the $KN_U \times KN_U$ lower-triangular matrix $\boldsymbol{B}$ that can also be obtained by an LQ decomposition. Amongst the appealing features of Tomlinson-Harashima pre-coding are its excellent bit-error rate and sum-rate performances, which are not far from dirty-paper coding, and its flexibility to incorporate channel coding. Future work on Tomlinson-Harashima pre-coding for massive MIMO networks should concentrate on the reduction of the computational cost to compute the feed-forward and feedback matrices, since existing factorization algorithms would be too costly for systems with hundreds of antenna elements.

Vector perturbation employs a modulo operation at the transmitter to perturb the transmitted signal vector, and to avoid the transmitted-power enhancement incurred by zero-forcing or minimum-mean-square error methods [43]. The task of finding the optimal perturbation involves solving a minimum-distance-type problem, which can be implemented using sphere encoding or full-search-based algorithms. Let $\boldsymbol{H}$ denote an $N_A \times KN_U$ multi-user composite channel. The idea of perturbation is to find a perturbing vector, $\boldsymbol{p}$, from an extended constellation to minimize the transmitted power. The perturbation $\boldsymbol{p}$ is obtained by solving

$$\boldsymbol{p}[i] = \arg \min_{\mathbf{p}'[i] \in ACZ^K} \left\| \boldsymbol{W}\left(\mathbf{s}[i] + \mathbf{p}'[i] \right) \right\|^2, \qquad (7)$$

where $\boldsymbol{W}$ is some linear transformation or pre-coder such that $Tr\left(\boldsymbol{W}^H \boldsymbol{W}\right) \leq P$, the scalar A is chosen depending on the constellation size (e.g., $A = 2$ for QPSK), and CZ^K is the K-dimensional complex lattice. The transmitter matched filter, linear zero-forcing, or minimum-mean-square error pre-coders can be used for $\boldsymbol{W}$. After pre-distortion using a linear pre-coder, the resulting constellation region also becomes distorted, and thus a modulo operation is employed. This problem can be regarded as a K-dimensional integer-lattice least-squares problem, which can be solved by search-based algorithms [43].

4. Receiving Processing

In this section, we discuss receiving processing in massive MIMO systems. In particular, we examine parameter-estimation and detection algorithms, iterative detection and decoding techniques, mitigation of RF impairments, and related signal-processing tasks.

4.1 Parameter-Estimation and Detection Algorithms

Amongst the key problems in the uplink of multi-user massive MIMO systems are the estimation of parameters, such as channel gains and receiving filter coefficients, and the detection of the transmitted symbols, $\boldsymbol{s}_k$, of each user, as described by the signal model in Equation (2). The parameter-estimation task usually relies on pilot (or training) sequences and signal-processing algorithms. In multi-user massive MIMO networks, nonorthogonal training sequences are likely to be used in most application scenarios, and the estimation algorithms must be able to provide the most accurate estimates, and to track the variations due to mobility. Standard MIMO linear minimum-mean-square error and least-squares (LS) channel-estimation algorithms [44] can be used for obtaining channel-state information. However, the cost associated with these algorithms is often cubic in the number of antenna elements at the receiver, i.e., N_A in the uplink. Moreover, in scenarios with mobility, the receiver will need to employ adaptive algorithms [73] that can track the channel variations. Interestingly, massive MIMO systems have an excess of degrees of freedom that translates into a reduced-rank structure to perform parameter estimation. This is an excellent opportunity that massive MIMO offers for applying reduced-rank algorithms [28-31] and to further develop these techniques.

In order to separate the data streams transmitted by the different users in a multi-user massive MIMO network, a designer must resort to detection techniques, which are similar to multi-user detection methods [45]. The optimal maximum-likelihood (ML) detector is described by

$$\hat{\mathbf{s}}_{\text{ML}}[i] = \arg \min_{\mathbf{s}[i]} \left\| \boldsymbol{r}[i] - \boldsymbol{H}\boldsymbol{s}[i] \right\|^2, \qquad (8)$$

where the $KN_U \times 1$ data vector, $\boldsymbol{s}[i]$, contains the symbols of all users. The maximum-likelihood detector has a cost that is exponential in the number of data streams, and a modulation order that is too complex to be implemented in systems with a large number of antennas. Even though the maximum-likelihood solution can be alternatively computed using sphere-decoder (SD) algorithms [46-50] that are very efficient for MIMO systems with a small number of antennas, the cost of sphere-decoder algorithms depends on the noise variance, the number of data streams to be detected, and the signal constellation. This results in high computational costs for low signal-to-noise ratios (SNR), high-order constellations, and a large number of data streams.

The high computational complexities of the maximum-likelihood detector and the sphere-decoder algorithms in the scenarios described above have motivated the development of numerous alternative strategies for MIMO detection, which often rely on signal processing with receiving filters. The key advantage of these approaches with receiving filters is that the cost is typically not dependent on the modulation, and the receiver can compute the receiving filter only once per data packet, and perform detection. Algorithms that can compute the parameters of receiving filters with low cost are of central importance to massive MIMO systems. In what follows, we will briefly review some relevant suboptimal detectors, which include linear and decision-driven strategies.

Linear detectors [51] include approaches based on the receiving matched filter (RMF), zero-forcing, and minimum-mean-square error designs. They are described by

$$\hat{\boldsymbol{s}}[i] = Q\left\{\boldsymbol{W}^H \boldsymbol{r}[i]\right\}, \qquad (9)$$

where the receiving filters are $\boldsymbol{W}_{\mathrm{RMF}} = \boldsymbol{H}$ for the receiving matched filter, $\boldsymbol{W}_{\mathrm{MMSE}} = \left(\boldsymbol{H}\boldsymbol{H}^H + \sigma_s^2/\sigma_n^2 \boldsymbol{I}\right)^{-1} \boldsymbol{H}$ for the minimum-mean-square error, and $\boldsymbol{W}_{\mathrm{ZF}} = \left(\boldsymbol{H}\boldsymbol{H}^H\right)^{-1} \boldsymbol{H}$ for the zero-forcing design, and $Q\{\bullet\}$ represents the slicer used for detection.

Decision-driven detection algorithms, such as successive interference-cancellation (SIC) approaches used in the Vertical-Bell Laboratories Layered Space-Time (VBLAST) systems [52-56], and decision-feedback (DF) [57] detectors are techniques that can offer attractive tradeoffs between performance and complexity. Prior work on successive interference-cancellation and decision-feedback schemes has been reported with decision-feedback detectors with successive interference cancellation (S-DF) [57, 63], and decision-feedback receivers with parallel interference cancellation (PIC) (P-DF) [66, 67], combinations of these schemes [24, 66, 70], and mechanisms to mitigate error propagation [71, 72]. Decision-feedback detectors [57, 63, 66] employ feed-forward and feedback matrices that can be based on the receiving matched filter (RMF), zero-forcing, and minimum-mean-square error designs, as described by

$$\hat{\boldsymbol{s}} = Q\left\{\boldsymbol{W}^H \boldsymbol{r}[i] - \boldsymbol{F}^H \hat{\boldsymbol{s}}_0[i]\right\}, \qquad (10)$$

where $\hat{\boldsymbol{s}}_0$ corresponds to the initial decision vector, which is usually performed by the linear section of the decision-feedback receiver (e.g., $\hat{\boldsymbol{s}}_0 = Q\left\{\boldsymbol{W}^H \boldsymbol{r}\right\}$) prior to the application of the feedback section. The receiving filters, $\boldsymbol{W}$ and $\boldsymbol{F}$ can be computed using design criteria and optimization algorithms.

An often criticized aspect of these suboptimal schemes is that they typically do not achieve the full receiving-diversity order of the maximum-likelihood algorithm. This led to the investigation of detection strategies such as lattice-reduction (LR) schemes [58, 59], QR decomposition, M-algorithm (QRD-M) detectors [60], probabilistic data association (PDA) [61, 62], and multi-branch [24-26] detectors, which can approach the maximum-likelihood performance at an acceptable cost for small to moderate systems. The development of cost-effective detection algorithms for massive MIMO systems is a formidable task that calls for new approaches and ideas in this exciting area.

4.2 Iterative Detection and Decoding Techniques

Iterative detection and decoding (IDD) schemes have received considerable attention in the last few years, following the discovery of turbo codes [74] and the use of the turbo principle for mitigation of several sources of interference [75-83]. More recently, work on iterative detection and decoding schemes has been extended to low-density parity-check codes (LDPC) [79, 81] and their variants, which rival turbo codes in terms of performance. The basic idea of an iterative detection and decoding system is to combine an efficient soft-input soft-output (SISO) detection algorithm and a soft-input soft-output decoding technique. In particular, the detector produces log-likelihood ratios (LLRs) associated with the encoded bits, and these log-likelihood ratios serve as input to the decoder. In the second phase of the detection/decoding iteration, the decoder then generates a posteriori probabilities (APPs) after a number of (inner) decoding iterations for encoded bits of each data stream. These a posteriori probabilities are fed to the detector to help in the next iterations between the detector and the decoder, which are called outer iterations. The joint process of detection/decoding is then repeated in an iterative manner, until the maximum number of (inner and outer) iterations is reached. In massive MIMO systems, it is likely that either turbo or low-density parity-check codes will be adopted in iterative detection and decoding schemes for mitigation of multi-user, multipath, inter-cell, and other sources of interference. Low-density parity-check codes exhibit some advantages over turbo codes, which include simpler decoding and implementation issues. However, low-density parity-check codes often require a higher number of decoding iterations, which translates into delays or increased complexity. The development of iterative detection and decoding schemes, and decoding algorithms that perform message passing with reduced delays [84-86], are of paramount importance in future wireless systems.

4.3 Mitigation of RF Impairments

The large antenna arrays used in massive MIMO systems will pose several issues for system designers, such as coupling effects, in-phase/quadrature (I/Q) imbalances [87], and failures of antenna elements, which will need to be addressed. The first potential major impairment in massive MIMO systems is due to reduced spacing between antenna elements, which results in coupling effects. In fact, for compact antenna arrays, a reduction of the physical size of the array inevitably leads to reduced spacing between antenna elements, which can severely reduce the multiplexing gain. In order to address these coupling effects, receiving processing approaches will have to work with transmitting processing techniques to undo the coupling induced by the relatively close spacing of radiating elements in the array. Another major impairment in massive MIMO systems is in-phase/quadrature imbalances in the RF chains of the large arrays. This problem can be addressed by receiving or transmitting processing techniques, and requires modeling of the impairments for subsequent mitigation. When working with large antenna arrays, a problem that might also occur is the failure of some antenna elements. Such sensor failures are responsible for a reduction in the degrees of freedom of the array, and must be dealt with by signal-processing algorithms.

5. Simulation Results

In this section, we illustrate some of the techniques outlined in this article using massive MIMO configurations, namely, a very large antenna array, an excess of degrees of freedom provided by the array, and a large number of users with multiple antennas. We consider QPSK modulation, and channels that are fixed during a data packet and that are modeled by complex Gaussian random variables with zero mean and variance equal to unity. The signal-to-noise ratio (SNR) in dB is defined as $\mathrm{SNR} = 10\log_{10}\frac{N_T\sigma_s^2}{\sigma^2}$, where σ_s^2 is the variance of the symbols, σ_n^2 is the noise variance, and we considered data packets of 1000 QPSK symbols.

In the first example, we compared the bit-error rate performance against the SNR of several detection algorithms, namely, the receiving matched filter with $K = 8$ users and with a single user; the linear minimum-mean-square error detector [51]; and the decision-feedback minimum-mean-square error detector using a successive interference cancellation [24, 54, 66]. In particular, a scenario with $N_A = 128$ antenna elements at the receiver, $K = 8$ users, and $N_U = 8$ antenna elements at the user devices was considered. This corresponded to an excess of degrees of freedom equal to $N_A - KN_U = 64$. The results shown in Figure 4 indicated that the receiving matched filter with a single user had the best performance, followed by the decision-feedback minimum-mean-square error, the linear minimum-mean-square error, and the receiving matched filter detectors. Unlike previous works [5] that advocated the use of the receiving matched filter, it was clear that the bit-error-rate performance loss experienced by the receiving matched filter should be avoided, and more advanced receivers should be considered. However, the cost of linear and decision-feedback receivers is dictated by the matrix inversion of $N_A \times N_A$ matrices, which must be reduced for large systems.

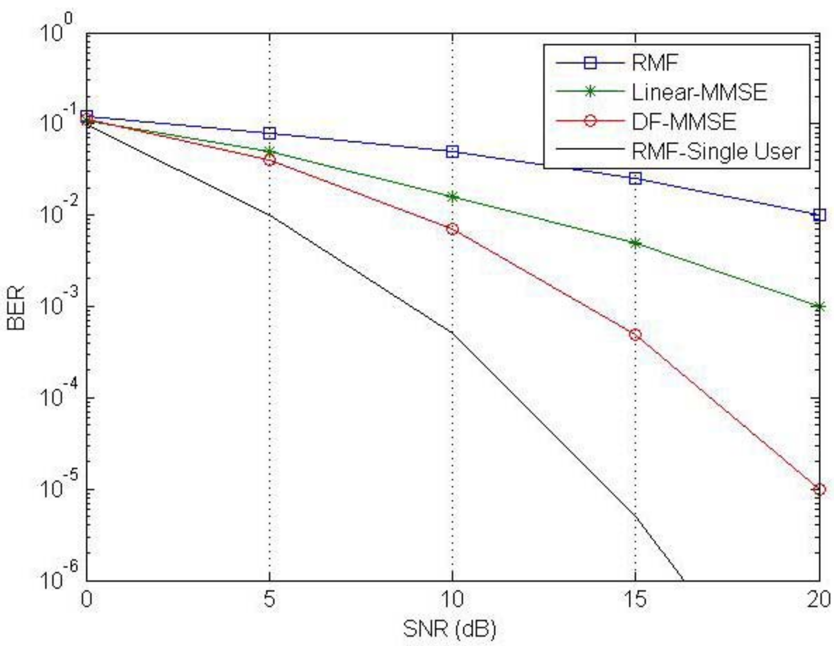


Figure 4. The bit-error-rate performance as a function of the SNR of detection algorithms in a scenario with $N_A = 128$, $K = 8$ users, and $N_U = 8$ antenna elements.

In the second example, we compared the sum-rate performance against the SNR of several pre-coding algorithms, namely, the transmitting matched filtering with a varying number of users and with a single user, the linear minimum-mean-square-error pre-coder, and the Tomlinson-Harashima pre-coding minimum-mean-square error pre-coder. The sum-rate was calculated using [90]:

$$C = \log\left[\det\left(\boldsymbol{I} + \sigma_n^{-2}\boldsymbol{HPP}^H\boldsymbol{H}^H\right)\right] \text{ [bits/Hz].} \quad (11)$$

We considered a similar scenario to the previous one, in which the transmitter was equipped with $N_A = 128$ antenna elements, and there were $K = 8$ users with $N_U = 8$ antenna elements. The results in Figure 5 showed that the transmitting matched filtering with a single user had the best sum-rate performance, followed by the Tomlinson-Harashima pre-coding minimum-mean-square error, the regularized block-diagonalization (RBD), the linear minimum-mean-square error, and the transmitting matched-filtering pre-coding algorithms. From the curves in Figure 5, we could notice that the performance of transmitting matched filtering was much worse than that of Tomlinson-Harashima pre-coding and of regularized block-diagonalization. This suggests that more sophisticated pre-coding techniques with lower complexity should be developed to maximize the capacity of massive MIMO systems.

6. Future Trends and Emerging Topics

In this section, we discuss some future signal-processing trends in the area of massive MIMO systems, and point out some emerging topics that might attract the interest of researchers. The topics are structured as follows:

- Transmitting processing:
  - Cost-effective scheduling algorithms: The development of methods that have low cost and are scalable, such as greedy algorithms [33] and discrete-optimization techniques [36], will play a crucial role in massive MIMO networks.
  - Calibration procedures: The transfer characteristics of the filters and amplifiers used for TDD operation will require designers to devise algorithms that can efficiently calibrate the links.
  - Pre-coders with scalability in terms of complexity: The use of divide-and-conquer approaches, methods based on sensor-array signal processing and sectorization, will play an important role in reducing the dimensionality of the transmitting-processing problem. Moreover, the investigation and development of transmitting matched-filtering strategies with nonlinear cancellation strategies and low-cost decompositions for linear and nonlinear pre-coders will be important for obtaining efficient transmitting methods.

- Receiving processing:
  - Cost-effective detection algorithms: Techniques for performing dimensionality reduction [28-31] for detection problems will play an important role in massive MIMO devices. By reducing the number of effective processing elements, detection algorithms could be applied. In addition, the development of schemes based on a receiving matched filter with nonlinear interference-cancellation capabilities might be a promising option that can close the gap between receiving matched filter and more costly detectors.

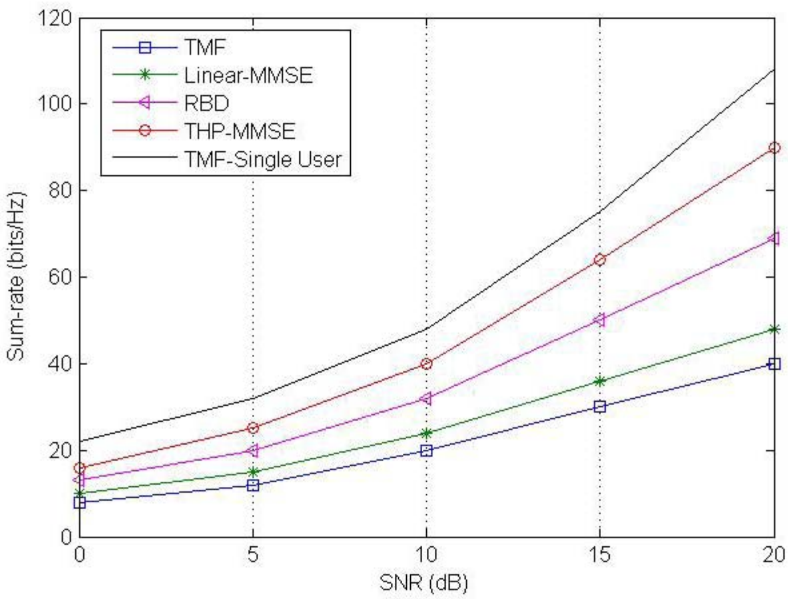


Figure 5. The sum-rate performance as a function of the SNR of pre-coding algorithms in a scenario with $N_A = 128$, $K = 8$ users, and $N_U = 8$ antenna elements.

– Decoding strategies with low delay: The development of decoding strategies with reduced delay will play a key role in applications such as audio and video streaming, because of their delay sensitivity. We therefore argue that novel message-passing algorithms with smarter strategies to exchange information should be investigated along with their application to iterative detection and decoding schemes.
– Mitigation of impairments: The identification of impairments originating in the RF chains of massive MIMO systems will need mitigation by smart signal-processing algorithms. For example, in-phase/quadrature imbalance might be dealt with using widely linear signal-processing algorithms [88, 89].

7. Concluding Remarks

This article has presented a tutorial on massive MIMO systems, and discussed signal-processing challenges and future trends in this exciting research topic. Key application scenarios, which include multibeam satellite, cellular, and local-area networks, have been examined, along with several operational requirements of massive MIMO networks. Transmitting and receiving processing tasks have been discussed, and fundamental signal-processing needs for future massive MIMO networks have been identified. Numerical results have illustrated some of the discussions on transmitting and receiving processing functions, and future trends have been highlighted. Massive MIMO technology is likely to be incorporated into the applications detailed in this article on a gradual basis, by the increase in the number of antenna elements and by the need for more-sophistical signal-processing tools to transmit and process a large amount of information.

8. Acknowledgment

The work of the author was supported by the Pontifical Catholic University of Rio de Janeiro, and by the University of York, York Y010 5DD, United Kingdom.

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Highly Efficient Class-F RF Power Amplifiers with Very Low Distortion

Mitra Gilasgar, Antoni Barlabé, and Lluís Pradell

Department of Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC)
Campus Nord UPC-08034 Barcelona, SPAIN
E-mail: mitra.gilasgar@tsc.upc.edu, barlabe@tsc.upc.edu, pradell@tsc.upc.edu

This paper was one of the second-prize winners in the Young Scientist best paper contest held as part of the Spanish Symposium of URSI, Santiago de Compostela, Spain, September 11-13, 2013.

Abstract

This paper presents novel class-F power amplifiers for mobile applications in which the need for an extra filtering section is eliminated with a proper harmonic tuning structure. Two class-F power amplifiers, employing a GaN HEMT device, were designed, fabricated, and measured at 900 MHz and 1800 MHz. The fabricated circuits achieved an excellent harmonic-suppression level, and the total harmonic distortion was around 1.2%. The proposed structure overcame the narrowband performance of class-F power amplifiers, giving more than 60% efficiency over a 200 MHz bandwidth, and more than 70% over a 100 MHz bandwidth, for the 900 MHz amplifier. More than 50% efficiency over a 150 MHz bandwidth for the 1800 MHz amplifier was achieved in a back-off region. Experimental results showed that at 900 MHz, the amplifier was able to deliver 38.6 dBm output power, while achieving a state-of-the-art PAE [power-added efficiency] of 80.5% with a drain efficiency of 84%, and a power gain of 13.6 dB for an input power of 25 dBm. The 1800 MHz amplifier showed an output power of 38.8 dBm, a power-added efficiency of 75%, a drain efficiency of 83.8%, and a gain of 9.8 dB at an input power of 29 dBm. Good agreement between measurement and simulation results was observed. Measured peak drain efficiencies of 85.5% and 87.7% were achieved for the 900 MHz and 1800 MHz amplifiers, respectively.

1. Introduction

Power amplifiers (PAs) are the most important part in transmitter design, because they consume most of transmitter's dc power. If this consumption is high, it leads to an undesired short battery lifetime. It is therefore important to design high-efficiency power amplifiers for mobile applications. Switching power amplifiers, such as class D, class E/E^{-1}, and class F/F^{-1} [1], have a minimum overlap between drain voltage and current waveforms, resulting in low dc power consumption and high efficiency. A large transistor output capacitance imposes a low impedance at high frequencies, which decreases the efficiency of class-E power amplifiers, but its effect is negligible in class-F power amplifiers, due to the harmonically tuned output network. A class-F power amplifier uses multiple resonators in its output matching network to obtain a half-sine drain-current waveform and a square drain-voltage waveform. In theory, class F can achieve 100% efficiency. However, in practice this figure is lowered, due to the limited number of harmonics that can be tuned through the output matching network [2].

Depending on the application and frequency, the matching network (MN) can be designed with lumped [3] or distributed [4] elements. An example of a lumped matching network and its equivalent transmission-line matching network for class-F/F^{-1} power amplifiers was given in [5]. At microwave frequencies, transmission-line matching networks are preferred, because implementing lumped-element multi-resonators at these frequencies is difficult. Possible load-matching networks for class-F/F^{-1} power amplifiers, designed specifically to overcome the effect of shunt capacitance and series inductance, were well illustrated in [6] and [7]. Studies in [4] showed that harmonic termination has an inverse relationship to the performance of the amplifier, and second-harmonic tuning has the most important effect.

In this paper, a novel class-F power-amplifier topology is proposed, using an output matching network that controls

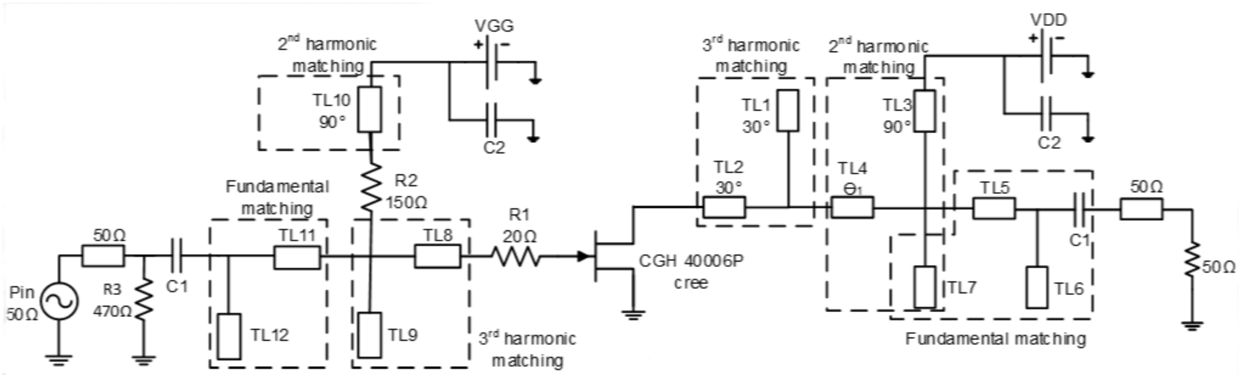

Figure 1a. The proposed class-F power amplifier.

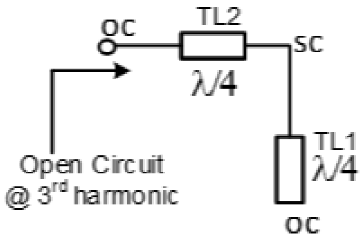

Figure 1b. The output network at the third harmonic for the amplifier of Figure 1a.

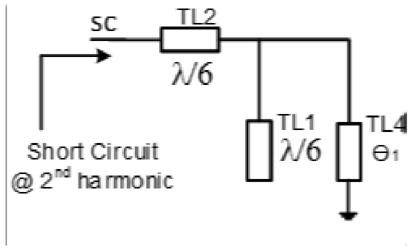

Figure 1c. The output network at the second harmonic for the amplifier of Figure 1a.

up to the third-harmonic component independently from fundamental matching. With a proper harmonic-tuning structure, the need for an extra filtering section is eliminated, and a very low harmonic distortion is achieved. The proposed topology, designed and fabricated at 900 MHz and 1800 MHz, exhibited a very high (state-of-the-art) drain efficiency and power-added efficiency. It also overcomes the narrowband behavior of class-F power amplifiers. A Cree GaN HEMT, with a breakdown voltage of 120 V, was used as active device to fulfill the high-voltage breakdown and high-power requirements.

Section 2 shows the proposed power-amplifier topology, and a comparison with three other power amplifiers from the literature. Section 3 shows the simulation, fabrication, and measurement results, followed by the conclusion in Section 4.

2. Class-F Power Amplifier Design

In class-F power amplifiers, the load impedance seen by the power transistor should be a short circuit at even harmonics, an open circuit at odd harmonics, and the optimized value at the fundamental frequency:

$$Z_1 = R_{optimal} \; , \tag{1}$$

$$Z_{2n} = 0 \; , \tag{2}$$

$$Z_{2n+1} = \infty \; . \tag{3}$$

The proposed design is illustrated in Figure 1, where transmission lines TL8, TL9, TL11, and TL12 match the power device to a $50\ \Omega$ input for a high power transfer. In the input-matching network, TL10 (grounded through a bypass capacitor) is $\lambda/4$ at the fundamental frequency (which provides an open circuit for the RF signal), and is $\lambda/2$ at the second harmonic (which provides a short circuit to the second-harmonic component). Resistors R1, R2, and R3 were added to ensure that the circuit works under stable conditions.

Concerning the output matching network, the proposed structure allows the control of several harmonics simultaneously but independently of each other. The output matching network provides an open circuit to the third harmonic through TL1 and TL2, with lengths $\lambda/12$ at the fundamental frequency (Figure 1b). At second harmonic, TL3 delivers a low impedance to the right-hand side of TL4 (electrical length of θ_1), as shown in Figure 1c. Transmission lines TL1, TL2, and TL4 together provide a short-circuit condition at the second harmonic. TL5, TL6, and TL7 create a π-shaped matching network, which increases the design freedom for the fundamental frequency, thus helping the designer to improve the power amplifier's performance in terms of efficiency and output-voltage waveform. The stub with the largest effect on the output waveform is TL7. This stub improves the output-voltage waveform, presenting a perfect sinusoidal shape without any distortion.

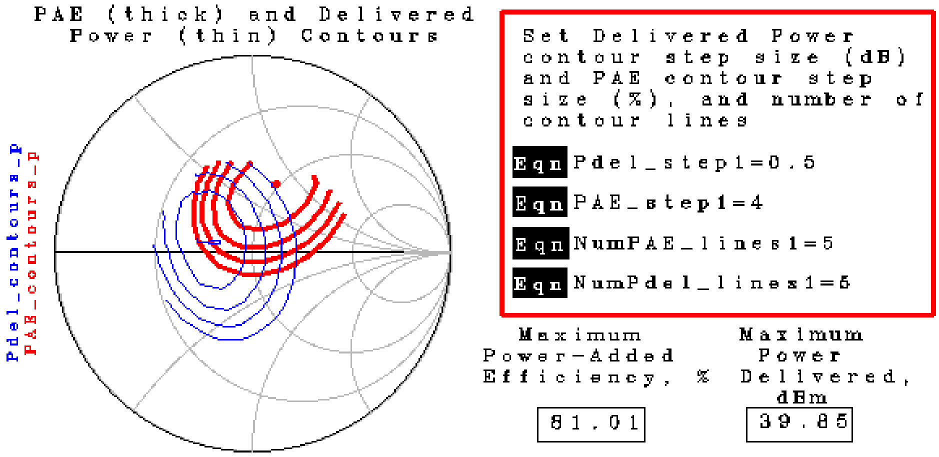

Figure 2. The power-added efficiency (PAE) and output power contours from load-pull analysis.

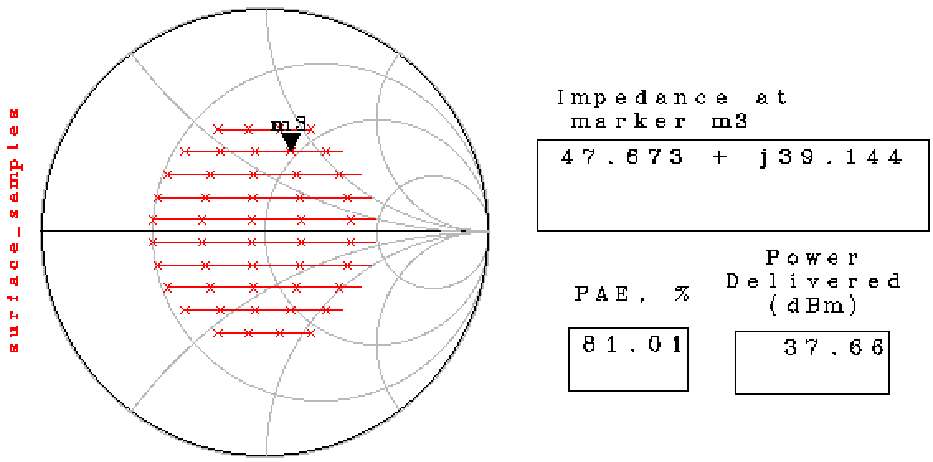

Figure 3. The simulated load impedances from load-pull analysis.

2.1 900 MHz Power Amplifier

In practice, due to nonlinearities and parasitics of the active device (Cree CGH40006P), ideal short and open circuits do not necessarily lead to the best results. To therefore achieve the best performance, an accurate load matching for the output of the transistor at the fundamental and harmonic frequencies is required. Calculated from load-pull analysis, ZL1, ZL2, and ZL3 were the load impedances that resulted in an optimum performance at the fundamental, second, and third harmonics, respectively. Figure 2 shows the power-added efficiency (PAE) and output power contours. The simulated load impedances are shown in Figure 3, giving a maximum power-added efficiency for a load impedance value of $47.673 + j39.144\ \Omega$ at the fundamental frequency. The same procedure was carried out for the second and third harmonics, and the calculated values are given in Table 1. An output matching network was designed to give these optimum impedances at the desired frequencies.

	Load Impedance (Ω)
Z_{L1} (@ 900 MHz)	$47.673 + j39.144$
Z_{L2} (@ 1800 MHz)	$2.31 - j13.121$
Z_{L3} (@ 3600 MHz)	$58.528 + j234.846$

Table 1. The load Impedances for the fundamental, second, and third harmonics, obtained from load-pull analysis, at 900 MHz.

To evaluate the performance of the proposed topology, large-signal *S*-parameter (LSSP), harmonic balance (HB),

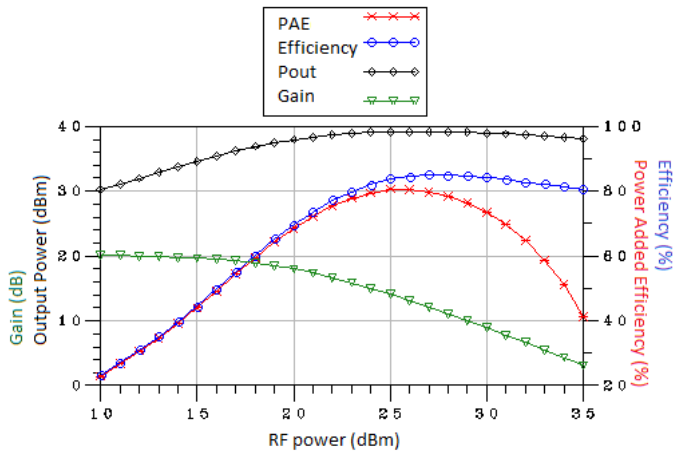

Figure 4 The simulated output power, gain, drain efficiency, and power-added efficiency as functions of input power ($V_{DS} = 28$ V, $V_{GS} = -2.8$ V, $f_0 = 900$ MHz).

Figure	PAE (%)	η (%)	Gain (dB)	P_{out} (dBm)	dc Power (Watts)	Thermal Dissipation (Watts)
5a	73.20	75.36	15.41	40.4	14.6	3.9
5b	79.57	83.26	13.53	38.5	8.56	1.74
5c	78.37	81.62	13.98	38.9	9.69	2.08
1	80.27	83.53	14.09	39	9.71	1.9

Figure	S_{11} (dB)	S_{22} (dB)	2nd (dBc)	3rd (dBc)	4th (dBc)	5th (dBc)
5a	–21	–6.8	–39	–39.8	–45	–45.62
5b	–18	–16.5	–48.46	–48.3	–48.29	–58.94
5c	–17	–19	–49	–29.7	–61.55	–48.45
1	–14.6	–23.8	–46.77	–46.83	–68.6	–49.24

Table 2. A comparison of simulation results for the three circuits of Figure 5.

and electromagnetic (Method of Moments) simulations were performed using Agilent™'s *Advanced Design System* (*ADS*). The simulation results of the output power, gain, drain efficiency, and power-added efficiency are plotted as functions of input power in Figure 4. This showed that a peak power-added efficiency of 80.2%, a drain efficiency of 83.5%, and a gain of 14.2 dB were obtained at an output power of 39.2 dBm.

The performance of the proposed topology (Figure 1) was compared to that of three class-F structures proposed in the literature. The output matching networks shown in Figures 5a, 5b, and 5c were retrieved from [6], [5], and [8], respectively. They were designed and simulated to give best results at 900 MHz for the same power device under the same conditions as our design. Harmonic balance and large-signal *S*-parameter simulations were carried out for these circuits, and the results are compared in Table 2. It could be seen from this that the structure proposed in this paper had the highest power-added efficiency, gain, and output power. It also exhibited good harmonic rejection up to the fifth harmonic, with good input and output matching.

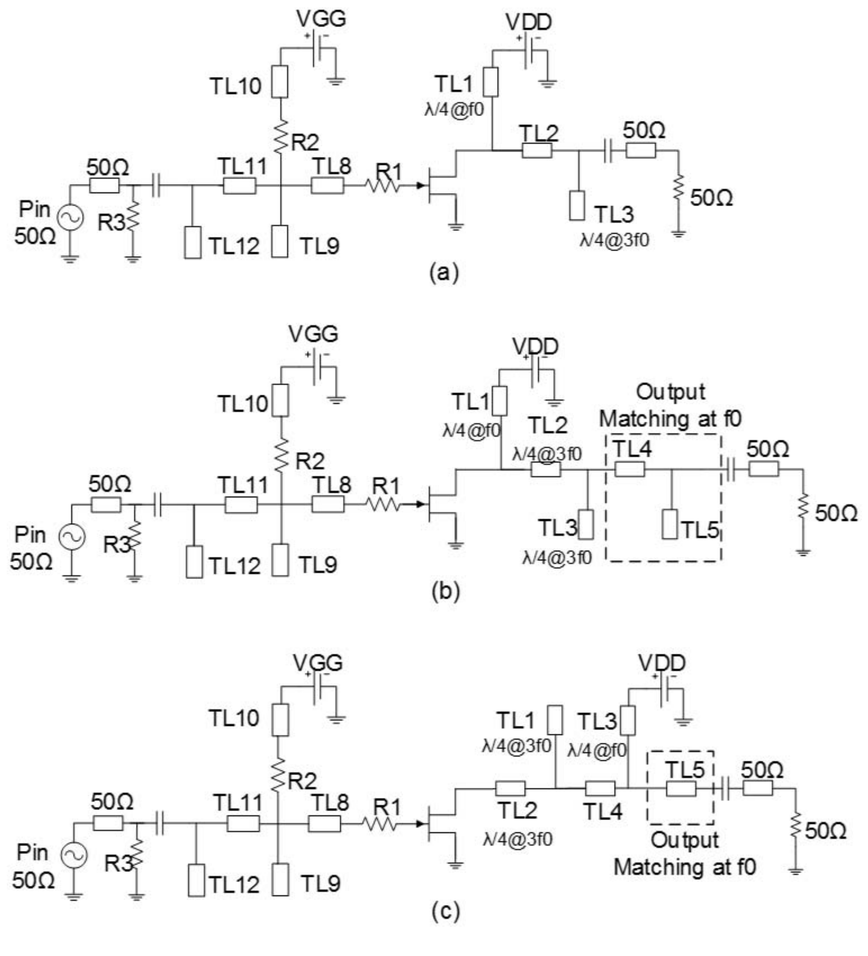

Figure 5. Three class-F power amplifiers: the output matching networks were retrieved (a) from [6], (b) from [5], and (c) from [8].

	Load Impedance (Ω)
Z_{L1} (@ 1800 MHz)	$57.166 + j83.424$
Z_{L2} (@ 3600 MHz)	$0 + j11.919$
Z_{L3} (@ 5400 MHz)	$0 - j275.94$

Table 3. The load Impedances for the fundamental, second, and third harmonics, obtained from load-pull analysis at 1800 MHz.

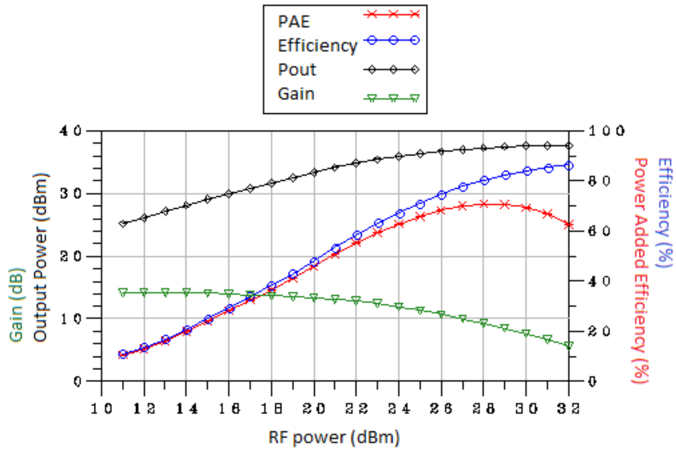

Figure 6. The simulated output power, gain, drain efficiency, and power-added efficiency (PAE) as functions of the input power ($V_{DS} = 28$ V, $V_{GS} = -2.8$ V, $f_0 = 1800$ MHz).

2.2 1800 MHz Power Amplifier

After the proposed structure proved to have better performance compared to other structures, another design was carried out at 1800 MHz. This design was done to obtain a reconfigurable power amplifier, which was a further step of this work. Taking into account this final goal, some of the lengths and widths of the stubs remained unchanged, giving a lower degree of freedom for this circuit and therefore poorer performance than for the 900 MHz power amplifier. The impedance values for the fundamental, second, and third harmonics at 1800 MHz, obtained using load-pull analysis, are shown in Table 3.

Simulation results of the output power, gain, drain efficiency, and power-added efficiency at 1800 MHz as functions of the input power are presented in Figure 6. A peak power-added efficiency of 71%, a drain efficiency of 80%, and a gain of 9.5 dB were obtained at an output power of 38 dBm.

The drain efficiency and power-added efficiency are also shown as functions of RF frequency in Figure 7a for the 900 MHz amplifier, and Figure 7b for the 1800 MHz amplifier. Maximum power-added efficiencies of 81% and 71% were obtained at 900 MHz and 1.8 GHz, respectively. The results as functions of frequency showed that the

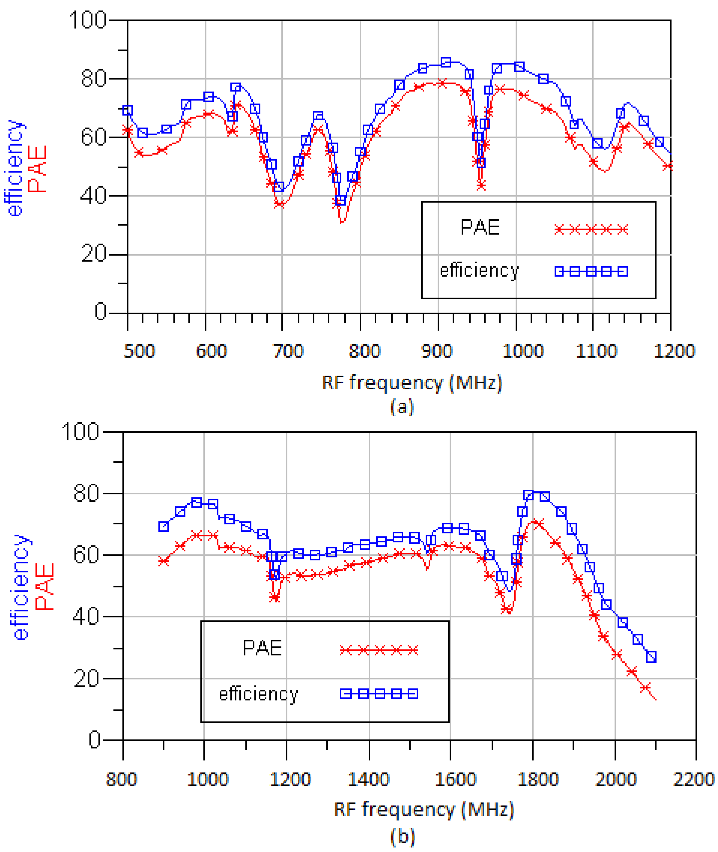

Figure 7. The simulated power-added efficiency (PAE) and drain efficiency as functions of the input frequency for (a) 900 MHz and (b) 1800 MHz.

Frequency	P_{in}	2nd (dBc)	3rd (dBc)	4th (dBc)	5th (dBc)
900 MHz	25 dBm	–46.82	–46.34	–66.23	–48
1800 MHz	28 dBm	–47.6	–50.81	–47.58	–47.81

Table 4. Harmonic rejection up to fifth order at both 900 MHz and 1800 MHz.

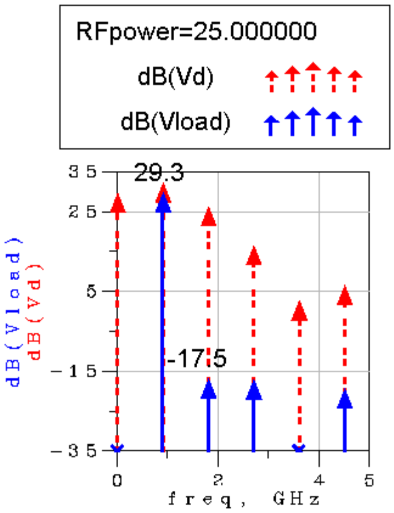

Figure 8a. The drain voltage (V_d) and load voltage (V_{load}) spectrums for the 900 MHz amplifier.

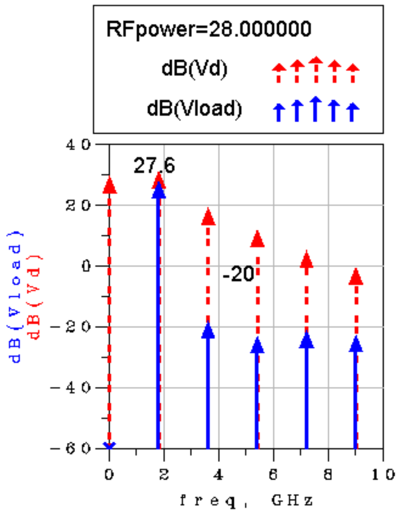

Figure 8b. The drain voltage (V_d) and load voltage (V_{load}) spectrums for the 1800 MHz amplifier.

amplifier was designed for the optimum value at the operating frequency. It could also be seen that the 900 MHz amplifier achieved a drain efficiency higher than 60% in a bandwidth from 805 MHz to 950 MHz. The amplifier at 1800 MHz achieved a drain efficiency of more than 60% for a bandwidth from 1760 MHz to 1940 MHz, and it showed a very wide response for drain efficiencies of more than 50%.

The output spectrum of the simulated class-F power amplifier is shown in Figure 8a at 900 MHz and in Figure 8b at 1.8 GHz. The differences between the desired output signal and the unwanted harmonics showed that the proposed topology has the ability to reject harmonics while maintaining the high performance of the class-F power amplifier, without the need for an extra filtering

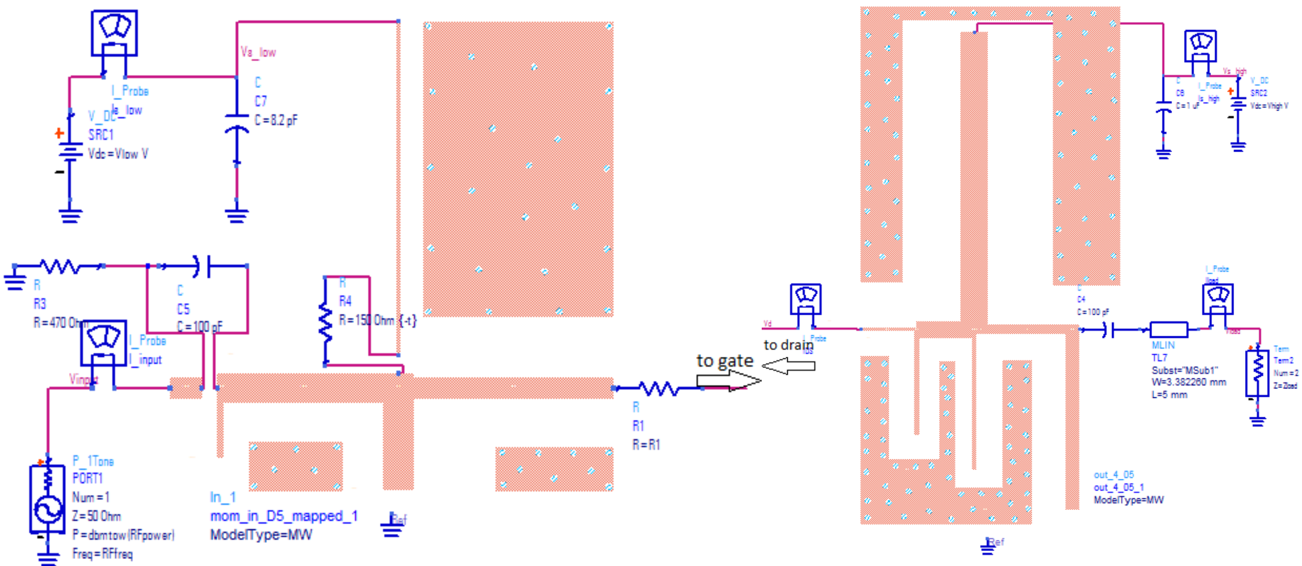

Figure 9. The input (a) and output (b) matching components created using *Momentum*, placed on the schematic.

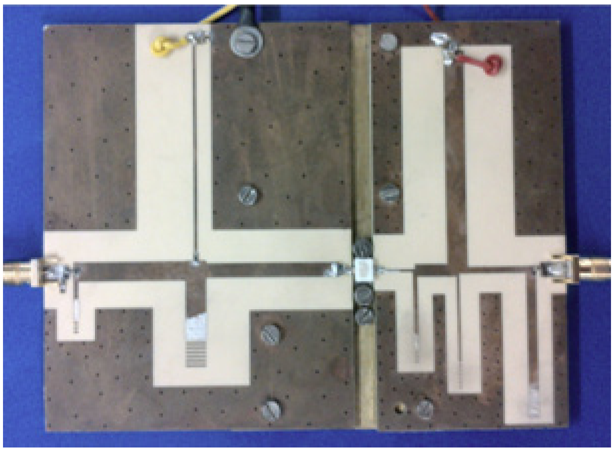

Figure 10a. The fabricated class-F power amplifier at 900 MHz.

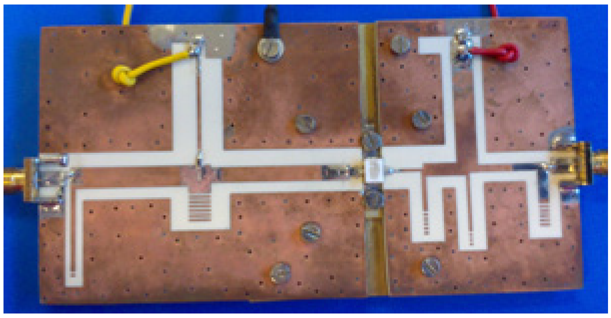

Figure 10b. The fabricated class-F power amplifier at 1800 MHz.

section. Simulated harmonic rejection values are presented in Table 4.

Before fabricating the circuit, an electromagnetic simulation using the Agilent *Momentum*™ tool was carried out, to determine the practical response of the circuit. Figures 9a and 9b respectively show the input and output matching networks, with the momentum component replaced in the schematic to simulate the circuit in such a way that the simulation took into account the electromagnetic couplings.

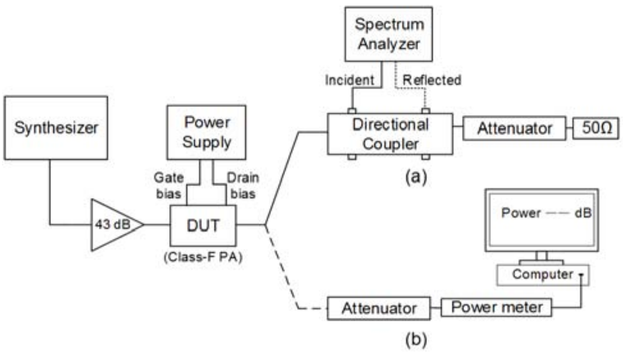

Figure 11. The measurement setups.

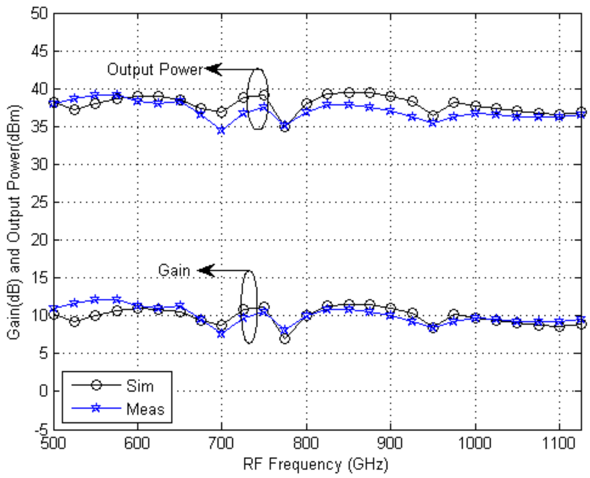

Figure 12. The output power and gain as functions of the RF frequency for the 900 MHz power amplifier ($V_{DS} = 30.2$ V, $V_{GS} = -2.7$ V, $P_{in} = 25$ dBm).

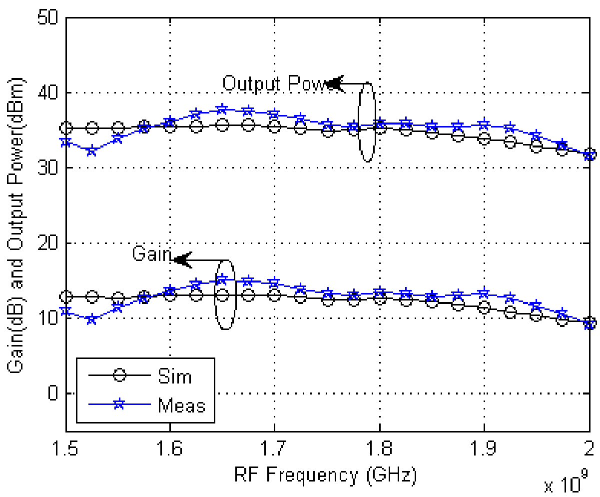

Figure 13. The output power and gain as functions of the RF frequency for the 1800 MHz power amplifier ($V_{DS} = 30.2$ V, $V_{GS} = -2$ V, $P_{in} = 22.5$ dBm).

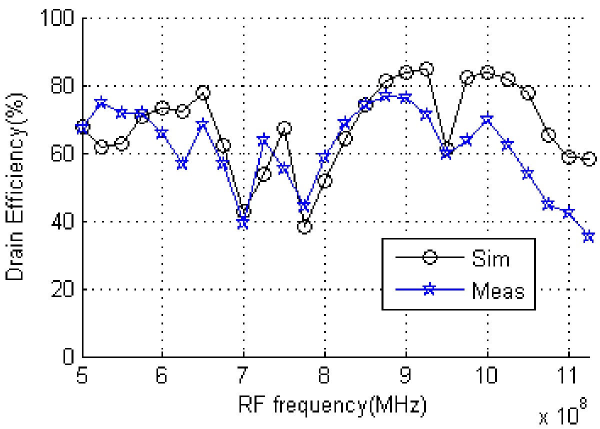

Figure 14. The drain efficiency as a function of the RF frequency for the 900 MHz power amplifier ($V_{DS} = 30.2$ V, $V_{GS} = -2.7$ V, $P_{in} = 25$ dBm).

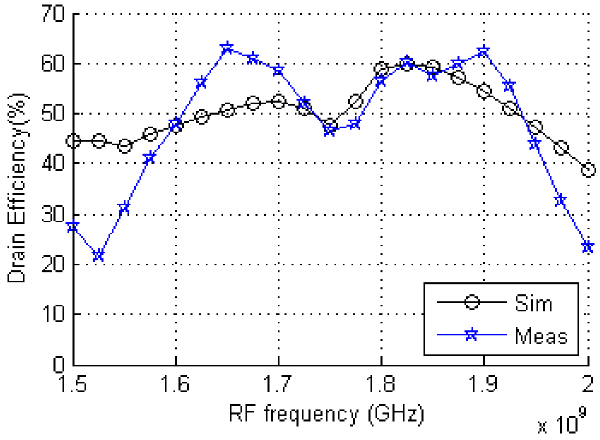

Figure 15. The drain efficiency as a function of the RF frequency for the 1800 MHz power amplifier ($V_{DS} = 30.2$ V, $V_{GS} = -2$ V, $P_{in} = 22.5$ dBm).

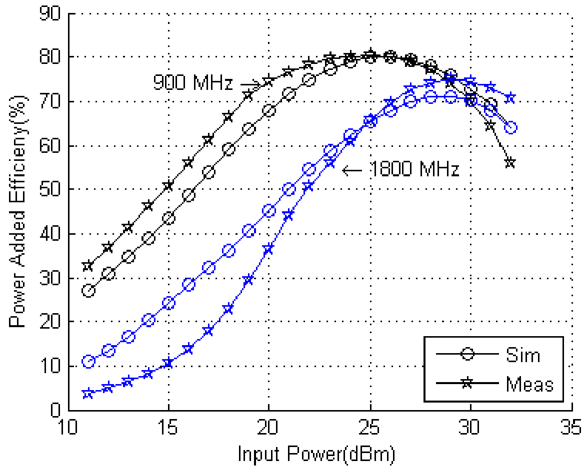

Figure 16. A comparison between simulation and measurement results for the power-added efficiency (PAE) as a function of the input power.

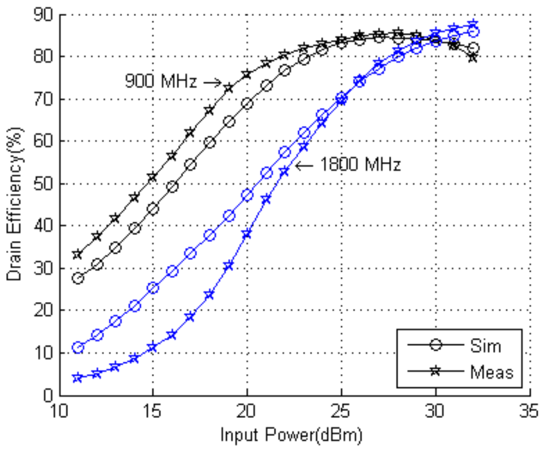

Figure 17. A comparison between simulation and measurement results for the drain efficiency as a function of the RF frequency.

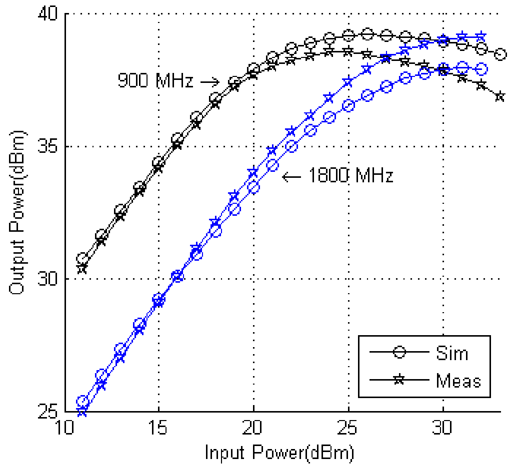

Figure 18. A comparison between simulation and measurement results for the output power as a function of the input power.

3. Fabrication and Measurements

In order to prove the simulation results, the proposed class-F power amplifier was fabricated on a 1.524 mm RO4003 Rogers substrate. The implemented class-F power amplifier is depicted in Figure 10, and the measurement setup is shown in Figure 11. A synthesizer was used to generate the input signal, and a 43 dB gain preamplifier was used to increase the maximum input power available to the device under test (DUT). While the output power was accurately measured using a calibrated attenuator and power meter (Figure 11b), the input reflection coefficient and output spectrum were obtained using a directional coupler (Figure 11a).

Measurements as functions of frequency were carried out at the following bias points: gate voltage, $V_{GS} = -2.8$ V, and drain voltage, $V_{DS} = 28$ V, for both amplifiers. The output power and gain results as functions of frequency are shown in Figures 12 and 13 for the amplifiers at 900 MHz and 1800 MHz, respectively. It could be seen that there was very good agreement between the measurements and simulation results for both circuits.

A comparison of the simulation and measurement results was done for drain efficiency as a function of frequency, shown in Figure 14 for the 900 MHz amplifier, and in Figure 15 for the 1800 MHz amplifier. The circuit at 900 MHz had a wide bandwidth of 225 MHz (805 MHz to 1030 MHz), giving efficiencies higher than 60%. It is interesting to note that the amplifier gave efficiencies higher than 70% for a bandwidth of 105 MHz. The 1800 MHz amplifier was measured at the back-off region, and it showed a high efficiency of 50% in this region in a wide bandwidth (1600 MHz to 1730 MHz and 1780 MHz to 1930 MHz).

For the case of the 900 MHz amplifier, the measurement results of efficiency as a function of frequency showed that the fabricated amplifier had maximum efficiency at a frequency of 875 MHz. $f = 875$ MHz was therefore considered the operating frequency of the circuit. The

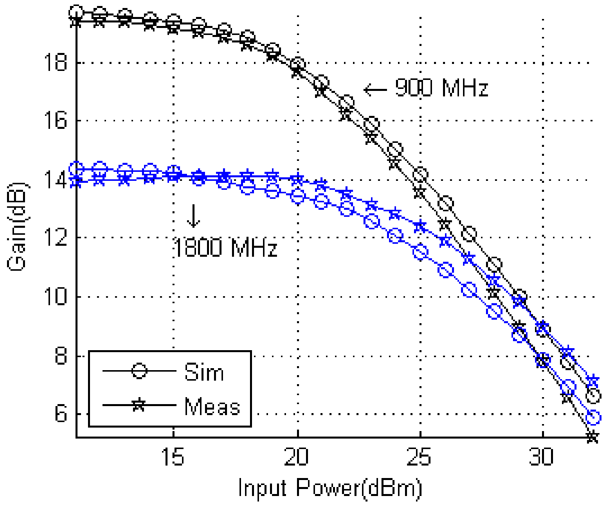

Figure 19. A comparison between simulation and measurement results for the power gain as a function of the input power.

biasing of the circuit was also optimized for the best results achievable. Measurements as functions of input power were carried out at a bias point of the drain voltage, $V_{DS} = 30.2$ V, and the gate voltage, $V_{GS} = -2$ V, for both amplifiers.

Figures 16 and 17 plot a comparison of experimental and simulated results for power-added efficiency and drain efficiency as functions of input power. The 900 MHz

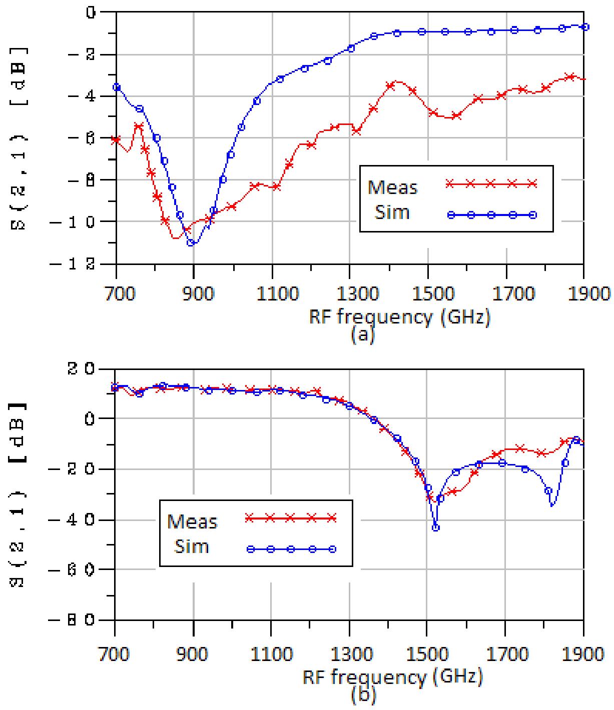

Figure 21. The simulation and measurement results for (a) $|S_{21}|$ and (b) $|S_{11}|$.

circuit featured a peak power-added efficiency of 80.5% and a drain efficiency of 84% at an input power level of

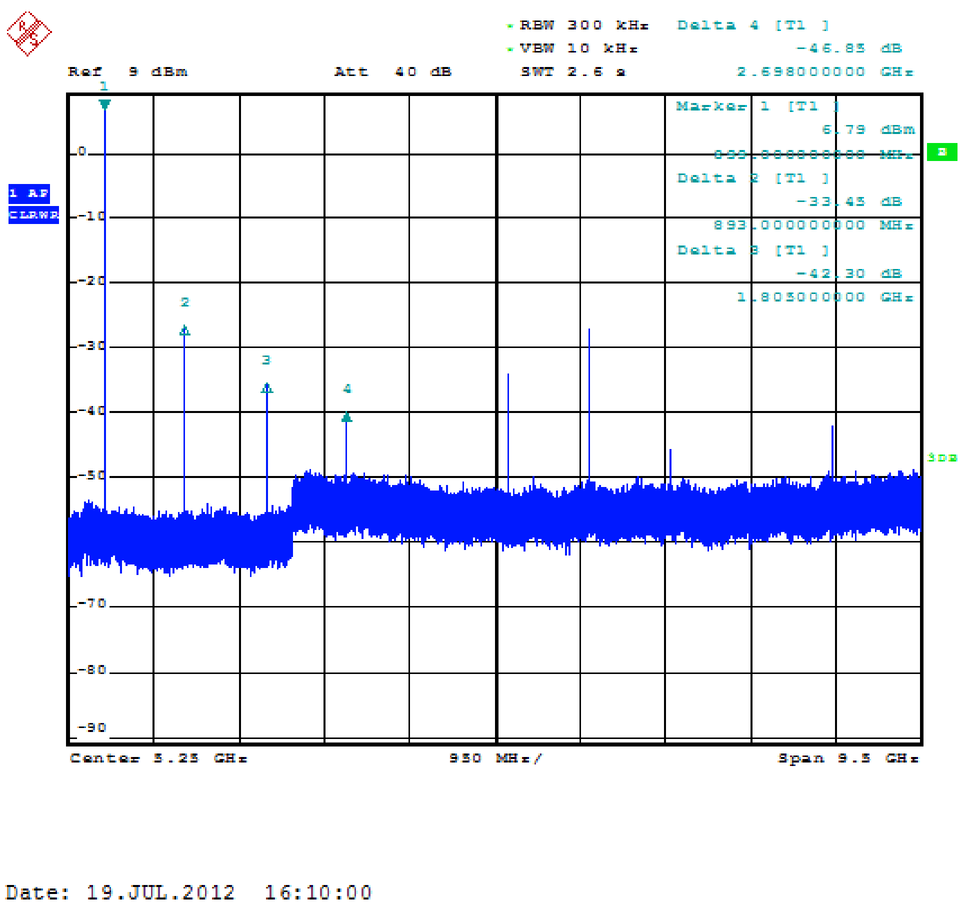

Figure 20. The measurement results for the load-voltage spectrum.

Reference	Device	Frequency (GHz)	PAE (%)	η (%)	Gain (dB)	P_{out} (dBm)
[5]	LDMOSFET	0.5	–	76	17	43
[8]	pHEMT	2.45	70.4	–	9	21
[9]	GaN HEMT	3.54	62.4	69.4	–	52.5
[10]	GaN HEMT	2.655	75	77.7	14.8	40.5
[11]	GaN HEMT	2.14	70.9	75	12.2	40.1
[12]	SiC MESFET	2.14	70.1	77.1	10.4	40.4
[13]	GaN HEMT	1.9	70	77	10	28
[This work]	GaN HEMT	0.9	80.5	84	13.6	38.6
[This work]	GaN HEMT	1.8	75	83.8	9.8	38.8

Table 5. A comparison of this work with other work.

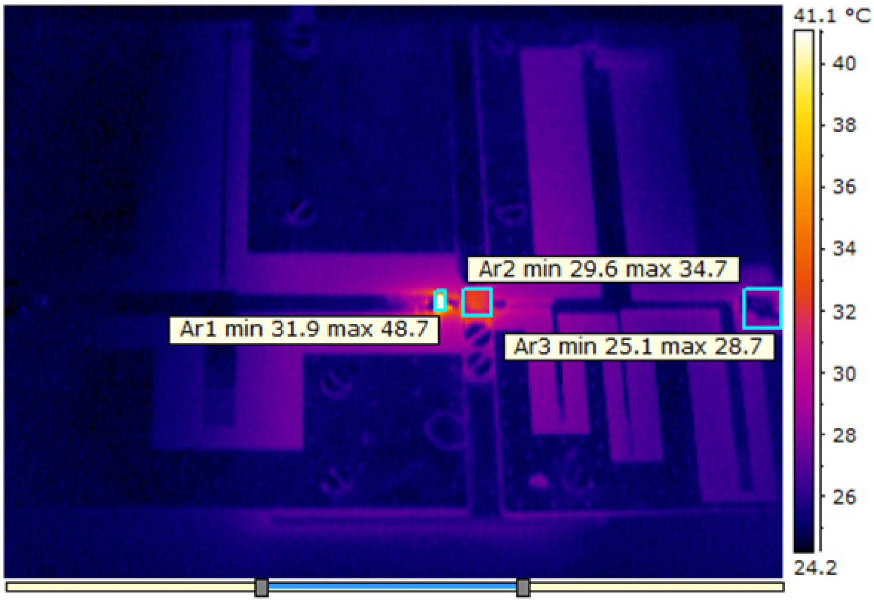

Figure 22. An infrared measurement of the circuit's heating.

25 dBm. This amplifier gave a peak drain efficiency of 85.5% for an input power of 28 dBm. At 1800 MHz, the peak power-added efficiency of 75% and drain efficiency of 83.8% were achieved for an input power of 29 dBm. The maximum drain efficiency obtained at this frequency was 87.7% at an input power level of 32 dBm.

The measured and simulated output power and gain results as functions of the input power are shown in Figures 18 and 19, where the measured gain and output power were respectively 13.6 dB and 38.6 dBm (7.2 W) for the 875 MHz design. A measured output power of 38.8 dBm (7.5 W) and a measured gain of 9.8 dB were obtained at 1800 MHz for an input power level of 29 dBm.

The power amplifier's output-voltage spectrum for 900 MHz is shown in Figure 20. The ratios between the fundamental output signal and harmonics were 33.45 dB and 42.3 dB for second ($2f_0$) and third ($3f_0$) harmonics, respectively. This showed that the proposed topology has the ability to reject harmonics while maintaining the high performance of the class-F power amplifier, and without the need for an extra filtering section. A low harmonic distortion was achieved, and the total harmonic distortion (THD) was 1.2%. Using large-signal *S*-parameter simulations, the power amplifier's large input reflection coefficient was simulated and is compared to measured results in Figure 21a ($|S_{11}|$) and Figure 21b ($|S_{21}|$). The simulation and measurement were in good agreement, and a good input matching was achieved.

An infrared camera was used to capture the thermal behavior of the circuit, and the image is shown in Figure 22. It could be seen that the circuit was thermally stable, and the transistor didn't get hot. The only point that got hot was resistor R1, but it still was within an acceptable range.

A comparison of this design to others in the literature is shown in Table 5. As it could be seen, the proposed structure achieved a drain efficiency and a power-added efficiency higher than other references, while providing high output power and gain.

4. Conclusion

A comprehensive study of the output matching network and performance of class-F power amplifiers was presented in this paper. A novel class-F power amplifier was proposed, which controls the fundamental matching independently from the harmonics by using a pi-shaped matching network, thus increasing the degree of freedom in design. The proposed topology provides high harmonic rejection without the need for extra filtering sections. Measurement results showed peak drain efficiencies of 85.5% and 87.7% for the 900 MHz and 1800 MHz amplifiers, respectively. For the 900 MHz amplifier at an input power of 25 dBm, a power-added efficiency of 80.5%, a drain efficiency of 84%, and a power gain of 13.6 dB were obtained while delivering 38.6 dBm. For the 1800 MHz amplifier, an output power of 38.8 dBm, a power-added efficiency of 75%, a drain efficiency of 83.8%, and a gain of 9.8 dB were achieved at an input power of 29 dBm. Both amplifiers showed wideband performance. A wide bandwidth of 225 MHz, giving efficiencies higher than 60%, and a wide bandwidth of 105 MHz, giving efficiencies higher than 70%, were obtained for the 900 MHz amplifier. At the back-off region, the 1800 MHz amplifier showed a high efficiency of 50% in the bandwidths of 1600 MHz to 1730 MHz and 1780 MHz to 1930 MHz. Experimental results for both amplifiers showed good agreement with simulation results.

5. Acknowledgement

This work was supported by the Spanish Government Project TEC2010-20318-C02/TCM and grant BES-2011-051305 (Ministerio de Economia y Competitividad). The authors wish to thank Ryan Baker from Cree Inc. for his support with the nonlinear transistor model.

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Simultaneous Retrieval of Sea-Surface Wind Speed and Sea-Surface Temperature from a Multi-Frequency Scanning Microwave Radiometer

Debadatta Swain

Indian Institute of Technology
Bhubaneswar - 751007, India
E-mail: debadatta.swain@gmail.com

This paper is based on a presentation by an URSI Young Scientist at the
XXXth URSI General Assembly and Scientific Symposium, Istanbul, Turkey.

Abstract

The derivation of geophysical parameters from satellite-measured brightness temperature (T_B) is an important aspect of satellite remote sensing. This primarily involves the development of complex inversion algorithms and empirical relations comprising T_B and *in situ* data for parameter retrieval and algorithm validation. In the present work, an artificial neural-network model was used to simultaneously obtain sea-surface wind speed (WS) and sea-surface temperature (SST) utilizing T_B from eight channels (including vertical and horizontal polarizations) of a multi-frequency scanning microwave radiometer onboard the Indian Remote Sensing Satellite (IRS-P4) and deep-sea ocean buoys in the North Indian Ocean region. The values obtained from the artificial neural network were then compared with actual *in situ* observations as a test for the performance of the model. Regression relationships were also individually developed for sea-surface wind speed and sea-surface temperature to provide an inter-comparison between the two approaches. It was concluded that the artificial-neural-network model was able to provide good estimates of sea-surface wind speed and sea-surface temperature within acceptable error limits. The goal of the present work is to pre-establish the suitability of the artificial-neural-network approach for geophysical parameter retrieval from satellite-measured T_B in the Indian context, particularly keeping in view the recently launched Megha Tropiques and forthcoming Oceansat-3 satellites.

1. Introduction

Sea-surface wind speed (WS) and sea-surface temperature (SST) are important geophysical parameters used in the estimation of heat flux at the air-sea interface. On the global scale, these satellite-derived products serve as important inputs for climate modeling, for studies of the Earth's heat balance, as well as for atmospheric and oceanic circulation. They are crucial parameters to understanding air-sea interactions; monsoonal forcing on oceanographic phenomena; assessing eddies, fronts, and upwellings for marine navigation; and tracking biological productivity (including potential fishing zones) at local scales [1, 2].

However, *in situ* observations of several parameters over vast portions of the global oceans are significantly under-sampled, both temporally and spatially, owing to measurements restricted to ships and buoys, the ranges of which are limited [3]. This limitation is partially overcome in the case of certain geophysical parameters, such as sea-surface wind speed and sea-surface temperature, mainly due to routine global measurements by space-borne radiometers and scatterometers, offering synoptic and temporal sampling advantages. The retrieval algorithms developed for this purpose are either based on theoretical, statistical, empirical, or combinations of these approaches. Since most of these attempt to parameterize the physical processes by which a geophysical parameter influences the electromagnetic radiation observed by the sensor (active or passive), the retrieval algorithms need to be fine tuned or improved until

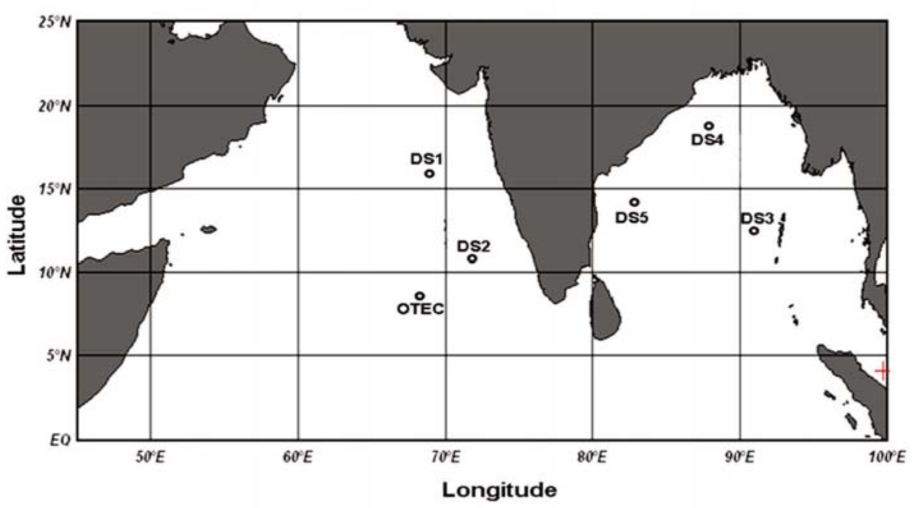

Figure 1. The study area and the moored buoy locations.

reliable information can be obtained. Given the complexity of the various parameter-retrieval processes from satellite measurements, advanced computer-based approaches – such as fuzzy logic, genetic algorithms, artificial neural networks (ANN), and fractals – have come to the rescue, serving as alternatives to the complex physics involved in geophysical parameter retrieval [4, 5].

India has launched several remote-sensing satellites under the series of the IRS (Indian Remote Sensing) satellites. IRS-P4, launched in May 1999, carried a multi-frequency scanning microwave radiometer (MSMR) onboard, measuring brightness temperature (T_B) at frequencies of 6.6 GHz, 10.65 GHz, 18 GHz, and 21 GHz in the horizontal and vertical polarizations. It is a day-night all-weather sensor, designed to measure sea-surface temperature, sea-surface wind speed, atmospheric water vapor, and liquid water content in the clouds [6, 7]. In the present work, an artificial-neural-network-based model was formulated to simultaneously retrieve sea-surface wind speed and sea-surface temperature values from IRS-P4 multi-frequency scanning microwave radiometer T_B over the North Indian Ocean (NIO). The multiple-regression technique (MRT) was also used for the retrieval of the above parameters one at a time. The artificial-neural-network- and multiple-regression-technique-based estimations were compared and validated with *in situ* measurements from moored buoys. The present work demonstrated the utility of such an approach in simplifying the complex geophysical-parameter retrieval processes.

2. Data and Methodology

IRS-P4 (Oceansat-1) carrying the multi-frequency scanning microwave radiometer and the ocean color monitor (OCM) onboard was launched on May 26, 1999, into a near-polar sun-synchronous orbit of 727 km altitude with an orbital time of ~102 minutes. It had an equator crossing at 12 noon for descending nodes, and 12 midnight for ascending nodes, both local times. The repetition frequency of the satellite was two days with a daily global coverage of ~80%. The IRS-P4 multi-frequency scanning microwave radiometer provided global microwave T_B measurements on eight channels, comprising 6.6 GHz, 10.65 GHz, 18 GHz, and 21 GHz frequencies with dual polarizations, and with spatial resolutions ranging between 120 km and 40 km over a swath of 1360 km [8, 9]. The post-launch multi-frequency scanning microwave radiometer sensor calibration in space was carried out using a temperature-controlled load, as well as by using the sky's temperature.

The grid-1 multi-frequency scanning microwave radiometer T_B values at the four frequencies at both polarizations, as mentioned above, were provided by the National Remote Sensing Centre Data Center for a one-year period during 2000. These were used in the present analysis for retrieving the sea-surface wind speed and sea-surface temperature, with data subsets selected for the study area (Figure 1).

The National Institute of Ocean Technology (NIOT) has deployed several buoys in the North Indian Ocean region (www.niot.res.in). Sea-surface wind speed and sea-surface temperature datasets, recorded by some of these deep-sea moored buoys (DS1, DS2, DS3, DS4, DS5, and OTEC: locations shown in Figure 1), corresponding to the study period, were collected from NIOT. The details of the buoy instrumentation and observations were given in [10]. For the present work, datasets from these buoys were consolidated and used to develop and validate the artificial neural network algorithm for simultaneous retrieval of sea-surface wind speed and sea-surface temperature from multi-frequency scanning microwave radiometer T_B. Additionally, the multiple-regression technique was utilized for retrieval of the individual sea-surface wind speed and sea-surface temperature parameters. For the purpose of collocation of satellite observations with *in situ* (buoy) observations, the nearest multi-frequency scanning microwave radiometer observations lying within a search radius of ~1.5° around the buoy locations, and a maximum temporal duration of three hours or less with respect to the data-buoy measurements, were considered to be collocated observations, based on the work in [5] and [7]. The buoy measures sea-surface wind speed at a height of ~3 m from the sea surface. These values were converted to equivalent winds at 10 m height to match up with the IRS-P4 multi-frequency scanning microwave radiometer measurements. This was done following a logarithmic wind profile as given in Equation (1), where, U_z is the mean wind speed [m/s] at height *z*, and U_{10} is the wind speed [m/s] at 10 m height [10]:

$$U_{10} = U_z \left(\frac{10}{z} \right)^{1/7} . \tag{1}$$

After adopting this methodology, a concurrent and collocated database of multi-frequency scanning microwave radiometer T_B values at frequencies of 6.6 GHz, 10.65 GHz, 18 GHz, and 21 GHz (vertical and horizontal polarization), and sea-surface wind speed and sea-surface temperature recorded by the buoys in the North Indian Ocean, was created for a one-year period spanning January to December 2000. This database was then used for constructing the artificial neural network model and its validation.

2.1 Artificial Neural Network Analysis

Artificial neural networks have found wide-scale application in various meteorological and oceanographic studies [11-13]. Several satellite-retrieval procedures have also utilized artificial neural networks for geophysical-parameter retrievals, including multiple parameters from other satellite radiometers [5, 14-18]. An artificial neural network is basically a parallel-distributed computer model, consisting of processing units called neurons. Mathematically modeled on the biological neuron, this has the capability to be dynamically constituted, based on the training sets of data utilized in the artificial neural network model formulation. A typical artificial neural network model architecture consists of several such neurons embedded into layers, which are interconnected through activation links modulated by synaptic weights. The resulting network has a natural propensity for storing experimental knowledge through learning or training [19]. Mathematically, the simplest form of an artificial neural network is given as

$$Y_j = f\left(w_0 + \sum_{i=1}^{N} X_i^* w_{ij} \right), \quad j = 1, 2, \ldots, n , \tag{2}$$

$$Z_k = f\left(w_0 + \sum_{j=1}^{M} Y_j^* w_{jk} \right), \quad k = 1, 2, \ldots, m , \tag{3}$$

where X_i is an *N*-element input vector, with Y_j being the output of hidden layers (with *n* neurons). Z_k is the *m*-element output of the artificial neural network (consisting of *M* hidden layers). The variable *w* represents the adaptable or synaptic weights, with *f* representing the threshold function. This is usually a sigmoid function, defined by

$$f(x) = \frac{1}{1 + e^{-x}} . \tag{4}$$

An artificial neural network can perform prediction after learning the underlying relationship between the input variables and the outputs. From a statistical view, neural networks are analogous to nonparametric, nonlinear regression models, with the added advantage of "generalization," which is the ability of the network to subsequently give reasonable outputs for inputs not contained in the training set [20].

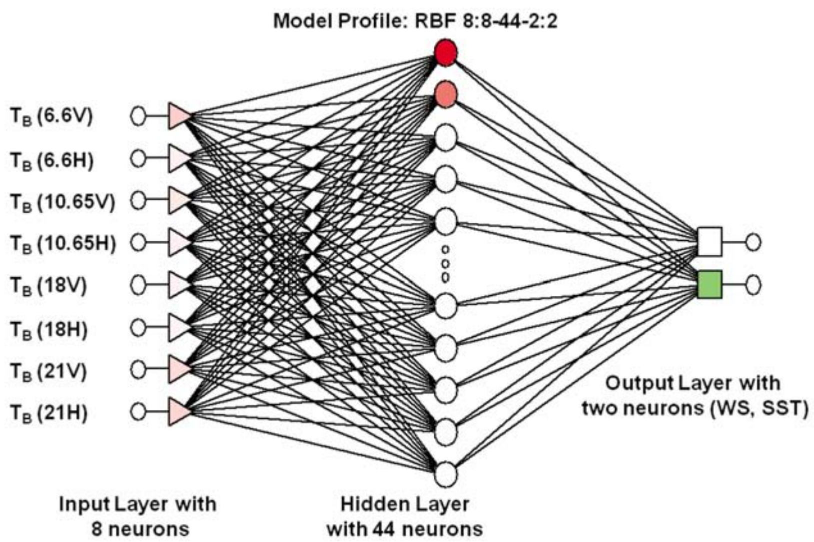

Figure 2. The artificial neural network model architecture for simultaneous estimation of sea-surface wind speed and sea-surface temperature.

Parameter	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
WS	61.003	–0.211	–0.056	0.013	0.260	–0.324	0.108	–0.016	0.034
SST	11.328	–0.041	0.026	0.055	–0.026	–0.005	–0.043	0.126	–0.037

Table 1. The regression coefficients used for obtaining sea-surface wind speed and sea-surface temperature from multi-frequency scanning microwave radiometer T_B values and buoy observations.

In the present work, a radial-basis-function- (RBF) based two-output artificial neural network model was developed for sea-surface wind speed and sea-surface temperature retrieval from satellite-measured T_B on eight channels. The network consisted of one input layer with eight neurons, one hidden layer with 44 hidden neurons, and one output layer consisting of two neurons (Figure 2). A radial-basis-function-based network was chosen because in addition to its simplicity, it combines a linear dependence on the weight variables with the ability to explicitly model nonlinear relationships [4, 20]. It may be noted that in this work, an automated artificial neural network modeling sequence was deployed with the condition of balancing error against diversity of the network components. In this process, an artificial neural network with a large number of hidden neurons (44) was obtained. Efforts were made to balance the compromise one has to make in terms network generalization with the enhanced ability of an artificial neural network to estimate/obtain a wide range of sea-surface temperature and sea-surface wind speed values. For instance, although sea-surface temperature in the study area varies from 26.5°C to 30.5°C, sea-surface wind speed varies from 1 m/s to 13 m/s.

The multi-frequency scanning microwave radiometer T_B values in the 6.6 GHz, 10.65 GHz, 18 GHz, and 21 GHz channels (with dual polarizations) were considered as the inputs (independent parameters) for the artificial neural network model, with the buoy sea-surface wind speed and sea-surface temperature being the outputs (dependent parameters), for each data set utilized in the artificial neural network model formulation. Furthermore, out of the total of 918 collocated and concurrent observations, 50% (459 observations) for training, 25% (230 sets) for verification, and 25% (229 sets) for artificial neural network prediction and validation of the predicted results were randomly segregated. A random segregation was applied as it was expected to eliminate any systematic bias in the data, as well as to sample all possible aspects of data variability in a given set of observations [13].

2.2 Multiple Regression Analysis

The data marked for artificial neural network training and verification were used to separately develop the multiple-regression-technique coefficients for sea-surface wind speed and sea-surface temperature. These were then utilized for multiple-regression technique estimation of sea-surface wind speed and sea-surface temperature for the data marked for artificial neural network predictions to have an inter-comparison. The general form of this is given as

$$\text{Geophysical Parameter} = A + BT_{B1} + CT_{B2} + DT_{B3}$$

$$+DT_{B3} + ET_{B4} + FT_{B5} + GT_{B6} + HT_{B7} + IT_{B8}\,, \quad (5)$$

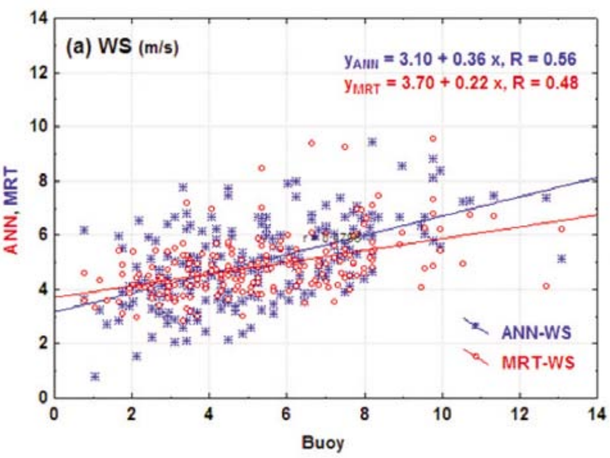

Figure 3a. A scatter plot of the multi-frequency scanning microwave radiometer estimations obtained using the artificial neural network and the multiple-regression technique and the corresponding collocated buoy observations for wind speed.

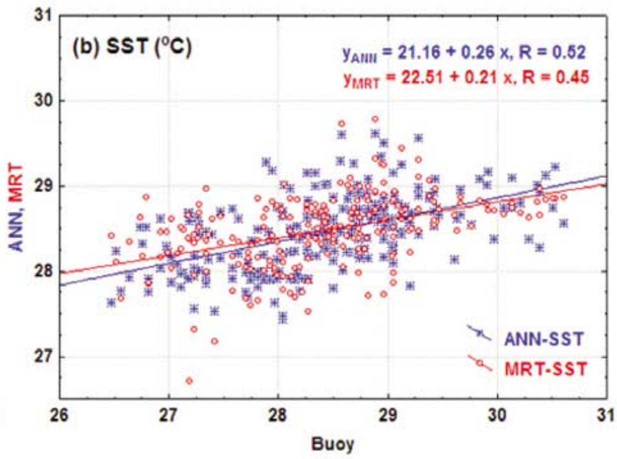

Figure 3b. A scatter plot of the multi-frequency scanning microwave radiometer estimations obtained using the artificial neural network and the multiple-regression technique and the corresponding collocated buoy observations for sea-surface temperature.

Parameter	WS		SST	
	(ANN vs. Buoy)	(MRT vs. Buoy)	(ANN vs. Buoy)	(MRT vs. Buoy)
RMSE	1.97 (m/s)	2.36 (m/s)	0.75 (°C)	0.80 (°C)
R	0.56	0.39	0.52	0.45
Slope	0.36	0.17	0.26	0.21
Intercept	3.10	3.99	21.16	22.58
Bias	–0.25 (m/s)	–0.12 (m/s)	0.04 (°C)	0.05 (°C)

Table 2. The statistical analyses of the artificial neural network and multiple-regression technique based multi-frequency scanning microwave radiometer sea-surface wind speed and sea-surface temperature estimations, and the corresponding buoy observations, for a set of 229 observations.

Table 2. (continued).

No. of Obs. for Validation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot.
	8	12	8	5	14	13	11	26	22	32	42	36	229
Total Obs.	43	49	43	25	66	56	46	77	96	140	137	140	918

where T_{B1} to T_{B8} correspond to the T_B values for the 6.6v GHz, 6.6h GHz, 10.6v GHz, 10.6h GHz, 18v GHz, 18h GHz, 21v GHz, and 21h GHz channels (with "v" and "h" representing the vertical and horizontal polarizations, respectively). The regression coefficients for sea-surface wind speed and sea-surface temperature and the eight T_B values (in both polarizations) as developed for the present work are given in Table 1.

3. Results and Discussions

Following the artificial neural network and multiple-regression technique model formulations, their performance was evaluated based on a comparison of 25% (229) of the sea-surface wind speed and sea-surface temperature values determined by the artificial neural network and multiple-regression techniques with values determined using collocated ocean buoy observations. We made sure this 25% of the data set was not part of the training and verification steps of the artificial neural network model formulation. Statistical analysis of the comparison indicated a correlation (R) of 0.56 and a root-mean-square error (RMSE) of 1.97 m/s for the sea-surface wind speed values obtained from the artificial neural network compared to the buoy observations. We found a correlation (R) of 0.39 and a root-mean-square error (RMSE) of 2.36 m/s for the sea-surface wind speed values obtained from the multiple-regression technique compared to the buoy observations. The correlation was 0.52 with a root-mean-square error of 0.75°C for the values of sea-surface temperature obtained from the artificial neural network and the corresponding buoy observations. The correlation was 0.45 with a root-mean-square error of 0.80°C for the values of sea-surface temperature obtained from the multiple-regression technique and the corresponding buoy observations.

The scatter plots of data between the artificial neural network estimations and the buoy values are provided in Figure 3. The statistical analyses, including the number of observations out of the total number of available observations for each month that were used for validation, are presented in Table 2.

A histogram analysis of the bias of the artificial neural network estimations compared to the buoy observations

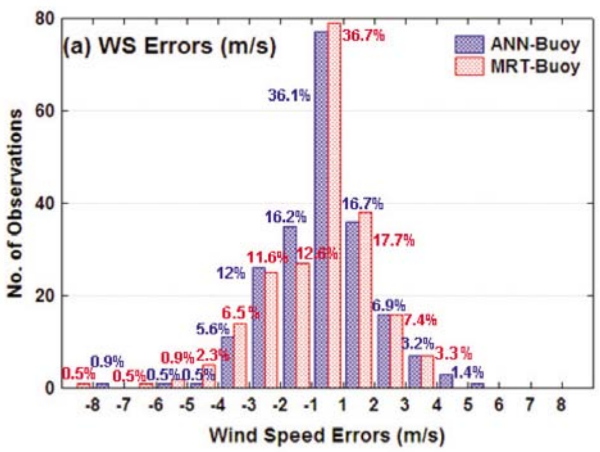

Figure 4a. The error histograms (ANN-Buoy and MRT-Buoy) for wind speed.

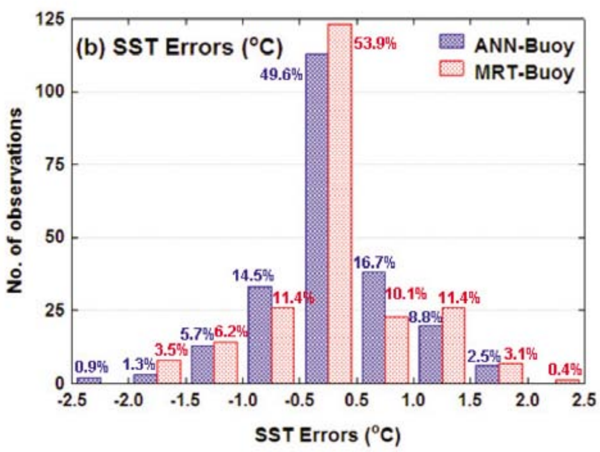

Figure 4b. The error histograms (ANN-Buoy and MRT-Buoy) for sea-surface temperature.

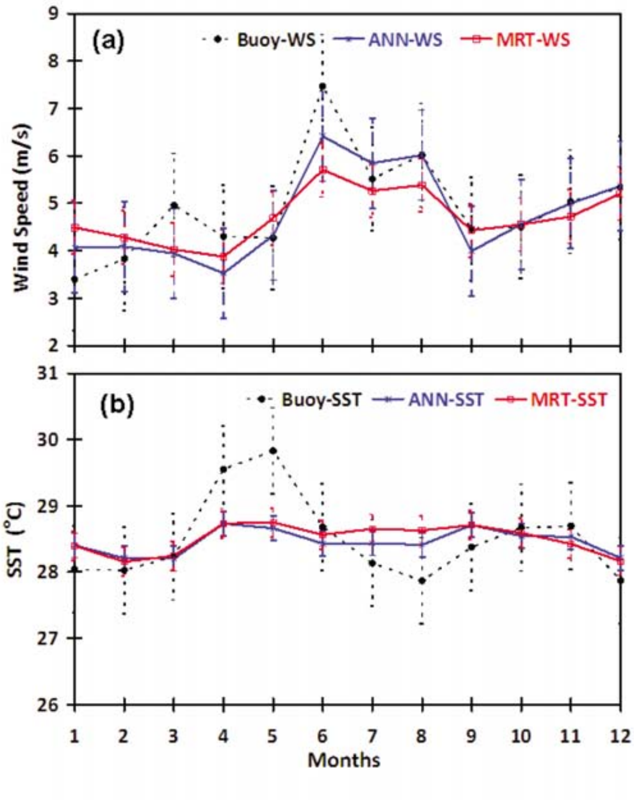

Figure 5. The monthly mean values of (a) sea-surface wind speed, and (b) sea-surface temperature from the buoys, the artificial neural network, and the multiple-regression technique during the year 2000.

(ANN-buoy) of the two parameters (Figure 4) indicated that ~69% of the sea-surface wind speed values estimated by the artificial neural network were within an error of ±2 m/s, and 89% were within ±3 m/s, when compared with the buoy values. 67% of the sea-surface wind speed values estimated by the multiple-regression technique were within an error of ±2 m/s, and 86% were within ±3 m/s, when compared to the buoy values. Similarly, for the case of the sea-surface temperature, ~50% of the artificial neural network estimations were within ±0.5° C, 81% were within ±1° C, and 95% could be estimated within ±1.5° C error, as compared to the buoy sea-surface temperatures. Again, for the case of the sea-surface temperature, 54% of the multiple-regression technique values were within ±0.5° C, 75.4% were within ±1° C, and 93% could be estimated within ±1.5° C error, as compared to the buoy sea-surface temperatures.

The monthly averaged variations of sea-surface wind speed and sea-surface temperature for the artificial neural network estimations and corresponding buoy observations during 2000 (using the validation data) are shown in Figures 5a and 5b, respectively. High sea-surface wind speeds were observed during the southwest monsoon (June-September), whereas higher sea-surface temperature was observed during the pre-summer monsoon months of April and May.

Overall, there was a good match between the artificial neural network estimations and the buoy observations, except for the months of April and May for sea-surface temperature, and March and April for sea-surface wind speed. It may be noted here that the number of observations that were used for the artificial neural network model formulation for these months was quite lower, owing to the very low number of collocated data available for these three months. Correspondingly, the number of validation data sets was only 8, 5, and 13 for March, April, and May, respectively.

From the statistical analysis of the results (Table 2), among other observations it was observed that the slope was quite lower than one. To be operational, any algorithm must strive to get a slope closer to one. Furthermore, the geophysical algorithms also need to be based on *in situ* match-up data that are representative of a wide range of locations, and conditions. Otherwise, the retrieval algorithm/methodology will be biased towards conditions represented by the match-up data where it performs well, while its performance may be much poorer in other conditions [21]. This is possible once a large data set covering wide spatial variability and a large temporal range is considered for the artificial neural network model formulation. However, this was beyond the scope of the present work, which utilized a total of just 689 available collocated data sets, spanning just a one year period, owing to limitations in terms of the multi-frequency scanning microwave radiometer coverage, operational duration, etc. Based on a comparative assessment of sea-surface temperature and sea-surface wind speed over the Indian Ocean from TMI [the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager], the multi-frequency scanning microwave radiometer, and ERA-40, it was also concluded that despite the multi-frequency scanning microwave radiometer having a lower-frequency channel, the bias and standard deviation were large compared to those of TMI [9]. Furthermore, a large bias at low winds in the case of the multi-frequency scanning microwave radiometer was observed. This was attributed to the possible poorer sensitivity of microwave emissivity variations at low sea-surface wind speeds [9]. These issues are thus innate to the multi-frequency scanning microwave radiometer, and are likely to figure in any retrievals utilizing the IRS-P4 multi-frequency scanning microwave radiometer. These further support the results obtained in the present work.

Further improvement in the present artificial neural network results obtained is possible by adopting a bias-correction strategy for the retrieved parameters. However, the results have been presented as they are to highlight the utility of the artificial neural network technique for simultaneous retrieval of geophysical parameters, although subject to certain limitations. Additionally, the collocation criteria used in this work for multi-frequency scanning microwave radiometer T_B and buoy observations was a spatial search radius of ~1.5° and within a duration of three hours (discussed in Section 2). It is therefore quite likely that any rainfall event resulting in sea-surface temperature cooling or high winds that are short-duration events could have easily escaped detection by the multi-frequency scanning microwave radiometer, even within the collocation criteria. Swain et al. [22] did in fact show such likely events but for modeled parameters. Within above-discussed limitations, the potential of the artificial neural network approach in simultaneously estimating multiple geophysical parameters such as sea-surface wind speed and sea-surface temperature from microwave-radiometer-measured T_B is evident from the work. This can possibly be made operational for existing and future satellite-based microwave sensors.

Additional validation of the artificial neural network technique can be carried out by comparison of the results with TMI sea-surface temperature and SSM/I winds. However, since the emphasis is on the artificial neural network retrieval of sea-surface wind speed and sea-surface temperature considering the multi-frequency scanning microwave radiometer on Oceansat-1, more comprehensive work in this direction involving adequate data coverage, probably from other available microwave radiometers, could be taken up in the future. As an immediate validation of the artificial neural network results, the sea-surface temperature and sea-surface wind speed obtained from the artificial neural network were compared with those obtained using the multiple-regression technique, a standard method used for satellite retrievals. The author would definitely like to carry out a similar study as a future study aimed towards an operational algorithm.

4. Conclusions

A radial-basis-function-based artificial neural network model was used to simultaneously retrieve sea-surface wind speed and sea-surface temperature from T_B values of the multiple channels of a multi-frequency scanning microwave radiometer. The values estimated by the artificial neural network model were within acceptable limits of error when compared with buoy observations. The present work involved only a year-long data set, consisting of 918 collocated cases for the IRS-P4 multi-frequency scanning microwave radiometer. This work was meant to demonstrate the utility of the artificial neural network approach in simultaneously obtaining multiple geophysical parameters (here, the sea-surface wind speed and sea-surface temperature) from the T_B of the multi-frequency scanning microwave radiometer. The performance of the artificial neural network approach was also found to be better than multiple-regression-technique results. However, a better-performing artificial neural network model could be developed with more collocated *in situ* observations, spanning larger and more widely varying sea-surface conditions and corresponding sensor responses. A similar technique may also be used for other microwave radiometers, provided more collocated *in situ* observations over the global oceans are available, covering larger spatial and temporal extents. It may be noted that even though microwave radiometers can be utilized to obtain sea-surface temperature even under cloudy conditions – unlike infrared channels, which are suitable only under clear-sky conditions, owing to the limitations of infrared remote sensing – the accuracy of sea-surface temperature derived from the microwave sensor is less, and has poor spatial resolution.

5. Acknowledgements

The author would like to thank the Director, National Remote Sensing Centre (NRSC), and colleagues of ECSA, NRSC, for their support and encouragement. Various institutions, such as NRSC, RSS, SAC, and NIOT, are gratefully acknowledged for providing the datasets. Thanks are also due to Dr. B. Jena, NCAOR, for his suggestions on the data pre-processing. An earlier version of this work was presented at the URSI-IGARSS-2011 [23]. The present article is a more detailed and updated version, and also includes additional analysis such as the comparison of the multiple-regression technique. The anonymous reviewers and the editor are gratefully acknowledged for their critical comments and suggestions, which have helped in further improving the quality of the work presented here.

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On the Road Towards Green Radio

Jacques Palicot [1], Honggang Zhang [2], and Christophe Moy [1]

[1] SUPELEC/IETR
Avenue de la Boulaie CS 47601
35576 Cesson-Sévigné, France
e-mail: jacques.palicot@supelec.fr; christophe.moy@supelec.fr.

[2] Université Européenne de Bretagne & SUPELEC
Avenue de la Boulaie CS 47601
35576 Cesson-Sévigné, France;
e-mail: honggang.zhang@supelec.fr

This is an invited paper from Commission C

Abstract

Decreasing the energy consumption of future wireless communication networks and improving their energy efficiency is demanding ever-growing attention around the world. Making ICT (information and communications technology) equipment and applications "greener" in terms of energy consumption and electromagnetic radiation will not only help telecommunication companies to attain their sustainable profitability, but will also have a profound positive impact on the global environment and human society. This article accordingly introduces the basic concept and features of green radio, and the relevant fundamental solutions for increasing energy efficiency at the network as well as the component levels. Moreover, the key role of cognitive green radio has been strengthened for improving energy efficiency, within which several representative learning algorithms, decision-making techniques, and design tools are thoroughly discussed, with power-consumption constraints. Finally, the electromagnetic-pollution issue in the scenario of opportunistic spectrum access (OSA) is also investigated.

1. Introduction

Not so many years ago, environmentally friendly sustainable development was the preoccupation of only environmental and ecological organizations. However, sustainable development has become a global paramount challenge and an aspiration of long-term civilization development for all human beings, since the Resolution 42/187 of the United Nations General Assembly, passed in December 1987. The Brundtland Commission of the United Nations (UN) has defined sustainable development as that development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." From then on, several United Nations' conferences (from Rio de Janeiro, 1992, to Copenhagen, 2009) have continually confirmed that this important issue must be on top of the agenda, and that the most obvious aspects and challenges of sustainable development are both the planet Earth's climate change, and the ever-growing CO_2 emission.

Currently, 3% of the world-wide energy is consumed by the ICT (information and communications technology) infrastructures, which generate about 2% of the world-wide CO_2 emissions. As surprising as it may seem, this figure is comparable to the world-wide CO_2 emissions from all commercial airplanes, or one-quarter of the world-wide CO_2 emissions from all vehicles. Moreover, the information and communications technology sector's carbon footprint is expected to quickly grow to 1.4 gigaton CO_2 equivalents by 2020, which represents nearly 2.7% of the overall carbon footprint from all human activities. These values of carbon footprint, which have been validated by a number of scientific studies and measurements around the world, are extremely surprising [1]. The European Council has therefore set forth a critical target, known as the "20 20 by 2020" initiative, which calls for a reduction of 20% in greenhouse gases (GHG) and a 20% share of renewable energies in the EU's energy consumption by 2020 [2].

There is no doubt that the telecommunications and information community is today facing huge challenges, but also embracing great opportunities. The enormous demand for ubiquitous wireless services has been on the rise in past years, and is ever growing with the proliferation of multimedia-rich mobile communication devices (e.g., smart phones). The volume of transmitted data continues to explode by a factor of approximately 10 every five years. Accordingly, the energy consumption, which is necessary for transporting this data, is increasing by 16% to 20% per year. This unprecedented thirst for increased data rates is resulting in a huge need for an ever-increasing capacity-density in broadband telecommunications networks. Even though this has been hugely beneficial for the development of contemporary society, this has also resulted in an unsustainable increase in systems' complexity, energy consumption, and a burgeoning environmental footprint. There is a worldwide concern that if the aggregated energy consumption of all networking systems and devices followed the astonishing growth trajectories of all Internet traffic (i.e., about 50% per year), then the associated environmental and economical consequences would lead to a daunting nightmare. A global consensus is therefore now taking shape to say that the information and communications technology industry has emerged as one of the major contributors to the world's power consumption and to the emission of greenhouse gases. An ever-increasing awareness of the potential environmental impact induced by the emission of greenhouse gases and the exhaustion of non-renewable energy resources also spurs the need to improve the energy efficiency of the telecommunication systems.

In addition to the environmental concerns, telecommunication network companies would also benefit from reducing the power consumption of their networks from a business point of view. Recently, it has been reported that energy costs could account for as much as half of a mobile-service-provider's annual operating expenses. A significant proportion of the overall cost reduction and significant savings in capital expenditure (CapEx) and operational expenditure (OpEx) can therefore be achieved through improved energy efficiency. In this context, the information and communications technology sector is expected to play a major active role in the reduction of world-wide energy consumption, through the optimization of energy generation, transportation, and consumption [3].

Making information and communications technology equipment and applications "greener" in terms of energy consumption can undoubtedly not only have a tangible positive impact on the environment, but can also help telecommunication companies to attain long-term profitability. Moreover, energy-efficient communications and networks can help the world to reduce its dependence on fossil fuel, enable on-demand response and fluent energy-resource distribution, and ultimately achieve sustainable prosperity around the world. As illustrated in Figure 1, the long-term evolution roadmap of the next-generation telecommunications systems from 2G, 3G, 4G, to 5G is strongly expected to point to the energy-efficiency dominated era from now on.

In summary, lowering the energy consumption of future telecommunication systems while increasing their total energy efficiency is demanding greater attention, not only within government, industry, and standardization bodies, but also among international research communities. Moreover, another big challenge of future wireless-radio-communications systems is to globally reduce electromagnetic radiation levels so as to achieve a better coexistence of the various wireless systems (interference alignment and harmonization), but also to reduce human exposure to harmful radio radiation.

The rest of the paper is organized as follows. The following section first introduces the metrics to characterize green features. It second introduces some solutions for increasing energy efficiency, both at the network and component levels. The third section briefly recalls the cognitive radio (CR) concept. It then introduces the cognitive green radio (CGR) concept we proposed in order to tackle the energy-efficiency problem. In the fourth section, we then deal with some remaining challenges that are very important to tackle from our point of view, so as to reach cognitive green radio. In particular, we will discuss decision-making techniques with green constraints, electromagnetic

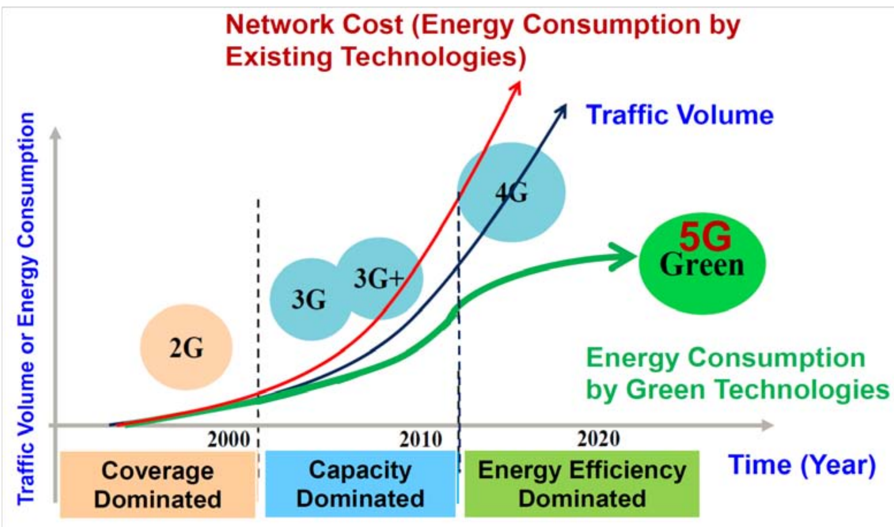

Figure 1. The evolution from coverage- and capacity-driven telecommunications to energy-efficient green radio communications.

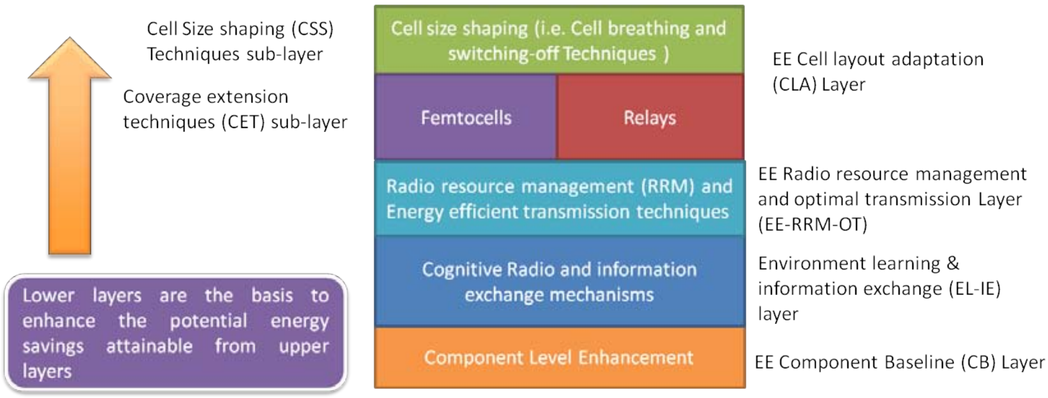

Figure 2. The classification proposed by Suarez, Nuaymi, and Bonnin in [4], used with the authors' permission.

pollution, and the tools used to design cognitive green radio equipment. Finally, section five concludes this article.

2. Some Studies

The classification of Figure 2, proposed by Luis Suarez, Loutfi Nuaymi, and Jean-Marie Bonnin in [4], seems very appropriate for presenting the different solutions for tackling the green problem. Referring to their sharing in the layers of the model, we will present solutions at the network level, equipment level, hardware level, etc. Before listing the different solutions for green radio, in the first section of the paper we will consider the characterization of their energy efficiency, and more generally, the characterization of the green features and the relevant metrics for measuring them.

2.1 Metrics for Characterizing the Green Feature

In this section, we deal with the basic definition of green energy metrics for wireless communications, so as to characterize the green behavior of a radio system. These metrics will also be used to qualify and quantify the effectiveness of the techniques used for improving the green aspect (mainly, to decrease the power consumption).

The metric which has been commonly proposed is the bit/s/Joule, which corresponds to the bit rate per Joule [6]. We also find the metric bit/s/Hz/Joule, which represents the traditional spectrum efficiency with respect to power consumption, in use. More generally, energy-efficiency metrics correspond to the ratio of a benefit or utility criteria to the cost in terms of power consumption. The utility criteria may be the throughput, the coverage, the bits successfully transmitted, etc. For example, in [7] the authors studied the best power-allocation policy in MIMO channels for optimizing the energy function. It should be noted that the utility criteria depends on the segment considered in the wireless network. At the hardware component level, high-power amplifiers (HPA) are the most interesting elements to consider, since they generally have a very low energy efficiency [9]. A lot of papers have presented and discussed different ways to improve this efficiency (see Section 2.2.2). At the execution-platform level, metrics such as MIPs/W or MFLOPS/W are traditionally used by the electronic community. At the base-station (BS) level, the commonly used metric is the bit/s/Hz/Joule or the bit/s/Hz/W, respectively for its energy consumption or energy efficiency. From the overall network perspective, the coverage should be considered, which means that the surface area (expressed in square meters) should be included in the metrics [10].

Very often, techniques for decreasing power consumption consider only the power consumed at the transmission side. If this power transmission is clearly dominant in the global power consumption of any wireless transmission system, the power consumption of equipment and hardware of the network should also be considered. Some green improvement techniques may deteriorate the quality-of-service (QoS), which is generally not acceptable. In this context, authors of [8] did a very interesting study in order to find the best energy efficiency while keeping the right quality-of-service. This study resulted in four different tradeoffs. However, as mentioned by the same authors, these tradeoffs have to be further investigated in cases featuring more realistic situations than that of the sole point-to-point transmission case they studied.

2.1.1 Spectrum Efficiency (SE)/ Energy Efficiency (EE) Tradeoff

These two criteria are very often contradictory. Starting from the Shannon formula, we may use the expression of the transmission rate, R, given by Equation (1), where P, N_0, and W are the transmitted power, the noise PSD (power spectral density), and the bandwidth, respectively:

$$R = W \log_2 \left(1 + \frac{P}{WN_0}\right). \quad (1)$$

In fact, taking into account the expressions of the spectrum efficiency and energy efficiency (Equations (2) and (3)), we may also deduce the relationship between spectrum efficiency and energy efficiency (Equation (4)):

$$SE = \log_2\left(1+\frac{P}{WN_0}\right), \qquad (2)$$

$$EE = \frac{W\log_2\left(1+\frac{P}{WN_0}\right)}{P}, \qquad (3)$$

$$EE = \frac{SE}{\left(2^{SE}-1\right)N_0}. \qquad (4)$$

The curve of this relationship is given in Figure 3a, from which it is clear that when the spectrum efficiency increases, the energy efficiency decreases. This curve is exact only for the simple "point-to-point transmission over an AWGN [additive white Gaussian noise] channel" case. The spectrum efficiency as a function of energy efficiency relationship becomes more complicated in realistic conditions.

2.1.2 Bandwidth Efficiency (BE)/ Power Consumption (PC) Tradeoff

In the school case of a point-to-point link, the relationship between these two criteria (bandwidth efficiency and power consumption) is given by Equation (5), from [8], and the curve is given in Figure 3b:

$$P = W\,N_0\left(2^{\frac{R}{W}}-1\right). \qquad (5)$$

In this ideal situation, increasing the bandwidth efficiency results in having a lower power consumption. However, in realistic conditions, this relationship again becomes more complicated.

2.1.3 Delay/Power Consumption (PC) Tradeoff

One of the critical metrics of quality-of-service at the applications/services level is the delay. In the theoretical case of a point-to-point link over an additive white Gaussian noise channel, if the accepted delay increases, then the power consumption decreases. This tradeoff is represented in Figure 3b. However, in more realistic conditions, this tradeoff is one again more complicated to analyze.

2.1.4 Deployment Efficiency (DE)/ Energy Efficiency (EE) Tradeoff

The deployment cost is a very important measure for a telecommunications company. It comprises the infrastructure costs, energy cost, operation cost, and maintenance cost. In Figure 3a, it is clear that the deployment efficiency increases when the energy efficiency decreases.

2.2 Solutions to Increase Energy Efficiency

In this section, it is not our key objective to give a new, complete overview of techniques and approaches for improving energy efficiency in wireless networks. Rather, it is a summary more or less based on the very interesting existing overviews given in [4, 5, 11]. In particular, we will use the classification of [4] as presented in Figure 4. We will conclude this section by showing that cognition and learning, the two preeminent aspects of cognitive radio, are very efficient for increasing energy efficiency.

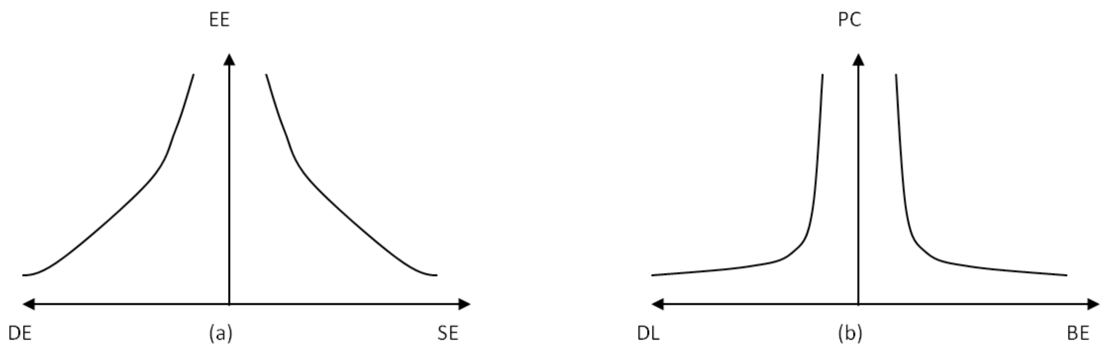

Figure 3. A schematic view of the tradeoffs in the ideal case for: (a) energy efficiency (EE) and spectrum efficiency (SE)/ deployment efficiency (DE), and (b) power consumption (PC) and bandwidth efficiency (BE)/delay (DL), from [8].

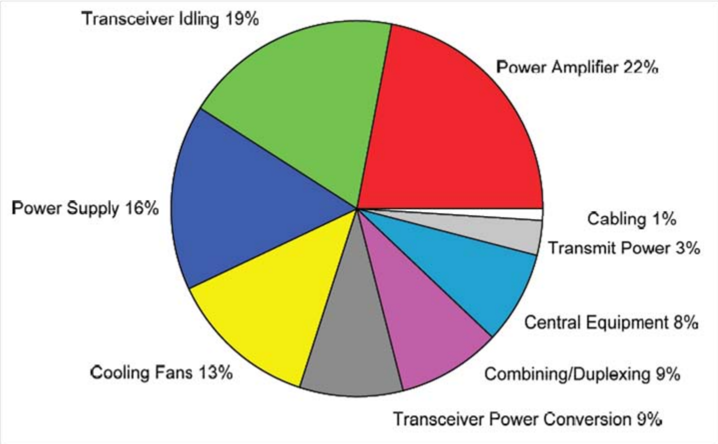

Figure 4. The division of power consumption at the base station.

2.2.1 At the Network Level

This subsection includes the CLA (cell layout adaptation) and the RRM (radio resource management) layers of Figure 2. The approaches at this level comprise the various solutions that can be used during network deployment, as well as their corresponding solutions that adapt the cells to existing traffic. In this context, we may cite strategies considering the cell's coverage reduction and the deployment of multi-tier cells, which include microcells, picocells, and femtocells, etc. Femtocells are mainly considered in indoor deployment.

During the network's running operation, and depending on the real traffic, cell shaping are techniques that adapt the cell coverage according to the traffic inside the cell. Among these techniques, we can find the "traditional" base-station switch on/off approach. In [22], the authors characterized the amount of energy that can be saved by switching off the cells experiencing low traffic. In [23], the authors studied a similar problem while modeling the traffic pattern in the network. From [29], it is possible to reduce the energy consumption by about 25% or even 30%. Another attractive solution to performing cell adaptation is cell breathing.

In the literature we found many other techniques that claim to allow a decrease in energy consumption. Among them, relaying techniques have been proposed with different approaches: relays may be repeaters or they may be nodes (whatever it is, mobile or base station, etc.) of the mobile network [12-14]. Another very popular technique is the so-called massive MIMO [15, 16], initially proposed within the GreenTouch project [17]. The massive MIMO technique dramatically increases the number of antennas at the base station (10 times the number of active users), and provides the ability to transmit the data by means of narrow beams. This drastically reduces the transmitted power by reducing the energy spent on channel training, and is therefore well suited for TDD technologies [18, 28]. The results show that the energy efficiency gains can still be verified when one takes into account the hardware discrepancies [19-21].

2.2.2 At the Component Level

If we consider the graph of Figure 4, we can see that about 30% of the base-station's power consumption is due to the high-power amplifier and the associated cooling. Depending on the various on-site implementation technologies, this value may reach 50% [25]. This explains the existence of a huge literature dedicated to the optimization of high-power amplifiers. This long-lasting problem may be tackled at different levels [24]:

- At the circuit and architecture levels: In fact, manufacturers have tried to improve the linearity and the efficiency curves of their high-power amplifiers, both at the electronic level as well as at the architecture level [25, 26]. For example, as in [27], an architecture featuring several Doherty steps may reach a theoretical efficiency of 70%.

- At the signal processing level: It is possible to decrease the peak-to-average power ratio (PAPR) so that it can decrease the input back-off (IBO), which results in an increase in energy efficiency. There exist many survey papers that describe many possible techniques to deal with peak-to-average-power-ratio mitigation [24, 30]. It is also possible to study new efficient orthogonal waveforms that by definition have a low peak-to-average power ratio.

At this component level, we also need to consider the hardware's execution platform. A lot of work have been performed by the microelectronics industry in order to decrease the consumption of electronics. Since the 65 nm CMOS technology emerged, it was stated in [50] that the leakage-power consumption is strongly correlated to the circuit area. Consequently, as shown by Figure 5 from [50], this leakage-power consumption should no longer be negligible. A new tradeoff between parallelism and power consumption should therefore be found. This was discussed in [48], for example. Practical solutions, using temperature and the moving of functions to decrease the leakage-power consumption, were also discussed in [49].

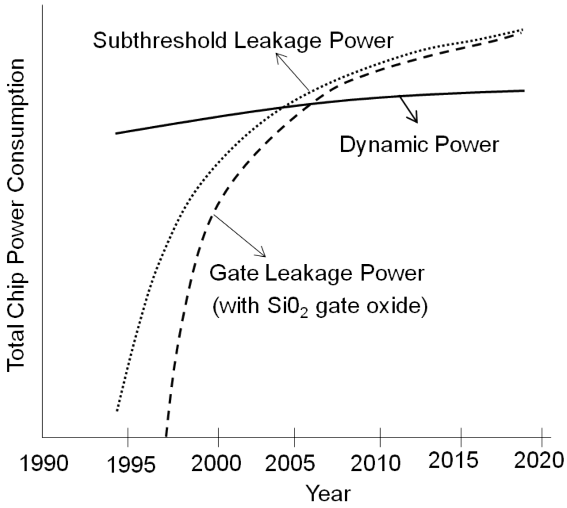

Figure 5. Power-consumption trends [50].

2.3 Other Solutions Based on Cognitive Radio

Radio communications have a lot to offer with respect to the performance improvement of the energy-efficiency of the future networks. In 2005 [31] and in 2008 [32] pointed out that intelligence is a key word when dealing with green-communications problems (energy efficiency, radio-spectrum pollution, interference control, etc.). They proposed to use cognitive radio [40] as an enabling technology for realizing green-radio communications [34, 35]. The so-called cognitive green radio (CGR) is an emerging research subject within a number of academic communities (GREENTIC WS, ISCIT conference, COST 0902 action, etc.). The number of relevant papers is increasing, as well [35-38, 44, 45].

From now on, the rest of this paper will be mainly devoted to cognitive green radio and the relevant approaches.

3. Cognitive Green Radio

As early as 1999, the term cognitive radio was first coined by Joseph Mitola III [40]. Mitola argued that

> ...radio will become more and more autonomous, and thanks to the support of flexible technology, namely Software Defined Radio (SDR), will acquire some self-autonomy to dynamically modify its functionality....

Cognitive radio is therefore an intelligent digital reconfigurable radio that can sense and understand its local radio spectrum's environment, identify temporarily vacant spectrum, and opportunistically use it. It can thus offer a great potential of providing higher-bandwidth services, but also increasing spectrum efficiency and mitigating the spectral "bottleneck" problem within the traditional centralized static spectrum management.

Basically, cognitive radio relies on a cognitive cycle, which can be summarized in three key steps [32, 37]:

- Observe (sense): all the sensing means of a cognitive radio with respect to the operating environment.
- Decide (learn, plan, and decide): implies various kind of intelligence, including learning, planning, and decision making.
- Act and adapt: reconfigures the radio, designed with software-defined radio functionalities, in order to be as flexible as possible.

A simplified view of the representative cognitive cycle is described in Figure 6.

As mentioned before, it has been pointed out that intelligence is a key word when dealing with

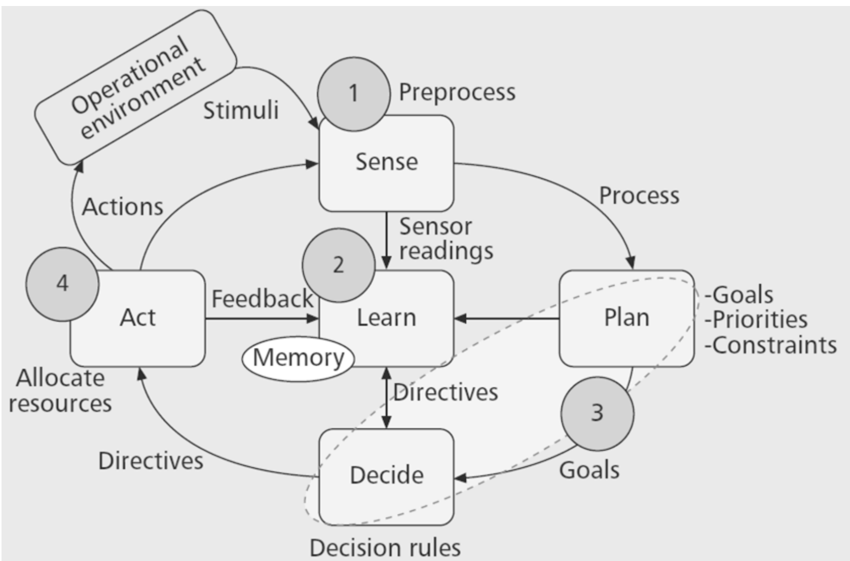

Figure 6. A simplified view of the cognitive cycle [37].

green communications problems (energy efficiency, radio-spectrum pollution, interference control, etc.). Cognitive radio could have an important role in being the enabling technology for achieving intelligent green radio communications and networking. This was shown and explained in 2005 [31] and in 2008 [32]. From then on, besides opportunistic dynamic spectrum accessing, cognitive radio has also been identified as a promising disruptive technology, with tremendous potential for realizing energy-efficient greener radio communications and reducing their carbon footprint [31, 32, 46, 47]. Accordingly, a cognitive green radio could be defined as a cognitive radio that is aware of the sustainable development objectives of both reducing the energy footprint and lowering electromagnetic (EM) exposure, and uses these as additional critical constraints in the decision-making function of the cognitive cycle.

Until now, on the one hand, the key industrial players (telecommunication companies and infrastructure manufacturers) have been heavily studying various means and architectures for saving power and increasing energy efficiency within the framework of ongoing 3G and 4G telecommunication systems. On the other hand, cognitive radio's approach for TV's white-space (TVWS) applications was recently initiated commercially. However, considering the future 5G telecommunications system, there are global interests and ever-growing necessities for designing a completely novel architecture and framework and to pave the path for disruptive enabling technologies when confronting the ever-serious challenges of the balance of spectrum and energy efficiency.

To date, little significant work has been carried out in order to bring cognitive radio and green radio together. Much of the cognitive-radio activity has mainly focused on the assignment of the radio spectrum in the presence of primary users, especially in the TV bands, while completely ignoring energy efficiency. Moreover, little work has dealt with the use of distributed artificial intelligence (learning and decision making) used to select spectrum or energy, to help reconfigure network topologies, and to manage network-wide energy consumption. The cognitive green radio approaches proposed here are significantly more adventurous in their scope than those of the state-of-the-art radios. To the best of our knowledge, none of the big industrial players has ever been concretely involved in research on cognitive green radio. Cognitive green radio is in its infancy. It expresses a revolutionary potential and roadmap for how energy usage in future generations (5G) of broadband wireless networks can be significantly reduced through the use of intelligence, in order to help manage network reconfiguration.

At first look, it seems contradictory to decrease the carbon footprint and to increase the throughput. In fact, various telecommunication companies and manufacturers – even though they are now aware of the energy-consumption problem – would like to increase their throughput, business revenue, market sharing, and so on. On the one hand having more network capacity and less energy consumption, and on the other hand reducing electromagnetic pollution, are thus two apparently contradictory future needs. It is our ambition to demonstrate that cognitive green radio could provide a new degree of freedom towards future greener communications that makes a good balance among energy consumption (reducing carbon footprint), energy efficiency, spectrum efficiency, the control of electromagnetic pollution, human exposure, the life cycle of equipment, increase of revenue, and sustainability.

Accordingly, it is meaningful to address the research challenges relating to the fundamental approach of cognitive green radio for solving the previously described problems. The first challenges addressed are the design and the implementation of an intelligent cooperative signal's processing, as well as learning and decision-making strategies, so as to decrease the equipment's power consumption and to optimize spectrum utilization for achieving the balance of energy-spectrum efficiency. As described in the former sections, the basic definition of energy-efficiency metrics for wireless communications needs to be addressed in order to characterize the greener behavior of a specific radio system. Moreover, the application of both learning and decision-making algorithms to energy efficiency (thanks to the design of an advanced multi-carrier waveform's adaptation, so as to use the high-power amplifier of the radio transmitter), and also to spectrum efficiency, will play key roles, as well.

In support of reaching the above strategic long-term goal, it is necessary to implement the cognitive green radio's approach to monitor the energy consumption of wireless systems. It is also essential to control the power switching (on/off) state, and the adaptive reconfiguration of both architectures and parameters that are related to the power consumption and spectrum harmonization of various wireless devices and subsystems that offer this capability. In particular, several advanced cognitive approaches, such as distributed artificial intelligence strategies, can significantly contribute to controlling the network and the reconfiguration of resources, taking into account different degrees of information and information sharing. Machine-learning techniques, including reinforcement learning and the new technique of transfer learning, are helpful, as well.

Furthermore, it is meaningful to further extend the traditional meaning of green radio to some broader aspects of sustainable development of future wireless communications, since sustainable development is not limited to the sole energy-consumption issue. In our minds, it is necessary to further address several social aspects, such as spectrum pollution, which may have a significant influence on astronomic observations, electromagnetic radiation levels, the exposure of the human body to radio radiation, and recycling and reuse of information and communications technology equipment. The radio spectrum is also considered a natural and public resource that should be carefully used, shared worldwide, and efficiently economized. The human aspects of the spectrum-pollution problem should be taken into account as well, mainly from the point of view of head exposure, but also in terms of the acceptance of public opinion.

4. Open Problems and Technical Challenges

4.1 Decision Making

4.1.1 Generalities on Decision Making

Since we consider cognitive green radio to be a sub-part of cognitive radio, then decision making for cognitive green radio does not use any specific tools or approaches. The same tools can be used for green purposes as well as for any other decision-making purposes in cognitive radio. As already stated in the paper, cognitive green radio is all about adapting the radio equipment in real time to its environment for green purposes. We then recall, in Figure 7, the classification of decision making made in [52].

Decisions may be made in an expert manner (Figure 7, left-hand side): i.e., the radio knows exactly how to react as a function of the input metrics it has sensed from the environment. This supposes that the designer of the radio has planned all the possible input combinations of the state of the environment and the most adapted reaction for each of those combinations. Such a level of a priori knowledge is only possible for a very simplistic scenario. Note also that a bad decision occurs if an error is made with respect to the evaluation of the input metrics.

The more the decision technique goes towards the right-hand side of Figure 7, the less knowledge it has a priori (i.e., introduced at design time) from the environment. It then has no other possibility but to learn. At the extreme right-hand side, we find techniques that can learn from scratch, i.e., with no initial knowledge at all [53]. This will be discussed in section 4.3.2. Moreover these techniques are intrinsically robust to sensing errors, which has been proven and demonstrated in the cognitive-radio context [54].

Learning and decision making are thus often merged in cognitive radio. It is only a question of a priori knowledge that determines how much learning should be included in the decision process. The efficiency of such an approach has been proven in cognitive radio, and there is no reason why it would not improve cognitive radio under green constraints. Learning means anticipating. Having more and more learning processes in cognitive green radio is also a challenge for the latter.

4.1.2 Decision-Making Algorithms for Energy Efficiency

The challenge of the next decade will be to find ways to use decision making for green purposes, as it is almost a virgin territory. As an example, we chose a context of statistical decision making, which enables bypassing at run-time some processing by way of a statistical analysis. The idea is to statistically model and characterize the radio environment using some techniques of statistical inference, such as statistical estimation and statistical detection. On the basis of the metrics that evaluate the quality of the channel and of their statistical characteristics, it can for instance be decided whether the equalizer is necessary or not, according to the current state of the channel [41]. The

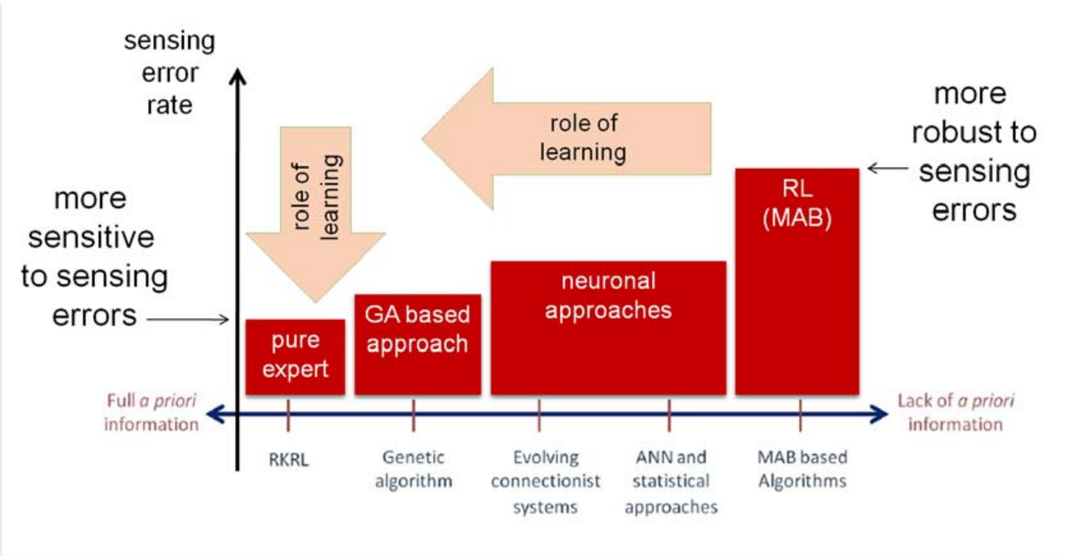

Figure 7. A classification of already explored decision-making strategies for cognitive-radio equipment.

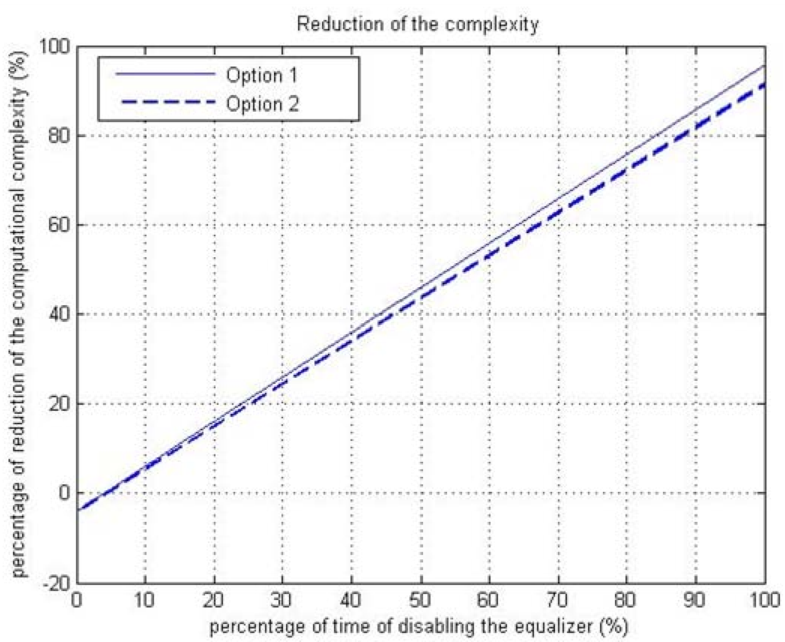

Figure 8. The reduction of computational complexity through turning off the equalizer, compared to that obtained with a traditional design featuring a permanent equalizer.

use of the statistical aspect of the channel's quality indicators allows taking into account the estimation errors of these metrics in the decision-making system, which affects the decision performance. It is assumed in this example that the interference from which the signal suffers is limited to the inter-symbol interference caused by the delay dispersion of the multipath channel. From this expression, two radio metrics are defined for driving the equalizer. The first metric, SNR_p , represents the signal-to-noise ratio transmitted on the path that has the highest energy. The second metric that we considered is the power of the inter-symbol interference: *ISI*. A tradeoff is made between a minimum estimation error and a minimum computational complexity. The observations of these metrics and their statistical parameters are considered to determine the decision rule used to decide when to turn off the equalizer. Two thresholds of evaluation are defined: first, the value of *ISI* when the *BER* (bit-error rate) reaches a given value, and secondly, the value of *SNR* under which the equalizer degrades the signal's quality. We determine new thresholds of evaluation by fixing a probability of false alarm, and by considering the estimation errors of the sensors by way of introducing their statistical parameters. The decision rule for turning off the equalizer is then obtained [41]. Thanks to this approach, Figure 8 illustrates the reduction in computational complexity, and consequently the potential energy saving, made in a Rician multipath channel featuring five paths and a Doppler frequency equal to 170 Hz. This corresponded to a mobile user moving at a speed equal to 100 km/h, assuming that the carrier frequency was 1800 MHz and the transmission time of the frame was 1 ms. Two options were compared. Option 1 entirely cut

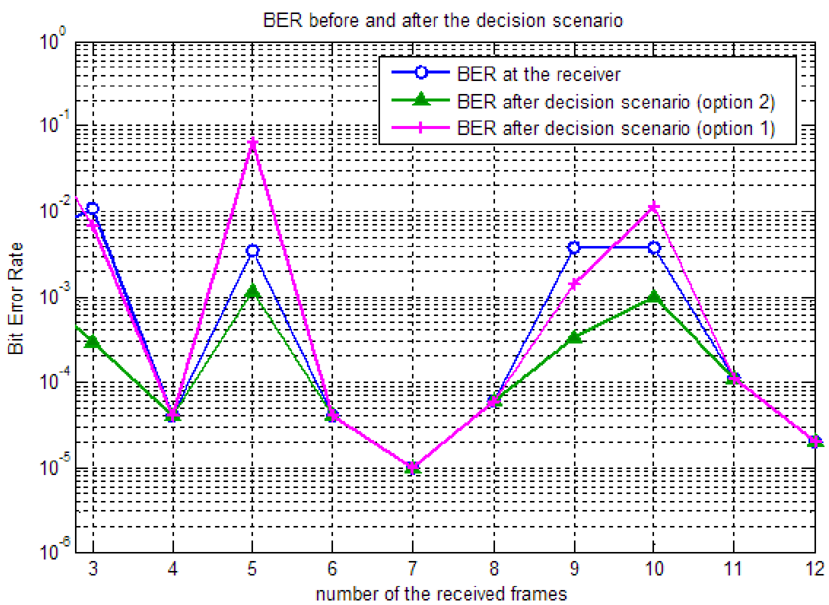

Figure 9. The bit-error rate (BER) before and after driving the equalizer. Option 2 enables keeping a lower bit-error rate

off the equalizer, including the channel's estimation, which provoked some loss of data when the equalizer was again switched on. Option 2 provided a tradeoff between energy economy and performance. The energy savings were almost the same for a better performance in bit-error rate, as shown in Figure 9. Note that the block diagrams for both options 1 and 2 are detailed in Section 4.4 from the perspective of the design of a cognitive radio.

The computational complexity of the receiver chain started to decrease when the equalizer was turned off for at least 4.36% of the total period of time for option 2, and 3.9% for option 1. When the equalizer was off during all the observation time, the maximum rate of the reduction of complexity obtained was 91.26% for option 2, and 95.83% for option 1.

4.2 Cooperative Algorithms

4.2.1 Generalities of Cooperative Algorithms

In regard to the networking environment of cognitive green radio, which features multiple nodes distributed across a certain area, cooperation approaches can play important roles for achieving various greener features and advantages. These include energy-efficiency improvement by virtue of the distributed nodes' collaboration mechanisms, such as swarm intelligence and transfer learning. Swarm intelligence is biologically inspired by the collective behavior of social insects, for instance ants or bees solving complex tasks such as building nests or foraging. It is based on the principle of the division of labor where the higher efficiency can be achieved by specialized workers performing simple specialized tasks in parallel.

The advantages of cooperation techniques in decision-making processes are scalability, knowledge transfer, fault tolerance, parallelism, and autonomy. Basically, collaborative schemes can greatly improve the performance of spectrum sensing, power allocation, and interference control in a complicated heterogeneous networking environment. Moreover, collaborative schemes are also suitable for lowering power consumption, interference avoidance, and control of electromagnetic pollution in a distributed but cooperative mode. The targeted balance of energy efficiency and spectrum efficiency can be potentially improved by distributed optimization approaches. The latter rely on the cooperation of distributed agents (nodes) so as to achieve the common optimization goal, with a collective complexity out of individual simplicity and effective knowledge transfer.

The next section will provide a concrete example with in-depth details on how a transfer-learning-based cooperation mechanism can be applied to decrease the power consumption of mobile cellular networks.

4.2.2 Example of Transfer Reinforcement Learning

Currently, around 80% of the total power consumption takes place in radio access networks (RANs), especially the base stations (BSs) [42, 43]. The key reason behind this phenomenon is that the present deployment of base stations is dimensioned on the basis of peak traffic loads, and generally stays active irrespective of the variation in traffic load, while the traffic loads actually vary heavily. Recently, there has been substantial interest and work towards traffic-load-aware base-station adaptation. This has

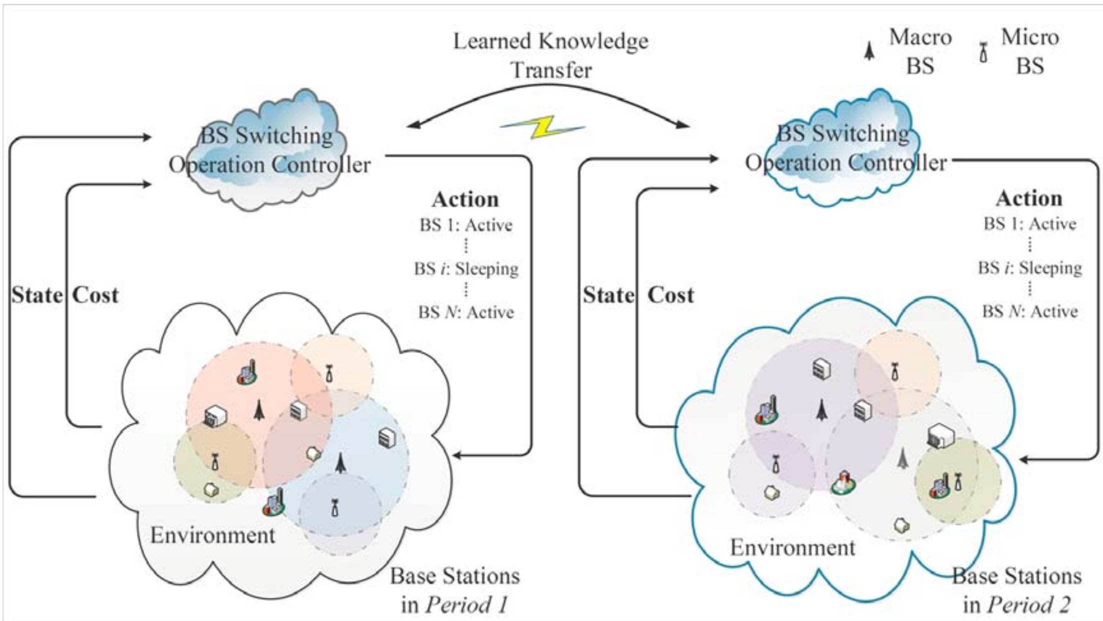

Figure 10. Transfer learning for reinforcement learning with cooperation, in the scenario of the switching operations of base stations.

validated the possibility of improving energy efficiency by means of dynamically adjusting the base station's working status, depending on the predicted variation pattern of the traffic loads. Moreover, dynamic base-station switching (on/off) algorithms that deal with the traffic loads a priori have preliminarily proven the effectiveness of energy saving.

However, a reliable prediction of the traffic loads is still quite challenging, which makes these approaches suffer in practical configurations. Instead of predicting the volume of traffic loads, the Markov decision process (MDP), which is based on reinforcement learning, can be used to model the variation of traffic loads. In particular, a solution to the formulated Markov decision process problem can be attained by making use of an actor-critic algorithm, which is an effective reinforcement-learning approach. One advantage of the actor-critic algorithm is that there is no necessity to possess any a priori knowledge about the traffic loads within the base stations. On the other hand, energy savings for mobile cellular networks will significantly benefit from an existing local controller for base-station switching operations, such as the base station's controller (BSC) in the second-generation (2G) cellular networks, or the radio network's controller (RNC) in the third-generation (3G) or LTE (long-term evolution) cellular networks.

As illustrated in Figure 10, a controller for base-station switching operations can be designed and implemented within the reinforcement-learning framework. The controller for base-station switching operations first estimates the traffic load's variations, based on the online experience. Consequently, the controller can select one of the possible base-station switching operations under the estimated circumstance, and then decreases or increases the probability of the same action to be selected lately, on the basis of the needed cost. Here, the cost primarily focuses on the energy consumption due to such a base-station switching operation, and also takes into account the quality-of-service performance metric in order to secure the user's experience. After repeating the actions and getting the corresponding costs, the controller would know how to switch the base stations for a specific traffic-load profile. Moreover, with the reinforcement-learning model, the resulting base-station switching strategy is foresighted, which can improve energy efficiency in the long term.

However, a critical challenge may arise, as reinforcement-learning approaches usually suffer from "*the curse of dimensionality*," and handle complex tasks with a large set of states and actions slowly. The direct application of reinforcement-learning algorithms may hence sometimes get into trouble, because a controller for base-station switching operations usually takes charge of tens or even hundreds of base stations.

On the other hand, cooperation mechanisms can potentially mitigate the above-mentioned problem by utilizing the philosophy and concept of transfer learning among the distributed cooperative control nodes (e.g., various base-station controllers or radio-network controllers). The cognition-inspired transfer-learning algorithms – which originally concerned how to recognize and apply the knowledge learned from one or more previous tasks (*source tasks*) in order to learn to solve more effectively a novel but related task (*target task*) – are intuitively appealing and effective in a cooperative mode. The temporal and spatial relevance in the traffic loads across various controllers for base-station switching operations make it meaningful to transfer the learned information for base-station switching operations at historical moments or

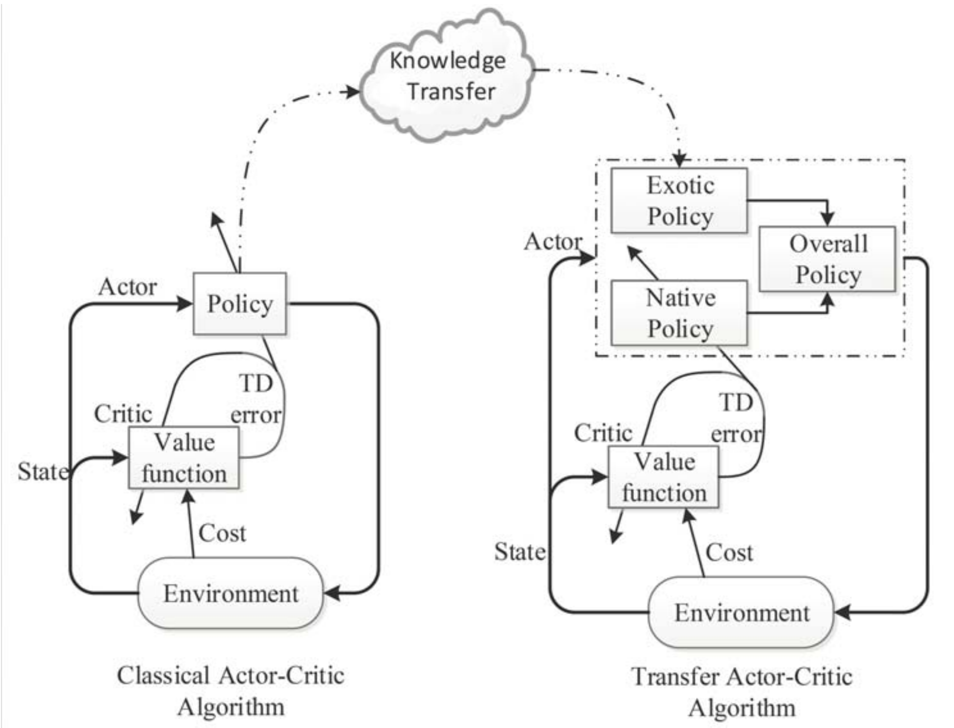

Figure 11. The architecture of the transfer actor-critic algorithm (TACT), obtained by way of incorporating transfer learning into the actor-critic algorithm.

in neighboring regions (source tasks), so as to help to speed up the ongoing learning process in the regions of interest (target tasks). Specifically, as depicted in Figure 11, the learning framework of the base-station switching operation can be further enhanced by incorporating the idea of transfer learning into the traditional actor-critic algorithm, namely the Transfer Actor-CriTic Algorithm (TACT).

4.3 Electromagnetic Pollution

In this paper, we extend the traditional green radio concept, which is generally limited and justified in the context of energy consumption, as noted above. This concept can also be viewed in a wider sense, such as in the optimization of spectrum usage, with the aim of reducing electromagnetic-radiation levels and enabling the coexistence of multiple wireless systems (i.e., less interference), as well as reducing human exposure to radiation, in the recycling and reuse of information and communications technology equipment, and in many other related contexts. This section deals with several aspects of electromagnetic pollution that belong to the green topic from our point of view.

4.3.1 Generalities

It is important to dedicate bands for astronomy observation, for instance. These bands should be neither polluted nor jammed by artificial radio signals. Increasing the density of already allocated bands so as to keep some bands unused can be achieved thanks to opportunistic spectrum access (OSA). Opportunistic spectrum access relies on the insertion of unlicensed secondary users in the vacant holes left by the licensed primary users in the band. Secondary users should have a transparent presence for primary users, i.e., they should not degrade the primary users' performance. This implies two constraints: a secondary user should not use a frequency band a primary user is already using, and a secondary user should not pollute primary users if it is in an adjacent channel, as stated in the FFC standard on TV white space.

Cognitive radio's opportunistic spectrum-access perspectives impose finding modulation schemes that have sharp spectrum shapes, so that they can be used to insert secondary users that do not interfere with primary users in an opportunistic spectrum-access scheme. These techniques, such as FBMC [44], are new modulation schemes that avoid degrading contiguous bands. This would enable enlarging unused bands that could be saved for astronomy observation, as well.

Even if there is no evidence of human disease due to wireless radio transmissions, we all agree that it is better to decrease as much as possible people's exposure to radio emissions. The small cell or femtocell approach may be considered a cognitive green radio approach in that sense. Public opinion often considers remote base stations a cause for this problem, whereas their own phone is much more concerned. Indeed, even if it is transmitting less power, it is of course much closer to human organs such as the brain, for instance. If less power is being transmitted thanks to small cells or home cells, the main human exposure to radio signals can be mitigated. Home cells consist of relaying radio signals outside people's homes through the ADSL network, for instance, and this thanks to an antenna inside the home, which can be reached at a very low power.

4.3.2 Upper Confidence Bound Example for Opportunistic Spectrum Access

The opportunistic spectrum access context may be modeled as a multi-armed bandit (MAB) problem. We can

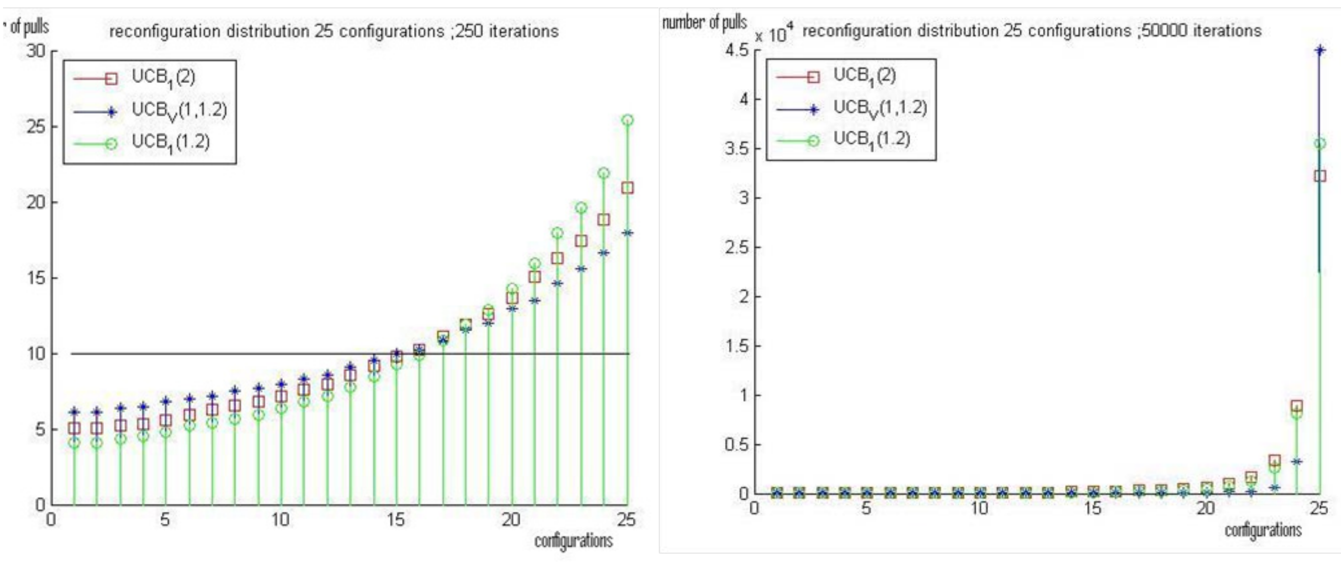

Figure 12. The number of trials for each of the 25 configurations after 250 iterations (left-hand side), and 50000 iterations (right-hand side).

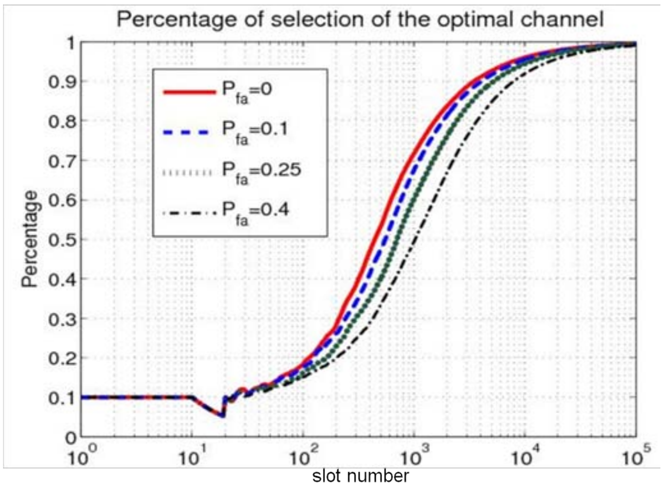

Figure 13. The effect of sensing errors on the convergence of the upper confidence bound.

indeed compare a set of *F* frequency bands to a set of *M* armed bandits. The hypothesis is that the cognitive radio knows nothing about the occupation rate of the *F* bands by primary users, just like a gambler knows nothing about the best machine to play when he or she enters a casino. From the multi-armed-bandit theoretical context, the machine-learning community [56] has derived algorithms that can learn about the machine's performance, i.e., the average money gain (respectively, transmitting a given amount of data), while minimizing the money to pay (respectively, avoiding bands to be occupied by primary users). This approach is based on a "try-and-evaluate" model that permits exploiting the resources (i.e., communicating for the opportunistic-spectrum-access scenario) as soon as the learning process starts, and improves its learning capabilities all along the operating process. Upper confidence bound algorithms are one family of solutions that solves the multi-armed bandit problem. The upper confidence bound converges in a proven manner to the best choice between a set of possible solutions.

Figure 12 gives the example of a choice among 25 configurations, each configuration being a set of PHY layer parameters, which is another cognitive-radio scenario, different from opportunistic-spectrum access. We could consider the "best" choice with respect to a green constraint, for instance. For the sake of clarity and without any loss of generality, the configurations were ordered from the worst at the left-hand side to the best at the right-hand side, on the basis of a given quality criterion. We can see how, after different numbers of trials, the upper confidence bound algorithm enables selecting the best configurations more and more. In Figure 12, on the left-hand side, we can see how different upper confidence bound algorithms behave and are compared to the uniform strategy (which results in 10 trails after 250 iterations on 25 possible configurations). In Figure 12 on the right-hand side, we then can see that the best configuration has been played almost 90% of the time after 50,000 iterations, and the three best configurations have been played almost 99% of the time.

Moreover, it has also been proven, as shown in Figure 13, that the upper confidence bound algorithms still converge in the presence of errors on the estimation metric. If we come back to the opportunistic spectrum-access scenario, detection errors may occur, e.g., a secondary user may detect a free band as being occupied. Even with a very unfavorable error rate of 40%, the upper confidence bound still converges. It just takes too much time to converge with the same level of selection.

4.3.3 Vertical Handover in Order to Decrease Electromagnetic Pollution

In this example, the blind standard recognition sensor was used [51]. It gives all the information about the standards existing in the vicinity of the equipment without connecting to them. On the basis of the information provided

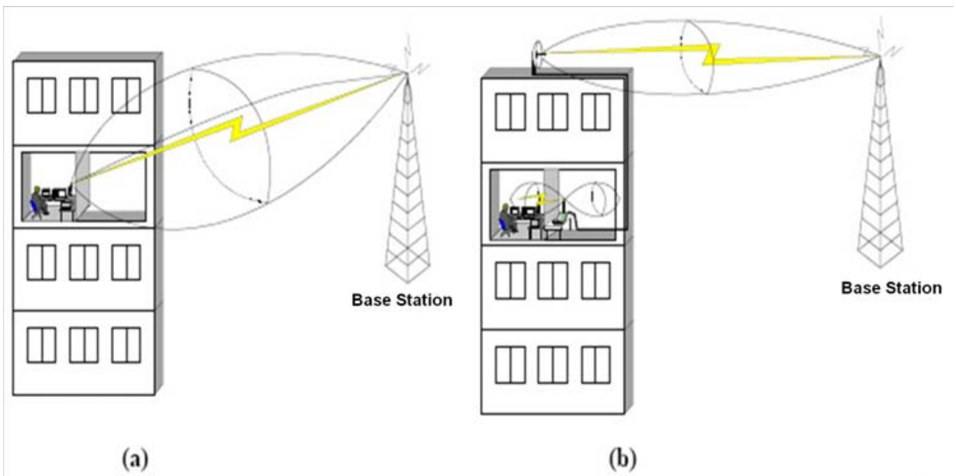

Figure 14. Wireless Internet access: (a) direct from the terminal; (b) wired inside the building and then through a centralized wireless directional access point outside the building, in order to decrease the transmission power.

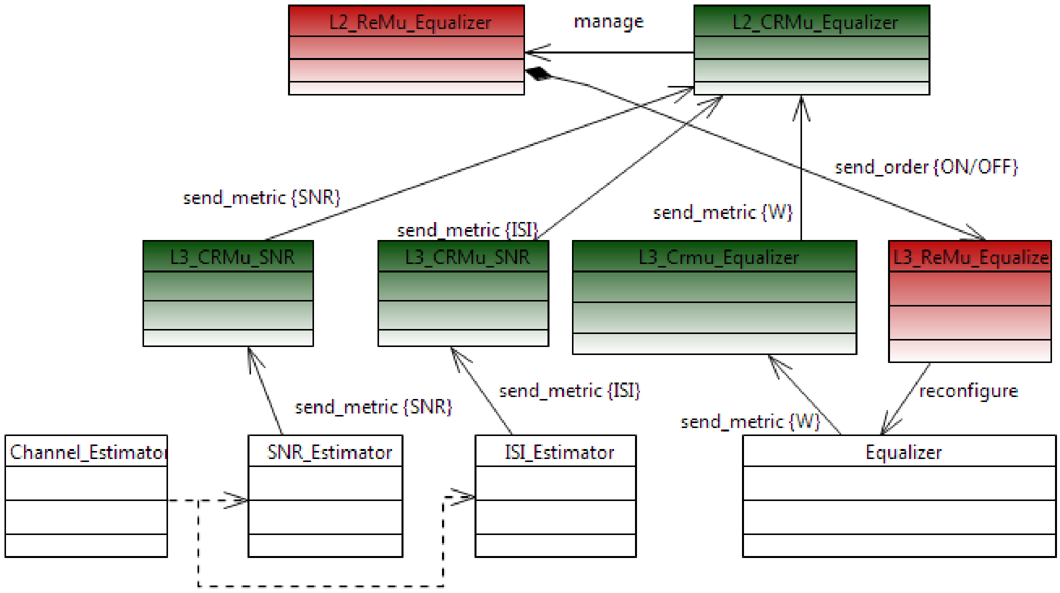

Figure 15. The deployment of HDCRAM modeling for equipment supporting the proposed cognitive green radio scenario with option 1.

by other sensors, such as the indoor/outdoor sensor, the cognitive-radio equipment may decide to use a less-powerful standard (Wi-Fi instead of cellular), for the same service. As a consequence, this scenario is another way of limiting a person's exposure to radiation.

Figure 14 presents the situation in which indoor Wi-Fi is present and connected to a cellular or broadband access network. In such a case, it is usually preferable to choose the local connection. From the point of view of the radiation level, it is always better to have a wired connection indoor and to have a roof connection with the cellular network. This is the kind of decision that modern radio equipment should be able to take, depending on the service requested by the user. The benefits here are twofold. On the one hand, the radiation power is limited inside the building, where people live. On the other hand, a reduced-power transmission is possible so as to access the network, since a directional antenna can be used on the roof to access the network.

4.4 Design Tools for Cognitive Green Radio Equipment

However, the cognitive green radio perspective is highly dependent on the ability of both the radio-research and industrial communities to provide design tools and design environments for cognitive radio equipment. For 15

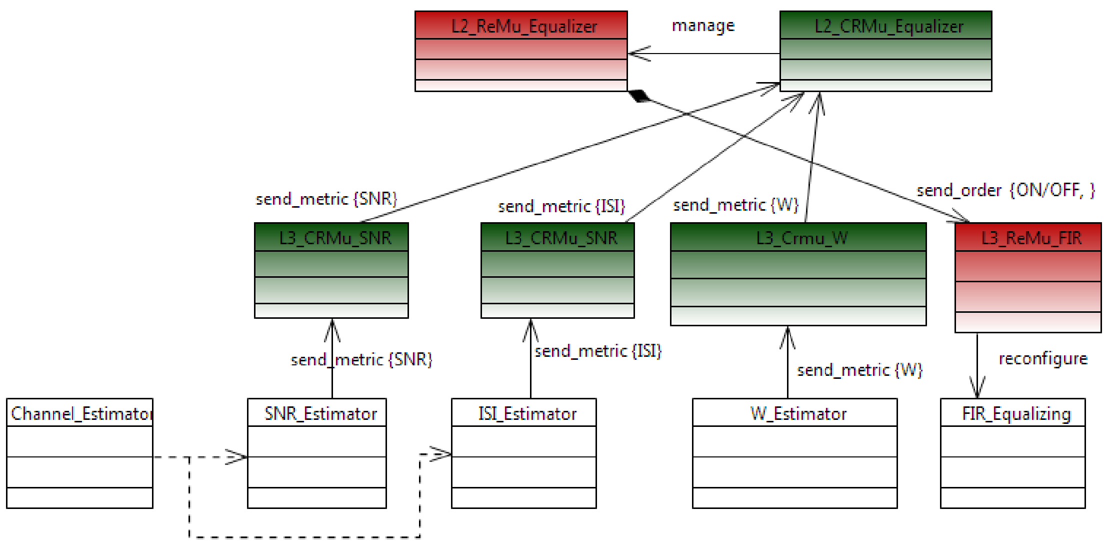

Figure 16. The deployment of HDCRAM modeling for equipment supporting the proposed cognitive green radio scenario with option 2.

years, the software-defined radio domain has been facing a lack of integrated design solutions. Software-defined radio design is still a manual process, where designers combine several environments from several domains (processor programming, reconfigurable hardware programming, hard-wired electronics, etc.) in their own way. This means that software-defined-radio design still needs to go a long way, and is still very complex. In other words, the current capabilities for implementation of software-defined radio are far from software-defined radio's promises.

A cognitive radio's design environment should thus provide facilities to implement:

- Highly flexible signal-processing functions;
- Means to sense the internal/external environment of the cognitive radio's equipment;
- Learning and decision-making algorithms that can make the decision to reconfigure the equipment in the best configuration at each instant.

This should be implemented on a highly flexible hardware platform, made of flexible electronic processing units. However, all of this is not enough without the associated management of flexibility that goes up to self-adaptivity in the cognitive-radio context. Some proposals are emerging in the research community, such as ALOE [55], which proposes real-time mapping facilities of processing on multi-processing platforms. HDCRAM is another approach, aiming at proposing an architecture that could include any decision-making, sensing, or flexible algorithm, while providing the necessary infrastructure to make them communicate and work together for global purposes of self-adaptation [33].

We can use the equalizer example of Section 4.1.3 as a design example based on HDCRAM. Figure 15 and Figure 16 detail the block diagram of options 1 and 2, respectively. These views are not views of signal-processing block diagrams, where the data flow between the various blocks is usually represented. They represent the architectural point of view of these two options in a cognitive-radio context. Metric flows, from white signal processing sensors to red cognitive managers, are represented, as well as the flows of reconfiguration orders, from red cognitive managers towards green configuration managers, down to white reconfigurable operators. Here, reconfiguration is just binary: switching on or switching off the reconfigurable operator.

In option 2, only the FIR [finite impulse response] of the equalizer is reconfigurable (switched on or switched off). Channel coefficients are always computed so that when the equalizer finite impulse response is switched on, it can directly run with good coefficients.

5. Conclusions

In summary, decreasing the energy consumption of future wireless communication networks while improving their energy efficiency is demanding ever-growing attention worldwide. This is true not only within government, industrial, and standardization bodies, but also within international research communities. Moreover, it has been widely recognized that future radio-communications systems should reduce their electromagnetic radiation levels in order to realize a harmonized coexistence of various wireless systems, as well as reduced human exposure to any kind of harmful radio radiation.

Doubtlessly, making information and communications technology equipment and applications "greener" in terms of energy consumption and electromagnetic radiation will not only help various telecommunication companies to attain their sustainable profitability, but will also have a profound positive impact on the global environment and human society. Surely, energy-efficient communications and networks are strongly expected by the world to reduce dependence on fossil fuel, to enable fluent on-demand response and efficient utilization of energy resources, and to ultimately achieve sustainable global long-term prosperity. It is believed that the long-term evolution roadmap of the next-generation telecommunications systems (5G) will point to an energy-efficiency dominated era.

In particular, this article has explained the basic features of green radio, and the relevant fundamental approaches to increasing energy efficiency at the network as well as the component level. Furthermore, the key role of cognitive green radio has been strengthened for improving energy efficiency, within which various learning algorithms, decision-making techniques, and design tools have been discussed, with power-consumption constraints. Finally, the electromagnetic-pollution issue in the scenario of opportunistic spectrum access has also been investigated.

6. Acknowledgments

This work received French state support granted to the CominLabs excellence laboratory, and managed by the National Research Agency in the "Investing for the Future" program, under reference No. ANR-10-LABX-07-01. The authors would also like to thank the Region Bretagne, France, for its support of this work.

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Book Reviews for Radioscientists

Modern Electrodynamics

by Andrew Zangwill, Cambridge, Cambridge University Press, 2013, ISBN 9780521896979, £50.00

I sincerely recommend *Modern Electrodynamics* by Andrew Zangwill. This book provides a *clear* and *modern* discussion over a broad range of topics in electrodynamics. *Clarity* is the key feature of this book. The author constructs the book like an adept house builder. It is very well structured. A blueprint is planned, based on the classical topics in electrodynamics. The author then lays the foundation and builds the framework of the book by developing and expanding on related physical concepts in each chapter. The "house" of electrodynamics is completed by adding boards, siding and a roof of a clearly mathematical origin. As mentioned in the introduction, all this is done with "an engaging writing style and strong focus on physical understanding." Different from many classical textbooks on electromagnetism that are mathematically heavy, the author uses mathematics as an enabling tool. He succeeds in using qualitative arguments to clarify complex mathematics. In this way, Zangwill gives prominence to the development of electrodynamics, and makes this book a real *electrodynamics* book.

The second key word, as in the title, is "*modern*." Many conventional topics, such as static fields, electromagnetic waves, special relativity, to name a few, which keep reoccurring in many classical textbooks on electrodynamics, are in Zangwill's book seamlessly integrated with their "modern" interpretation. Zangwill shows the connections of electrodynamics to all other aspects of *modern* physics. The book contains 24 chapters, and covers the most important topics of electromagnetic field theory. This includes important issues such as retardation and radiation effects, but also fields of moving particles, a glimpse of quantum electrodynamics in Chapter 2, the recent developments in metamaterials in Chapter 18, and even Noether's theorem in field theory. At the end of each chapter, there is a section called "Sources, References and Additional Reading." Each chapter is rather self-consistent, and can be consulted to refresh or increase deeper understanding of a selected topic. The additional application notes and examples also make this book very attractive for the curious reader.

In short, I believe Zangwill's *Modern Electrodynamics* could make a hit in the textbook market and, more importantly, could have a serious impact on the future writing style of books on electromagnetics. This book is one of the best books about electrodynamics I have read, up to now. It greatly contributes to the development of physical understanding, is already used heavily within my research group, and is thus highly recommended.

Guy Vandenbosch
ESAT-TELEMIC
Kasteelpark Arenberg 10 bus 2444
B-3001 Heverlee (Leuven), België
E-mail: guy.vandenbosch@esat.kuleuven.be

Have you written a book? Do you know a book written by a colleague that might be of interest for the URSI community? We would be glad to publish a review of such books in our URSI *Radio Science Bulletin*. Please contact our Associate Editor on book reviews, Kristian Schlegel (ks-ursi@email.de).

Conferences

CONFERENCE REPORTS

AFRICON

Mauritius, Africa, 9 - 12 September 2013

From September 9 to 12, 2013, the IEEE AFRICON conference was held on the island of Mauritius in Africa. IEEE AFRICON is the premier biennial event of the IEEE in Africa. This flagship conference provides a platform for academics and industry professionals to share ideas and present their latest research. The event was co-sponsored by the IEEE Region 8 and the IEEE South Africa Section.

In order to strengthen the science connections between Europe and Africa, and to connect URSI and the IEEE, the URSI Commissions B, E, and J organized a special 1.5 day session during AFRICON 2013 entitled "Large-Scale Science Projects: Europe-Africa Connects," emphasizing each of the scientific Commissions (Figure 1).

The program covered an interesting and wide range of talks. There was the official welcome by the General Chair, Arnold van Ardenne (ASTRON, The Netherlands), and a welcome by Takalani Namaungani (Director, Global Projects Department of Science & Technology, South Africa) who introduced the African-European Radio Astronomy Platform, co-sponsor of the event. Three keynote speakers then presented their latest work. Prof. Howard Reader (Stellenbosch University, South Africa) presented interesting work on new robust approaches to designing large radio research instruments. There were of course highlights of the SKA, the Square Kilometer Array, the world largest radio telescope. Prof. Per Simon Kildal from Chalmers Technical University in Sweden (and also an IEEE AP-S Distinguished Lecturer) talked about "Some Reflector and Feed Antenna Inventions that Made a Difference." The third keynote speaker was from the island of Mauritius, Dr. Girish Kumar Beeharry (University of Mauritius). He presented the "Multi-Frequency Interferometry Telescope for Radio Astronomy (MITRA)," the radio telescope on Mauritius. The day before the conference, some attendees of the event visited the MITRA site, and discussed connections between the project and so-called aperture array developments (Figure 2).

Figure 1. Participants of the special URSI-BEJ session at the AFRICON 2013 conference.

Figure 2. A visit to the MITRA site on Mauritius, prior to the meeting.

After this opening session, there was a session on "Field and Waves," with papers on the optical design for the Square Kilometer Array (Isak Theron, EMSS Antennes), aperture arrays for the SKS (Jan Geralt bij de Vaate, ASTRON), and a prototype dual-polarized log-periodic antenna array for the MITRA (Jaisridevi Shibchurn, University of Mauritius). This concluded the first day of the special URSI-BEJ session.

The next day, we continued with a session on electromagnetic environment and interference. David Giri (University of New Mexico) presented the control of electromagnetic effects using topological concepts. Franz Schlagenhaufer (ICRAR, Australia) talked about the RFI assessment of photovoltaic modules for radio-astronomy applications. Nikola Djuric (SEMONT) presented a monitoring system and its influence on EM pollution protection. Domingos Barbosa (IT, Portugal) finished this session with a discussion on the design, sustainability, and environmental considerations for new African observatories.

The fourth session was devoted to large radio-astronomy instruments. Mark Bentum (University of Twente/ASTRON) presented a unique concept for a radio telescope for very low frequencies in space, OLFAR (Orbiting Low-Frequency Antennas for Radio Astronomy).

Figure 3. The URSI booth at the conference, hosted by Truus van den Brink (ASTRON).

Rob Millenaar (SKA office) presented considerations for an optimal radio-astronomy site. The content of his talk was used in the consideration of where to locate the Square Kilometer Array. Dominique Ingala (Durban University of Technology) presented details of the MITRA radio telescope. Finally, Stefan Wijnholds presented his interesting work on computing the cost of sensitivity and survey speed for aperture-array and phased-array feeding systems.

After the break, we continued with radio-astronomy instruments. Michael Garrett (ASTRON) gave an interesting talk about astronomy and wide-field antenna developments. Oleg Smirnov (SKA South Africa) presented the SKA Africa project, and discussed the performance limits of future instruments and surveys. VLBI (very large baseline interferometry) was also a topic of this conference. Michael Lindqvist (Chalmers Technical University) presented both the technical and the science parts of the European VLBI Network. Oleg Smirnov presented the African counterpart, the African VLBI Network. Sergio Colafrancesco completed the URSI session with a nice talk on a high-frequency radio-polarization look at the sky: from Africa to deep space.

The event was a great success and all participants considered it extremely useful. As intended, it was also considered an important step in enlarging radio science (including radio astronomy) collaboration between Europe and Africa. As this URSI event (Figure 3) was held in connection with the AFRICON 2013 event, excellent contacts were established between the AFRICON organizers, which emphasized the engineering sciences associated with IEEE Region 8 (which includes Europe and Africa), URSI, and the framework of RadioNet. In fact, one could contemplate an African connected to RadioNet to broaden its base, and to the new radio-astronomy projects in Africa (e.g., the SKA, African VLBI array, etc.).

Mark Bentum
University of Twente
E-mail: m.j.bentum@utwente.nl

OCOSS 2013

Nice, France, 28 - 30 October 2013

OCOSS 2013 (Ocean and Coastal Observation Sensors and Observing Systems 2013) was held October 28-30, 2013, in Nice, France. Not surprisingly, OCOSS 2013 illustrated the complexity, the variety, and the wide range of subjects covered by the observation of coasts and oceans. Thanks to the enthusiasm of participants coming from various French and foreign laboratories and institutions, the discussions were particularly intense and enriching.

The four invited speakers perfectly reflected the wide range of topics:

- "The Oceans Observed from Space" by Benoît Messygnac (CNES-LATMOS)
- "Radio Sciences Involvement in Disaster Management" by Prof. François Lefeuvre (CNRS LPC2E Orléans, France, URSI past President)
- "New Technologies Applied to the Marine Biology" by Prof. Denis Allemand (Scientific center of Monaco)
- "Recent Developments and Emerging Trends in Radar Remote Sensing" by Prof. Madhu Chandra (Technische Universität Chemnitz, Germany)

The scientific committee bravely succeeded in arranging the wide variety of selected papers (65% of submitted papers) into nine oral sessions and one poster session. It had been decided beforehand to structure the conference into a single plenary session, so as to allow participants to benefit from all presentations. As a result, presentations were very dense, and the short coffee breaks were not enough to exhaust all the questions. Exchanges of views will probably continue by e-mail with the initial contacts having been established. This can unquestionably be considered as a success of this third edition of OCOSS, after the editions that took place in Paris in 2007, and in Brest in 2010. Despite this tight program, several URSI members (see Figure 1) were able to discuss among themselves regarding presenting projects at the next URSI GASS 2014 (Beijing, August 17-23, 2014).

Another remarkable point is that the meeting attracted a great number of young, motivated researchers (the median age of participants was well below 40 years), to judge from the many questions and lively discussions during lunch hours and even at the gala dinner.

It goes without saying that remote sensing was given a lion's share (three oral sessions and the poster session). The S4 session, "Awareness System and Risk Management," was a rather unusual session because it regrouped very cleverly presentations as diverse as the following. There was a presentation by the European Maritime Safety Agency (EMSA, Portugal), entitled "Integrated Maritime Data Environment (IMDatE) Platform: EMSA Capability to Provide Real Time Integrated Maritime Information Services," by its Director, Marin Chintoan-Uta. There was a presentation by Séverine Borderon and Johan Thomas (GREDEG-UNS and Mines ParisTech), entitled "Confronting Marine Exploitation to the Legal and Technical Aspects Of Ecological Compensatory Mitigation: French Example," which dealt with the relationship between sea exploitation and ecological compensation seen from a legal standpoint. There were two less-exotic presentations. One covered "Real-time Monitoring of Energy Efficiency and its Application," by Weidong Chen (Center for Maritime Studies, National University of Singapore). The other was on "Simplification of the Display Maritime Routes Using an Adapted Mean-Shift Algorithm," by Romain Gallen (CETMEF, France). The latter won the prize (see Figure 2) for "Best Young Researcher Paper."

Sessions S7 and S8 were on "Sensors for Environmental Ecosystem Assessment: Multiscales & Multi-Physics Models," and "Innovative Multifunctional Sensors for In-Situ Monitoring of Marine Environment and

Figure 1. URSI members (l-r: J. Isnard, T. Tanzi, M. Chandra, and F. Lefeuvre).

Figure 2. The Best Young Researcher Paper was awarded to Romain Gallen.

Figure 3. The Best Student Paper was awarded to Loïca Avanthey.

Related Maritime Activities.” During these, we noted the presentation on risk evaluation, “Analysis of the Impact of the Tohoku Tsunami (11th March 2011) on the Marine Environment and Coastal Area of Fukushima (Japan),” by Justine Caniac et al. (IRSN and Univeristy Sud Toulon-Var, France).

Two papers dealt with measurements. “2.4 GHz Radio Transmission Measurements in a Basin Filled with Sea Water” was by François Le Pennec et al. (LabSTIC/MoM-Telecom Bretagne et Ifremer, France). “First Measurements of Ocean Currents in the Mediterranean Sea with a Bistatic Phase Coded Radar” was by Samuel Grosdidier et al. (DIGINEXT et ANTHEOP, France). The paper on autonomous underwater vehicles (AUVs), “First Steps for Operational Dense and High-Resolution Mapping of Shallow Water Using Dedicated Robots,” by Loïca Avanthey et al. (Institut Mines-Télécom, Télécom Paristech CNRS-LTCI, France) won the “Best Student Paper” prize (see Figure 3).

Two demonstrations were presented during the meeting:

- “Indoor Autonomous Navigation Drone Demonstration,” by Ludovic Apvrille and Jean-Luc Dugelay (Institut Mines-Telecom, Telecom Paristech CNRS-LTCI and Eurécom). They flew an *indoor* UAV among participants during the cocktail reception given by the Nice town hall.
- “Autonomous Wireless Sensors Networks,” presented by Alain Pegatoquet (LEAT UNS CNRS UMR 7248), showed some aspects of the work of LEAT on energy management applied to sensor networks.

When participating in such a manifestation, one necessarily comes to reflect upon the interdisciplinary aspect! Several contributions, coming from various scientific fields, dealt with concepts based on experimental work. These, transformed into mathematical terms and extricated from their original experimental domain, could well become candidates for playing an interdisciplinary role: let us wait for volunteers!

Each participant was given upon his/her arrival the proceedings of the meeting, which helped people to follow

Figure 4. The gala dinner.

Figure 5. Some participants after lively discussions on new trends in remote sensing

the various sessions. Moreover, the summary report of the previous OCOSS 2010 meeting in Brest (REE 2011-4), together with various general information, was distributed.

At the closing session, Tullio Tanzi presented a brief summing up of OCOSS 2013. He announced that the next meeting would be held in 2015, probably in the Far East, according to various rumors.

In short, a straightforward, efficient, and amicable organization resulted in a dense and fruitful manifestation. This was continued during the gala dinner (see Figure 4), where local gastronomy was served (starting with “bagna càuda!”).

The Institut Mines-Telecom, the University of Nice-Sophia Antipolis, and the City of Nice also contributed to the success of the meeting. The success of this kind of meeting very much depends on the commitment of a competent and efficient local team. This was definitively the case of the team set up by Prof. Tullio Tanzi and Jean-Pierre Damiano. Let us say a hearty thank you to both of them, as well as to all backstage actors.

It is now up to our colleagues in the Far East to take up the challenge for 2015.

Jean Isnard
URSI France (Commission F)
E-mail: jisnard-isti@club-internet.fr

URSI CONFERENCE CALENDAR

An up-to-date version of this conference calendar, with links to various conference web sites can be found at http://www.ursi.org/en/events.asp

January 2014

RCRS 2014 – Regional Conference in Radio Science
Pune, India, 2-5 January 2014
Contact: Prof. Akshay Malhotra, Deputy Director, SIT, Pune, Symbiosis Institute of Technology (SIT), Symbiosis International University, Tel : +91 20 39116300, 6404 / 6407, e-mail: rcrs2014@sitpune.edu.in, http://www.sitpune.edu.in/abstract_submission_form.php

URSI National Radio Science Meeting
Boulder, Colorado, USA, 8-11 January 2014
Contact: Prof. Steven C. Reising, Director of Microwave Systems Laboratory, Colorado State University, 1373 Campus Delivery, Fort Collins, CO 80523-1373, USA, Fax: +1-970-491-2249, Email: steven.reising@colostate.edu, http://www.nrsmboulder.org/

VERSIM-6 - Sixth VERSIM Workshop
Dunedin, New Zealand, 20-23 January 2014
Contact: Prof. Craig J. Rodger, Department of Physics, University of Otago, PO Box 56, Dunedin 9016, NEW ZEALAND, Fax: +64 3 479 0964, E-mail: crodger@physics.otago.ac.nz, http://www.physics.otago.ac.nz/versim/VERSIM_workshop_Dunedin_2014.html

February 2014

SPIN 2014 International Conference on Signal Processing and Integrated Networks
Noida, India, 21-22 February 2014
Contact: Dr. P. Banerjee, Dept of Electronics and Communication Eng., Amity School of Engineering and Technology, Amity University Uttar Pradesh, Sector 125, Noida 201301, (U.P.), INDIA, E-mail: spin2014@amity.edu, http://www.spin2014.com

April 2014

RADIO 2014 - Radio and Antenna Days of the Indian Ocean 2014
Flic-en-Flac, Mauritius, 7-10 April 2014
Contact: Conference Secretariat RADIO 2012, University of Mauritius, Réduit, Mauritius, Fax: +230 4656928, E-mail: radio@uom.ac.mu, http://sites.uom.ac.mu/radio2012/

May 2014

EMC'2014 - 2014 International Symposium on Electromagnetic Compatibility
Tokyo, Japan, 13-26 May 2014
Contact: E-mail: emc14-contact@mail.ieice.org, http://www.ieice.org/~emc14/

June 2014

EUSAR 2014 – 10th European Conference on Synthetic Aperture Radar
Berlin, Germany, 2-6 June 2014
Contact: Mr. Jens Fischer (DLR), EUSAR 2014 Executive, Oberpfaffenhofen, 82234 Wessling, Germany, Fax: +49 8153-28-1449, E-mail: eusar2014@dlr.de, http://conference.vde.com/eusar/2014

August 2014

COSPAR 2014 ("COSMOS")
40th Scientific Assembly of the Committee on Space Research (COSPAR) and Associated Events
Moscow, Russia, 2-10 August 2014
Contact: COSPAR Secretariat, c/o CNES, 2 place Maurice Quentin, 75039 Paris Cedex 01, France, Tel: +33 1 44 76 75 10, Fax: +33 1 44 76 74 37, cospar@cosparhq.cnes.fr, http://www.cospar-assembly.org/

ICEAA 2014 - International Conference on Electromagnetics in Advanced Applications
Palm Beach, Aruba, 3-9 August 2014
Contact: Prof. P.L.E. Uslenghi, Dept. of ECE (MC 154), University of Illinois at Chicago, 851 So. Morgan St., Chicago, IL 60607-7053, USA, E-mail: uslenghi@uic.edu, http://www.iceaa.net/

URSI GASS 2014 - XXXIst General Assembly and Scientific Symposium of the International Union of Radio Science
Beijing, China CIE, 16-23 August 2014
Contact: URSI Secretariat, Sint-Pietersnieuwstraat 4, B-9000 Ghent, Belgium, E-mail: info@ursi.org, http://www.chinaursigass.com and http://www.ursi.org

Metamaterials 2014 - Eight International Congress on Advances Electromagnetic Materials in Microwaves and Optics
Copenhagen, Denmark, 25-28 August 2014
Contact: Prof. R.W. ZIOLKOWSKI, Dept. of Electrical and Computer Engineering, University of Arizona, 1230

E. Speedway Blvd., Tucson, AZ 85721-0104, USA, Fax : +1 520 621-8076, E-mail : ziolkowski@ece.arizona.edu http://congress2014.metamorphose-vi.org

September 2014

EMC Europe 2014
Gothenburg, Sweden, 1-4 September 2014
Contacts: Symposium Chair: jan.carlsson@sp.se, Technical Program Chair: peterst@foi.se, http://www.emceurope2014.org/

November 2014

APMC 2014 – Asia-Pacific Microwave Conference
Sendai, Japan, 4-7 November 2014
Contacts: Prof. Noriharu Suematsu [Chair, Steering Committee] c/o Real Communications Corp., 3F Shinmatsudo S bldg., 1-409 Shinmatsudo, Matsudo 270-0034, Japan, Fax: +81-47-309-3617, E-mail: 2014secrt@apmc2014.org, http://apmc2014.org/

May 2015

URSI Mid-Atlantic Meeting 2015
ExpoMeloneras Convention Centre, Gran Canaria, Spain, 18-25 May 2015
Contact: Prof. Peter Van Daele, URSI, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium, E-mail: peter.vandaele@intec.ugent.be

URSI cannot be held responsible for any errors contained in this list of meetings

News from the URSI Community

NEWS FROM A MEMBER COMMITTEE

GERMANY

Symposium in Honour of Karl Rawer

Prof. Dr. Karl Rawer (March, Germany) was able to celebrate his 100th birthday in good health this year.

Karl Rawer was born in Neunkirchen/Saarland on April 19, 1913, i.e., not long after the ionosphere was discovered, and he has dedicated his life to the exploration of this part of Earth's environment. The horrible events of World Wars I and II shaped Rawer's early life, but they also launched his career as one of the eminent geophysics scientists of the twentieth century. After studies in mathematics with Gustav Doetsch in Freiburg, and physics with Arnold Sommerfeld in München, he wrote his doctoral dissertation with Jonathan Zenneck, developing the theory of high-frequency radiowave propagation and reflection in the ionosphere. At the end of WWII, Rawer assembled a team of scientists and engineers to establish ionospheric research institutes near Freiburg, under the auspices of the French Service de Prévision Ionosphérique de la Marine and the Deutsche Post. In 1953, Rawer's book *Die Ionosphäre* appeared. This was the first book ever that discussed wave propagation in the context of ionospheric morphology. It was reissued in English in 1957.

In 1954, Rawer's team participated in the first launch of the Veronique rocket for ionospheric exploration in Hammaguir, Algeria. In 1963, he founded the Arbeitsgruppe für Physikalische Weltraumforschung (APW) in Freiburg, with support from the Fraunhofer Gesellschat. This eventually transitioned into the Institut für Physikalische Weltraumforschung. With project funding from the Deutsche Forschungsgemeinschaft, and in cooperation with NASA and the European Space Agency ESRO, instruments for the measurement of temperature and ion composition were launched on the AEROS-A (1972) and AEROS-B (1974) satellites. The AEROS satellite measurements complemented the ionosonde and incoherent-scatter-radar measurements used for the development of the International Reference Ionosphere (IRI). In 1968, COSPAR – joint with URSI in 1969 – formed the IRI Task Force, and appointed Karl Rawer its first chair. Today, the empirical IRI model, which is periodically revised after ingestion of new observational data, has become the world's most trusted ionospheric model, and an ISO standard.

To honor this outstanding scientist, the German National URSI Landesverband organized a special session during its annual National URSI Meeting (Kleinheubacher Tagung 2013) in Miltenberg on September 24, 2013. Karl Rawer attended this session, following the presentations with great interest, and commenting on the progress of today's ionospheric research.

The session started with welcome addresses by Wolfgang Mathis (President of the German URSI Landesverband) and Matthias Förster (German Commission G Chair, and co-organizer of the session). Two invited presentations followed. Bodo Reinisch (Lowell Digisonde International, Lowell, Massachusetts USA; a former student of Rawer, and co-organizer of the session) summarized Rawer's scientific achievements in "Space Research and International Cooperation – Laudation on the Occasion of the 100th Birthday of Professor Karl Rawer." Helmut Rucker (Space Research Institute, Austrian Academy of Sciences, Graz, Austria) recalled Rawer's contribution to radiowave propagation with respect to radio astronomy in "Planetary Radio Astronomy: Earth, Giant Planets and Beyond."

In the following presentations, Rawer's former students and collaborators highlighted several aspects of Rawer's scientific achievements, work inspired by or related to him, and his international activities:

- Dieter Bielitza (NASA Goddard Space Flight Center, Greenbelt Maryland, USA): "The International Reference Ionosphere – Rawer's IRI and its Status Today"
- Kristian Schlegel (Copernicus Gesellschaft, Göttingen, Germany): "Ionospheric Research in Germany Prior to Karl Rawer"
- Thomas Dambold (Darmstadt, Germany): "Karl Rawer and HF Radio Propagation Predictions"
- Francois Lefeuvre (LPE2C/CNRS, Orleans, France): "Following Karl Rawer's Research"
- Jürgen Röttger (Max-Planck-Institut für Sonnensystemfosrchung, Katlenburg-Lindau, Germany): "Past Decades of Research on Shortwave Oblique Incidence Sounding at MPAe"
- Gerard Schmidtke (Fraunhofer-Institut für Physikalische Messtechnik, Freiburg, Germany): "State of the Art: Solar Spectral Irradiance in the Extreme Ultraviolet Region"
- Sandro Radicella (The Abdus Salam International Centre for Theoretical Physics, Trieste Italy): "IRI Task Force Activities in Trieste Inspired by Karl Rawer"
- Ernst-Dieter Schmitter (University of Applied Sciences Osnabrück, Germany): "VLF/LF Radio Wave Remote Sensing and Propagation Modeling of Lightning-Caused Long Recovery Events within the Lower Ionosphere
- Werner Singer, R. Latteck, J. Bremer (Leibniz-Institut für Atmosphärenphysik, Universität Rostock, Kühlungsborn, Germany) and M. Friedrich (Technical University of Graz, Austria): "D-Region Electron Densities from Radio Wave Propagation Experiments at Mid and High Northern Latitudes"
- Gerd K. Hartmann (Bilshausen, Germany): Kleinheubach-URSI: "48 Years Home for the German-Austrian Beacon Satellite Community (BSC)"
- Ljiljana R. Cander (STFC Rutherford Appleton Laboratory, Harwell Oxford, UK) and Bruno Zolesi (Istituto Nazionale di Geoficia e Vulcanologia, Rome, Italy): "Four Ionospheric COST Actions – Effects of the Upper Atmosphere on Terrestrial and Earth-Space Communications and Navigation"
- L. Kozienko, S. Kolesnik, N. Klimov, and K. Cherkashin (Irkutsk State Transport University, Irkutsk, Russia): Analysis of Positioning Variations of a Spatial Placed Single-Frequency GPS_GLONASS Receiver"
- Michael Rietveld (EISCAT Scientific Association, Ramfjordbotn, Norway): "High Latitude Ionospheric Research in Europe After Three Decades: EISCAT at a Turning Point"
- S. P. Gupta (Physical Research Laboratory, Ahmedabad, India): "Long Term Changes in Nature of Type-1 Plasma Irregularities in Electrojet Region Over India"
- T. L. Gulyaeva (IZMIRAN, Moscow, Russia), F. Arikan (Hacettepe University, Ankara, Turkey), and I. Stanislawska (Space Research Center, PAS, Warsaw, Poland): "Probability of Occurrence of Planetary Ionospheric Storms Associated with the Magnetosphere Disturbance Storm Time Events"
- Matthias Förster (GFZ German Research Centre for Geosciences, Potsdam, Germany) and M. Vellante (Dipartimento di Scienze Fisiche e Chemiche, Univeta dell'Aquila, Italy): "The Dynamics of the Ionosphere-Plasmasphere System"
- A. V. Mikhailov (Pushkov institute of Terrestrial Magnetism, Troitsk, Moscow, Russia) and L. Perrone (Istituto Nazionale di Geofisica e Vulcanologia, Rome Italy): "A Method for foF2 Short-Term (1-24 Hour) Predictions Over Europe"

The abstracts of the presentations can be found at the Web page of the National German URSI Landesausschuss at http://www.kh2013.de/ kleinheubacher_tagung_2013_abstracts.pdf. They will be published in the open-access journal *Advances in Radio Science* (*ARS*): http://www.advances-in-radio-science.net/.

Kristian Schlegel
Copernicus Gesellschaft e.V. Göttingen, Germany
E-mail: ks-ursi@email.de

Bodo Reinisch
Lowell Digisonde International, Lowell, MA 01854, USA

International Geophysical Calendar 2014

U.R.S.I.

	S	M	T	W	T	F	S
JANUARY				1 N	2	3	4
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21+	22 N*+	(23)*	●24*	(25)	26	27	
28	29	30	31	1	2	3	2015 JANUARY
4	5 F	6	7	8	9	10	
11	12	13	14	15	16	17	
18	19*	(20) N*	●21*	(22)	23	24	
25	26	27	28	29	30	31	
S	M	T	W	T	F	S	

(14) Regular World Day (RWD)

● 12 Priority Regular World Day (PRWD)

■ 15 Quarterly World Day (QWD) also a PRWD and RWD

1 Regular Geophysical Day (RGD)

13 14 World Geophysical Interval (WGI)

\+ Incoherent Scatter Coordinated Observation Day (The period Jan 14-Feb 15 is a StratWarm Alert interval with a fallback interval of Feb 9-15. The period March 24-April 7 is a magnetic storm alert interval with a fallback period of Sept 14-Oct 2. In the case of no magnetic storm, the run will fulfill the alternating year quiet time measurements that will start Sept 27.)

N NEW MOON F FULL MOON

29 Days of Solar Eclipse: April 29, annular; Oct 23, partial

30 31 Airglow and Aurora Period

29* Dark Moon Geophysical Day (DMGD)

This Calendar continues the series begun for the IGY years 1957-58, and is issued annually to recommend dates for solar and geophysical observations, which cannot be carried out continuously. Thus, the amount of observational data in existence tends to be larger on Calendar days. The recommendations on data reduction and especially the flow of data to World Data Centers (WDCs) in many instances emphasize Calendar days. The Calendar is prepared by the International Space Environment Service (ISES) with the advice of spokesmen for the various scientific disciplines.

The Calendar provides links to many international programs, giving an opportunity for scientists to become involved with data monitoring and research efforts. International scientists are encouraged to contact the key people and join the worldwide community effort to understand the Sun-Earth environment.

The definitions of the designated days remain as described on previous Calendars. Universal Time (UT) is the standard time for all world days. Regular Geophysical Days (RGD) are each Wednesday. Regular World Days (RWD) are three consecutive days each month (always Tuesday, Wednesday and Thursday near the middle of the month). Priority Regular World Days (PRWD) are the RWD which fall on Wednesdays. World Geophysical Intervals (WGI) are fourteen consecutive days in each season, beginning on Monday of the selected month, and normally shift from year to year. In 2014 the WGI are January, April, July, and September. Quarterly World Days (QWD) are one day each quarter and are the PRWD which fall in the WGI. The 2014 FINAL Calendar is available in PDF format.

2014 Solar Eclipses:
The year 2014 has one annular and one partial eclipse, but no total eclipse. The area of annularity of the annular eclipse is so small and difficult to reach it is unlikely that anyone will see that phase. Maps are accessible through http://www.eclipses.info, the site for the International Astronomical Union's Working Group on Eclipses.

a. **29 Apr 2014, annular solar eclipse**. An annular eclipse with 98.7% of the sun's diameter covered would be visible from a small region in Antarctica due south of Australia, centered at 06:04:32 UTC, if anybody could get there and could detect the sun on the southwestern horizon. A partial eclipse of about 60% coverage will be available in Australia from Perth, diminishing to the north (about 10% at Darwin), and farther east near sunset. The eclipse will not reach to New Zealand on the East or to Papua New Guinea on the North, though it barely reaches southernmost and easternmost parts of Indonesia as well as East Timor.

b. **23 October 2014, partial solar eclipse**. A partial solar eclipse will be visible from the continental United States plus Alaska (but not Hawaii in the west or extreme eastern New England in the east), all but easternmost Canada, and Mexico. Western states and provinces will be favored. Partial phases will range from about 40% near the US-Mexican border up to about 65% at the Canadian border and in Alaska. Partiality will barely reach extreme northeastern Russia. In the US, 47% of the sun's diameter will be covered at sunset on the horizon at New York City; 55% of the sun will be covered in Chicago low on the western horizon; 45% of the sun will be covered at Los Angeles; and 64% of the sun will be covered in Seattle. An amateur-professional Solar Eclipse Conference (http://www.eclipse-chasers.com/SEC2014.html) will be held 23-26 October in Alamogordo, New Mexico, with eclipse observing (43% coverage) from the nearby Sacramento Peak Observatory in Sunspot, the latest in a series held in years with no real total or annular eclipse.

Information assembled by Jay M. Pasachoff, Williams College (Williamstown, Massachusetts), Chair, International Astronomical Union's Working Group on Eclipses, with thanks to Fred Espenak (Arizona, NASA's Goddard Space Flight Center, ret.) and Xavier Jubier (Paris) for their data and maps.

Eclipse References:

- Fred Espenak, Five Millennium Canon of Solar Eclipses: -1999 to +3000, 2006 (NASA/TP-2006-214141); http://eclipse.gsfc.nasa.gov; http://eclipse.gsfc.nasa.gov/OH/OH2014.html
- Leon Golub and Jay M. Pasachoff, The Solar Corona, 2nd ed., Cambridge University Press, 2010.
- Jay M. Pasachoff and Alex Filippenko, The Cosmos: Astronomy in the New Millennium, 4th ed., Cambridge University Press, 2014.
- Leon Golub and Jay M. Pasachoff, Nearest Star: The Surprising Science of Our Sun, 2nd edition, Cambridge University Press, 2014.
- Jay M. Pasachoff, The Complete Idiot's Guide to the Sun, Alpha Books, 2003.

2014 Meteor Showers
(Selected from data compiled by Alastair McBeath for the International Meteor Organization Shower Calendar):

a. **Meteor outbursts** are unusual showers (often of short duration) from the crossing of relatively recent comet ejecta. Dates are for the year 2014.

- May 24, possible peaks estimated at 07:03 UT, 07:21 UT, or 07:40 UT, Comet 209P/LINEAR. Peak activity may be of short duration (a few minutes to a fraction of an hour), but it is possible there will be multiple maxima. Lower activity may persist for several hours around the expected maxima.

b. **Annual meteor showers liable to have geophysical effects:** Dates (based on UT in year 2014) are:

- Dec 28-Jan 12, Jan 03 19h35m, Quadrantids (QUA)
- Apr 16-Apr 25, Apr 22 17h45m, Lyrids (LYR)
- Apr 19-May 28, May 06 07h10m, η-Aquariids (ETA)
- May 22-Jul 02, Jun 07 18h, Daytime Arietids (Ari)
- May 20-Jul 05, Jun 09 17h, Daytime ζ-Perseids (Zeta Per)

- Jun 05-Jul 17, Jun 28 16h, Daytime β-Taurids (Beta Tau)
- Jul 12-Aug 23, Jul 30 (possibly Jul 28-30), Southern δ-Aquariids (SDA)
- Jul 17-Aug 24, Aug 13 00h15m to 02h45m, Perseids (PER)
- Sep 09-Oct 09, Sep 27 17h, Daytime Sextantids (Sex)
- Oct 02-Nov 07, Oct 21 (possible strong sub-peak Oct 17-18), Orionids (ORI)
- Nov 06-Nov 30, Nov 17 22h05m (possibly 16h), Leonids (LEO)
- Dec 04-Dec 17, Dec 13 19h30m - Dec 14 16h45m, Geminids (GEM)
- Dec 17-Dec 26, Dec 22 20h25m, Ursids (URS)

c. **Annual meteor showers which may have geophysical effects**: Dates (based on UT in year 2014) are:

- Apr 15-Apr 28, April 23 22h45m, η-Puppids(PPU)
- Jun 22-Jul 02, June 27 15h10m, June Bootids (JBO)
- Aug 28-Sep 05, Sep 1 07h30m, α-Aurigids (AUR)
- Sep 05-Sep 21, Sep 9 20h55m - 21h35m, September ε-Perseids(SPE)
- Oct 06-Oct 10, (see note below)**, Draconids (DRA)
- Nov 15-Nov 25, Nov 21 22h25m, α-Monocerotids (AMO)

**Draconids: Their usual potential maximum interval, probably at some point between ~15h UT on October 8 to 08h on October 9 (the nodal crossing point is at 23h30m UT on the 8th), will be very badly affected by full Moon also on October 8, although no activity has been predicted for these dates. However, Jeremie Vaubaillon has suggested the Earth may encounter two Draconid dust trails on October 6 instead, the first from 1900 AD at 19h10m UT, which could, based on the 2011 Draconid activity, produce ZHRs up to ~30, the second from 1907 at 19h53m UT, which might yield ZHRs around 10. Mikhail Maslov's calculations made some time earlier, and apparently not taking the actual more recent events into account, had indicated these two trail encounters could happen at 20h10m and 20h16m UT instead, with ZHRs of ~10-15, the meteors possibly very faint, so maybe detectable only by radio/radar. October 6 thus has the possibility of being a very interesting meteoric day, despite the reduced dark-sky interval then thanks to the waxing Moon! The post-moonset period would allow full coverage of the ~19h-20h30m interval then from northern-hemisphere sites at east Asian longitudes especially, although the importance of confirming what, if anything, occurs means all observers at suitable locations with clear skies that night should be on alert.

Meteor Shower Websites:

- Shower activity near-real time reports -- International Meteor Organization
- Meteor shower activity forecast from your own location -- Meteor Shower Flux Estimator
- Shower names and data -- IAU Meteor Data Center
- Announcements and reports of meteor outbursts -- IAU Minor Planet Center
- Shower outburst activity forecast -- Institut de Mecanique celeste et de calcul des ephemerides (IMCCE)

References:

Peter Jenniskens, Meteor showers and their parent comets. Cambridge University Press, 2006, 790 pp.

Real Time Space Weather and Earth Effects

The occurrence of unusual solar or geophysical conditions is announced or forecast by ISES through various types of geophysical "Alerts" (which are widely distributed via the internet on a current schedule). Stratospheric warmings (STRATWARM) were also designated for many years. The meteorological telecommunications network coordinated by the World Meteorological Organization (WMO) carries these worldwide Alerts once daily soon after 0400 UT. For definitions of Alerts see ISES URSIgram Codes.

RECOMMENDED SCIENTIFIC PROGRAMS (FINAL EDITION)

(The following material was reviewed in 2013 by the ISES committee with the advice of representatives from the various scientific disciplines and programs represented as suitable for coordinated geophysical programs in 2014.)

Airglow and Aurora Phenomena.

Airglow and auroral observatories operate with their full capacity around the New Moon periods. However, for progress in understanding the mechanism of many phenomena, such as low latitude aurora, the coordinated use of all available techniques, optical and radio, from the ground and in space is required. Thus, for the airglow and aurora 7-day periods on the Calendar, ionosonde, incoherent scatter, special satellite or balloon observations, etc., are especially encouraged. Periods of approximately one weeks' duration centered on the New Moon are proposed for high resolution of ionospheric, auroral and magnetospheric observations at high latitudes during northern winter.

Atmospheric Electricity.

Non-continuous measurements and data reduction for continuous measurements of atmospheric electric current density, field, conductivities, space charges, ion number densities, ionosphere potentials, condensation nuclei, etc.; both at ground as well as with radiosondes, aircraft, rockets; should be done with first priority on the RGD each Wednesday, beginning on 1 January 2014 at 0000 UT, 08 January at 0600 UT, 15 January at 1200 UT, 22 January at 1800 UT, etc. (beginning hour shifts six hours each week, but is always on Wednesday). Minimum program is at the same time on PRWD beginning with 15 January at 1200 UT. Data reduction for continuous measurements should be extended, if possible, to cover at least the full RGD including, in addition, at least 6 hours prior to indicated beginning time. Measurements prohibited by bad weather should be done 24 hours later. Results on sferics and ELF are wanted with first priority for the same hours, short-period measurements centered around minutes 35-50 of the hours indicated. Priority Weeks are the weeks that contain a PRWD; minimum priority weeks are the ones with a QWD. The World Data Centre for Atmospheric Electricity, 7 Karbysheva, St. Petersburg 194018, USSR, is the collection point for data and information on measurements.

Geomagnetic Phenomena.

It has always been a leading principle for geomagnetic observatories that operations should be as continuous as possible and the great majority of stations undertake the same program without regard to the Calendar.

Stations equipped for making magnetic observations, but which cannot carry out such observations and reductions on a continuous schedule are encouraged to carry out such work at least on RWD (and during times of MAGSTORM Alert).

Ionospheric Phenomena.
Special attention is continuing on particular events that cannot be forecast in advance with reasonable certainty. The importance of obtaining full observational coverage is therefore stressed even if it is only possible to analyze the detailed data for the chosen events. In the case of vertical incidence sounding, the need to obtain quarter-hourly ionograms at as many stations as possible is particularly stressed and takes priority over recommendation (a) below when both are not practical.

For the **vertical incidence (VI) sounding program**, the summary recommendations are:

a. All stations should make soundings on the hour and every quarter hour;
b. On RWDs, ionogram soundings should be made at least every quarter hour and preferably every five minutes or more frequently, particularly at high latitudes;
c. All stations are encouraged to make f-plots on RWDs; f-plots should be made for high latitude stations, and for so-called “representative” stations at lower latitudes for all days (i.e., including RWDs and WGIs) (Continuous records of ionospheric parameters are acceptable in place of f-plots at temperate and low latitude stations);
d. Copies of all ionogram scaled parameters, in digital form if possible, be sent to WDCs;
e. Stations in the eclipse zone and its conjugate area should take continuous observations on solar eclipse days and special observations on adjacent days. See also recommendations under Airglow and Aurora Phenomena.

For the 2014 incoherent scatter observation program, every effort should be made to obtain measurements at least on the Incoherent Scatter Coordinated Observation Days, and intensive series should be attempted whenever possible in WGIs, on Dark Moon Geophysical Days (DMGD) or the Airglow and Aurora Periods. The need for collateral VI observations with not more than quarter-hourly spacing at least during all observation periods is stressed.

Special programs include:

- **Sudden Stratospheric Warming (StratWarm)**: Dynamics, electrodynamics, temperature and electron density in the lower and upper thermosphere and ionosphere during a sudden stratospheric warming event
  Key objectives:
  To extend studies of stratospheric warming effects to the lower and upper thermosphere and investigate coupling with the ionosphere
  To document variations in multiple thermospheric and ionospheric parameters in response to different stratospheric sudden warming events
  To capture and document ionospheric response to stratospheric sudden warmings during the rising solar activity
  To measure electric field, neutral wind, electron and ion temperatures and electron density in the ionosphere and lower and upper thermosphere before and during sudden stratospheric warming
  To compare variations in ionospheric and thermospheric parameters observed during SSW to average wintertime behavior of ionosphere and thermosphere
  To compare variations in temperatures and winds to mesospheric response as given by MF and meteor radars and lidars
  To examine mechanisms responsible for variations in lower and upper thermospheric dynamics, temperatures, electric field, and ionospheric electron density and investigate to what degree they can be related to sudden stratospheric warming
  Background condition: The observations need to be made before and during the sudden stratospheric warming. A 10-day campaign is requested.
  Primary parameters to measure: LTCS mode - electron and ion temperatures from lowest possible altitudes throughout the F-region, zonal and meridional components of the neutral wind in the lower thermosphere (95-140km), E×B drift, F-region meridional wind. Temporal resolution can be sacrificed and data integration period increased in order to obtain data at lower altitudes.
  Need for simultaneous data: The idea is to measure how variations in temperatures, electric field and winds associated with sudden stratospheric warming change with latitude and altitude and relate to variations in electron density.
  Principle investigator: Larisa P. Goncharenko, lpg@haystack.mit.edu, MIT Haystack Observatory, Westford, MA 01886, USA. Larisa is responsible for issuing the alert. She anticipates one week’s notice.
  Co-investigators: Jorge Chau (Leibniz-Institute for Atmospheric Physics, Rostock University, Germany), Hanli Liu (NCAR, USA), Peter Hoffmann (Institute for Atmospheric Physics, Germany).
- **Hemispheric and Latitudinal Stormtime Behavior**
  Scientific focus: The latitudinal variations and their east-west hemispheric differences during solar storms and/or under quiet magnetic conditions.
  Need for simultaneous data: This coordinated observation involves ISR world day participants as well as the Chinese Meridian Project facilities. This major Chinese project for science and technology infrastructure provides comprehensive ground-based space weather observing in the Eastern Hemisphere, in particular along the 120E longitude where 15 observatories distributed from northern China to the South Pole are established. They are equipped with, among other instruments, ionospheric radio sensors (digisonds, GPS receivers, MF radars, coherent radars, etc) and optical sensors

(Lidars, FPIs, all-sky imagers). For this campaign, intensive observational modes will be adopted for most of the instruments.
Principle investigator: Shunrong Zhang (MIT Haystack Observatory), email: shunrong@haystack.mit.edu
Co-investigators: Guotao Yang and Zhaohui Huang (National Space Science Center, China), and John Foster (MIT Haystack Observatory).
Time: Four days in the alert period from March 24 - April 6 or September 14 - October 01.
Modes: Synoptic for all radars, except for Millstone Hill where low elevation azimuth scans are preferred.

- **Northern Deep Water Observations**
Scientific focus: Because of the proximity of the December 2014 New Moon to the solstice, this is a unique opportunity to capitalize on northern high-latitude measurements by optical instruments. This could be a prime time to study the formation, evolution, and decay of SAPS (Sub-Auroral Polarization Streams) and SED (Storm-Enhanced Densities) by measuring the penetration electric fields at low latitudes, the formation of SAPS electric fields and SED at mid-latitudes, and the motion of enhanced electron densities across the polar cap at high latitudes. This period will also be in high demand at the high-latitude ISRs, so proposals will be accepted up through the 2014 CEDAR Workshop for other science goals as well.
Principle investigator: Kjellmar Oksavik (University of Bergen, Norway), email: kjellmar.oksavik@uib.no
Co-investigators: TBD
Need for simultaneous data: Geomagnetic storms are known to impact the ionosphere on a global scale. Penetration electric fields occur at low latitudes, enhanced SAPS flows occur at mid-latitudes, the plasma flow is enhanced in the polar cap, and dense F-region plasma is transported all the way from lower latitudes, into and across the polar cap. Therefore, all radars should be operating at the same time.
- **AO** -- Arecibo Observatory
- **JRO** -- Jicamarca Radio Observatory.
- **Special programs**: Mary McCready, Center for Geospace Studies, SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA; tel:+1-650-859-5084; Fax:+1-650-322-2318; email: mary.mccready@sri.com, chair of URSI ISWG Commission G. See the 2014 Incoherent Scatter Coordinated Observation Days (URSI-ISWG) webpage for complete 2014 definitions.
- For the **ionospheric drift** or wind measurement by the various radio techniques, observations are recommended to be concentrated on the weeks including RWDs.
- For **travelling ionosphere disturbances**, propose special periods for coordinated measurements of gravity waves induced by magnetospheric activity, probably on selected PRWDs and RWDs.
- For the **ionospheric absorption program** half-hourly observations are made at least on all RWDs and half-hourly tabulations sent to WDCs. Observations should be continuous on solar eclipse days for stations in the eclipse zone and in its conjugate area. Special efforts should be made to obtain daily absorption measurements at temperate latitude stations during the period of Absorption Winter Anomaly, particularly on days of abnormally high or abnormally low absorption (approximately October-March, Northern Hemisphere; April-September, Southern Hemisphere).
- For **back-scatter and forward scatter programs**, observations should be made and analyzed at least on all RWDs.
- For **synoptic observations of mesospheric** (D region) electron densities, several groups have agreed on using the RGD for the hours around noon.
- For **ELF noise** measurements of earth-ionosphere cavity resonances any special effort should be concentrated during WGIs.
It is recommended that more intensive observations in all programs be considered on days of unusual meteor activity.

Meteorology.

Particular efforts should be made to carry out an intensified program on the RGD -- each Wednesday, UT. A desirable goal would be the scheduling of meteorological rocketsondes, ozone sondes and radiometer sondes on these days, together with maximum-altitude rawinsonde ascents at both 0000 and 1200 UT.

During WGI and STRATWARM Alert Intervals, intensified programs are also desirable, preferably by the implementation of RGD-type programs (see above) on Mondays and Fridays, as well as on Wednesdays.

Global Atmosphere Watch (GAW).

The World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) integrates many monitoring and research activities involving measurement of atmospheric composition, and serves as an early warning system to detect further changes in atmospheric concentrations of greenhouse gases, changes in the ozone layer and in the long range transport of pollutants, including acidity and toxicity of rain as well as of atmospheric burden of aerosols (dirt and dust particles). Contact WMO, 7 bis avenue de la Paix, P.O. Box 2300, CH-1211 Geneva 2, Switzerland or wmo@wmo.int.

Solar Phenomena.

Observatories making specialized studies of solar phenomena, particularly using new or complex techniques, such that continuous observation or reporting is impractical, are requested to make special efforts to provide to WDCs data for solar eclipse days, RWDs and during PROTON/FLARE ALERTS. The attention of those recording solar noise spectra, solar magnetic fields and doing specialized optical studies is particularly drawn to this recommendation.

Variability of the Sun and Its Terrestrial Impact (VarSITI).

Program within the SCOSTEP (Scientific Committee on Solar-Terrestrial Physics): 2014-2018. The VarSITI program will strive for international collaboration in data analysis, modeling, and theory to understand how the solar variability affects Earth. The VarSITI program will have four scientific elements that address solar terrestrial problems keeping the current low solar activity as the common thread: SEE (Solar evolution and Extrema), MiniMax24/ISEST (International Study of Earth-affecting Solar Transients), SPeCIMEN (Specification and Prediction of the Coupled Inner-Magnetospheric Environment), and ROSMIC (Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate). Contact is Prof. Marianna Shepherd (mshepher@yorku.ca), President of SCOSTEP. Co-chairs are Katya Georgieva (SRTI, Bulgaria) and Kazuo Shiokawa (STEL, Japan).

ILWS (International Living With a Star) International effort to stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity. Contact info@ilwsonline.org.

ISWI (International Space Weather Initiative) -- a program of international cooperation to advance space weather science by a combination of instrument deployment, analysis and interpretation of space weather data from the deployed instruments in conjunction with space data, and communicate the results to the public and students. The goal of the ISWI is to develop the scientific insight necessary to understand the science, and to reconstruct and forecast near-Earth space weather. This includes instrumentation, data analysis, modelling, education, training, and public outreach. Contact J. Davila at Joseph.M.Davila@nasa.gov.

Space Research, Interplanetary Phenomena, Cosmic Rays, Aeronomy.

Experimenters should take into account that observational efforts in other disciplines tend to be intensified on the days marked on the Calendar, and schedule balloon and rocket experiments accordingly if there are no other geophysical reasons for choice. In particular it is desirable to make rocket measurements of ionospheric characteristics on the same day at as many locations as possible; where feasible, experimenters should endeavor to launch rockets to monitor at least normal conditions on the Quarterly World Days (QWDs) or on RWDs, since these are also days when there will be maximum support from ground observations. Also, special efforts should be made to assure recording of telemetry on QWDs and Airglow and Aurora Periods of experiments on satellites and of experiments on spacecraft in orbit around the Sun.

Meteor showers.

Of particular interest are both predicted and unexpected showers from the encounter with recent dust ejecta of comets (meteor outbursts). The period of activity, level of activity, and magnitude distributions need to be determined in order to provide ground truth for comet dust ejection and meteoroid stream dynamics models. Individual orbits of meteoroids can also provide insight into the ejection circumstances. If a new (1-2 hour duration) shower is observed due to the crossing of the 1-revolution dust trail of a (yet unknown) Earth threatening long-period comet, observers should pay particular attention to a correct determination of the radiant and time of peak activity in order to facilitate predictions of future encounters. Observations of meteor outbursts should be reported to the I.A.U. Minor Planet Center (mpc@cfa.harvard.edu) and International Meteor Organization (visual@imo.net). The activity curve, mean orbit, and particle size distribution of minor annual showers need to be characterised in order to understand their relationship to the dormant comets among near-Earth objects. Annual shower observations should be reported to national meteor organizations, or directly to the International Meteor Organization. Meteoroid orbits are collected by the IAU Meteor Data Center.

The International Space Environment Services (ISES) is a space weather service organization currently comprised of 14 Regional Warning Centers around the globe, three Associate Warning Centers (China), and one Collaborative Expert Center (European Space Agency). ISES is a Network Member of the International Council for Science World Data System (ICSU-WDS) and collaborates with the World Meteorological Organization (WMO) and other international organizations, including the Committee on Space Research (COSPAR), the International Union of Radio Science (URSI), and the International Union of Geodesy and Geophysics (IUGG). The mission of ISES is to improve, to coordinate, and to deliver operational space weather services. ISES is organized and operated for the benefit of the international space weather user community.

ISES members share data and forecasts among the Regional Warning Centers (RWCs) and provide space weather services to users in their regions. The RWCs provide a broad range of services, including: forecasts, warnings, and alerts of solar, magnetospheric, and ionospheric conditions; extensive space environment data; customer-focused event analyses; and long-range predictions of the solar cycle. While each RWC concentrates on its own region, ISES serves as a forum to share data, to exchange and compare forecasts, to discuss user needs, and to identify the highest priorities for improving services.

ISES works in close cooperation with the World Meteorological Organization, recognizing the mutual interest in global data acquisition and information exchange, in common application sectors, and in understanding and predicting the coupled Earth-Sun environment.

This Calendar for 2014 has been drawn up by Dr. R. A. D. Fiori of the ISES Steering Committee, in association with spokesmen for the various scientific disciplines in the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP), the International Association of Geomagnetism and Aeronomy (IAGA), URSI and other

ICSU organizations. Similar Calendars are issued annually beginning with the IGY, 1957-58. PDF versions of the past calendars are available online.

Published for the International Council of Scientific Unions and with financial assistance of UNESCO for many years.

Copies are available upon request to ISES Director, Dr. Terry Onsager, NOAA Space Weather Prediction Center, 325 Broadway, Boulder, CO, 80305, USA, telephone +1-303-497-5713, FAX +1-303-497-3645, e-mail Terry.Onsager@noaa.gov, or ISES Secretary for World Days, Dr. Robyn Fiori, Geomagnetic Laboratory, Natural Resources Canada, 2617 Anderson Road, Ottawa, Ontario, Canada, K1A 0E7, telephone +1-613-837-5137, e-mail rfiori@NRCan.gc.ca.

Beginning with the 2008 Calendar, all calendars are available only in digital form at http://www.ises-spaceweather.org.

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ICEAA 2014
International Conference on Electromagnetics in Advanced Applications

IEEE APWC 2014
IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications

The sixteenth edition of the International Conference on Electromagnetics in Advanced Applications (ICEAA 2014) is supported by the Politecnico di Torino, by the University of Illinois at Chicago, by the Istituto Superiore Mario Boella and by the Torino Wireless Foundation, with the principal cosponsorship of the IEEE Antennas and Propagation Society and the technical cosponsorship of the International Union of Radio Science (URSI). It is coupled to the fourth edition of the IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (IEEE APWC 2014). The two conferences consist of invited and contributed papers, and share a common organization, registration fee, submission site, workshops and short courses, and social events. The proceedings of both conferences will be published on IEEE Xplore.

Suggested Topics for ICEAA

Adaptive antennas
Complex media
Electromagnetic applications to biomedicine
Electromagnetic applications to nanotechnology
Electromagnetic education
Electromagnetic measurements
Electromagnetic modeling of devices and circuits
Electromagnetic packaging
Electromagnetic properties of materials
Electromagnetic theory
EMC/EMI/EMP
Finite methods
Frequency selective surfaces
Integral equation and hybrid methods
Intentional EMI
Inverse scattering and remote sensing
Metamaterials
Optoelectronics and photonics
Phased and adaptive arrays
Plasma and plasma-wave interactions
Printed and conformal antennas
Radar cross section and asymptotic techniques
Radar imaging
Radio astronomy (including SKA)
Random and nonlinear electromagnetics
Reflector antennas
Technologies for mm and sub-mm waves

Suggested Topics for APWC

Active antennas
Antennas and arrays for security systems
Channel modeling
Channel sounding techniques for MIMO systems
Cognitive radio
Communication satellite antennas
DOA estimation
EMC in communication systems
Emergency communication technologies
Indoor and urban propagation
Low-profile wideband antennas
MIMO systems
3.5G and 4G mobile networks
Multi-band and UWB antennas
OFDM and multi-carrier systems
Propagation over rough terrain
Propagation through forested areas
Radio astronomy (including SKA)
RFID technologies
Signal processing antennas and arrays
Small mobile device antennas
Smart antennas and arrays
Space-time coding
Vehicular antennas
Wireless mesh networks
Wireless security
Wireless sensor networks

ICEAA - IEEE APWC 2014
PALM BEACH, ARUBA 3-9 August 2014

Information for Authors

Authors must submit a full-page abstract electronically by March 7, 2014. Authors of accepted contributions must submit the full paper, executed copyright form and registration electronically by June 6, 2014. Instructions are found on the website. Each registered author may present no more than two papers. All papers must be presented by one of the authors.

Deadlines

Abstract submission	March 7, 2014
Notification of acceptance	April 11, 2014
Full paper and presenter registration	June 6, 2014

Inquiries

Prof. Roberto D. Graglia
Chair of Organizing Committee
Politecnico di Torino
roberto.graglia@polito.it

Prof. Piergiorgio L. E. Uslenghi
Chair of Scientific Committee
University of Illinois at Chicago
uslenghi@uic.edu

2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting

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Submission Deadline - January 15, 2014

The **2014 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting** will be held jointly on July 6–12, 2014, at the Memphis Convention Center in Memphis, Tennessee, USA. The symposium and meeting are cosponsored by the IEEE Antennas and Propagation Society (AP-S) and the U. S. National Committee of the International Union of Radio Science (USNC-URSI) Commissions A, B, C, D, E, F, and K. The joint meeting is intended to provide an international forum for the exchange of information on state-of-the-art research in antennas, propagation, electromagnetics, and radio science. For more information, please visit the meeting website at: **www.2014apsursi.org**

Meeting Dates: July 6–12, 2014
Technical sessions will be held over a five-day period from July 7 through July 11, and workshops and short courses will occur on July 6 and July 12.

General Submission Information

Authors are invited to submit contributions for review and possible presentation at the symposium on topics of interest to AP-S and URSI. Topics and general information are listed in this call. Papers will be presented in either oral or poster sessions. Assignment to oral or poster sessions will be based solely on a paper's topic. All paper submissions are due **Wednesday, January 15, 2014**. This is a firm deadline. Papers will not be accepted after this date.

All paper and abstract submissions must be received in PDF format via the symposium Web site on or before Wednesday, January 15, 2014. This is a firm deadline. Papers will not be accepted after this date. Only electronic submissions in PDF format will be accepted. Please consult the symposium web site for the latest instructions, templates, and format examples. Only the author who submits the paper will receive an acknowledgement of the submission. Please do not include page numbers on submitted documents. All papers must be written in clear, idiomatic English. Please note that the symposium reserves the right to exclude a paper from distribution after the conference (e.g., removal from the proceedings submitted to IEEE Xplore) if the paper is not presented at the symposium. Address all AP-S and URSI correspondence, including inquiries concerning papers, abstracts, technical program, and copyright forms, to Fan Yang, Veysel Demir, or James Rautio, via email at **tpc@2014apsursi.org**.

Specific submission instructors for AP-S and URSI authors may be found online at the meeting website.

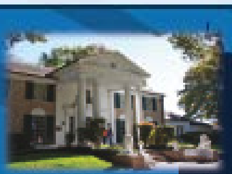
Exhibits and Sponsors

Exhibits

Industrial, academic, and book exhibits will be open July 8–10, 2014. Exhibitor registration and additional information can be found on the symposium web site. For additional information, contact Serhend Arvas or Rhonda Rodriguez, via email at **exhibits@2014apsursi.org**

Sponsors

The 2014 APS-URSI Symposium is the premier international forum for the exchange of information on state-of-the-art research in antennas, electromagnetic wave propagation, radio science, and electromagnetic wave propagation, radio science, and electromagnetic engineering. For additional information, contact C. J. Reddy or Jay Kralovec, via email at **sponsors@2014apsursi.org**



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Additional Activities

AP-S Student Paper Competition

Eligible entries in the Student Paper Competition must have only one student author, and that student must be the first author. Each additional coauthor must submit a signed letter indicating that his/her contribution is primarily advisory. Letters must be in PDF format and must be uploaded to the symposium's student paper web site in the indicated area at the time the paper is submitted. All Student Paper Competition entries will be evaluated using a double-blind review process in addition to the normal review process used for regular submissions. Detailed instructions will be available on the symposium Web site. For additional information, contact Reyhan Baktur, via email at spc@2014apsursi.org.

AP-S Student Design Contest

Students are invited to join the annual IEEE AP-S Student Design Challenge. In this competition, teams of students design and build an antenna or electromagnetic system to solve a specific problem. The top three teams will receive up to $2,500 in travel funds to attend the international symposium to demonstrate their working systems. From these top teams, first, second, and third place winners will be announced at the 2014 IEEE AP-S Awards Banquet at the Symposium and will receive cash prizes of $1500, $750, and $250, respectively. Further details, including submission deadlines, will be announced in Fall 2013 by e-mail, in the IEEE Antennas and Propagation Magazine, and on the IEEE Antennas and Propagation Society website at http://www.ieeeaps.org. For additional information, contact Buon K. Lau, via email at designcontest@2014apsursi.org.

Special Sessions

Requests to organize special sessions should be submitted to Kubilay Sertel via email at specialsessions@2014apsursi.org no later than October 15, 2013. Each proposal should include the title of the special session, a brief description of the topic, and justification for its designation as a special session. All proposals should be submitted in PDF format. Special sessions will be selected and finalized by the end of November 2013. At that time, additional instructions will be provided to the organizers of the special sessions chosen for inclusion in the symposium and/or the meeting. The associated papers or abstracts will be due January 15, 2014. A list of special sessions will be posted on the symposium Web site in December 2013.

General Topics

APS Topics

Antennas

1. Antenna theory
2. Antenna feeds and matching circuits
3. Antenna near fields and mutual couplings
4. Dielectric resonator antennas
5. Microstrip antennas, arrays, and circuits
6. Slotted and guided wave antennas
7. Phased-array antennas
8. Reflector and reflectarray antennas
9. Small antennas
10. Broadband/wideband antennas and systems
11. Multi-frequency antennas
12. Adaptive, active, and smart antennas
13. Reconfigurable antennas and arrays
14. Software control of antennas

Electromagnetics and Materials

15. Electromagnetic theory
16. Electromagnetic properties of materials
17. Electromagnetic measurement techniques
18. Frequency-selective surfaces
19. Electromagnetic bandgap materials
20. Metamaterials
21. Nano-electromagnetics
22. Electromagnetic education

Computational and Numerical Techniques

23. High frequency and asymptotic methods
24. Numerical methods
25. Integral equation methods
26. FDTD methods
27. FEM methods
28. Transients and time-domain techniques
29. Optimization methods in EM designs
30. Parallel and special-processor based numerical methods

Propagations and Scatterings

31. Indoor, urban, terrestrial, and ionospheric propagation
32. Propagation and scattering in random or complex media
33. Scattering, diffraction, and RCS
34. Inverse scattering and imaging
35. Remote sensing Wireless Applications
36. Biomedical applications
37. MIMO implementations and applications
38. Mobile and PCS antennas
39. Radar imagery
40. RFID antennas and systems
41. Ultra wideband antennas and systems
42. Vehicular antennas and electromagnetics
43. Wireless antennas and applications

URSI Topics

Commission A - Electromagnetic Metrology
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christopher.holloway@nist.gov

A.1 Microwave to sub-millimeter measurements/standards
A.2 Quantum metrology and fundamental concepts
A.3 Time and frequency
A.4 Time-domain metrology, EM-field metrology
A.5 EMC and EM metrology
A.6 Noise
A.7 Materials
A.8 Bioeffects and medical applications
A.9 Antennas
A.10 Impulse radar
A.11 Interconnect and packaging
A.12 Test facilities
A.13 THz metrology
A.14 High-Frequency and Millimeter Wireless metrology

Commission B - Fields and Waves
Chair: Sembiam Rengarajan
sembiam.rengarajan@csun.edu

B.1 Antenna arrays
B.2 Antenna theory, design, and measurements
B.3 Complex, novel, or specialized media:
B.3.1 Electromagnetic bandgap (EBG structures)
B.3.2 Biological media
B.3.3 Geophysical media
B.3.4 Metamaterials
B.4 Educational methods and tools
B.5 Electromagnetic interaction and coupling
B.6 Guided waves and wave-guiding structures
B.7 High-frequency techniques
B.8 Imaging, inverse scattering and remote sensing
B.9 Microstrip antennas and printed devices
B.10 Nanoscale electromagnetics
B.11 Nonlinear electromagnetics
B.12 Numerical Methods
B.12.1 Fast Methods
B.12.2 Finite-Difference methods
B.12.3 Frequency-Domain methods
B.12.4 Hybrid methods
B.12.5 Integral-Equation methods
B.12.6 Time-Domain methods
B.13 Optimization techniques
B.14 Propagation phenomena and effects
B.15 Rough surfaces and random media
B.16 Scattering and diffraction
B.17 Theoretical electro magnetics
B.18 Transient fields, effects, and systems
B.19 Ultra-wideband electromagnetics
B.20 Wireless communications
B.21 Cognitive Radio

Commission C - Radiocommunication and Signal Processing Systems
Chair: Amir I. Zaghloul - amirz@vt.edu

C.1 Cognitive radio and software defined radio
C.2 Computational imaging and inverse methods
C.3 Information theory, coding, modulation and detection
C.4 MIMO and MISO systems
C.5 Radar systems, target detection, localization, and tracking
C.6 Radio communication systems
C.7 Sensor networks, and sensor array processing and calibration
C.8 Signal and image processing
C.9 Spectrum and medium utilization
C.10 Synthetic aperture and space-time processing
C.11 Ground Penetrating Radar (GPR)

Commission D - Electronics and Photonics
Chair: Jennifer T. Bernhard
jbernhar@illinois.edu

D.1 Novel transmission line structures and materials
D.2 Electronic devices, circuits and applications
D.3 Photonic devices, circuits and applications
D.4 Physics, materials, CAD, technology and reliability of electronic and photonic devices

Commission E - Electromagnetic Environment and Interference
Chair: Everett G. Farr
efarr@farr-research.com

E.1 Electromagnetic environment
E.1.1 Electromagnetic noise of natural origin
E.1.2 Man-made noise
E.2 Electromagnetic compatibility measurement technologies
E.3 Electromagnetic compatibility standards
E.4 Legal aspects of electromagnetic compatibility
E.5 Electromagnetic radiation hazards
E.6 Electromagnetic compatibility education
E.7 Computational electromagnetics in electromagnetic compatibility
E.7.1 Computer Modeling
E.7.2 Model Validation
E.7.3 Statistical Analysis
E.8 Effects of natural and intentional emissions on system performance
E.8.1 Crosstalk
E.8.2 Effects of transients
E.8.3 System analysis
E.8.4 Signal integrity
E.8.5 Electromagnetic compatibility in communication systems
E.8.6 Statistical analysis
E.9 High-power electromagnetics
E.9.1 Electrostatic discharge
E.9.2 Electromagnetic pulse and lightning
E.9.3 Transients
E.9.4 Power transmission
E.10 Spectrum management

Commission F - Wave Propagation and Remote Sensing
Chair: V. Chandrasekar
chandra@engr.colostate.edu

F.1 Point-to-point propagation effects
F.1.1 Measurements
F.1.2 Propagation models
F.1.3 Multipath/mitigation
F.1.4 Land or water paths
F.1.5 Scattering/diffraction
F.1.6 Indoor/outdoor links
F.1.7 Mobile/fixed paths
F.1.8 Horizontal/slant paths
F.1.9 Surface/atmosphere interactions
F.1.10 Atmospheric constituents
F.1.11 Dispersion/delay
F.1.12 Natural/man-made structures
F.2 Remote sensing of the Earth by radio waves
F.2.1 Atmospheric sensing
F.2.2 Ocean and sea ice
F.2.3 Field campaigns
F.2.4 Interferometry and SAR
F.2.5 Subsurface sensing
F.2.6 Scattering/diffraction
F.2.7 Radiation and emission
F.2.8 Propagation effects
F.2.9 Urban environments
F.2.10 Soil moisture & terrain
F.3 Propagation and remote sensing in complex and random media

Commission K - Electromagnetics in Biology and Medicine
Chair: Erdem Topsakal
topsakal@ece.msstate.edu

K.1 Biological effects
K.2 Dosimetry and exposure assessment
K.3 Electromagnetic imaging and sensing applications
K.4 Therapeutic, rehabilitative, and other biomedical applications
K.5 Human body interactions with antennas and other electromagnetic devices

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Note: an alphabetical index of names with coordinates and page references is given on pages 84-98

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ABULDAHAB, Prof. M. A., Faculty of of Engineering and Technology, Arab Academy for Science & Technology , P.O. Box 2033 Al-Horria, Heliopolis, Cairo, EGYPT, Tel. +2022 379273 95, Fax +2022 379273 95, E-mail mdahab@aast.edu (78)

ADIMULA, Prof. I.A., Physics Department, University of Ilorin, Ilorin,NIGERIA, Tel. 234 802 629 2655, E-mail iaadimula@hotmail.com (82)

AGUILERA, Mr. R., Centro de Estudios Espaciales, Universidad de Chile, Casilla 411-3, SANTIAGO 3, CHILE, Tel. +56 2-556 8382, Fax +56 2-844 1003 (78)

AIKIO, Dr. A., Dept. of Physical Sciences, University of Oulu, PO Box 3000, FI-90014 OULU,FINLAND, Tel. +358 8 5531 363, Fax +358 8 5531 287, E-mail Anita.Aikio@oulu.fi (79)

AJEWOLE, Prof. Oludare, Department of Physics, Federal University of Technology, Pmb 704, 340001 Akure,NIGERIA, Tel. 234 803 455 0871, E-mail oludare.ajewole@futa.edu.ng, oludareajewole61@yahoo.com (78)

AKSUN, Prof. I., College of Engineering, Koc University, Rumelifeneri Yolu, 34450 Sarıyer Istanbul,TURKEY, Tel. +90 212 338 1539, Fax +90 212 338 1548, E-mail iaksun@ku.edu.tr (76)

AL-BADRANI, Mr. M., Director, Directorate of International Cooperation, KACST, P.O Box 6086, RIYADH 11442,SAUDI ARABIA, Tel. +966 1 481 3384, Fax +966 1 481 3441, E-mail int_coop@kacst.edu.sa, mbadrani@kacst.edu.sa (82)

ALENCAR, Prof. Luiz , Pontificia Universidade Catolica do Rio de Janeiro, Centro Técnico-Cientifico, Centro de Estudos em Telecommunicaçoes, CETUC-PUC/Rio, Rua Marquês de S. Vicente 225, Gavea, 22453-900 Rio de Janeiro,BRAZIL, Tel. +55 21 31141618, E-mail semello@cetuc.puc-rio.br, lamello@inmetro.gov.br, larsmello@gmail.com (76)

ALENCAR, Prof. M.S. de, Centro de Ciencias e Tecnologia, Departamento de Engenharia Eletrica, Universidade Federal de Campina Grande, Av. Aprigio Veloso 882, Bodocongo, 58109-970 Campina Grande, BP,BRASIL, Tel. + 55 83 3310 1122, E-mail malencar@ufcg.edu.br, malencar@iecom.org.br (77)

AL-MIKATI, Prof. Dr. H.A., Faculty of Engineering, Mansoura University, Mansoura, Dakahlia,EGYPT, E-mail h.elmikati@gmail.com (80)

AL-RAJEHI, Dr. A., Astronomy and Geophysics Research Institute King Abdulaziz City for Science & Technology, P. O. Box 6086, RIYADH 11442, SAUDI ARABIA, Tel. +966 1 481 3535, Fax +966 1 481 3526, E-mail arrajehi@kacst.edu.sa (76, 78, 79, 80)

ALTINTAS, Prof. A., Dept. of Electr. & Electronics Eng. , Bilkent University, Faculty of Engineering, 06533 Bilkent ANKARA,TURKEY, Tel. +90 312 290 1489, Fax +90 312 266 4192, E-mail altintas@ee.bilkent.edu.tr (75, 82)

ALVAREZ, Prof. H., Departamento de Astronomia, Universidad de Chile, Casilla 36-D, SANTIAGO 16, CHILE, Tel. +56 2-229 4002, Fax +56 2-229 4101, E-mail halvarez@das.uchile.cl (80)

AMAYA, Dr. A, , Communications Research Centre Canada, 3701 Carling Avenue, P.O. Box 11490, ON K2H 8S2 Ottawa,Canada, Tel. +1 613 998 2197, Fax +1 613 990 6339, E-mail cesar.amaya@crc.gc.ca (78)

AMBROSINI, Dr. R., Institute of Radioastronomy, INAF, Via Gobetti 101, 40129 BOLOGNA,ITALY, E-mail r.ambrosini@ira.inaf.it (80)

AMMANN, Dr. M., School of Electronic & Communications Engineering, Dublin Institute of Technology, Kevin Street, DUBLIN 8,IRELAND, Tel. +353 1 4024905, Fax +353 1 4024690, E-mail max.ammann@dit.ie (80)

ANANTHAKRISHNAN, Prof. S., Electronic Science Department, Pune University, Ganeshkhind, PUNE 411007,INDIA, Tel. +91 20 2569 9841, Fax +91 20 6521 4552, E-mail subra.anan@gmail.com (75, 83)

ANDERSEN, Prof. J. Bach, Aalborg University, Inst. of Electronic Systems, Center for Personal Communication, Niels Jernes Vej 12, DK-9220 AALBORG EAST,DENMARK, Tel. +4598314213, E-mail jba@es.aau.dk (80)

ANDO, Prof. M., Dept. of Electrical & Electronic Eng., Graduate School of Science and Engineering, Tokyo Institute of Technology, S3-19, 2-12-1 O-okayama, Meguro, TOKYO 152-8552, JAPAN, Tel. +81 3 5734-2563, Fax +81 3 5734-2901, E-mail mando@antenna.ee.titech.ac.jp (75)

ANGELSEN, Prof. B.A.J., Department of Circulation and Medical Imaging, NTNU, N-7487 TRONDHEIM, NORWAY, Tel. +47 91 320934, E-mail bjorn.angelsen@ntnu.no (80)

ARBESSER-RASTBURG, Dr. B., ESA-ESTEC, TOS-EEP, Postbus 299, 2200 AG NOORDWIJK,NETHERLANDS, Tel. +31 71 565 4541, Fax +31 71 565 4999, E-mail bertram.arbesser-rastburg@esa.int (81, 83)

ARES-PENA, Prof. F., Dpto. Fisica Aplicada, Facultad de Fisica, Universidad de Santiago de Compostela, 15782 Santiago de Compostela, SPAIN, Tel. +34 8818 140 16, Fax +34 8818 140 72, E-mail francisco.ares@usc.es (82)

ARIKAN, Dr. F., Faculty of Engineering, Haceteppe University, Beytepe, Ankara,TURKEY, Tel. +312 297 7095, Fax +312 299 2125, E-mail arikan@hacettepe.edu.tr (79)

ARMSTRONG, Dr. T.R., Measurement Standards laboratory, Industrial Research Limited, P.O. Box 31-310, Lower Hutt,NEW ZEALAND, Tel. +64 4 931 3199, Fax +64 4 931 3194, E-mail t.armstrong@irl.cri.nz (76)

ARNAUT, Prof. L.R., George Green Institute for Electromagnetic Research, University of Nottingham, University Park, Nottingham, NG7 2RD,UNITED KINGDOM, Tel. +44 1833 562 356, E-mail luk.arnaut@googlemail.com (76)

AROGUNJO, Prof. A.M., Department of Physics, Federal University of Technology, Akure,NIGERIA, Tel. 234 703 655 5992, E-mail arogmuyi@yahoo.com (80)

ARTHABER, Dr. H., Institute of Electrodynamics, Microwave and Circuit Engineering, Vienna University of Technology, Gusshausstrasse 25/354, 1040 Vienna, AUSTRIA, Tel. +43 1 58801 35 420, Fax +43 1 58801 935 420, E-mail holger.arthaber@tuwien.ac.at (76)

ASSIS, Prof M.S., Rua Coelho Neto, 17 Ap.301, Laranjeiras, 22231-110 Rio de Janeiro,Brazil, Tel. +55 21 255 29487, E-mail msassis@openlink.com.br (78, 82)

AZI, Dr. S.O., University of Benin, Benin City, NIGERIA, Tel. 234 803 239 5000, E-mail saozi1@yahoo.com (77)

BAAN, Prof. W.A., Netherlands Foundation for Research, in Astronomy - Westerbork Observatory, P.O. Box 2, NL-7990 AA DWINGELOO, NETHERLANDS, Tel. +31 521-595 773/100, Fax +31 521-595 101, E-mail baan@astron.nl (80, 83)

BAARS, Dr J.W.M., mm-astronomy, Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, 53121 Bonn, Germany, Tel. +49-228-525303, E-mail jacobbaars@arcor.de (83)

BÄCKSTRÖM, Dr. M., Saab AB, SE-581 88 LINKÖPING,SWEDEN, Tel. +46 734 18 15 12, Fax +46 13 18 55 20, E-mail mats.backstrom@saabgroup.com (78, 81)

BAGGALEY, Prof. W.J., Department of Physics and Astronomy, University of Canterbury, Private Bag, CHRISTCHURCH 1, NEW ZEALAND, Tel. +64 3-364-2558, Fax +64 3-364-2469, E-mail jack.baggaley@canterbury.ac.nz (79)

BAJAJA, Dr. E., Inst. Arg. de Radioastronomia, CC. No 5, 1894 VILLA ELISA, B.A., ARGENTINA, Tel. +54 221-4254909 , Fax +54 221-4824903, E-mail bajaja@irma.iar.unlp.edu.ar (80)

BANERJEE, Dr. P., ECE, ASET, Amity University, Uttar Pradesh (AUUP), Sector 125, NOIDA (Adjoining Delhi)-201 303, INDIA, Tel. +91 9899045038, Fax +91 11 25841506, E-mail pbanerje150@gmail.com (75, 83)

BARBOSA, Prof. A.M., Instituto Superior Técnico, Instituto de Telecomunicações, Avenida Rovisco Pais n°1, 1049-001 LISBOA CODEX, PORTUGAL, Tel. +351 21 841 8482, Fax +351 21 841 8472, E-mail afonso.barbosa@lx.it.pt (76)

BATISTA, Dr. I.S., INPE - Instituto Nacional de Pesquisas Espaciais, Av. dos Astronautas 1758, Jd. da Granja, 12227-010 Sao José dos Campos, SP, BRAZIL, Tel. +55 12 39456000, E-mail inez@dae.inpe.br (79)

BAUER, Dr. P., 17, Route des Bardis, F-31320 Rebigue, FRANCE, E-mail pierre.bauer3@orange.fr (83)

BEBBINGTON, Dr. D., School of Computer Science & Electronic Engineering, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, UNITED KINGDOM, Tel. +44 1206 872819, Fax +44 1206 872900, E-mail david@essex.ac.uk (78)

BEHRENS, Dr. P., The Royal Society of New Zealand, P.O. Box 598, Wellington 6140, NEW ZEALAND, Tel. +64 4 470 5777, E-mail Paul.Behrens@royalsociety.org.nz (82)

BENCZE, Prof. P., Geof. Kut. Labor, MTA (Hungarian Academy of Sciences), Csatkai E. u. 6, H-9400 SOPRON, HUNGARY, Tel. +36 99-314291, Fax +36 99-313267, E-mail bencze@ggki.hu (79)

BENTUM, Dr. Ir. M.J., Fac. of Electrical Eng. Mathematics & Computer Science, University of Twente, Postbus 217, 7500 AE Enschede, Netherlands, Tel. +31 53 489 2108/3856, Fax +31 53 489 5640, E-mail m.j.bentum@utwente.nl (77, 82)

BERNARDI, Prof. P., Department of Electronic Engineering, University La Sapienza, Via Eudossiana 18, 000184 ROME, ITALY, Tel. +390 6-4458 5855, Fax +390 6-474 2647, E-mail bernardi@die.uniroma1.it (80)

BERNHARD, Prof. J., ECE, University of Illinois at Urbana-Champaign, 1020 W. Daniel St, Champaign, IL 61821, USA, Tel. +1 (217) 333 0293, E-mail jtbernhard@ieee.org, jbernhar@illinois.edu (77)

BETSKIY, Dr. O.V., FIRE, Russian Academy of Sciences, Vvedenskogo pl. 1, Fryasino, Moscow Region 141120,RUSSIA, Tel. +7 495 629 33 80, Fax +7 495 629 3678, E-mail ehf@cplire.ru (80)

BEUNZA, Eng. O.M., Cnel. Ramon L. Falcon 1535, 3rd floor, Apt. A, C1407GND BUENOS AIRES, ARGENTINA, Tel. +54 1-772-1471, Fax +54 11 47760410, E-mail postmast@caerce.edu.ar (78)

BHATTACHARYYA, Dr A., , Indian Institute of Geomagnetism, Plot-5; sector-18, Kalamboli Highway, New Panvel (W), Navi Mumbai, maharastra 410218, India, Tel. +91 22 2748 4147, Fax +91 22 2748 0762, E-mail archana.bhattacharyya@gmail.com (79, 82)

BILITZA, Dr. D., Space Weather Laboratory, George Mason University, 1856 Ingleside Terrace Nw, 20010 Washington, USA, Tel. +1 301 286-0190, Fax +1 301 286-1771, E-mail dieter.bilitza-1@nasa.gov, dbilitza@gmu.edu (81, 83)

BIOLEK, Prof. D., Brno University of Technology/University of Defence Brno, Kounicova 65, BRNO 616 00, CZECH REPUBLIC, Tel. +420 973 442 487, Fax +420 541 149 192, E-mail dalibor.biolek@unob.cz (77)

BITTENCOURT, Dr. J.A., INPE - Instituto Nacional de Pesquisas Espaciais, Av. dos Astronautas 1758, Jd. da Granja, 12227-010 Sao José dos Camos, S.P, BRAZIL, Tel. +55 12-39456000, E-mail jabittencourt@hotmail.com (79)

BOGENFELD, Dr. E., Deutsche Telekom AG, T-Labs (Research & Development), Wireless Technologies & Networks, Deutsche-Telekom-Allee 7, D-64295 DARMSTADT, GERMANY, Tel. +49 (0)6151 58 35834, Fax +49 (0)391 580216 938, E-mail eckard.bogenfeld@telekom.de (82)

BOLAS, Prof. T.E., LCDR, DITIC, Rua do Arsenal, 1149-001 LISBOA, PORTUGAL, Tel. +351 9177 44 784, E-mail ludovico.bolas@marinha.pt (79)

BORREGO, Eng. J.P., ICP-ANACOM, Centro de Monitorizaçao e Controlo do Espectro do Sul, Alto do Paimão, 2730-216 BARCARENA, PORTUGAL, Tel. +351 21 434 85 00, Fax +351 21 434 85 90, E-mail jose.borrego@anacom.pt (78)

BÖSCH, Prof. W., Institute of Microwave and Photonic Engineering, Graz University of Technology, Inffeldgasse 12, 8010 Graz, AUSTRIA, Tel. +43 316 873 3301, Fax +43 316 873 3302, E-mail wolfgang.boesch@tugraz.at (77)

BOSKA, Dr. J., Institute of Atmospheric Physics, Academy of Sciences of Czech Republic, Bocni II-1401, PRAGUE 4 141 31, CZECH REPUBLIC, Tel. +420 272 016 065, Fax +420 272 762 528, E-mail boska@ufa.cas.cz (79)

BRADLEY, Dr. R., Technology Center, National Radio Astronomy Observatory, 1180 Boxwood Estate Road, VA 22903 Charlottesville, United States, Tel. +1 434-296-0291, Fax +1 434-296-0324, E-mail rbradley@nrao.edu (80)

BRAZIL, Prof. T., UCD School of Electrical, Electronic and Mechanical Engineering, University College Dublin, DUBLIN, BELFIELD 4, IRELAND, Tel. +353 1 716 1929, Fax +353 1 283 0921, E-mail Tom.Brazil@ucd.ie (77)

BREINBJERG, Prof. O., DTU Electrical Engineering, Technical University of Denmark, Oersteds Plads, Bldg. 348, DK-2800 LYNGBY, DENMARK, Tel. +45 4525 3814, Fax +45 4588 1634, E-mail ob@elektro.dtu.dk (76, 78, 82)

BREKKE, Prof. A., Institute for Physics and Technology, University of Tromso, N-9037 TROMSO, NORWAY, Tel. +47 77 645167, E-mail asgeir.brekke@uit.no (79)

BRENNAN, Dr. C., School of Electronic Engineering, Dublin City University, DUBLIN 9, IRELAND, Tel. +353 1 7007649, E-mail BrennanC@eeng.dcu.ie (78)

BROSCH, Dr. N., Wise Observatory, Tel Aviv University, Chayim Levanon St., Ramat Aviv, 69978 TEL AVIV, ISRAEL, Tel. +9723 640-7413, Fax +9723 640-8179, E-mail noah@wise.tau.ac.il (80)

BRYNILDSEN, Ms. , Institute of Theoretical Astrophysics, , P.O. Box 1029 Blindern, N-0315 OSLO, NORWAY, Tel. +47 22 856502, Fax +47 22 856505, E-mail nilsbr@astro.uio.no (82)

CALOZ, Dr. C., Pavillon Lassonde, M-6025, École Polytechnique, 2500, Chemin de Polytechnique, Montréal, Québec H3T IJ4, CANADA, Tel. +1 514 340 4711 ext. 3326, Fax +1 514 340 5892, E-mail christophe.caloz@polymtl.ca (77)

CANAVERO, Prof. F.G., Dipartimento di Elettronica, Politecnico di Torino, Corso Duca Degli Abruzzi, 24, I-10129 TORINO, ITALY, Tel. +39 011 564-4060, Fax +39 011 564-4099, E-mail flavio.canavero@polito.it (78)

CANNON, Prof. P.S., Gisbert Kapp Building , University of Birmingham, Edgbaston, Birmingham B15 2TT, UNITED KINGDOM, Tel. +44 (0) 7990 564772, Fax +44 (0)121 414 4323, E-mail p.cannon@poynting.bham.ac.uk (75)

CAO, Dr. Space Science Institute, Beihang University, 37, Xueyuan Road, Haidian District, 100191 Beijing, China, Tel. 86.10.62582644, Fax 86.10.82338856, E-mail jbcao@buaa.edu.cn (79)

CAPSALIS, Prof. C., Division of Information Transmission Systems and Material Technology, School of Electrical and Computer Engineering, National Technical University of Athens, Iroon Polytechniou 9, GR-15773 ATHENS, GREECE, Tel. +30 210 772 3517, Fax +30 210 772 2281, E-mail ccaps@central.ntua.gr (78)

CARVALHO, Prof. Instituto de Telecomunicacoes, Universidade de Aveiro, Campus Universitario, 3810-193 Aveiro, PORTUGAL, Tel. +351 234377900, Fax +351 234377901, E-mail nbcarvalho@ua.pt (76)

CERDEIRA, Dr. R.P., ESA-ESTEC, TEC-EEP, Postbus 299, 2200 AG NOORDWIJK, NETHERLANDS, Tel. +31 71 565 8658, E-mail roberto.prieto.cerdeira@esa.int (79)

CHAKRABARTI, Dr. N., Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Kolkata, 700064, INDIA, Tel. +91 33 23375345, Fax+913323374637, E-mail nikhil.chakrabarti@saha.ac.in (79)

CHANDRA, Prof. Dr. M., Chair-holder for Microwave Engineering and Photonics, Chemnitz University of Technology, Reichenhainer Strasse 70, D-09126 CHEMNITZ, GERMANY, Tel. +49 (0)371 531 33168, Fax +49 (0)371 531 8 33168, E-mail madhu.chandra@etit.tu-chemnitz.de (75, 78, 81)

CHANDRASEKAR, Prof. V., Engineering B117, Colorado State University, Fort Collins, Colorado 80523, USA, Tel. +1 970 491 7981, E-mail chandra@engr.colostate.edu (78)

CHANG, Prof. D-C, Oriental institute of Technology, 58,Sec.2, Sihchuan Rd.,Pan-Chiao City, Taipei County 22061, TAIWAN, E-mail dcchang@mail.oit.edu.tw (76)

CHANG, Prof. H-C, Department of Electrical Engineering, National Taiwan University, No. 1, Roosevelt Road Sec. 4, TAIPEI 106, CHINA (SRS), Tel. +886-2-23635251ext.51, Fax +886-2-23638247, E-mail hcchang@cc.ee.ntu.edu.tw (76)

CHAU, Dr. Jorge L., Jicamarca Radio Observatory, Instituto Geofisico del Peru, Apartado 13-0207, LIMA 13, PERU, Tel. +51 1-3172313, Fax +51 1-4344563, E-mail jchau@jro.igp.gob.pe, jorge.chau@jro.igp.gob.pe (79)

CHAVEZ MUÑOZ, Ing. D., Departamento de Ingenierìa, Universidad Católica del Perú, Grupo de Telecomunicaciones Rurales , Av.Universitaria 1801, San Miguel, LIMA 32, PERU, Tel. +51-1-626-2452, Fax +51-1-626-2116, E-mail dchavez@pucp.edu.pe (77, 82)

CHEN, Prof. K-S, Center for Space and Remote Sensing Research, National Central University, No. 300, Jung-da Road, Jhongli City, TAOYUAN 320, CHINA (SRS), Tel. +886-3-4227151 ext7617, Fax +886-3-4273586, E-mail dkschen@csrsr.ncu.edu.tw (78, 82)

CHERPAK, Prof. N.T., A. Usikov Institute of Radiophysics and Electronics, NASU, 12, ac. Proskura Str., KHARKOV 61085, UKRAINE, Tel. +380 57 7203363, Fax +380 57 3152105, E-mail cherpak@ire.kharkov.ua (78)

CHINEKE, Dr. T.C., Department of Physics and Industrial Physics, Imo State University, Owerri, Imo State, NIGERIA, Tel. 234 803 722 9905, E-mail chidiezie@yahoo.com (76)

CHOUDHARY, Dr R.K., Space Physics Laboratory, Vikram Sarabhai Space Center, Thumba, ISRO P.O. , Trivandrum, Kerla 695 022, INDIA, Tel. +91 471 2562156, Fax +91 471 2706535, E-mail rajkumar_choudhary@vssc.gov.in, rajkumar.choudhary@gmail.com (78)

CHRISSOULIDIS, Prof. D.P., Division of Telecommunications, Dept. of Electrical and Computer Eng., Aristotle University of Thessaloniki, P.O. Box 1562, GR- 54124 THESSALONIKI, GREECE, Tel. +30 231 099 6334, Fax +30 231 099 6334, E-mail dpchriss@eng.auth.gr (78)

CHRISTOPOULOS, Prof. C., George Green Institute for Electromagnetics Research, School of EEE, University of Nottingham, University Park, NOTTINGHAM, NG7 2RD, UNITED KINGDOM, Tel. +44 115 846 8296, Fax +44 115 951 5616, E-mail christos.christopoulos@nottingham.ac.uk, kathryn.sanderson@nottingham.ac.uk (75)

CHU, Prof. Y-H, Secretary General Office, National Central University, No. 300, Jungda Road, CHUNG-LI, TAOYUAN 320, CHINA (SRS), Tel. +886 3-4227151 ext. 57010, Fax +886 3-4254842, E-mail yhchu@jupiter.ss.ncu.edu.tw (79)

CHUGUNOV, Prof. Yu.V., Institute of Applied Physics, Russian Academy of Sciences, Ul'yanova Street 46, NIZHNY NOVGOROD 603600, RUSSIA, Tel. +7 8314 384 232, Fax +7 8314 362 061, E-mail chugun@appl.sci-nnov.ru (79)

CHUKHLANTSEV, Dr. A.A., Institute of Radio-engineering and Electronics, Russian Academy of Sciences, 1 Acad. Vvedensky Sq., Fryazino, Moscow Region, 141190, RUSSIA, E-mail chukhlantsev@ms.ire.rssi.ru (78)

CHUKHRAY, Dr. G.I., Institute of Radioengineering and Electronics (IRE), Russian Academy of Science, Mokhovaya str. 11, MOSCOW 125009, RUSSIA, Tel. +7 495 311 6978, Fax +7 495 629 3678, E-mail australia2@yandex.ru, gulyaev@cplire.ru (80, 82)

CLARK, Prof. A.R., School of Electrical and Information Eng., University of Witwatersrand, Room CM4-236, 3050 WITS, SOUTH AFRICA, Tel. +27 11 717 7223, Fax +27 11 403 1929, E-mail alanrobertclark@gmail.com (76)

CLAUDE, Dr. S., National Research Council Canada, NRC Herzberg, 5071 West Saanich Road, VICTORIA, BC V9E 2E7, CANADA, Tel. +1 250 363 0030, Fax +1 250 363 0045, E-mail Stephane.Claude@nrc-cnrc.gc.ca (80)

CLEMENTE, M.D. Pais, Director Serviço Otorrinolaringologia, Faculdade De Medicina Do Porto, Hospital De São Joãoporto, Porto,Portugal, Tel. +351217212201, E-mail pais.clemente@mail.telepac.pt (80)

CLENET, Dr. M., Defence Research and Development Canada-Ottawa, 3701 Carling Avenue, OTTAWA ON K1A 0Z4, CANADA, Tel. +1 613 998 7397, Fax +1 613 990 8906, E-mail Michel.Clenet@drdc-rddc.gc.ca (76)

CLETTE, Dr. F., SIDC - Solar Physics, Royal Observatory of Belgium, 3, avenue Circulaire, B-1180 Bruxelles, Belgium, Tel. (322) 373-0233, Fax (322) 374-9822, E-mail frederic.clette@oma.be (80)

CLILVERD, Dr. M.A., British Antarctic Survey, High Cross, Madingley Road, CAMBRIDGE, CB3 0ET, UNITED KINGDOM, Tel. +44 1223 221541, Fax +44 1223 221226, E-mail macl@bas.ac.uk (83)

COHEN, Prof. A., The Institute of Earth Science, The Hebrew University, Givat-Ram, P.O.B. 9137, 91091 JERUSALEM, ISRAEL, Tel. +972 2-658 6645, Fax +972 2-662 581, E-mail ariel@vms.huji.ac.il (78)

COLLIER, Dr. , School of Physics, University of KwaZulu-Natal, Hospital Road, 4041 DURBAN, South Africa, Tel. +27 31 260 3158, Fax +27 31 261 6550, E-mail collierab@gmail.com (79)

CONSTANTINOU, Dr. CC, School of Electrical & Electronic Engineering, University of Birmingham, Edgbaston, BIRMINGHAM B15 2TT, UNITED KINGDOM, Tel. +44 121 4144 303, Fax +44 121 4144 291, E-mail C.Constantinou@bham.ac.uk (82)

COSTA, Dr E., Centro Técnico-Cientifico, Centro de Estudos em Telecommunicaçoes, Pontificia Universidade Catolica do Rio de Janeiro, CETUC-PUC/Rio, Rua Marquês de São Vicente 225, Gavea, 22453 - 900 Rio de Janeiro,Brazil, Tel. +55 21 311 41618, E-mail epoc@cetuc.puc-rio.br (76)

CRYAN, Prof. M., Dept. of Electrical and Electronic Engineering, University of Bristol, Merchant Venturers Building, Woodland Road, Bristol, BS8 1UB, UNITED KINGDOM, Tel. +44 117 9545176, E-mail m.cryan@bristol.ac.uk (77)

CUPIDO, Prof. L., IPFN - Aveiro, Instituto de Telecomunicaçoes - Polo de Aveiro, Campus Universitario de Santiago, P- 3810-193 AVEIRO, PORTUGAL, Tel. +351 23 437 02 00, E-mail cupido@ua.pt (80)

DANILOV, Prof. V.V., Radiophysical Department, T. Shevchenko Kiev National University, 2 Glushkova avenue, Building 5, KIEV 03127, UKRAINE, Tel. +380 44 5260551, E-mail danilov@univ.kiev.ua (77)

DAVIS, Dr W.A., VA Tech, 302 Whittemore Hall - 0111, Blacksburg, VA 24061, USA, Tel. +1 540-231-6307, Fax +1 540-231-3362, E-mail wadavis@vt.edu (76)

DAVIS, Prof. R., JBCA, School of Physics and Astronomy, University of Manchester, Alan Turing Building, Manchester M139PL, UNITED KINGDOM, Tel. +44 161 275 4164, Fax +44 161 275 4247, E-mail richard.davis@manchester.ac.uk (80)

DEFORNEL, Prof. F., Directeur de recherche au CNRS, LPUB/UMR, 6, avenue A. Savary, BP 47870 , F-21078 DIJON, FRANCE, Tel. +33 3 80 39 60 50, Fax +33 3 80 39 59 56, E-mail ffornel@u-bourgogne.fr, Frederique.de-Fornel@u-bourgogne.fr (82)

DECHAMBRE, Dr. M., LATMOS, Quartier des garennes, 11 boulevard d'Alembert , F-78280 GUYANCOURT, FRANCE, Tel. + 33 1 80 28 50 80, E-mail monique.dechambre@latmos.ipsl.fr (78)

DEHOLLAIN, Dr. C., EPFL, STI, IMM, LEG, ELB-Ecublens, Station 11, CH-1015 LAUSANNE, SWITZERLAND, Tel. +41 21 693 69 71, Fax +41 21 693 36 40, E-mail catherine.dehollain@epfl.ch (77)

DEMIR, Assoc. Prof. S., Department of Electrical and Electronics Engineering, Faculty of Engineering, Middle East Technical University , Balgat, Ankara 06531, TURKEY, Tel. +90 312 210 2354, Fax +90 312 210 2304, E-mail simsek@metu.edu.tr (78)

DESCHAMPS, Mr. A., LERMA, Oberatoire de Paris, 61 Avenue de l'Observatoire, F-75014 PARIS, FRANCE, Tel. +33 140 51 52 43, E-mail andre.deschamps@obspm.fr (80)

D'INZEO, Prof. G., DIET, University of Rome "La Sapienza", Via Eudossiana, 18, I-00184 ROME, ITALY, Tel. +39 06 4458 5853, Fax +39 06 4742 647, E-mail dinzeo@die.uniroma1.it (75)

DOHERTY, Prof. P., Co-Director/Research Scientist, Institute for Scientific Research, Boston College, 140 Commonwealth Avenue, CHESTNUT HILL, MA 02467, USA, Tel. +1 617 552 8767, Fax +1 617 552 2818, E-mail Patricia.Doherty@bc.edu (81)

DOMINGUEZ, Eng. N.A., CORCA, Avenida del Liberta dor 327, 1638 VICENTE LOPEZ, B.A., ARGENTINA, Tel. +54 1-772-1471, Fax +54 1 1477 60410, E-mail postmast@caerce.edu.ar (82)

DONG, Mr. Q-S, China Research Institute of Radio Wave Propagation, Beijing Research Center, PO Box 6301, 102206 BEIJING, CHINA (CIE), Tel. +86 37 3371 2001, E-mail qsdong22s@sina.com (78)

DOWDEN, Prof. R.L., 16 Carlton Street, Dunedin, North East Valley 9010, NEW ZEALAND, Tel. +64 3 473 0524 (2000-0900 UT only), Fax +64 3 473 0526 (any time), E-mail dowdenz@physics.otago.ac.nz (78)

DOWNING, Dr. C., School of Electronic & Communications Engineering, Dublin Institute of Technology, Kevin Street, DUBLIN 2, IRELAND, Tel. +353 1 4024578, Fax +353 1 4024690, E-mail cdowning@dit.ie (82)

DUNLOP, Prof. M.W., Space Sciences Division, SSTD, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UNITED KINGDOM, Tel. +44 1235 44 5427, Fax +44 1235 44 5848, E-mail malcolm.dunlop@stfc.ac.uk (79)

ELHADIDI, Prof. Dr. M., Faculty of Engineering, Cairo University, Giza, EGYPT, E-mail hadidi@eun.eg (80)

EL-HENNAWY, Prof. H.M., Faculty of Engineering, Ain Shams University, 1 El-Sarayat Street, Abassio, Cairo, EGYPT, Tel. +202 2682 1800, Fax +202 26850617, E-mail helhennawy@ieee.org (76)

ELKHAMY, Prof. S.E., Dept. of Electrical Engineering, Alexandria University - Faculty of Engineering, Abou-Keer Street, ALEXANDRIA 21544, EGYPT, Tel. +2010-1497360, Fax +203 5971853, E-mail elkhamy@ieee.org, said.elkhamy@gmail.com, elkhamy@alex.edu.eg (77, 82)

FAHMY, Prof. Dr. M., Faculty of Engineering, Assiut University, 71515 Assiut, EGYPT, E-mail mamdouhffahmy@gmail.com (76)

FALODUN, Dr. S.E., Department of Physics, Federal University of Technology, AKURE, NIGERIA, Tel. 234 803 353 4973, E-mail bestal@yahoo.com (77)

FARINA, Dr. D., Istituto di Fisica del Plasma 'Piero Caldirola', Dipartimento Energia e Trasporti, Consiglio Nazionale delle Ricerche, Via Roberto Cozzi 53, 20125 Milano, ITALY, E-mail farina@ifp.cnr.it (79)

FARKAS, Prof. P., Fac. of Electrical Engineering & Information Technology, Slovak University of Technology, Ilkovicova 3, BRATISLAVA 812 19, SLOVAKIA, Tel. +421-2-60 29 18 44, Fax +421-2-68 27 96 01, E-mail p.farkas@ieee.org (77)

FARR, Dr. E., Research Dept., Farr Fields, LC, 1801 Count Fleet St Se, NM 87123 Albuquerque, USA, Tel. +1(505)293-3886, E-mail efarr@farr-research.com (78)

FAVENNEC, Dr. P.N., 2, impasse Krec'h Liarch, Beg Leguer, F-22300 LANNION, FRANCE, Tel. +33 6-8155 8392, E-mail pierre-noel.favennec@wanadoo.fr (75, 83)

FEICK, Dr. R., Depto. de Electronica, Universidad Técnica Federido Santa Maria, Casillo 110 V, VALPARAISO, CHILE, Tel. +56 32-626 364 ext. 209, Fax +56 32-665 010, E-mail rodolfo.feick@usm.cl (77)

FEJES, Prof I., Moriczzs.u. 16/A, SOLYMAR 2083, HUNGARY, Tel. +3627374980, Fax +3627374982, E-mail fejes@gpsnet.hu (79)

FERDINANDOV, Prof. E., Technical University of Sofia, 8, Kliment Ohridski Str., 1756 SOFIA, BULGARIA, Tel. +359 2 965 3275 (76)

FERENCZ, Prof. Cs., ELTE Department of Geophysics, Space Research Group, Pazmany Peter setany 1/A, H-1117 BUDAPEST, HUNGARY, Tel. +36 1 209 0555/6652, Fax +36 1 372 2927, E-mail spacerg@sas.elte.hu, csaba@sas.elte.hu (79)

FISER, Assoc. Prof. O., Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Bocní II - 1401, PRAGUE 4 141 31, CZECH REPUBLIC, Tel. +420 272 016 038, Fax +420 272 763 745, E-mail ondrej@ufa.cas.cz (82)

FÖRSTER, Dr., Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany, Tel. +49 (0) 331 288 1776, Fax +49 (0) 331 288 1235, E-mail mfo@gfz-potsdam.de (79)

FORTOV, Prof. V., Russia Academy of Sciences, Leninsky Prospect 14, 119991 Moscow, RUSSIA, Tel. +7 (495) 485-79-88, E-mail fortov@ihed.ras.ru (82)

FOPPIANO, Dr. A., Departamento de Geofísica, Universidad de Concepción, Casilla 160-C, Correo 3, CONCEPCION, CHILE, Tel. +56 41-312 413, Fax +56 41-312 863, E-mail alberto.foppiano@dgeo.udec.cl (79)

FORSSELL, Prof. B., Department of Electronics and Telecommunications, NTNU O.S., Bragstads plass 2, N-7491 TRONDHEIM, NORWAY, E-mail borje.forssell@iet.ntnu.no (77)

FRANCHOIS, Prof. A.I., Information Technology (INTEC), Ghent University, Sint Pietersnieuwstraat 41 , B-9000 GHENT, BELGIUM, Tel. +32 9 264 89 37, Fax +32 9 264 99 69, E-mail Ann.Franchois@intec.ugent.be (80)

FROLLO, Prof. I., Institute of Measurement Science, Slovak Academy of Sciences, Dubravska Cesta 9, BRATISLAVA 841 04, SLOVAKIA, Tel. +421 2-591 04 422, Fax +421 2-5477 5943, E-mail frollo@savba.sk (80)

FRØYSTEIN, Dr. H.A., Justervesenet, Festveien 99, N-2007 Kjeller, NORWAY, Tel. +47 64 848484, Fax +47 64 848485, E-mail haf@justervesenet.no (76)

FUJISAWA, Dr K., Yamaguchi University, Yoshida 1677-1, Yamaguchi-city, Yamaguchi 753-8511, Japan, Tel. +81-83-933-5973, Fax +81-83-933-5973, E-mail kenta@yamaguchi-u.ac.jp (80)

FULLEKRUG, Dr M., Dept. of Electronic and Electrical Engineering, Centre for Space, Atmospheric and Oceanic Science, University of Bath, 2 East 3.8, Claverton Down, Bath, BA2 7AY, UNITED KINGDOM, Tel. +44 1225 386053, Fax +44 1225 386305, E-mail eesmf@bath.ac.uk (78)

FUSCO, Prof. V.F., ECIT Institute, The Queen's University of Belfast, Northern Ireland Science Park, Queens Road, Queen's Island, BELFAST BT3 9DT, NORTHERN IRELAND, Tel. +44 28 9097 1700, Fax +44 28 9097 1702, E-mail michelle.mccusker@ecit.qub.ac.uk (76)

GAGLIARDINI, Dr. D.A., Julian Alvarez 1218, 1414 BUENOS AIRES, ARGENTINA, Tel. +54 1-772-1471, Fax +54 11 4776 0410, E-mail postmast@caerce.edu.ar (78)

GAGNON, Prof. F., Comunity Director, école de technologie supérieure de Montréal, 1100 rue Notre-Dame Ouest, MONTREAL QC H3C H3C 1K3, CANADA, Tel. +1 514 396 8997, Fax +1 514 396 8684, E-mail francois.gagnon@etsmtl.ca (77)

GALKIN, Mr. I.A., Center for Atmospheric Research, University of Massachusetts, 600 Suffolk Street, LOWELL, MA 01854, USA, Tel. +1 978 934-4912, Fax +1 978 459-7915, E-mail ivan_galkin@uml.edu (81)

GALLEGO PUJOL, Dr. J.D., Observatorio Astronomico Nacional, Apdo 1143, ALCALA DE HENARES, 28800 MADRID, SPAIN, Tel. +34 91 885 5060, Fax +34 91 885 5062, E-mail gallego@oan.es (78)

GARAVAGLIA, Prof., Departamento De Física, Centro De Investigaciones Opticas, Camino Centenario Y 506, Gonnet, CC31897 La Plata, Argentina, Tel. + 54 221 471 4341, Fax + 54 221 471 4341, E-mail garavagliam@ciop.unlp.edu.ar (77)

GARBINI, Ing. A., CORCA, Avenida del Liberta dor 327, 1638 VICENTE LOPEZ, B.A., ARGENTINA, Tel. +54 11 4772 1471, Fax +54 11 4776 0410, E-mail postmast@caerce.edu.ar (82)

GARDNER, Dr. R.L., 6152 Manchester Park Circle, ALEXANDRIA, VA 22310-4957, USA, Tel. +1 703-924-9370, Fax +1 703-313-4179, E-mail Robert.L.Gardner@verizon.net (81)

GAVAN, Prof. J., Sami Shamoon College of Engineering, Jabutinsky 84, ASHDOD, ISRAEL, E-mail jacobg@sce.ac.il (81)

GEZICI, Dr. S., Faculty of Engineering, Bilkent, Ankara 06800, TURKEY, Tel. +312 290 3139, Fax +312 266 4192, E-mail gezici@ee.bilkent.edu.tr (78)

GIMM, Prof. Y.M., School of Electronics and Electrical Engineering, Dankook University, Jukjeon-dong 126, Suji-gu, YONGIN-SI 448-701, SOUTH KOREA, Tel. +82 2 793 8732, Fax +82 2 793 1150, E-mail gimm@dku.edu (80)

GIRALDEZ, Prof. A., LIARA, avda. del Libertador 327, 1638 VICENTE LOPEZ, B.A., ARGENTINA, Tel. +54 1-791-5001, Fax +54 1-776-0410 (79)

GIRI, Adj. Prof. D.V., Dept of ECE, University of new Mexico, Pro-Tech, 11-C Orchard Court, ALAMO, CA 94507 1541, USA, Tel. +1 925 552 0510, Fax +1 925 552 0532, E-mail Giri@DVGiri.com (78, 83)

GLOVER, Prof. Andrew, Department of Engineering & Technology, University of Huddersfield, Queensgate, Huddersfield HD1 3DH, United Kingdom, Tel. +44 1484 473 133, Fax +44 1484 421 106, E-mail i.a.glover@hud.ac.uk (82)

GÖTZE, Prof. Dr. J., Arbeitsgebiet Datentechnik, Technische Universitaet Dortmund, Fakultaet ET/IT, Otto-Hahn Strasse 4, D-44227 Dortmund, GERMANY, Tel. +49 (0)231 755 2091, Fax +49 (0)231 755 7019, E-mail juergen.goetze@uni-dortmund.de (77)

GOMBEROFF, Prof. L., Depto de Fisica - Facultad de Ciencias, Universidad de Chile, Casilla 653, SANTIAGO, CHILE, Tel. +56 2-271 2865, Fax +56 2-271 3882, E-mail lgombero@abello.dic.uchile.cl (79)

GOUGH, Dr. P.T., Dept. of Electrical and Computer Engineering, University of Canterbury, Private Bag 4800, CHRISTCHURCH 1, NEW ZEALAND, Tel. +64 3 364-2297, Fax +64 3 364-2761, E-mail peter.gough@canterbury.ac.nz (77)

GRAY, Dr. A.D., National Research Council Canada, NRC Herzberg, P.O. Box 248, PENTICTON, BC V2A 6J9, CANADA, Tel. +1 250 497 2313, Fax +1 250 497 2355, E-mail Andrew.Gray@nrc-cnrc.gc.ca (82)

GRONWALD, Prof., Hamburg University of Technology, Electromagnetic Theory, Harburger Schloss Str. 20, 21079 Hamburg, Germany, Tel. +49-40-42878-2177, E-mail gronwald@tu-harburg.de (81)

GROVES, Dr. K., US Air Force Research Laboratory, AFRL/VSBXI, 29 Randolph Road, Hanscom AFB, MA 1731, USA, E-mail keith.groves@hanscom.af.mil (81)

GUEVARA DAY, Dr. W.R., National Commission on Aerospace Research and Development (CONIDA), Felipe Villaran 1069, San Isidro, LIMA 27, PERU, Tel. +51 1-4429973, Fax +51 1-4419081, E-mail walter@conida.gob.pe (79)

GUHA, Dr D., RMC, Institute of Radiophysics and Electronics, University of Calcutta, 92 Acharya Prafulla Chandra Road, Kolkata, WB, 700 009, India, Tel. 033 2481 2263, Fax 033 2351 5828, E-mail debatoshguha@rediffmail.com (76)

GULYAEV, Prof. S., Auckland University of Technology, Institute For Radio Astronomy And Space Research, Private Bag 92006, 1142 Auckland, NEW ZEALAND, Tel. +64 9 921 9999 ext 8709, 9541, Fax +64 9 921 9973, E-mail sergei.gulyaev@aut.ac.nz (80)

GUO, Dr., H., School of Electronics Eng. & Computer Science, Peking University, Beijing, 100871, CHINA (CIE), Tel. +86 10 6275 7035, E-mail hongguo@pku.edu.cn (77)

GUTIERREZ DE LA CRUZ, Dr. C.M., Instituto de Astrofisica de Canarias, C/ Via Lactea, s/n, 38205 LA LAGUNA, TENERIFE, SPAIN, E-mail cgc@iac.es (80)

HÄGGSTRÖM, Prof. I., EISCAT Scientific Association, Box 812, S-981 28 KIRUNA, SWEDEN, Tel. +46 9807 87 01, Fax +46 9807 87 09, E-mail ingemar@eiscat.se (83)

HALEVY-POLITCH, Dr. J., P.O. Box 7205, 31071 HAIFA, ISRAEL, Tel. +972 4-879 4862, Fax +972 4-879 4875, E-mail aeryapo@tx.technion.ac.il (76)

HALLIKAINEN, Prof. M.T., Dept. of Radio Science and Engineering, Aalto University, P.O. Box 13000, FI-00076 AALTO, FINLAND, Tel. +358 9 470 22371, E-mail Martti.Hallikainen@aalto.fi (78)

HAMELIN, Mr. J., Conseiller Scientifique, Centre d'analyse stratégique (CAS), 18, rue de Martignac, F-75700 Paris Cedex 07, FRANCE, Tel. +33 1 42 75 60 35, E-mail ursi-france@institut-telecom.fr (75)

HAMNERIUS, Prof. Y., Signals and Systems, Chalmers University of Technology, 412 96 GÖTEBORG, SWEDEN, Tel. +46 31 772 19 05, Fax +46 31 772 17 48, E-mail yngve.hamnerius@chalmers.se (80)

HAN, Dr. S-T, Korea Astronomy & Space Science Institute, 667 Daeduckdae-ro, Yuseong-gu, DAEJEON 305-340, SOUTH KOREA, Tel. +82 42 865 3283, Fax +82 42 865 5610, E-mail sthan@kasi.re.kr (80)

HARTAL, Mr. O., RAFAEL, P.O. Box 2250, 31021 HAIFA, ISRAEL, Tel. +972 4-8792931, Fax +972 4-8795329 (78)

HASHIMOTO, Prof. K., Research Institute for Sustainable Humanosphere, Kyoto University, Gokasho, Uji, KYOTO 611-0011, JAPAN, Tel. +81 774 383 807, Fax +81 774 383 836, E-mail kozo@rish.kyoto-u.ac.jp (81)

HATTORI, Dr. K., Department of Earth Sciences, Faculty of Science, Chiba University, Yaoi, 1-33, Inage, CHIBA 263-8522, JAPAN, Tel. +81 43 290 28 01, Fax +81 43 290 28 59, E-mail hattori@earth.s.chiba-u.ac.jp (81)

HAYAKAWA, Prof. M., Dept. of Electronic Engineering, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, TOKYO 182-8585, JAPAN, Tel. +81 424-43 5159, Fax +81 424-43 5783, E-mail hayakawa@whistler.ee.uec.ac.jp (81)

HELEU, Mrs. Inge, URSI Secretariaat, URSI, c/o INTEC, Sint-Pietersnieuwstraat 41, B-9000 GHENT, BELGIUM, Tel. +32 9-264.33.20, Fax +32 9-264.42.88, E-mail info@ursi.org (75)

HERAUD, Dr. J., Instituto de Radioastronomia INRAS-PUCP, Pontificia Universidad Catolica del Peru, Av. Universitaria 1801, San Miguel, LIMA 32, PERU, Tel. +51 1 6262000 (ext. 4735), E-mail jheraud@pucp.edu.pe (80)

HERNANDEZ-PAJARES, Dr. M., Res. Group Of Astronomy & Geomatics (gage, Technical University of Catalonia (GAGE/UPC), Mod. C3 Campus Nord UPC, Jordi Girona 1, 08034 Barcelona, Spain, Tel. +34 93 4016029, Fax +34 93 4015981, E-mail manuel@mat.upc.es (81)

HEYMAN, Prof. E., The Iby and Aladar Fleischman Faculty of Engineering, Tel Aviv University, 69978 TEL AVIV, ISRAEL, Tel. +972 3 6408738/8736/8147, Fax +972 3 6407221, E-mail heyman@tau.ac.il (82)

HJELMSTAD, Dr. J.Fr., Department of Electronics and Telecommunications, NTNU, O.S. Bragstads plass 2, 7491 TRONDHEIM, NORWAY, Tel. +47 45 249613, E-mail jens@hjelmstad.no (78)

HO, Prof. T.P., Academia Sinica, Institute of Astronomy and Astrophysics, P.O. Box 23-141, TAPEI 106, TAIWAN, Tel. +886 2 33652200 x700, Fax +886 2 23677849, E-mail pho@asiaa.sinica.edu.tw (80)

HOBARA, Prof., Dept. of Communication Engineering and informatics, The University of Electro-Communications, 1-5-1, Chofugaoka, 182-858 Chofu, Japan, Tel. +81-424435154, E-mail hobara@ee.uec.ac.jp (81)

HØEG, Prof. P., DTU Space, Technical University of Denmark, National Space Institute, Department for Geodesy, Juliane Maries Vej 30, 2100 Copenhagen, DENMARK, Tel. +45 3532 5702, E-mail hoeg@space.dtu.dk, per.hoeg@gmail.com (79)

HOLLOWAY, Dr. C., Electromagnetics Division, NIST, 325 Broadway, Boulder, CO, 80305, USA, Tel. +1 (303) 497-6184, E-mail holloway@boulder.nist.gov (76)

HONARY, Prof F., Physics Department, Lancaster University, Lancaster, LA1 4YB, UNITED KINGDOM, Tel. +44 152 4510 402, Fax +44 1524 844037, E-mail f.honary@lancaster.ac.uk (79)

HOUMINER, Dr. Z., Asher Space Research Institute, Technion, Israel Institute of Technology, 32000 HAIFA, ISRAEL, Tel. +972 4-829 3512, Fax +972 4-823 0956, E-mail zwih@tx.technion.ac.il (79)

HUBBARD, Mr. R., EMC/EMF, Eskom Resources & Strategy, Tel. +27 11 629 5236 (80)

ILMONIEMI, Prof. , Dept. Biomedical Eng. and Computational Science, Aalto University, P.O. Box 12200, FI-00076 AALTO, Finland, Tel. +358 50 5562964, Fax +358 9 470 23182, E-mail risto.ilmoniemi@aalto.fi (80)

ISNARD, Dr. J.J., CNFRS, 28, avenue de Breteuil, F-75007 PARIS, FRANCE, Tel. +33 1-45 66 55 99, Fax +33 1 45 66 55 99, E-mail jisnard-isti@club-internet.fr (81)

JACARD, Prof. B., Depto. de Ingenieria Electrica, Universidad de Chile, Casilla 412-3, SANTIAGO 3, CHILE, Tel. +56 2-698 2071 ext. 204, Fax +56 2-695 3881 (76)

JACKSON, Prof. R, Electrical And Computer Engineering, University Of Houston, n308 Engineering Building 1, TX 77204-4005 Houston, United States, Tel. +1 713-743-4426, Fax +1 713-743-4444, E-mail djackson@uh.edu (82)

JANARDHAN, Prof. P., Physical Research Laboratory, Ahmedabad 380009, INDIA, Tel. +91 79 2631 4505, E-mail jerry@prl.res.in (80)

JAYACHANDRAN, Mr. P.T., Department of Physics, University of New Brunswick, 8 Bailey Drive, P.O. Box 4440, Fredericton, NB E3B 5A3, CANADA, Tel. +1 506 447 3330, Fax +1 506 453 4583, E-mail jaya@unb.ca (79)

JIMBO, Prof. Y., Graduate School of Frontier Sciences, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, CHIBA 277-8563, JAPAN, Tel. +81 4 7136 4648, Fax +81 4 7136 4649, E-mail jimbo@k.u-tokyo.ac.jp (80)

JIRICKA, Dr. K., Astronomical Institute, Academy of Sciences of the Czech Republic, Fricova 1, ONDREJOV 251 65, CZECH REPUBLIC, Tel. +420 323 620 154, Fax +420 323 620 110, E-mail jiricka@asu.cas.cz (80)

JOHANSSON, Dr. J, SP, P.O. Box 857, SE-501 15 Boras, SWEDEN, Tel. +46 10 516 55 04, Fax +46 33 12 50 38, E-mail jan .johansson@sp.se (76)

JOHANSSON, Dr. J.F., RUAG Space AB, , SE-405 15 GÖTEBORG,SWEDEN, Tel. +46 31 735 4286, Fax +46 31 735 4000, E-mail joakim.johansson@ruag.com (78)

JONAS, Prof J., Department of Physics and Electronics, Rhodes University, PO Box 94, 6140 GRAHAMSTOWN, SOUTH AFRICA, Tel. +27 46 603 8452, Fax +27 46 622 5049, E-mail j.jonas@ru.ac.za (80)

JULL, Prof. E.V., Department of Electrical Engineering, University of British Columbia, 2356 Main Mall, VANCOUVER, BC V6T 1W5, CANADA, Tel. +1 604-822 3282/2872, Fax +1 604-822 5949, E-mail jull@ece.ubc.ca (75)

KAERTNER, Prof. F.X., Massachusetts Institute of Technology, Room 36-351, 77 Massachusetts Avenue, CAMBRIDGE, MA 02139-4307, USA, Tel. +1 617 452 3616, Fax +1 617 253 9611, E-mail kaertner@mit.edu (75)

KALINOWSKI, Prof. H.J., Depog - Departamento de Pos Graduaçao e Pesquisa, Universidade Tecnologica Federal do Parana, Av. Sete de Setembro 3165, REbouças, 80230-901 CURITIBA, PR, BRAZIL, Tel. +55 41 33104689, Fax +55 41 33104683, E-mail hjkalin@gmail.com (77)

KALOUPTSIDIS, Prof. N., Division of Communications and Signal Processing, Dept. of Informatics, University of Athens , TYPA Buildings, Panepistimiopolis, GR-15771 ILISSIA, ATHENS, GREECE, Tel. +30 210 727 5304, Fax +30 210 727 5601, E-mail kalou@di.uoa.gr (77)

KANELLOPOULOS, Prof. J., Division of Information Transmission Systems and Material Technology, School of Electrical & Computer Engineering, National Technical University of Athens, Iroon Polytechniou 9, GR-15773 ATHENS, GREECE, Tel. +30 210 772 3524, Fax +30 210 772 2281, E-mail ikanell@cc.ece.ntua.gr (79)

KARLSSON, Prof. A., Electrical and Information Technology, Lund University, P.O Box 118, SE -221 00 LUND, SWEDEN, Tel. +46 222 40 89, E-mail Anders.Karlsson@eit.lth.se (76)

KARWOWSKI, Prof. A., Silesian University of Technology, ul. Akademicka 2, 44-100 Gliwice, POLAND, Tel. +48 32 237 1594, E-mail andrzej.karwowski@gmail.com (76)

KASTNER, Prof. R., Dept. Electrical Eng.-Physical Electronics, Tel Aviv University, 243 Wolfson Electrical Eng Bldg, 62978 TEL AVIV, ISRAEL, Tel. +972 3-640 7447, Fax +972 3-642 3508, E-mail kast@eng.tau.ac.il (76, 82)

KATAMZI, Ms., Space Science, South African National Space Agency (SANSA), P O Box 32, Hermanus 7200, UNITED KINGDOM, Tel. +27 (0)28 312 1196, Fax +27 (0)28 312 2039, E-mail zkatamzi@sansa.org.za (79)

KAUFMANN, Prof. P., CRAAM/CRAAE (Mackenzie,Inpe,USP,Unicamp), Universidade Presbiteriano Mackenzie, Rua da Consolacao 896, 1321907 Sao Paulo, BRAZIL, Tel. +55 11 236 8331, Fax +55 11 214 2300, E-mail kaufmann@craam.mackenzie.br, pierrekau@gmail.com (80)

KAWASAKI, Dr. Z., Dept. of Communications Engineering, Osaka University, Graduate School of Engineering, Yamada-Oka 2-1, Suita, OSAKA 565-087, JAPAN, Tel. +81 6 879-7690, Fax +81 6 879-7774, E-mail Zen@comm.eng.osaka-u.ac.jp (81)

KENDERESSY, Prof. M., Ribary u. 7, H-1022 BUDAPEST, HUNGARY, Tel. +36 1-461-3348 (76)

KEYDEL, Prof. Dr. W., Mittelfeld 4, 82229 Hechendorf, GERMANY, Tel. +49 (0)8152-980 523, Fax +49 (0)8152-980 525, E-mail wolfgang@keydel.com (81)

KHALIL, Dr. D.A., Faculty of Engineering, Ain Shams University, 1 Elsarayat St. - Abbasia, CAIRO, EGYPT, E-mail Diaa.khalil@ieee.org (77)

KILIFARSKA, Dr. N., National Institute of Geophysics, Geodesy and Geography (NIGGG), Bulgarian Academy of Sciences, Acad. G. Bonchev St., bl. 3, 1113 SOFIA, BULGARIA, Tel. +359 2 979 3329, E-mail nkilifarska@geophys.bas.bg (79)

KILLAT, Prof. Dr. D., Lehrstuhl Mikroelecktronik, Brandenburgische Technische Universitaet Cottbus, Konrad-Wachsmann-Allee 1, D-03046 Cottbus, GERMANY, Tel. +49 (0) 355 692811, Fax +49 (0) 355 69 28 12, E-mail killat@tu-cottbus.de (77)

KIM, Dr. J.H., Electromagnetic Wave Center, Korea Research Institute of Standards & Science, 267 Gajeong-ro, Yuseong-gu, DAEJEON 305-340, SOUTH KOREA, Tel. +82 42 868 5170, Fax +82 42 868 5018, E-mail kimjh@kriss.re.kr (76)

KLOS, Dr. Z., Space Research Center, Polish Academy of Sciences, ul. Bartycka 18A, 00-716 WARSAW, POLAND, Tel. +48 22-8511810, +48 39-121273, Fax +48 22-8511810, E-mail klos@cbk.waw.pl (83)

KNEPPO, Prof. I., Faculty of Special Technology, Alexander Dubcek University of Trencin, Pri parku 19, TRENCIN 911 06, SLOVAKIA, Tel. +421 32 7400 275, E-mail kneppo@tnuni.sk (76)

KNUDE, Dr. J., Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, DK 2100 COPENHAGEN, DENMARK, Tel. +45 3532 5986, Fax +45 3532 5989, E-mail indus@astro.ku.dk (80)

KOBAYASHI, Prof. K., Department of Electrical, and Communication Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, TOKYO, 112-8551, JAPAN, Tel. +81 3 3817 1846/69, Fax +81 3 3817 1847, E-mail kazuya@tamacc.chuo-u.ac.jp (82)

KÖKSAL, Dr. , Electrical And Electronics Engineering, Hacatepe University, 06800 Ankara, Türkiye, Tel. 3122977085, Fax 3122992125, E-mail koksal@hacettepe.edu.tr (80)

KONOVALENKO, Prof. A.A., Institute of Radioastronomy, NASU, ul. Krasnoznamennaya 4, KHARKOV 61002, UKRAINE, Tel. +380 572-47-1134, Fax +380 572-47-6506, E-mail rian@rian.kharkov.ua (80)

KORDI, Dr. B., Department of Electrical & Computer Engineering, E1-556, University of Manitoba, 75A Chancellors Circle, Winnipeg, MB R3T5V6, CANADA, Tel. +1 204 474 7851, Fax +1 204 261 4639, E-mail bkordi@ee.umanitoba.ca (78)

KORENSTEIN, Prof. R., Physiology And Pharmacology, Tel-Aviv University, Haim Levanon 5000, 69978 TEL AVIV, ISRAEL, Tel. +972 3640 6042, Fax +972 3640 9113, E-mail korens@post.tau.ac.il (80)

KOUDELKA, Prof. O., Institute of Communication Networks and Satellite Communications, Graz University of Technology, Inffeldgasse 12, 8010 Graz, AUSTRIA, Tel. +43 316 873 7440, Fax +43 316 873 7941, E-mail koudelka@tugraz.at (77)

KOYAMA, Prof. Y., Space-Time Standards Group, New Generation Network Research Center, National Institute of Information and Communication Technology (NICT), 4-2-1, Nukuikitamachi, Koganei, TOKYO 184-8795, JAPAN, Tel. +81 42 327 7557, Fax +81 42 327 6834, E-mail koyama@nict.go.jp (76)

KRAJCUSKOVA, Dr. Z., Fac. of Electrical Eng.&Information Technology, Slovak University of Technology, Ilkovicova 3, BRATISLAVA 81219, SLOVAKIA, Tel. +421-2-6029 1137, Fax +421-2-6542 9683, E-mail zuzana.krajcuskova@stuba.sk (82)

KRAUS, Dr. A., Max-Planck-Institut fuer Radioastronomie, Radioobservatorium Effelsberg, Max-Planck-strasse 28, D-53902 Bad Muenstereifel-Effelsberg, GERMANY, Tel. +49 (0)2257 301 120, Fax +49 (0)2257 301 105, E-mail akraus@mpifr.de (80)

KRAWCZYK, Prof. A., Military Institute of Hygiene & Epidemology, 4 Kozielska St., 01-163 Warsaw, POLAND, Tel. +48 22 8724 282, E-mail ankra.new@gmail.com (80)

KRIEZIS, Prof. E., Dept. of Electrical and Computer Engineering, Aristotle University of Thessaloniki, , GR-54124 THESSALONIKI, GREECE, Tel. +30 2310 995920, Fax +30 2310 996312, E-mail mkriezis@auth.gr (77)

KRISTENSSON, Prof. G., Electrical and Information Technology, Lund University, P.O. Box 118, 221 00 LUND, SWEDEN, Tel. +46 46 222 45 62, E-mail gerhard.kristensson@eit.lth.se (82)

KUDELA, Prof. K., Institute of Experimental Physics, Slovak Academy of Science, Watsonova 47, KOSICE 040 01, SLOVAKIA, Tel. +421 55-622 4554, Fax +421 55-633 6292, E-mail kkudela@kosice.upjs.sk (79)

KULAH, Assoc. Prof. H., Faculty of Engineering, Middle East Technical University, Balgat, Ankara 06531, TURKEY, Tel. +312 210 2345, Fax , E-mail kulah@metu.edu.tr (77)

KULEMIN, Prof. G.P., Institute of Radiophysics and Electronics, NASU, 12, ac. Proskura Str., KHARKOV 61085, UKRAINE, Tel. +380 572-448508, E-mail secretar@ire.kharkov.ua (78)

KULPA, Prof. K., Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 WARSAW, POLAND, Tel. +48 606 209 225, E-mail kulpa@ise.pw.edu.pl (78)

KUROCHKIN, Dr. A.P., NPO VEGA, Kutuzovsky Prospekt 34, MOSCOW 121170, RUSSIA, Tel. +7 499 249 4308, Fax +7 499 258 2504, E-mail kurochkin@vega.su (76)

KUSTER, Prof. N., IT'IS Foundation, Zeughausstraße 43, CH-8004 ZURICH, SWITZERLAND, Tel. +41 44 245 96 96, Fax +41 44 245 96 99, E-mail nk@itis.ethz.ch (80)

KUZMAK, Dr. O.M., Institute of Magnetism, NASU, 36-b, Vernadsky Blvd., KIEV 03142, UKRAINE, Tel. +380 44-4249095, Fax +380 44 4241020, E-mail kuzmak@imag.kiev.ua (82)

KUZNETSOV, Prof. Yu. V., Theoretical Radio Engineering Department, State University of Technology, Volorjkfvcrjt shosse 4, MOSCOW 125993, RUSSIA, Tel. +7 499 158 68 39, Fax +7 499 158 68 39, E-mail kuznetsov@mai-trt.ru, kuznetsov@ieee.org (77)

KYRIACOU, Prof. G.A., Lab. of Microwaves, Dept. of Electrical and Computer Engineering, Demokritos University of Thrace, Vas. Sofias 12 , 67 100 XANTHI, GREECE, Tel. +30 5410 795 93, Fax +30 5410 272 64, E-mail gkyriac@ee.duth.gr (76)

LAGASSE, Prof. P., URSI c/o INTEC, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 GENT, BELGIUM, Tel. +32 9-264 33 20, Fax +32 9-264 42 88, E-mail lagasse@intec.ugent.be (75, 83)

LANG, Dr R.H., Dept of Electrical Eng. & Computer Science, George Washington University, Phillips Hall, Washington, DC 20052, USA, Tel. +1 202-994-6199, Fax +1 202-994-0227, E-mail lang@gwu.edu (78, 83)

LANGENBERG, Prof. K.J., Electromagnetic Theory, FB 16, University of Kassel, Wilhelmshöher Allee 71, D-34121 KASSEL, GERMANY, Tel. +49 561-804 6368, Fax +49 561-804 6489, E-mail langenberg@uni-kassel.de (75)

LARKINA, Prof. V.I., IZMIRAN, Moscow Region, TROITSK, MOSCOW REGION 142092, RUSSIA, Tel. +7 496 751 9742, Fax +7 496 751 0124, E-mail larkina@izmiran.ru (78)

LAURENSON, Dr. D., School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, UNITED KINGDOM, Tel. +44 131 650 5579, Fax +44 131 650 6554, E-mail dave.laurenson@ed.ac.uk (77)

LAZAROV, Prof. A., Bourgas Free University (BFU), , 62 San Stefano Str., BG-8000 BOURGAS, BULGARIA, Tel. +359 56 900 485, E-mail lazarov@bfu.bg (76)

LEE, Prof. J-S, Research Center for Integrative Neuroimaging and Neuroinformatics, National Yang-Ming University, No. 155, Sec. 2, Linong Street, Beitou District, TAPEI 112, TAIWAN, Tel. +886 2 28267134, Fax +886 2 28224860, E-mail jslee@ym.edu.tw (80)

LEE, Prof. L-C, President Office, National Central University, No. 300, Jhongda Road, Jhongli City, Taoyuan, CHUNG-Li, TAOYAN 320, CHINA (SRS), Tel. +886 3 422 7151ext. 57000, Fax +886 3 425 4842, E-mail loulee@cc.ncu.edu.tw (80, 82)

LEFEUVRE, Prof. F., LPCE/CNRS, 3A, av. de la Recherche Scientifique, F-45071 Orléans Cedex 2, FRANCE, Tel. +33 2-38-255284, Fax +33 2-38-631234, E-mail lefeuvre@cnrs-orleans.fr (75, 83)

LEITGEB, Prof. N., Institute of Health Care Engineering with European Notified Body of Medical Devices, Graz University of Technology, Kopernikusgasse 24/1, 8010 Graz, AUSTRIA, Tel. +43 316 873 7397, Fax +43 316 873 4412, E-mail norbert.leitgeb@tugraz.at (80)

LEITINGER, Prof. R., Institute for Geophysics, Astrophysics and Meteorology, University of Graz, Universitaetsplatz 5, A-8010 GRAZ, AUSTRIA, Tel. +43 316 380 5257, Fax +43 316 380 9825, E-mail reinhart.leitinger@kfunigraz.ac.at (81)

LEMBEGE, Dr. B., Heppi, LATMOS-UVSQ-IPSL-CNRS, Quartier Des Garennes 11 Boulevard D'alembert 78280 Guyancourt, 78280 Guyancourt,France, Tel. +331 80 28 50 70, Fax +33 1 80 28 52 97, E-mail bertrand.lembege@latmos.ipsl.fr (81)

LICHTENBERGER, Dr. J., Pazmany Peter Setany 1/a, H-1111 BUDAPEST, HUNGARY, Tel. +36 1 209 0555 x6654, Fax +36 1 372 2927, E-mail lityi@sas.elte.hu (80)

LIEVENS, Mrs. I., URSI, c/o INTEC, , Sint-Pietersnieuwstraat 41, B-9000 GENT,BELGIUM, Tel. +32 9-264.33.20, Fax +32 9-264.42.88, E-mail ingeursi@intec.ugent.be (75)

LIGTHART, Prof. dr. ir. L.P., Director IRCTR, Delft University, Microwaves Laboratory, Mekelweg 4, NL-2628 CD DELFT, NETHERLANDS, Tel. +31 15-278 1034, Fax +31 15-278 4046, E-mail leoligthart@kpnmail.nl (78)

LILJE, Prof. P., Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 OSLO, NORWAY, Tel. +47 22 856517, E-mail per.lilje@astro.uio.no (80)

LIN, Dr. K-H, Dept. of Electrical Engineering, National Sun Yat-Sen University, 70 Lien Hai Road, KAOHSIUNG 80424, CHINA SRS, Tel. +886 7 5252000 ext 4165, E-mail khlin@mail.nsysu.edu.tw (78)

LIN, Mr. R-H, , Chinese Institute of Electronics, P.O. Box 165, Beijing 100036,CHINA CIE, Tel. +86 10 6827 6577, E-mail lin_runhua@ciecloud.org.cn (82)

LIND, Dr. F.D., MIT Haystack Observatory, Route 40, WESTFORD, MA 01886, USA, Tel. +1 781 - 981 - 5570, Fax +1 781 - 981 - 5766, E-mail flind@haystack.mit.edu (79)

LINDQVIST, Dr. M., Onsala Space Observatory, Chalmers University of Technology, SE-439 92 ONSALA, SWEDEN, Tel. +46 31 772 55 08, Fax +46 31 772 55 90, E-mail Michael.Lindqvist@chalmers.se (80)

LIPSANEN, Prof. H., Dept. of Micro and Nanosciences, Aalto University, P.O. Box 13500, FI-00076 AALTO, FINLAND, Tel. +358 50 4339 740, Fax +358 9 470 25008, E-mail Harri.Lipsanen@aalto.fi (77)

LITOVCHENKO, Prof. V.G., Institute of Physics of Semiconductors, NASU, prosp. Nauki 45, KIEV 03039, UKRAINE, Tel. +380 44-265-6290, Fax +380 44-265-8342, E-mail mickle@semicond.kiev.ua (77)

LITSYN, Dr. S., Dept. Electrical Eng./Faculty of Engineering, Tel Aviv University, Ramat-Aviv, 69978 TEL AVIV, ISRAEL, Tel. +972 3-631 4139, Fax +972 3-642 3508, E-mail litsyn@eng.tau.ac.il (77)

LIU, Dr. M., 514th Institute , China Academy of Space Technology, Zhichun Road, Haidan District, BEIJING 100086, CHINA (CIE), Tel. +86 10 687 44 667, Fax +86 10 683 78 158, E-mail run_low@sina.com (76)

LIU, Prof. C.H., National Central University, No. 300, Jung-da Rd., CHUNG-LI 320,CHINA (SRS), Tel. +886 3-4227151 ext. 7000,7001, Fax +886 3-425-4842, E-mail chliu@cc.ncu.edu.tw (81)

LUISE, Prof. M., Department of Information Engineering, University of Pisa, Via Diotisalvi 2, I-56122 PISA, ITALY, Tel. +390 50-569662, Fax +390 50-568522, E-mail marco.luise@iet.unipi.it (77)

MAEKAWA, Prof. Y., Dept. of Telecommunications & Computer Networks, Osaka Electro-Communication University, 18-8 Hatsucho, Neyagawa, OSAKA 572-8530, JAPAN, Tel. +81 72 820 90 47, Fax +81 72 820 90 44, E-mail maekawa@maelab.osakac.ac.jp (78)

MAHARAJ, Mr. B.T.J., Department of Electrical, Electronic and Computer Engineering, University of Pretoria, 0002 Pretoria, SOUTH AFRICA, Tel. +27 12 420 4636, E-mail sunil.maharaj@up.ac.za (77)

MAHMOUD, Prof. I.I., Atomic Energy Authority, Engineering Dept., NRC, Cairo, EGYPT, E-mail imbabyisma@yahoo.com (79)

MAITRA, Prof A.J.S., Institute of Radio Physics, University of Calcutta, 92 Acharya Prafulla Chandra Road, Kolkata, WB, 700009, India, Tel. +91 33 23509115, E-mail animesh.maitra@gmail.com (78)

MANARA, Prof G., Dipartimento di Ingegneria dell'Informazione, Universita di Pisa, Via G. Caruso 16, 56122 Pisa, Italy, Tel. +39-050-2217552 , Fax +39-050-2217522 , E-mail g.manara@iet.unipi.it (76)

MANN, Appl. Prof. Dr. G., Leibniz Institut fuer Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 POTSDAM, GERMANY, Tel. +49 (0)331 749 9292, Fax +49 (0)331 749 9352, E-mail gmann@aip.de (79)

MANNINEN, Dr. A., Centre for Metrology and Accreditation, PO Box 9, Tekniikantie 1, FI-02151 ESPOO, FINLAND, Tel. +358 10 6054 416, Fax +358 10 6054 498, E-mail antti.Manninen@mikes.fi (76)

MANSO, Prof. M.E., Centro de Fusão Nuclear do IST, Avenida Rovisco Pais, 1049 LISBOA CODEX, PORTUGAL, Tel. +351 21 841 76 96, E-mail emilia@cfn.ist.utl.pt (79)

MARGINEDA PUIGPELAT, Prof. J., Facultad de Quimica - Dpto. Fisica, Universidad de Murcia, Apdo. 4021, 30071 ESPINARDO, MURCIA, SPAIN, Tel. +34 968 367374, Fax +34 968 364148, E-mail jmargi@um.es (78)

MARKSTROM, Mr. K.-A., AF Technology AB, SE-169 99 STOCKHOLM, SWEDEN, Tel. +46 10 505 40 62, Fax +46 10 505 00 10, E-mail karl-arne.markstrom@afconsult.com (77)

MARROCCO, Dr. G., Dipartimento di Informatica Sistemi e Produzione, University of Roma Tor Vergata, Via del Politecnico, 1, 00133 Roma, ITALY, E-mail marrocco@disp.uniroma2.it (81)

MARTIN RODRIGUEZ, Prof. E., Facultad de Quimica - Dpto. Fisica, Universidad de Murcia Apdo. 4021, 30071 ESPINARDO, MURCIA, SPAIN, Tel. +34 968 367373, Fax +34 968 364148, E-mail ernesto@um.es (76)

MATHEWS, Prof J.D., Communications and Space Sciences Lab (CSSL), The Pennsylvania State University, 323A, EE East, University Park, PA 16802-2707, USA, Tel. +1(814) 777-5875, Fax +1 814 863 8457, E-mail JDMathews@psu.edu (79, 83)

MATHIS, Prof. Dr. W., Institute of Theoretical Electrical Engineering, Leibniz Universität Hannover, Appelstrasse 9A, D-30167 HANNOVER, GERMANY, Tel. +49 511 7623201, Fax +49 511 762 3204, E-mail mathis@tet.uni-hannover.de (82)

MATHUR, Mr. RASHMI, Department of Physiology, All India Institute of Medical Sciences, Andari Nagar, NEW DELHI 110 029, INDIA, Tel. +91 11 659 4765, Fax +91 11 686 2663, E-mail mathurashmi@yahoo.co.in (80)

MATSUMOTO, Prof. H., Kyoto University, Yoshida-Honmachi, Sakyo-ku, KYOTO 606-8501, JAPAN, Tel. +81 75 753 2001, Fax +81 75 753 2091, E-mail matsumoto@hq.kyoto-u.ac.jp (75, 81)

MAY, Prof. J., Depto. de Astronomia, Universidad de Chile, Casilla 36-D, Santioago de Chile, CHILE, Tel. +56 2-229 4002, Fax +56 2-229 4101, E-mail jmay@das.uchile.cl (82)

MAYORGA MONTOYA, ing. M., Departamento de Ingenierìa, Universidad Católica del Perú, Sección Ingeniería de las Telecomunicaciones, Av.Universitaria 1801, San Miguel, LIMA32, PERU, Tel. +51-1-626-2452, Fax +51-1-626-2116, E-mail mayorga.ma@pucp.edu.pe (76)

MAZANEK, Prof. M., Faculty of Electrical Engineering, Czech Technical University, Technická 2, PRAGUE 6 166 27, CZECH REPUBLIC, Tel. +420 224 352 282, Fax +420 233 339 958, E-mail mazanekm@feld.cvut.cz (82)

MAZELLE, Mr. C., GPPS, CNRS, 9, avenue du Colonel Roche, F-31400 TOULOUSE CEDEX, FRANCE, Tel. +33 5 61 55 66 50, E-mail christian.mazelle@cesr.fr (79)

MAZZA, Ing. H.F., INTI, CC. 157, 1650 San Martin-B.A.,ARGENTINA, Tel. +54 1-753 4064, Fax +54 1-755 2102 (76)

McCARTHY, Dr. K., Dept. of Electrical and Electronic Engineering, University College Cork, CORK, IRELAND, Tel. +353 21 490 2214, Fax +353 1 283 0921/830 921 , E-mail K.McCarthy@ucc.ie (78)

McCREADY, Ms. M., The Center for Geospace Studies, SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA, Tel. +1 650 859 5084, Fax +1 650 322 2318, E-mail mary.mccready@sri.com (81)

McKINNELL, Dr. L.A., South African National Space Agency (SANSA), Space Science, P.O. Box 32, 7200 HERMANUS, SOUTH AFRICA, Tel. +27 28 312 1196, Fax +27 28 312 2039, E-mail lmckinnell@sansa.org.za, lmckinnell@hmo.ac.za (81,82,83)

MEDINA-MENA, Prof. F., Departamento de Electronica y Electromagnetismo, Facultad de Fisica, Universidad de Sevilla, Av. Reina Mercedes s/n, 41012 SEVILLA, SPAIN, Tel. +34 954 553891, Fax +34 954 239434, E-mail medina@us.es (76)

MENDES, Eng. M.L., ICP-ANACOM, Av. José Malhoa 12, 1099-017 LISBOA, PORTUGAL, Tel. +351 21 721 2222, Fax +351 21 721 1006, E-mail ursi.por@anacom.pt (82)

MIAS, Dr. C., School of Engineering, University of Warwick, COVENTRY CV4 7AL, UNITED KINGDOM, Tel. +44 2476 522343, Fax +44 2476 418922, E-mail christos.mias@warwick.ac.uk (76)

MISHRA, Dr. A., Electrical Engineering, Menzis Building, University of Cape Town, Rondebosch 7701, SOUTH AFRICA, E-mail akmishra@ieee.org (78)

MITCHELL, Dr. C.N., Electronic and Electrical Engineering, University of Bath, Clavertown Down, BATH, BA2 7AY, UNITED KINGDOM, Tel. +44 1225 82 66 10, Fax +44 1225 82 63 05, E-mail c.n.mitchell@bath.ac.uk (81)

MODELSKI, Prof. J., Institute of Radioelectronics, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 WARSAW, POLAND, Tel. +48 22 825 39 29, Fax +48 22 825 5248, E-mail j.modelski@ire.pw.edu.pl (82)

MOITRA, Dr. A., Indian National Science Academy, Bahadur Shah Zafar Marg, NEW DELHI, 110 002, INDIA, Tel. +91 11-322 1931/1950, Fax +91 11-323 5648/1095 (82)

MOLINA FERNANDEZ, Dr. I., Departamento de Ingenieria de Communicaciones, E.T.S.I. Telecomunicacion, Universidad de Malaga, Campus Universitario de Taetinos s/n, E-29071 MALAGA, SPAIN, Tel. +34 952 13 13 11, Fax +34 952 13 20 27, E-mail imolina@uma.es (77)

MOND, Prof. M., Dept of Electrical and Computer Eng., Ben Gurion University, P.O. Box 653, 84105 BEER SHEVA, ISRAEL, Fax +972 7 6472990, E-mail mond@menix.bgu.ac.il (79)

MORIKURA, Prof. M., Communications & Computer Engineering, Graduate School of Informatics, Kyoto University, Sakyo-ku Yoshida-honmachi, KYOTO 606-8501, JAPAN, Tel. +81 75 753 5348, Fax +81 75 753 5349, E-mail morikura@i.kyoto-u.ac.jp (77)

MROZOWSKI, Prof. M., Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, ul. Gabriela Narutowicza 11/12, 80-952 Gdansk-Wrzeszcz, POLAND, Tel. +48 58 347 25 49, E-mail mim@pg.gda.pl (76)

MURPHY, Prof. A., Dept. of Experimental Physics, National University of Ireland Maynooth, CO. KILDARE, IRELAND, Tel. +351 1 6285 222 ext. 209, Fax +351 1 708 3771, E-mail anthony.murphy@nuim.ie (80)

MURPHY, Prof. P., Dept. of Electrical Eng. & Microelectronics, National University of Ireland, CORK, IRELAND, Tel. +353 21 490 2214, Fax +353 21 427 1698, E-mail P.Murphy@ucc.ie (76)

MURSULA, Prof. K., Department of Physical Sciences, University of Oulu, P.O. Box 3000, FI-90014 OULU, FINLAND, Tel. +358-8-5531366, Fax +358-8-5531287, E-mail Kalevi.Mursula@oulu.fi (79)

MUSHA, Dr. M., Institute for Laser Science, University of Electro-communications, 1-5-1 Chofugaoka, Chofu-shi, TOKYO 182 8585, JAPAN, Tel. +81 424 435 705, Fax +81 424 858 960, E-mail musha@ils.uec.ac.jp (76)

NAGATSUMA, Prof. T., Division of Advanced Electronics and Optical Science, Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, JAPAN, Tel. +81 6 6850 6335, Fax +81 6 6850 6335, E-mail nagatuma@ee.es.osaka-u.ac.jp (77)

NAGY, Dr. L., Department of Broadband Infocommunication Systems, BME - Budapest University of Technology and Economics, Goldmann Gyorgy ter 3 , 1111 BUDAPEST, HUNGARY, Tel. +36 1 463 15 59, Fax +36 1 463 32 89, E-mail nagy@mht.bme.hu (77, 82)

NAM, Prof. S., School of Electrical & Computer Engineering, Seoul National University, Sillim-dong, Kwanak-gu, SEOUL 151-742, SOUTH KOREA, Tel. +82 2 880 8412, Fax +82 2 880 8212, E-mail snam@snu.ac.kr (76, 82)

NAPIERALSKI, Prof. A., University of Lodz, Narutowicza 65, 90-131 LODZ, POLAND, E-mail napier@dmcs.p.lodz.pl (77)

NEMIROVSKY, Prof. Y., Dept. of Electrical Engineering, Technion - Israel Institute of Technology, 32000 HAIFA, ISRAEL, Tel. +972 4-829 3450, Fax +972 4-832 3041, E-mail nemirov@ee.technion.ac.il (77)

NENCHEV, Prof. M., Technical University of Sofia, , 8, Kliment Ohridi Str., 1756 SOFIA, BULGARIA, Tel. +359 32 659 711, E-mail marnenchev@yahoo.com (77, 82)

NEVES, Prof. Dr. J.C. da Silva, Instituto de Telecomunicaçoes, Universidade de Aveiro, Campus Universitario, 3810-193 AVEIRO, PORTUGAL, Tel. +351 23 437 7900, Fax +351 23 437 7901, E-mail jneves@av.it.pt (78)

NGWENYA, Ms. L., Programme Officer, SA International Council for Science, Meiring Naude Road Brummeria, P.O. Box 2600, PRETORIA 0001, SOUTH AFRICA, E-mail lynn.ngwenya@nrf.ac.za (82)

NICKOLAENKO, Prof. A., Remote Sensing, Inst. for Radio-Physics and Electronics Nat. Acad. of Sciences of the Ukraine, 12 Acad. Proskura street , KHARKOV 61085, UKRAINE, Tel. +38 (057) 720 3369, Fax +38 (257) 315 2105, E-mail sasha@ire.kharkov.ua, sashanickolaenko@gmail.com (81)

NICKOLOV, Prof. E., National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G. Bonchev St., bl. 3, 1113 SOFIA, BULGARIA, Tel. +359 2 987 4624, E-mail eugene.nickolov@cu.bas.bg (78)

NOEL, Prof. Fernando, Depto de Astronomia, Universidad de Chile, Casilla 36-D, SANTIAGO, CHILE, Tel. +56 2-229 4002, Fax +56 2-229 4101, E-mail fnoel@das.uchile.cl (76)

NOVAK, Dr. J., Institute of Electrical Engineering, Slovak Academy of Sciences, Dubravska cesta 9, BRATISLAVA 84104, SLOVAKIA, Tel. +421 2-59222761, Fax +421 2-54775816, E-mail jozef.novak@savba.sk (77)

O'BRIEN, Ms. Meaghan, National Committees Officer/ Fasas Secretariat, Australian Academy of Science, Ian Potter House, Gordon Street, Box 783, Acton ACT 2601, AUSTRALIA, Tel. 02 6201 9456, Fax 02 6201 9494, E-mail meaghan.obrien@science.org.au (82)

O'DROMA, Dr. M., Director Telecommunications Research Centre, Dept. of Electrical & Computer Eng., Electrical and Computer Eng Dept, University of Limerick, LIMERICK, IRELAND, Tel. +353-61-202364, Fax +353-61-338176, E-mail mairtin.odroma@ul.ie (77, 82)

OHIRA, Prof. T., Toyohashi University of Technology (TUT), Tempaku, Toyohashi City 441-8580, JAPAN, Tel. +81-532-44-6761, Fax +81-532-44-6757, E-mail ohira@tut.jp (75)

OHISHI, Dr. M., National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo, 181-8588, Japan, Tel. +81 422 34 3575, Fax +81422 34 3840, E-mail iucafchair@iucaf.org, masatoshi.ohishi@nao.ac.jp (83)

OJO, Dr. J.S., Department of Physics, Federal University of Technology , P.M.B 704, AKURE, NIGERIA, Tel. +234 806 653 2234, E-mail josnno@yahoo.com (82)

OKONIEWSKI, Prof. M., Electrical and Computer Engineering, ICT 354, University of Calgary, 2500 University Drive NW, CALGARY, ALBERTA, T2N 1N4, CANADA, Tel. +1 403 220 6175, E-mail okoniews@ucalgary.ca (80)

OMURA, Prof. Y., Laboratory of Computer Space Science, Kyoto University - RISH, Gokasho, Uji , KYOTO 611-0011, JAPAN, Tel. +81 774 38-3811, Fax +81 744 31-8463, E-mail omura@rish.kyoto-u.ac.jp (75, 79, 81)

ONSAGER, Dr. T., NOAA, 1401 Constitution Avenue NW Room 6217, Washington, DC 20230, USA, Tel. +1 (301) 713-0645 ext.105, E-mail Terry.Onsager@noaa.gov (83)

ONUU, Prof. M., Electronics & Computer Technology Unit, Department of Physics, University of Calabar, GPO 2772, Calabar, Cross River State, NIGERIA, Tel. 234 803 507 2076, E-mail michaelonuu@yahoo.com (78)

OPPENHEIM, Prof. M., Center for Space Physics, Astronomy Dept., Boston University, Commonwealth Ave. 725, BOSTON, MA 02215, USA, Tel. +1 617 353 61 39, Fax +1 617 353 57 04, E-mail meerso@bu.edu (79, 83)

ØSTERBERG, Prof. U., Department of Electronics and Telecommunications, NTNU, O.S. Bragstads plass 2, N-7491 Trondheim, NORWAY (76)

O'SULLIVAN, Dr J.D., Australian Telescope National Facility, CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW 1710, AUSTRALIA, Tel. +612 9372 4604, E-mail john.osullivan@csiro.au (78)

OTMIANOWSKA-MAZUR, prof. K., Jagiellonian University in Krakov, ul. Gołębia 24, 31-007 Kraków, POLAND, Tel. +48 12 425 145735, E-mail otmian@oa.uj.edu.pl (80)

ÖZEREN, Assist. Prof. F.F., Faculty of Sciences, Erciyes University, Kayseri, TURKEY, Tel. +90 352 207 6666 ext 33256, E-mail ozeren@erciyes.edu.tr (80)

PADULA-PINTOS, Prof. V.H., Director Dept. Coord. R&D, Instituto Tecnologico de Buenos Aires, Pena 2446, 7" A", 1125 BUENOS AIRES, ARGENTINA, Tel. +54 1-314 7779 ext. 263, Fax +54 1-314 0270, E-mail vpadula@itba.edu.ar (80)

PALADIAN, Prof. F., Université Blaise Pascal, LASMEA, 24, avenue des Landais, F-63177 Aubière Cedex, FRANCE, Tel. +33 4 73 40 72 09, E-mail paladian@lasmea.univ-bpclermont.fr (78)

PALICOT, Dr. J., Supélec, Avenue de la Boulaie, CS 47601, F-35576 Cesson-Sévigné, FRANCE, Tel. +33 2 99 84 45 41, E-mail jacques.palicot@supelec.fr (77)

PALOSCIA, Dr. S., CNR-IFAC, Via Madonna del Piano, 10, I - 50019 Sesto Fiorentino, FIRENZE, ITALY, E-mail S.Paloscia@ifac.cnr.it (78, 83)

PAMPALONI, Dr. PAOLO, Institute of Applied Physics, IFAC-CNR, Via Madonna Del Piano 10, 50019 Sesto Fiorentino, FIRENZE, ITALY, Tel. +39 055 4235205, Fax +39 055 4235290 or +39 055 410893, E-mail P.Pampaloni@ifac.cnr.it (78)

PANAYIRCI, Dr. E., Dept. of Electr. & Electronics Eng., Kadir Has University, Faculty of Engineering, Cibali Merkez Kampusu, 34230-01 CIBALI, ISTANBUL, TURKEY, Tel. +90 212 533 6532, E-mail eepanay@khas.edu.tr, eepanay@Princeton.edu (77)

PARFITT, Prof. A.J., Pro Vice Chancellor, Division of ITEE, University of South Australia, Mawson Centre, MAWSON LAKES, SA 5095, AUSTRALIA, Tel. +61 8 8302 3310, Fax +61 8 8302 3873 , E-mail andrew.parfitt@unisa.edu.au (77, 82)

PARK, Prof. S-O, EE Department, Korea Advanced Institute of Science and Technology, 291 Daehak-Ro, Yuseong-gu, DAEJEON 305-701, SOUTH KOREA, Tel. +82 42 350 7414, Fax +82 42 350 8268, E-mail sopark@ee.kaist.ac.kr (82)

PARKER, Prof. T., Collaborative Nonlinear Electronics Research Facility, Macquarie University, North Ryde, NSW 2109, AUSTRALIA, Tel. +61 2 9850 9131, Fax +61 2 9850 9128, E-mail tonyp@ics.mq.edu.au (77)

PARMENTIER, Dr. , ONERA, DEMR (Electromagnetics & Radar Department), CDE group (Electromagnetic Compatibility & Detection), BP4025, Avenue Edouard Belin, 31055 TOULOUSE Cedex 4, FRANCE, Tel. +33 5 62 25 27 89, Fax +33 5 62 25 25 77, E-mail hipar@onecert.fr, hipar@onera.fr (81)

PARROT, Dr. M., CNRS/LPCE, , 3A, avenue de la Recherche Scientifique, F-45071 ORLEANS CEDEX 2, FRANCE, Tel. +33 2-3825 5291, Fax +33 2-3863 1234, E-mail mparrot@cnrs-orleans.fr (81)

PASKO, Prof. V., Electrical Engineering, Penn State University, 211B EE East, 16802 University Park, United States, Tel. +1 814 865 34 67, E-mail vpasko@psu.edu (79)

PAZ RETUERTO, Mr. P., Comisión Nacional de Investigación y Desarrollo Aeroespacial CONIDA, Av. Luis Felipe Villarán 1069, San Isidro - LIMA 27 ,PERU, Fax + 51 1 441 - 9081 (77)

PELLINEN-WANNBERG, Mrs. A., Umea University, Swedish Institute of Space Physics, BOX 812, SE-981 37 KIRUNA, SWEDEN, Tel. +46 980 79118, Fax +46 980 79050, E-mail asta@irf.se, asta.pellinen-wannberg@irf.se (83)

PERRIN, Dr. A., Radiobiology, Ministry For Defence-irba/crssa, 24 Avenue Des Maquis Du Grésivaudan, 38700 La Tronche, France, Tel. 33 (0)4 76 63 68 79, E-mail aperrin.crssa@gmail.com (80)

PERRUISSEAU-CARRIER, Prof. J., Ecole Polytechnique Fédérale de Lausanne, EPFL-STI-IEL-GR-JPC, Station 11, CH-1015 LAUSANNE, SWITZERLAND, Tel. +41 21 693 78 71, Fax +41 21 693 26 73, E-mail julien.perruisseau-carrier@epfl.ch (76)

PIERRARD, Dr. V., Belgisch Instituut voor Ruimte-Aëronomie (BIRA), Ringlaan 3, B-1180 BRUSSEL, BELGIUM, Tel. +32 2 3730 418, Fax +32 2 374 84 23, E-mail viviane.pierrard@aeronomie.be (79)

PIJOAN VIDAL, Prof. J.L., Dpto. Comunicaciones y Teoria de la Senal, Universidad Ramon Llull, Escuela Tecnica Superior de Ingenieria e Informatica La Salle, 08022 BARCELONA, SPAIN, Tel. +34 93 290 24 00, Fax +34 93 290 24 70, E-mail joanp@salle.url.edu (79)

PIRJOLA, Ph.D R.J., Finnish Meteorological Institute, P.O. Box 503 , FI-00101 HELSINKI, FINLAND, Tel. +358 919 29 46 52, +358-50-5996893, Fax +358-9-19294604, E-mail risto.pirjola@fmi.fi (83)

PITOUT, Mr. F., Institut de Recherche en Astrophysique et Planétologie, 9, rue de Colonel Roche, BP 44346, 31028 TOULOUSE Cedex 4, FRANCE, Tel. +33 5 61 55 66 81, E-mail pitout@cesr.fr (79)

POGORILY, Prof. A.N., Institute of Magnetism, NASU, 36-b, Vernadsky Blvd., KIEV 03142, UKRAINE, Tel. +380 44 4249095, Fax +380444241020, E-mail apogorily@aol.com (82)

POULTER, Dr. E. M., National Institute of Water and Atmospheric Research Ltd, NIWA, P.O.Box 14-901, Kilbirnie, Wellington, NEW ZEALAND, Tel. +64-4-386-0560, Fax +64-4-386-2153, E-mail m.poulter@niwa.cri.nz (78)

PRATO, Dr. F., Lawson Imaging, Room B5-004, Lawson Health Research Institute, 268 Grosvenor Str., LONDON, ON N6A 4V2, CANADA, Tel. +1 519-646-6100x64140, Fax +1 519-646-6205, E-mail prato@lawsonimaging.ca (82)

PRAZERES, Eng. H. P., ICP-ANACOM, , Av. José Malhoa 12, 1099-017 LISBOA, PORTUGAL, Tel. +351 21 721 2232, Fax +351 21 721 1006, E-mail ursi.por@anacom.pt, helena.prazeres@anacom.pt (82)

PRICE, Prof C.G., Geophysics and Planetary Sciences, Tel Aviv University, Levanon Road, 69978 Tel Aviv, Israel, Tel. +972-36406029, Fax +972-3-6409282, E-mail cprice@flash.tau.ac.il (81)

PRIOU, Dr. A., LEME, University Paris Ouest Ville d'Avray, 50 rue de Sèvres, 92794 Ville d'Avray, FRANCE, Tel. +33 1 40 97 41 00, E-mail alain.priou@u-paris10.fr (76)

PULINETS, Prof. S.A., IZMIRAN, Russian Academy of Sciences, Troitsk, Moscow Region 142190, RUSSIA, E-mail pulya1@hotmail.com (81)

QUIJANO, Prof. A., Calle 48 y 116, 1900 LA PLATA, B.A., ARGENTINA, Tel. (54) 21-243 709, Fax (54) 21-250 8 04, E-mail adrian.quijano@gmail.com (77)

RABIU, Dr. A.B., Department of Physics, Federal University of Technology, Akure, Ondo State, NIGERIA, Tel. 234 803 070 5787, E-mail tunderabiu@yahoo.com (76, 79)

RACHIDI, Prof F., EPFL-SCI-STI-FR, ELL-138, Station 11, CH-1015 Lausanne, Switzerland, Tel. +41-21-693 26 20, Fax +41-21-693 46 62, E-mail Farhad.Rachidi@epfl.ch (78, 82)

RADASKY, Dr. W.A., Metatech Corporation, , 358 S. Fairview Ave., Suite E, Goleta, CA 93117, USA, Tel. +1-805-683-5681, Fax +1-805-683-3023, E-mail Wradasky@aol.com (81)

RADEV, Prof. D., Ruse University, Angel Kanchev, 8 Studentska str., 7017 RUSE, BULGARIA, Tel. +359 82 888 673, E-mail dradev@abv.bg (78)

RADICELLA, Prof. S.M., Julian Alvarez 1210, 1414 BUENOS AIRES, ARGENTINA, Tel. +54 1-772-1471, Fax +54 11 4776 0410, E-mail postmast@caerce.edu.ar (79)

RAKOV, Prof V., Ece, University of Florida, 553 Engineering Bldg. #33, Gainesville, FL 32611-6130,USA, E-mail rakov@ece.ufl.edu (81)

RAMA RAO, Mr. P.V.S., Space Physics Laboratory, Department of Physics, Andhra University, VISAKHAPATNAM 530 003, INDIA, Tel. +91 891 539049, Fax +91 891-555 547 (81)

RAMAKRISHNA, Dr A., Department of Physics, Indian Institute of Technology, , Kanpur, Uttar Pradesh, 208 016, India, Tel. +91 512 259 7449, Fax +91 512 259 0914, E-mail sar@iitk.ac.in (76)

RASMUSSEN, Prof. J., RISOE, Optics & Fluid Dynamics Department, P.O. Box 49, DK 4000 ROSKILDE, DENMARK, Tel. +45 4677 4537, Fax +45 4677 4565, E-mail jens.juul.rasmussen@risoe.dk (79)

RAULIN, Prof. J-P, Escola de Engenharia, Centro de Radio-Astronomia e Astrofisica Mackenzie - CRAAM, Universidade Presbiteriana Mackenzie, Rua da Consolaçao 896, Consolaçao, 01302-907 Sao Paulo, SP, BRAZIL, Tel. +55 11 21148724, Fax +55 11 21142300, E-mail raulin@craam.mackenzie.br (78)

READER, Prof. H. Charles, Dept. of Electrical & Electronic Eng., University of Stellenbosch, Private Bag XI, 7602 Stellenbosch, SOUTH AFRICA, Tel. +27 21-808-3623/4478, Fax +27 21-808-4981, E-mail hcreader@sun.ac.za (78, 81)

REISING, Prof S.C., Electrical and Computer Engineering Department, Colorado State University, 1373 Campus Delivery, Fort Collins, CO 80523-1373, USA, Tel. +1 970 491 2228, Fax +1 9704912249, E-mail Steven.Reising@ColoState.edu (75,82,83)

RENGARAJAN, Prof. R, Electrical And Computer Engineering, California State University, 18111 Nordhoff Street, 91330 Northridge, USA, Tel. +1 818 677 3571, E-mail srengarajan@csun.edu (76)

ROBINSON, Dr. M.P., Department of Electronics, University of York, Heslington, YORK, YO10 5DD, UNITED KINGDOM, Tel. +44 1904 432 385, Fax +44 1904 433 224, E-mail mpr@ohm.york.ac.uk (80)

ROCCO GIRALDI, Prof. M.T.M., Instituto Militar de Engenharia - IME, , Praça General Tiburcio 80, Urca, 22290-270 Rio de Janeiro, BRAZIL, Tel. +55 21 3820 4183, Fax +55 21 9641 8217, E-mail mtmrocco@ime.eb.br, mtmrocco@gmail.com (82)

RODGER, Assoc. Prof. C.J., Department of Physics, University of Otago, Po Box 56, Dunedin 9016, NEW ZEALAND, Tel. +64 3 479 4120, Fax +64 3-479 0964, E-mail crodger@physics.otago.ac.nz (79, 81)

RODRIGUES, Prof. Dr. A., Instituto Superior Técnico, Instituto de Telecomuniçoes, Avenida Rovisco Pais n1, 1096 LISBOA CODEX, PORTUGAL, Tel. +351 2 8418484, E-mail antonio.rodrigues@lx.it.pt (77)

RODRIGUEZ-GONZALEZ, Prof. J.A., Dpto. Fisica Aplicada, Facultad de Fisica, Universidad de Santiago de Compostela, 15782 Santiago de Compostela, SPAIN, Tel. +34 8818 140 30, Fax +34 8818 140 72, E-mail ja.rodriguez@usc.es (82)

ROGIER, Prof. H., Information Technology, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium, Tel. (329) 264-3343, Fax (329) 264-9969, E-mail hendrik.rogier@intec.ugent.be (76)

RÖNNEKLEIV, Prof. Arne, Department of Electronics and Telecommunications, NTNU, O.S. Bragstads plass 2, N-7491 TRONDHEIM, NORWAY, Tel. +47 73-594413, E-mail arne.ronnekleiv@iet.ntnu.no (77)

ROZTOCIL, Dr. J., Facukty of Electrical Engineering, Czech Technical University, Technická 2, PRAGUE 6 166 27, CZECH REPUBLIC, Tel. +420 224 352 869, Fax +420 233 339 929, E-mail roztocil@feld.cvut.cz (76)

RUBINSTEIN, Prof. M., IICT, HEIG-VD, Route de Cheseaux 1, 1401 Yverdon-les-bains, Switzerland, Tel. 41245576296, E-mail marcos.rubinstein@heig-vd.ch (77)

RUCKER, Prof. H.O., Space Research Institute, Schmiedlstrasse 6, 8042 Graz, AUSTRIA, Tel. +43 316 4120 601, Fax +43 316 4120 690, E-mail rucker@oeaw.ac.at (79, 80, 82)

RUZHIN, Prof. Yu. Ya., IZMIRAN, TROITSK, MOSCOW REGION 142092, RUSSIA, Tel. +7 496 751 0291, Fax +7 496 751 0124, E-mail ruzhin@izmiran.ru (79)

RYDBERG, Prof. A., Angstrom Laboratory, Uppsala University, Dept. of Engineering Sciences, P.O. Box 534, SE-751 21 UPPSALA, SWEDEN, Tel. +46 18 471 32 28, Fax +46 18 55 50 95, E-mail anders.rydberg@angstrom.uu.se (77)

SAAD, Prof. E.M., Faculty of Engineering, Helwan University, Helwan, Cairo, EGYPT, Tel. +202 5048291, Fax +202 2558294, E-mail elsayedmos@hotmail.com (78, 82)

SABATH, Dr. F., Wehrwissenschaftliches Institut fuer Schutztechnologien, ABC-Schutz, GB 300, Humboldstrasse 100, D-29623 MUNSTER, GERMANY, Tel.

+49 (0)5192 136 300, Fax +49 (0)5192 136 355, E-mail FrankSabath@bundeswehr.org (78, 81)

SADKHAN, Bay, Chairman of IEEE, Iraq section, University of Babylon, Computer Technology College, Babylon,Iraq, Tel. 00964 7707119529, Fax 00964 7801884154, E-mail drengsattar@yahoo.com (82)

SAKA, Prof. B., Dept. of Electrical & Electronics Engineering, Hacettepe University, Faculty of Engineering, 06532 BEYTEPE, ANKARA, TURKEY, Tel. +90 312 297 7045, Fax +90 312 299 2125, E-mail birsen@hacettepe.edu.tr (82)

SALOUS, Prof. S., School of Engineering, Centre for Communication Systems, University of Durham, South Road, DURHAM, DH1 3LE, UNITED KINGDOM, Tel. +44 191 334 2532, Fax +44 191 334 2407, E-mail sana.salous@durham.ac.uk (77, 83)

SAMARAS, Prof. T., Dept. of Physics, Radiocommunications Lab., Aristotle University of Thessaloniki, GR-54124 THESSALONIKI, GREECE, Tel. +30 2310 998232, Fax +30 2310 998069, E-mail theosama@auth.gr (82)

SANCHO RUIZ, Prof. M., Dep. Fisica Aplicada III - Fac. de Fisicas, Universidad Complutense, 28040 MADRID, SPAIN, Tel. +34 91 394 4388, Fax +34 91 394 5196, E-mail msancho@fis.ucm.es (79)

SANTOLIK, Assoc. Prof. O., Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Bocni II, 1401, 141 31 PRAGUE 4, CZECH REPUBLIC, Tel. +420 267 103 083, Fax +420 272 762 528, E-mail os@ufa.cas.cz (79, 83)

SARANGO, Dr. Martin F., M Sarango CT, Industrias Tecnologicas, Av. Javier Prado Este 3040 Piso 4, San Borja, LIMA 41, PERU, Tel. +51 1-3588700, Fax +51 1-2500969, E-mail ursiperu@msarangoct.com (78)

SARMA, Dr. T.V.C., National Atmospheric Research Laboratory, P.O. Box 123, SVU PO, TIRUPATI 517 502, INDIA, Tel. +91 8585 272008/272024, Fax +91 8585 272018/272021, E-mail tvcsarma@narl.gov.in, tvcsarma@gmail.com (77)

SCHLEGEL, Prof. Kristian, Copernicus Gesellschaft e.V., Max-Planck-Str. 13, D-37191 KATLENBURG-LINDAU, GERMANY, Tel. +49 5556-979451/468, Fax +49 5556-979240, E-mail kristianschlegel@web.de, KS-URSI@email.de (75, 81)

SCHÖNHUBER, Dr. M., Joanneum Research, Space and Acoustics, DIGITAL – Institute of Information and Communication Technologies, Steyrergasse 17-19, 8010 Graz, AUSTRIA, Tel. +43 316 876 2511, Fax +43 316 8769 92511, E-mail Michael.Schoenhuber@joanneum.at (78)

SCHRADER, Dr. T., Dept. High Frequency and Fields, Physikalisch-Tecnische Bundesanstalt, Bundesallee 100, D-38116 BRAUNSCHWEIG, GERMANY, Tel. +49 (0)531 592-2200, Fax +49 (0)531 592-2205, E-mail thorsten.schrader@ptb.de (76)

SCHWEICHER, Prof. E., 79, rue de Bruxelles, 1480 TUBIZE, BELGIUM, Tel. +32 2 355 0636, E-mail schweicher.emile@gmail.com (81)

SEBASTIAN FRANCO, Prof. J.L., Dpto. Fisica Aplicada III, Facultad de Ciencias Fisicas, Universidad Complutense de Madrid, 28040 MADRID, SPAIN, Tel. +34 91-394-4393, Fax +34 91-394-5196, E-mail jlsf@fis.ucm.es (80)

SEIRADAKIS, Prof. J.H., Department of Physics, Section Astrophysics, Astronomy and Mechanics, Aristotle University of Thessaloniki, GR-54124 THESSALONIKI, GREECE, Tel. +30 2310 998173, Fax +30 2310 995384, E-mail jhs@astro.auth.gr (80)

SELLER, Dr. R., Department of Broadband Infocommunication Systems, BME - Budapest University of Technology and Economics, Goldman Gyorgy ter 3, 1111 BUDAPESt, HUNGARY, Tel. +36 1 463 3687, Fax +36 1 463 3289, E-mail seller@mht.bme.hu (78)

SELLERI, Prof. S., Dip. di Ingegneria dell'Informazione, University of Parma, Viale G.P. Usberti 181/A, 43124 Parma, ITALY, E-mail stefano.selleri@unipr.it (77)

SEXTON, Prof. M.C., University College Cork, 6 Brighton Villas, Western Road, CORK, IRELAND, Tel. +353 21 490 2893/2210, Fax +353 21 427 1698, E-mail eleceng@ucc.ie (79)

SHAFAI, Dr. L., Canadian Space Agency, David Florida Laboratory, 6767 route de l'Aeroport, ST-HUVERT, QC J3Y 8Y, CANADA, Tel. +1 613 990 3204, Fax +1 613 993 6103 (76)

SHIBATA, Prof. K., Kwasan Observatory, Kyoto University, Yamashina, KYOTO 607-8471, JAPAN, Tel. +81 75-581 1235, Fax +81 75-593 9617, E-mail shibata@kwasan.kyoto-u.ac.jp (81)

SHIRAI, Prof. H., Dept. Eece, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan, Tel. +81-3-3817-1863, Fax +81-3-3817-1847, E-mail shirai@m.ieice.org (76)

SHISHKOV, Prof. B.B., Institute of Mathematics & Informatics, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., bl. 8, 1618 SOFIA, BULGARIA, Tel. +359.2.9793858, Fax +359 2 971 3649, E-mail bshishkov@math.bas.bg (77, 82)

SHMELEV, Dr. A.B., Radiotechn. Inst. by name of Academic Mints, OAO, 8 Marta Street, bld. 10, MOSCOW 125083, RUSSIA, Tel. +7 495 614 2841, Fax +7 495 614 0662, E-mail abshmelev@yahoo.com (77)

SIBILLE, Prof A., Dept Comelec, TELECOM ParisTech, 46 rue Barrault , F-75634 Paris Cedex 13, FRANCE, Tel. +33 01 45 81 70 60, Fax +33 01 45 80 40 36, E-mail alain.sibille@telecom-paristech.fr (82)

SIERRA-PEREZ, Prof. , Signals, Sistems And Radiocommunications, Universidad Politecnica De Madrid, Etsi. De Telecomunicación, av. Complutense 30, 28040 Madrid, Spain, Tel. +34913365873, E-mail manuel.sierra.perez@upm.es (77)

SIGALO, Dr. F.B., Department of Physics, Rivers State University of Science and Technology, PMB 5080, Port Harcourt, Rivers State, NIGERIA, Tel. 234 803 342 7133, E-mail fbsigalo@hotmail.com (80)

SIHVOLA, Prof. A., Dept. Radio Science & Engineering, Aalto University, PO Box 13000, FI-00076 AALTO, FINLAND, Tel. +358 9 470 22261, E-mail Ari.Sihvola@aalto.fi (76, 82, 83)

SINHA, Prof. S., Department of Electrical, Electronic and Computer Engineering, University of Pretoria, SOUTH AFRICA, Tel. +27 12 420 2950, E-mail saurabh.sinha@up.ac.za (77)

SKOU, Prof. N., Electromagnetic Systems, Denmarks Technical University, Oersted Plads, Building 348, DK 2800 LYNGBY, DENMARK, Tel. (454) 525-3768, Fax (454) 593-1654, E-mail ns@space.dtu.dk (78)

SKVOR, Prof. Z., Faculty of Electrical Engineering, Czech Technical University, Technická 2, PRAGUE 6 166 27, CZECH REPUBLIC, Tel. +420 224 352 278, Fax +420 233 339 958, E-mail skvor@feld.cvut.cz (76)

SLAVOVA POPIVANOVA, Prof., Mathematical Physics, Institute Of Mathematics and Informatics, Bulgarian Academy Of Sciences, Acad.g.bonchev Str., Bl.8, 1113 Sofia, Bulgaria, Tel. +359 2 979 2841, Fax +3592 971 3649, E-mail slavova@math.bas.bg (80)

SLOBODZIAN, Prof. P., Wroclaw University of Technology, 27 Wybrzeże Wyspiańskiego St, 50-370 Wrocław, POLAND, Tel. +48 71 320 4583, E-mail piotr.slobodzian@pwr.wroc.pl (78)

SMIESKO, Prof. V., Fac. of Electrical Eng. & Information Technology, Slovak University of Technology, Ilkovicova 3, BRATISLAVA 812 19, SLOVAKIA, Tel. +421 2-60291894, Fax +421 2-65429600, E-mail viktor.smiesko@stuba.sk (78)

SMITH, Prof. P.D., Department of Mathematics, EA7 402, Macquarie University, North Ryde, NSW, 2109, AUSTRALIA, Tel. +61 2 9850 8944, Fax +61 2 9850 8114, E-mail paul.smith@mq.edu.au (76)

SOBIESKI, Prof. P., U.C.L. - TELE, Bâtiment Stévin, Place du Levant, 2, 1348 LOUVAIN-LA-NEUVE, BELGIUM, Tel. +32 10-47 23 03, Fax +32 10-47 20 89, E-mail Piotr.Sobieski@uclouvain.be (78)

SORRENTINO, Prof. R., Department of Electronic and Information Eng., University of Perugia, Via Duranti 93, I-06125 PERUGIA, ITALY, Tel. +390 75-585 3658, Fax +390 75-585 3568, E-mail roberto.sorrentino@unipg.it, r.sorrentino@ieee.org (82)

SOUSA, Prof. L., Instituto Superior Tecnico (Instituto de Telecmunicaçoes), Avenida Rovisco Pais N°1, 1096 LISBOA CODEX, PORTUGAL, E-mail leonel.sousa@lx.it.pt (77)

STANISLAWSKA, Dr. I., Polish Academy of Sciences, Space Research Centre, ul. Bartycka 18 A, 00-716 WARSAW, POLAND, Tel. +48 22 840 37 66 ext. 380, E-mail stanis@cbk.waw.pl (79, 83)

STEINMEYER, prof. G., Max-Born-Institut (MBI), Department C2, Haus C, 3.7, Max-Born-Straße 2 A, 12489 BERLIN, GERMANY, E-mail steinmey@mbi-berlin.de (77)

STOFANIK, Dr. V., Faculty of Electrical Eng. & Inf. Technology, Slovak University of Technology, Ilkovicova 3, SK- 81219 BRATISLAVA, SLOVAKIA, Tel. +421 2 602 91 394, Fax +421 2 654 29 683, E-mail vladimir.stofanik@stuba.sk (78, 82)

STONE, Dr. W.R., 840 Armada Terrace, San Diego, CA 92106, USA, Tel. +1-619 222 1915, Fax +1-619 222 1606, E-mail r.stone@ieee.org (75, 83)

STRUZAK, Dr. R.G., Z21, Instytut Lacznosci Panstwowy Instytut Badawczy, Ul Swojczycka 38, 51-501 Wroclaw, POLAND, Tel. +48 515195562, Fax +48 713614474, E-mail r.struzak@ieee.org, struzak@gmail.com (81)

SU, Dr. D., Beijing University of Aeronautics & Astronautics, XueYuan Road No.37, HaiDian District, Beijing, CHINA (CIE), Tel. +86 10 8231 7224, E-mail sdl@buaa.edu.cn (76)

SU, Prof. Y-K, Office of Academic Affairs, National Cheng Kung University, No. 1, Ta-Hsueh Road, TAIWAN 701, CHINA (SRS), Tel. +886-6 2757575ext50109, E-mail yksu@mail.ncku.edu.tw (77)

SUMICHRAST, Prof. L., Fac. of Electrical Eng.&Information Technology, Slovak University of Technology, Ilkovicova 3, BRATISLAVA81219, SLOVAKIA, Tel. +421-2-65423502, Fax +421-2-65420415, E-mail lubomir.sumichrast@stuba.sk (76)

SUWAIYEL, Dr. M.I., Directorate of International Cooperation, KACST, P.O. Box 6086, RIYADH 11442, SAUDI ARABIA, Tel. +966 1 488 3555 ext 3490, Fax +966 1 4813441, E-mail int_coop@kacst.edu.sa (82)

SVOBODA, Dr. M., Czech Metrology Institute, Hvozdanska 3, PRAGUE 4 148 01, CZECH REPUBLIC, Tel. +420 271 192 125, Fax +420 272 934 560, E-mail msvoboda@cmi.cz (78)

SZABO, Dr. L.D., National Research Institute, for Radiobiology and Radiohygiene, Pentz K. u. 5, H-1221 BUDAPEST, HUNGARY, Tel. +36 1-1264 160, Fax +36 1-2266 974 (80)

SZEKELY, Prof. V., Department of Electron Devices, BME - Budapest University of Technology and Economics, Goldmann Gy. tér 3., H-1111 BUDAPEST, HUNGARY, Tel. +36 1-463-2703, Fax +36 1-463-2973, E-mail szekely@eet.bme.hu (77)

TAKI, Prof. M., Department of Electrical Engineering, Tokyo Metropolitan University, 1-1 Minami-osawa, Hachioji, TOKYO 192-0397, JAPAN, Tel. +81 426 77 2763, Fax +81 426 77 2756, E-mail masao@tmu.ac.jp (80)

TAO, Dr. R., Department of Electronic Engineering, Beijing Institute of Technology, 5 South Zhongguancan Street, Haidan District, Beijing, 100081, CHINA (CIE), Tel. +0086 10 6891 8332, E-mail rantao@bit.edu.cn (77)

TAVELLA, Dr. P., INRIM, Strada delle Cacce 91, 10135 TORINO, ITALY, Tel. +39 011 3919235, Fax +39 011 3919259, E-mail tavella@inrim.it (76, 82)

TEDJINI, DR. S., INPG-ESISAR, LCIS, 50, rue B. de Laffemas, BP 54, F-26902 VALENCE CEDEX 9, FRANCE, Tel. +33 4 75 75 9420, Fax +33 4 75 43 5642, E-mail smail.tedjini@lcis.grenoble-inp.fr (77, 81)

TETELIN, Dr. C., RFID, CNRFID, 5, Avenue De Manéou, 13790 Rousset,France, Tel. +33 442 37 09 37, E-mail ctetelin@centrenational-rfid.com (77)

THIDE, Dr. Bo, Mathematics and Systems Engineering, Växjö University, SE-35195 VAXJO, SWEDEN, E-mail bt@irfu.se, btmobile@irfu.se (79, 81)

THOMSON, Dr. N.R., Department of Physics, University of Otago, P.O. Box 56, DUNEDIN, NEW ZEALAND, Tel. +64 3-479 7802, Fax +64 3-479 0964 , E-mail n_thomson@physics.otago.ac.nz (82)

TIAN, Prof. J., Intelligent Medical Research Center, Institute Of Automation, Chinese Academy Of Sciences, Rm. 933, No. 95, Zhongguancun East Rd., Haidian District, 100190 Beijing, Haidian District, China, Tel. 86-10-52628760, E-mail tian@ieee.org (80)

TJELTA, Dr. T., Telenor GBDR, Snaroyveien 30, 1331 FORNEBU, NORWAY, Tel. +47 90 786424, E-mail terje.tjelta@telenor.com (78, 81)

TOBAR, Prof. M.E., School of Physics M013, Frequency Standards and Metrology Research Group, University of Western Australia, 35 Stirling Highway, CRAWLEY, WA 6009, AUSTRALIA, Tel. +61 8 6488 3443, Fax +61 8 6488 1235, E-mail mike@physics.uwa.edu.au (76)

TOPSAKAL, Prof. E., Electrical And Computer Engineering, Mississippi State Universitiy, 405 Simhall Hall, Hordy Street, MS 39762-9571, Mississippi,United States, Tel. (+1 662) 325-3669, Fax +1 (662) 325-2298, E-mail topsakal@ece.msstate.edu (80, 83)

TORKAR, Prof. K.M., , Space Research Institute, Schmiedlstrasse 6, A 8042 Graz, AUSTRIA, Tel. +43 316 4120 531, Fax +43 316 4120 590, E-mail klaus.torkar@oeaw.ac.at (79)

TORNIKOSKI, Prof. M., Aalto University, Metsähovi Radio Observatory, Metsähovintie 114, 02540 KYLMÄLÄ, FINLAND, Tel. +358 9-2564 831, Fax +358 9-2564 531, E-mail Merja.Tornikoski@aalto.fi (80)

TRAINOTTI, Prof. V., Bernardo de Irigoyen 650 2 10, 1072 BUENOS AIRES, ARGENTINA, Tel. +541 4334 3529, Fax +541 4709 3210, E-mail vtrainotti@ieee.org (76)

TRETYAKOV, Prof. O.A., Department of Theoretical Radio Physics, Kharkov National University, Svoboda Sq. 4, Kharkov 61077, UKRAINE, Tel. +380 572-457163/457257, Fax +380 572-476506, E-mail Oleg.A.Tretyakov@univer.kharkov.ua (76)

TRUHLIK, Dr. V., Department Of Upper Atmosphere, Institute Of Atmospheric Physics, Acad. Sci. Czech Rep., Bocni Ii, 1401, 14131 Praha, Czech Republic, Tel. 00420267103058, E-mail vtr@ufa.cas.cz (81)

TRULSEN, Prof. J., Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 OSLO, NORWAY, Tel. +47 22 856540, Fax +47 22 856505, E-mail jan.trulsen@astro.uio.no (79, 82)

TSIBOUKIS, Prof. T., Division of Telecommunications, Dept. of Electrical & Computer Eng., Aristotle University of Thessaloniki, GR-54124 THESSALONIKI, GREECE, Tel. +30 23 1099 6323, Fax +30 23 1099 6312, E-mail tsibukis@auth.gr (76)

TU, Dr. Y-K, Chunghwa Telecom Laboratories, , 12, Lane 551, Min-Tsu Road, Sec. 5, TAOYUAN 326, TAIWAN, Tel. +886 3 4244202, Fax +886 3 4244208, E-mail yktu@cht.com.tw (77)

TZIOUMIS, Dr. A., CSIRO, Australia Telescope National Facility, PO Box 76, EPPING, NSW 2121, AUSTRALIA, Tel. +61 2 9372 4350, Fax +61 2 9372 4310, E-mail Tasso.Tzioumis@csiro.au, atzioumi@atnf.csiro.au (83)

ÜNAL, Assist. Prof. I., Inönü University, 44280 Malatya, TURKEY, Tel. +90 422 377 4210, E-mail ibrahim.unal@inonu.edu.tr (79)

USLENGHI, Prof. P.L.E., Dept. of ECE (MC 154), University of Illinois at Chicago, 851 S. Morgan Street, CHICAGO, IL 60607-7053, USA, Tel. +1 312 996-6059, Fax +1 312 996 8664, E-mail uslenghi@uic.edu (75)

USTUNER, Dr. TUBITAK UME, TUBITAK Gebze Campus, Baris Mah. Dr. ZEki Acar Cad. No1, 41470 Gebze KOCAELI, Türkiye, Tel. +90 262 679 5031, Fax +90 262 679 5035, E-mail fatih.ustuner@tubitak.gov.tr (76)

UZUNOGLU, Prof. N.K., Division of Information Transmission Systems and Material Technology, School of Electrical and Computer Eng., National Technical University of Athens, Iroon Polytechniou 9, GR-15773 ATHENS, GREECE, Tel. +30 210 7722289, E-mail nuzu@cc.ece.ntua.gr (80, 82)

VAN ARDENNE, Prof. Ir. A., ASTRON, Oude Hogeveensedijk 4, Postbus 2, NL-7990 AA DWINGELOO, NETHERLANDS, Tel. +31 521 595 134, Fax +31 521 595 101, E-mail Ardenne@astron.nl, brink@astron.nl (80, 82)

VAN BLADEL, Prof. J., G. De Smetlaan 22, B-9831 DEURLE, BELGIUM, Tel. +32 9-282 4488, Fax +32 9-264 4288, E-mail hvanbladel@skynet.be (75)

VAN DAELE, Prof. Dr. P., Dept. of Information Technology (INTEC), IBBT - Ghent University, Gaston Crommenlaan 8 bus 201, B-9050 GENT, BELGIUM, Tel. +32 9 331 49 06, Fax +32 9 331 48 99, E-mail peter.vandaele@intec.Ugent.be (75, 77)

VAN DEN BOGAART, Ir. F.L.M., TNO Defence, Security and Safety, Postbus 96864, 2509 JG ‘S-GRAVENHAGE, NETHERLANDS, Tel. +31 70 374 0042, Fax +31 70 374 0653, E-mail frank.vandenbogaart@tno.nl (77)

VAN DEURSEN, Prof. A.P.J., Faculteit Electrotechniek, Technische Universiteit Eindhoven, PO Box 513, NL-5600 MB EINDHOVEN, NETHERLANDS, Tel. +31 40 247 4434/3993, Fax +31 40 245 0735, E-mail A.P.J.v.Deursen@tue.nl (78)

VAN DRIEL, Dr. W., GEPI, Observatoire de Paris, 5, Place Jules Janssen, F-92195 MEUDON CEDEX, FRANCE, Tel. +33 1 4507 7731, Fax +33 1 4507 7709, E-mail wim.vandriel@obspm.fr (83)

VANLIL, Prof. E., DIV. ESAT-TELEMIC, K.U. Leuven, Kasteelpark Arenberg 10, Bus 2444, B-3001 HEVERLEE,BELGIUM, Tel. +32 16 32 1113, Fax +32 16 32 1986, E-mail Emmanuel.VanLil@ESAT.KULeuven.Be (76, 82)

VAN RIENEN, Prof. Dr. U., Fakultaet fuer Informatik und Elektrotechnik, Institut fuer Allgemeine Elektrotechniek, Universitaet Rostock, Albert-Einstein-Strasse 2, D-18051 Rostock,GERMANY, Tel. +49 381 498 7070 , Fax +49 381 498 7081, E-mail ursula.van-rienen@uni-rostock.de (76)

VANDENBOSCH, Prof. G.A.E., DIV. ESAT-TELEMIC, Katholieke Universiteit Leuven, Kasteelpark Arenberg 10, Bus 2444, B-3001 LEUVEN, BELGIUM, Tel. +32 16 32 11 10, Fax +32 16 32 19 86, E-mail Guy.Vandenbosch@ESAT.KULeuven.Be (78, 82)

VANDENDORPE, Prof. L., UCL, TELE, Batiment Stévin, Place du Levant, 2, B-1348 LOUVAIN-LA-NEUVE, BELGIUM, Tel. + 32 10-47 23 12, Fax + 32 10-47 20 89, E-mail Vandendorpe@tele.ucl.ac.be (77)

VARJU, Dr. G., Department of Electric Power Engineering, Budapest University of Technology and Economics, Egry J. u., H-1111 BUDAPEST, HUNGARY, Tel. +36 1 463 3016, Fax +36 1 463 3600, E-mail varju.gyorgy@vet.bme.hu (78)

VAUGHAN, Prof. R., Engineering Science, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, CANADA, Tel. +1-7787826889, Fax +001 604 291 4951, E-mail rvaughan@sfu.ca, rodney_vaughan@sfu.ca (76)

VELASQUEZ-LOPEZ, Dr. C. V., Director General de la Secretaria de Comunicaciones, Ministerio de TRansportes y Comunicaciones, Jiron Zorritos N° 1203, LIMA, PERU, Tel. +51 1 615 7800, E-mail cavaldez@mtc.gob.pe (78)

VELINOV, Prof. P., Institute for Space and Solar Terrestrial Research, Bulgarian Academy of Sciences, 6 Moskovska Str., 1000 SOFIA, BULGARIA, Tel. +359 2 979 3434, E-mail pvelinov@bas.bg (80)

VERGERES, Mr. D., Chef de section, Office Fédéral de la Communication, Gestion des fréquences radio, Rue de l’Avenir 44, 2501 BIENNE, SWITZERLAND, Tel. +41 32 327 57 20, Fax +41 32 327 57 77, E-mail daniel.vergeres@bakom.admin.ch (78)

VESZELY, Dr. Gy., Department of Broadband Infocommunication Systems, BME - Budapest University of Technology and Economics, H-1521 BUDAPEST, HUNGARY, Tel. +36 1-463-3188, Fax +36 1-463-3189, E-mail Veszely@evt.bme.hu (76)

VEYRET, Dr. B., Laboratoire PIOM CNRS / EPHE, Université de Bordeaux 1, ENSCPB, 16, Av. Pey Berland, F-33607 PESSAC CEDEX, FRANCE, Tel. +33 5 40 00 66 29, Fax +33 5 40 00 66 29, E-mail b.veyret@icnirp.org (83)

VILCAHUAMAN CAJACURI, Prof. L., Seccion Electricidad y Electricidad, Pontificia Universidad Catolica del Peru, Av. Universitaria 1800, San Miguel, LIMA 32, PERU, Tel. +51 1 6262000 (ext. 5030), E-mail lvilcah@pucp.edu.pe (80)

VILJANEN, Dr. A., Finnish Metereological Institute, Arctic Research, P.O. Box 503, 00101 HELSINKI, FINLAND, Tel. +358 9 1929 4668, Fax +358 9 1929 4603, E-mail Ari.Viljanen@fmi.fi (78, 81)

VOMVORIDIS, Prof. I., School of Electrical & Computer Eng., National Technical University of Athens, Iroon Polytechniou 9, GR-15773 ATHENS, GREECE, Tel. +30 210 7723684, Fax +30 210 7723513, E-mail vomvor@central.ntua.gr (79)

VRBA, Professor J., Em Field (k13117), Czech Technical University In Prague, Technicka 2, 16627 Prague, Czech Republic, Tel. +420 224 352 298, Fax +420 233 339 958, E-mail vrba@fel.cvut.cz (80)

WADA, Prof. O., Department of Electrical Engineering, Graduate School of Engineering, Kyoto University, Kyoto Daigaku Katsura, Nishikyo-ku, KYOTO 615-8510,JAPAN, Tel. +81 75 383 2244, Fax +81 75 383 2245, E-mail wada@kuee.kyoto-u.ac.jp (78)

WALDE, Mr. C.-H., Tornvägen 7, 183 52 TÄBY,SWEDEN, Tel. +46 8 756 61 60, E-mail info@walde.se (82)

WALLEN, Dr. H., Dept. Radio Science and Engineering, Aalto University, P.O. Box 13000, Otakaari 5 A, FI-00076 AALTO, FINLAND, Tel. +358 9 470 25668, E-mail henrik.wallen@aalto.fi (82)

WANNBERG, Dr. G., Wannberg radarkonsult AB, Duvvägen 22, SE-981 37 Kiruna, Sweden, Tel. +46 980 811 48, E-mail gudmund@wannberg.net (79)

WARNANT, Mr R., Department of Geography, Geomatics - Geodesy and GNSS, Bâtiment B5a, Allée du 6 août 17, B-4000 LIEGE,BELGIUM, Tel. +32 4 366 90 16, Fax +32 4 366 56 93, E-mail Rene.Warnant@ulg.ac.be (79)

WATANABE, Dr S., Department of Cosmosciences, Hokkaido University, Sapporo 060-0810, JAPAN, Tel. +81 11 706 2757, Fax +81 11 706 2760, E-mail shw@ep.sci.hokudai.ac.jp (81)

WATERS, Assoc. Prof. C., Centre for Space Physics, School of Mathematical and Physical Sciences, University of Newcastle, University Drive, CALLAGHAN NSW 2308, AUSTRALIA, Tel. +61 2 4921 6907, Fax +61 2 4921 5421, E-mail colin.waters@newcastle.edu.au (79)

WATSON, Prof. P.A., Cairnlea, Littleworth, Winchcombe, Gloucestershire,GL54 5BT, UNITED KINGDOM, E-mail peter.watson43@btinternet.com (83)

WEN, Prof., Emc Lab., Beijing Jiaotong University, 100044 Beijing, China, Tel. 86-10-51688096x808, E-mail yinghongwen@vip.sina.com (78)

WERNIK, Prof. A.W., Space Research Center, Polish Academy of Sciences, Ul. Bartycka 18 A, 00-716 WARSAW, POLAND, Tel. +48 508 951 988, E-mail aww@cbk.waw.pl (79)

WESOLOWSKI, Prof. K., Poznan University of Technology, 5 M.Skłodowskiej-Curie Sq, 60-965 Poznan, POLAND, E-mail wesolows@et.put.poznan.pl (77)

WIART, Dr. J., Orange Labs, , 38-40, rue du Général Leclerc, F-92131 ISSY LES MOULINEAUX CEDEX, FRANCE, Tel. +33 1 45 29 58 44, E-mail joe.wiart@orange-ftgroup.com (80)

WICHMAN, Prof. R., Department of Signal Processing and Acoustics, Aalto University, PO BOx 13000, FI-00076 AALTO, FINLAND, Tel. +358 9 470 22484, E-mail Risto.Wichman@aalto.fi (77)

WILFERT, Prof. O., Brno University of Technology, , Purkynova 118, BRNO 612 00, CZECH REPUBLIC, Tel. +420 541 149 130, Fax +420 541 149 224, E-mail wilfert@feec.vutbr.cz (77)

WILKINSON, Dr. Phil, Dept. of Industry, Tourism and Resources, IPS Radio and Space Services, P.O. Box 1386, Haymarket, NSW 1240, AUSTRALIA, Tel. +61 2-9213 8003, Fax +61 2-9213 8060, E-mail p.wilkinson@bom.gov.au (75, 79, 81, 83)

WILSON, Mrs C., Propagation and Spectrum Wireless Technologies Lab., CSIRO ICT Centre, P.O. Box 76 , EPPING, NSW 1710, AUSTRALIA, Tel. +61 29 372 42 64, Fax +61 29 372 44 90, E-mail carol.wilson@csiro.au (78)

WITCZAK, Dr. A., Institute of Radioelectronics, Military University of Technology, Ul. Kaliskiego 2, 00-908 WARSAW, POLAND, Tel. +48 22 683 96 46, Fax +48 22 683 74 61, E-mail andrzej.witczak@wat.edu.pl, awitczak@wat.edu.pl (82)

WOODMAN, Dr. R.F., Jicamarca Radio Observatory, Instituto Geofisico del Peru, Calle Badajoz 169, Urb. Mayorazgo 4ta Etapa, Ate, Apartado 13-0207, LIMA 13, PERU, Tel. +51-1-3172320, E-mail ronw@geo.igp.gob.pe (82)

WU, Dr. J., Director General CETC, No 27 Wanshoulou, 100846 BEIJING, CHINA (CIE), Tel. +86 10 68207371, Fax +86 10 68218354, E-mail jian.wu@263.net (82)

YAGITANI, Prof. S., Faculty of Electrical and Computer Engineering, Institute of Science & Engineering, Kanazawa University, Kakuma-machi, Kanazawa 920-1192, Japan, Tel. +81-76-234-4858, Fax +81-76-234-4859, E-mail yagitani@is.t.kanazawa-u.ac.jp (82)

YAMAMOTO, Dr M., Research Institute for Sustainable Humanosphere, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan, Tel. +81 774 38 3814, Fax +81 774 31 8463, E-mail yamamoto@rish.kyoto-u.ac.jp (79)

YAMPOLSKY, Prof. Yu. M., Institute of Radioastronomy, NASU, ul. Krasnoznamennaya 4, KHARKOV 310002, UKRAINE, Tel. +380 572-44-8579, Fax +380 572-44-6506, E-mail yampol@rian.kharkov.ua (79)

YAN, Dr. Y., Key Laboratory Of Solar Activity, National Astronomical Observatories, A20 Datun Road, Chaoyang District, BEIJING 100012, CHINA (CIE), Tel. +86 10 6485 1674, Fax +86 10 6486 3314, E-mail yyh@nao.cas.cn (75, 80)

YARLEQUE MEDINA, Dr. M., Departamento de Ingenierìa, Pontificia Universidad Católica del Perú, Sección Ingeniería de las Telecomunicaciones Av.Universitaria 1801, San Miguel, LIMA32, PERU, Tel. +51-1-626-2452, Fax +51-1-626-2116, E-mail myarleq@pucp.edu.pe (76)

YAROVOY, Prof. dr. A., Faculteit Elecktotechniek, Wiskunde en Informatica, Technische Universiteit Delft, Mekelweg 4, 2628 CD DELFT, NETHERLANDS, Tel. +31 15 278 2496, Fax +31 15 278 4046, E-mail a.yarovoy@ewi.tudelft.nl (76)

YOSHIDA, Mr. S., YOKOWO CO., LTD., 1112 KANOHARA, TOMIOKA, GUNMA, 370-2495, JAPAN, Tel. +81-274-62-7133, Fax +81-274-62-7133, E-mail mc@yokowo.co.jp (81)

ZAGHLOUL, Dr. I, Ece, Virginia Tech, 7054 Haycock Rd, 22043 Falls Church, USA, Tel. +1-703-538-8435, Fax +1-703-538-8450, E-mail amirz@vt.edu (77)

ZAGORODNIY, Prof. A.G., Institute for Theoretical Physics, NASU, 14b, Metrologichna street, KIEV 03143,UKRAINE, Tel. +380 44 492 1423, Fax +380 44 526 5998, E-mail azagorodny@bitp.kiev.ua (79)

ZAIN-EL-DEEN, Prof. S., Faculty of Electronic Engineering, Menufia University, Menufia, EGYPT, E-mail anssaber@yahoo.com (79)

ZEDDAM, Dr. A., FT R&D, DTD/SFE, 2 avenue Pierre Marzin, BP 40, F-22307 LANNION CEDEX, FRANCE, Tel. +33 2-9605 3938, Fax +33 2-9605 3427, E-mail ahmed.zeddam@orange-ftgroup.com (81)

ZERROUKI, Dr. C., Laboratoire de Physique, , 2, rue Conté, F-75003 PARIS cedex, FRANCE, Tel. +33 1 58 80 84 34, Fax , E-mail chouki.zerrouki@cnam.fr (76)

ZHAO, Prof., School Of Electronic Information, Wuhan University, 129 Luoyu Road, Wuhan, Hubei, China, Wuhan, China, Tel. 86-27-68756343, Fax 86-27-68756343, E-mail dicilab@yahoo.com.cn (79)

ZHELYAZKOV, Prof. I., Faculty of Physics, Sofia University, 5 James Boucher Blvd., BG-1164 SOFIA, BULGARIA, Tel. +359 2 816 1641, E-mail izh@phys.uni-sofia.bg (79)

ZHOGUN, Dr. V.N., VNIIFTRI, Mendeleevo, Moscow Region, 141570, RUSSIA, Tel. +7 495 744 81 21, Fax +7 499 720 9334, E-mail zhogun@vniiftri.ru (76)

ZINCHENKO, Dr. , Radio Engineering And Millimeter Wave Astronomy, Institute Of Applied Physics Of The Russian Academy Of Sciences, 46 Ulyanov Str., 603950 Nizhny Novgorod, Russia, Tel. +7 831 4367253, E-mail zin@appl.sci-nnov.ru (80)

ZOLESI, Dr. B., Roma2, Istituto Nazionale Di Geofisica E Vulcanologia, Via Di Vigna Murata 605, 00143 Roma, ITALY, Tel. +39 06 51860320, Fax +39 06 51860397, E-mail bruno.zolesi@ingv.it (79)

ZOMBORY, Prof. L., Department of Broadband Infocommunication Systems, BME - Budapest University of Technology and Economics, Goldmann Gy. tér 3., H-1111 BUDAPEST, HUNGARY, Tel. +36 1-463-1559/1824, Fax +36 1-463-3289, E-mail zombory@mht.bme.hu (82)

ZOZULYA, Prof. Yu.O., Academy of Medical Sciences of Ukraine, Inst. of Neurosurgery, Acad. A. Romodanov, 32, Manuilsky st., KIEV 04050, UKRAINE, Tel. +380 44-213 9573, Fax +380 44-213 9573, E-mail brain@neuro.kiev.ua (80)

ZVANOVEC, Assoc. Prof. S., Faculty of Electrical Engineering, Czech Technical university, Technicka 2, Prague 6 16627, CZECH REPUBLIC, Tel. +420 224 355 966, Fax +420 233 339 958, E-mail xzvanove@fel.cvut.cz (78)

ZWAMBORN, Prof. dr. ir A.P.M., TNO Defence, Security and Safety, Postbus 96864, 2509 JG ‘S-GRAVENHAGE, NETHERLANDS, Tel. +31 70 374 0033, Fax +31 70 374 0653, E-mail Peter.Zwamborn@tno.nl (80)

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