Hybrid Static-Dynamic Modeling and Experimental Analysis of Multi-Scale Complex Environments: Application to Ubiquitous Interactions

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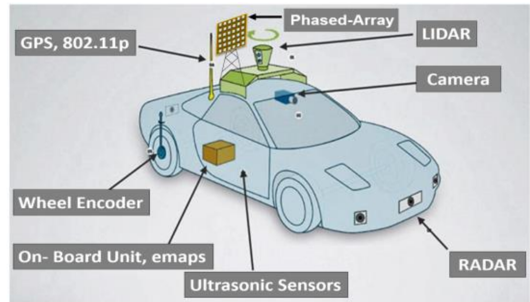
***Abstract*— Hybridization of agile mm-Wave MIMO and Phased-Array technologies with static (*Capacitive-Resistive-Inductive effects*) and dynamic multi-physics (*coupled ultrasonic and optical waves*) sensing solutions is proposed toward new functionalities for environmental perceptions and ubiquitous interactions. The resulting paradigms will operate the unification of *Contact-driven* actions and contactless *Gesture-driven* interactions for enabling emerging technologies relative to interactions of humans with smart devices and systems in randomly changing environments. Perspectives for Autonomous Vehicles with Advanced Driver Assistance Systems (ADAS) including Gesture-Recognition (GR) through ubiquitous interactions based on hybrid agile mm-Wave RFIC technologies and optical systems are drawn.**

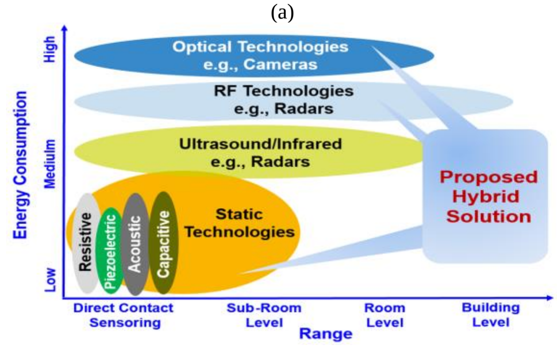
***Index Terms*—Hybrid agile mm-Wave and Optical Sensing, Co-Design, Ubiquitous Interactions, ADAS, MIMO, Phased-Array.**

I. INTRODUCTION

It is expected to witness in near future increased interactions between human beings, devices, machines and tools: this will create new paradigms where *Contact-driven* actions will be replaced or extended by *Gesture-driven* interactions. In order to support the evolutions or transitions from *Contact-driven* actions to *Gesture-driven* interactions, it is important to operate the required change in mindset and technology enablers for deployment to emerging IoT and Artificial-Intelligence (AI) devices. *Gesture-driven* interactions will operate the unification between NFC (Near-Field-Communication) and Radar (Far-Field) technologies which will need hybrid static-dynamic multi-scale approaches. Combination of hybrid static-dynamic and agile RF/mm-Wave design technologies is very suitable for enabling low-cost, low-power and miniature Chip-Package-PCB-Antenna co-integration. In addition, agile design technologies at RF and mm-Wave frequencies offer very attracting features. These features complement classical LIDAR and camera-based technologies in the detection and avoidance of objects such as for ADAS toward autonomous vehicles (Fig.1(a)). Beyond the simple sensing principle of agile mm-Wave design technologies, new functionalities can be implemented for environmental perception and ubiquitous interaction following the famous article by Mark Weiser [1] on computer paradigms for the 21st century and the notion of proxemic interactions introduced by Greenberg [2]. The resulting ubiquitous interactions are impacted by desired accessible range, resolution and energy consumption. Fig.1(b) shows measurement range versus energy consumption of a single sensor [3] including peripherals for installations within the environment. While static capacitive, resistive and inductive sensing lead to limited detection range, techniques that rely on propagating waves in the air (sound, light, or RF/mm-Wave) can support relatively large detection ranges with beam-steering and beam-forming functionality.



(a)



(b)

Fig.1: Autonomous connected vehicle including ADAS with Multiphysics sensors (a). Measurement range versus energy consumption of a single sensor (b) including peripherals for installations within the environment.

This paper proposes hybrid technology solutions for efficiently coupling multiphysics sensors with agile RF/mm-Wave technologies [4-5] including MIMO (Multi-Input-Multi-Output) and Phased-Array systems toward new functionalities for environmental perception and ubiquitous interactions. The proposed hybridization opens new perspectives in the use of ubiquitous interactions including the following emerging applications:

- Gesture Recognition with ubiquitous interactions.
- Human-Machine and Machine-Machine Cooperations.
- Cognitive Signal-Processing algorithms.

All these applications require the development of advanced stochastic Field-Field Correlation [6-9] techniques using Energy based [7] metrics both in Frequency and Time Domains backed-up by innovative modeling and measurement solutions.

II. MAIN RESULTS AND DISCUSSIONS

A. Toward Smart MIMO and Phased-Array Systems

The emerging New-Radio (NR) mobile communication systems are specified to meet challenging requirements for higher data rates transfer and increased bandwidth with improved awareness to environmental changes. The associated integration constraints impose global Chip-

Package-PCB-Antenna co-design and co-analysis strategies for realizing the required tradeoffs between area constraints, power consumption and broadband RF performances in terms of matching and isolation between antenna array elements subject to random EM fields exposure. Use of MIMO and Phased-Array technologies to improve communication capabilities with reduced antenna separation, needed for compact mobile devices, drives new applications. In [5], requirements for electromagnetic (EM) theory-based fundamental analysis of wireless communication systems including impedance matching, interferences and couplings between noisy radiating elements is discussed. Several MIMO [5] configurations are built for extracting multiport models of the transmission links based both on EM modeling and measurement accounting for physical noise sources. These noise sources occur due to radiated interference within the link or due to conducted interference and can be modeled by equivalent noise sources connected to the ports of a noiseless multiport link model. Analysis of such a scenario is two-fold and requires analysis of noise interference and the transmission of statistical signals as well as analysis of statistical ensembles of variable scenarios and statistical characterization of their relevant properties. The wireless link with scatterers is shown in Fig. 2(a),(b).

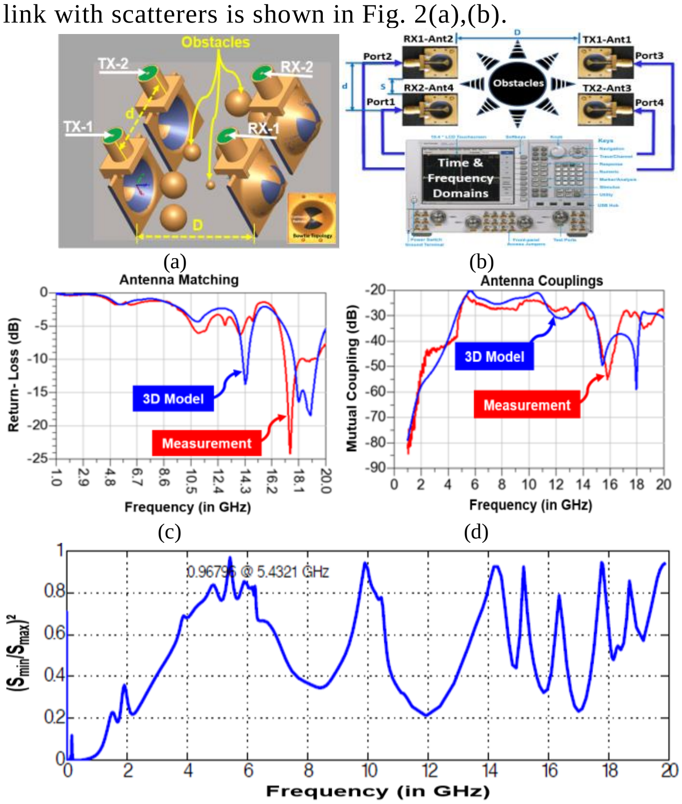


Fig.2: MIMO [5] in 4-Port (a) configuration using 3D Antenna-In-Package (AiP) with obstacles and associated measurement setup (b). Simulation versus measurement of Return-Loss (c), mutual coupling (d) and $(S_{min}/S_{max})^2$ (e).

It is shown that the capacity of a multi-channel link can be cast in the following expression based on the derivations of Shannon in 1948:

$$\text{Channel Capacity} = N\,B\,\log_2(1 + SNR) \qquad (1)$$

where N is the number of parallel channels, B is the frequency bandwidth and SNR is the signal-to-noise ratio in each channels. Considering N=2 channels, one obtains a saving of 7dB in the required SNR per channel compared to a single channel system. The realization of N parallel radio channels requires N independently excitable antenna ports at both the receiving and the transmitting ends of the radio link. This is shown for the case of Nopt = 2,4,6,10 in Fig. 3(a),(b), where D is the distance between the transmitter and the receiver, and d denotes the separation between the two antennas used at each end of the link.

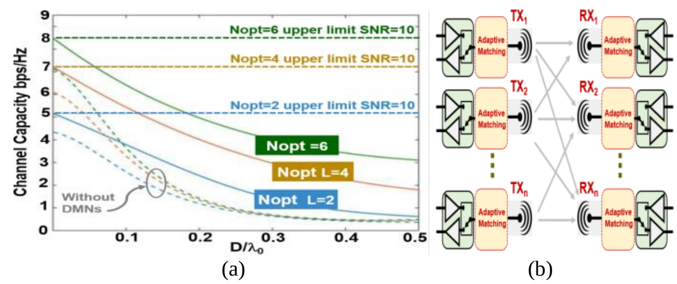


Fig.3: Extracted channel capacity as function of normalized separation distance D/λ_0 (a). Multiport MIMO representation including RX & TX front-End modules (LNA, PA, Switches) and adaptive matching.

Fig.4(a) presents measured multi-port 2x2 MIMO signal amplitudes as function of TX-RX separation distance and input power levels for 5G sub-6GHz applications operating at 2.4GHz and 5.8GHz in reference to the experimental setup shown in Fig.4(b). The experimental setup is built using Front-End-Modules (FEM) with RFIC building blocks and smart antennas.

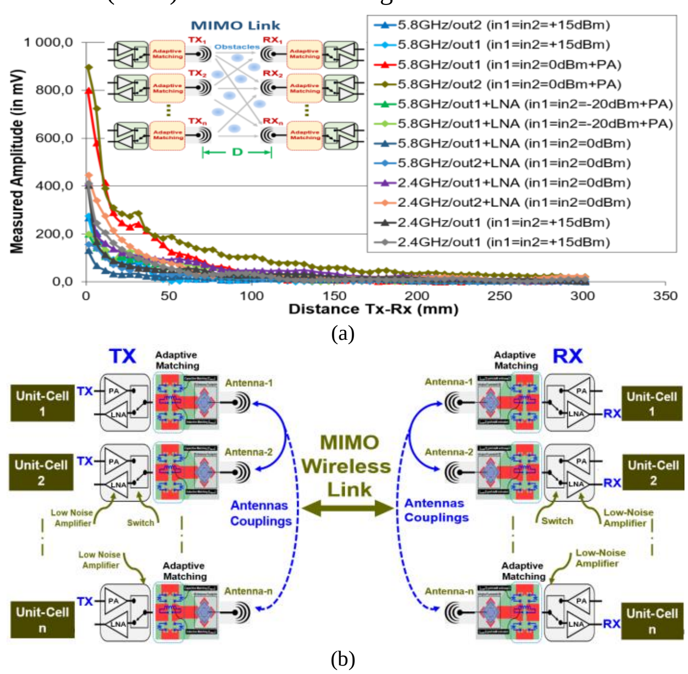
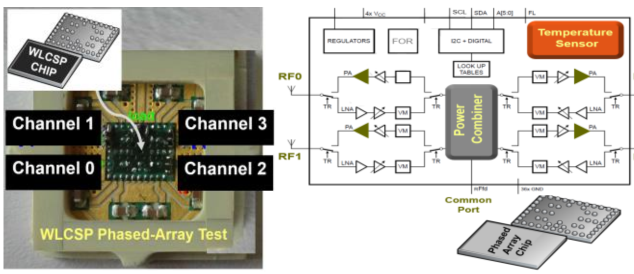


Fig.4: Measured Multi-port 2x2 MIMO signal amplitudes as function of TX-RX separation and input power-levels for 5G Sub-6GHz applications operating at 2.4GHz and 5.8GHz (a). Multiport MIMO representation in Near-Field and Far-Field operations including Front-End-Module (FEM) circuits in TX and RX.

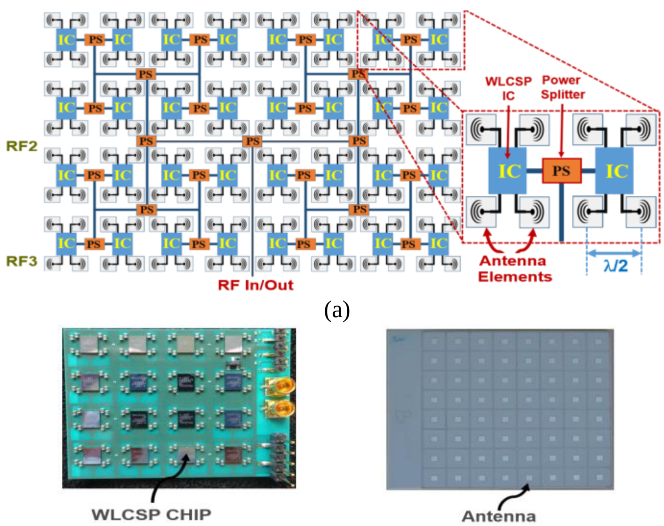
At mm-Waves, MIMO and phased-array systems can be realized using monolithic integration as illustrated in Fig.5(a) showing unitary RFIC phased-array cell composed of 4 channels with a common access terminal for Input/Output feed to power combiners/splitters. Fig.5(b) represents the hardware implementation of the Test-Board designed for the reliability test and verification of the WLCSP phased-array chips. The unitary RFIC phased-array cells include integrated 4 PA's, 4 LNA's, 8 Vector Modulators (VM's), 1 to 8 splitter, Digital bus in I²C and SPI implementations, TDD support 2x Switch (SPDT), Package WLCSP with RDL in reference to a Base-Station mission profile.



(a) (b)

Fig.5: Hardware realization of Test-Board (a) for reliability test of 4 Channel WLCSP Phased-Array Chip (b) with Temperature sensor and digital controls: S. Wane, "*Thermo-Electric Harvesting and Co-Design Strategies Toward Improved Energy Efficiency of Emerging Wireless Technologies*", IEEE Texas Symposium on Wireless and Microwave Circuits and Systems, 2018.

A hardware implementation of 4x4 WLCSP RFIC cells in Fig.6(b) are combined with 64 antenna elements in Fig.6 (c) to form a phased-array system for Base-Station mission profile. The unitary RFIC cells are combined with power splitters (PS) to build MIMO and Phased-Array systems as illustrated in Fig.6(a):



(a)

(b) (c)

Fig.6: Phased-Array system with mm-Wave Chips combined with Power-Splitters and antenna elements (a). Practical realization of 64 antenna elements array using WLCSP mm-Wave Chips (b) with Power-Combiners (c).

While Far-Field (FF) communication (e.g., mobile link) exploits relatively weak-coupling with low SNR, Near-Field (NF) operation can benefit from higher SNR (reduced distance to sources) at lower power operation and stronger-coupling. Further reduction of input power, power savings per channel referenced as $PS_{\text{per channel}}$ in (2), can be achieved by MIMO operations:

$$PS_{\text{per Channel}} \propto = \frac{SNR_{\text{Total}}}{SNR_{\text{per Channel}}} \qquad (2)$$

For noisy stochastic fields, the mutual information to be related to entropy can be cast in the following form:

$$Mutual\ Information = log_2\, det\left[I + \frac{1}{\sigma_v^2} H R_v^{-1} H^H R_X\right] \qquad (3)$$

where H represents the channel transfer matrix [10], $R_X = E[XX^H]$ and $R_v = \frac{1}{\sigma_v^2} E[vv^H]$ being correlation [6] matrices.

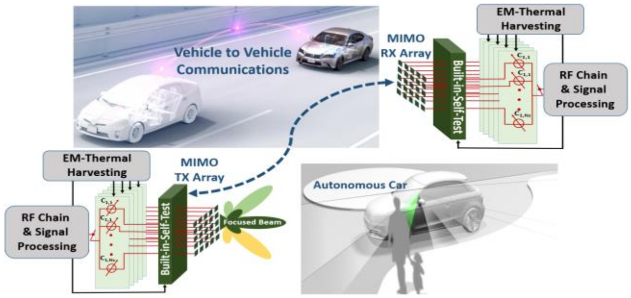
The noise and signal correlation matrices are characterised using Energy-based stochastic approaches with possible control through Energy-Entropy-Geometry Co-Design [7]. Field-Field correlation analysis in a wider sense, *including higher order correlations* (coupled particles described by k-fold interactions), represents a powerful tool for relating energy, entropy and geometry [7]. The use of microscopic correlations to obtain the macroscopic entropy for an equilibrium system was studied by Lindgren [7]. The conventional definition of the physical entropy S of a system with a particular macrostate – e.g., energy, composition, volume, (U,N,V) – in statistical physics and that of information H(z), can be linked by the following equation adopting the notation in [7]:

$$H(z) = S(U,N,V)/k\ln(2) = -\sum_s P_z(s)\log_2 P_z(s) \quad (4)$$

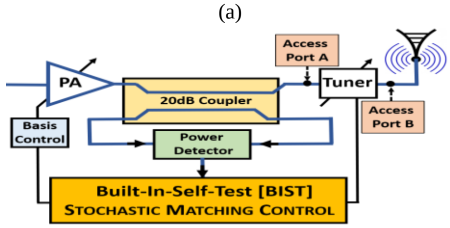
The *Shannon–McMillan–Breiman* theorem provides a formal bridge [11] between the Boltzmann entropy and the Shannon entropy. In (4), the average information in a set of messages associated to probabilities $P_z(s)$ map onto the ensemble of the microstates of the physical system. The variable z is a label for the set of possible messages and the probability over this set, s is a particular value from the set. Equation (4) being valid in the case of non-equilibrium systems, for a well-defined ensemble probability distribution, $P_z(s)$, several conceptual difficulties arises from the physical interpretation of system complexity in link with equilibrium entropy.

B. *Perspectives for Ubiquitous Interactions in Stochastic Environments using Smart Hybrid Multiphysics Sensors based on mm-Wave and Optical Technologies*

The concept [7] of BIST is proposed for real-time compensation of stochastic changes in the environmental conditions. In Fig.7(a) illustrative hybrid Analog-Digital beamforming and beam-steering architecture with Nz×Ny antenna array elements including a BIST control-loop is shown. Hybrid analog-digital beamforming, when assisted by BIST functionality, offers the required trade-offs between Analog performances and Digital flexibility with reduced complexity. The BIST-assisted MIMO control includes temperature-dependent dynamic monitoring and adjustment of power-levels. The implementation of BIST-control and regulation solutions can be combined with monolithically integrated correlators for real-time estimation of MIMO performances accounting for Field-Field correlations [5-9] based on energy metrics [7]. Fig.7 (a) depicts phased-array TX and RX systems with adaptive power-levels adjustmentsfor Vehicle-to-Vehicle (V2V) communications and ADAS applications, see Fig.7(b).



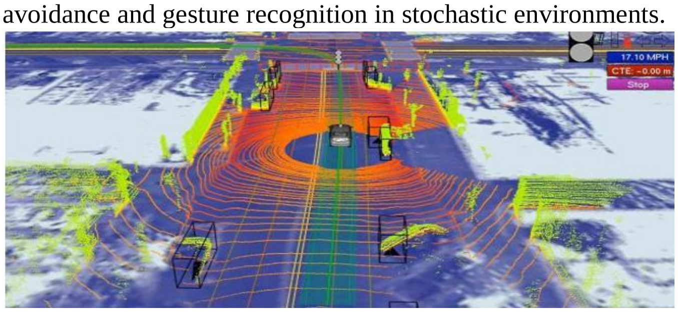
(a)



(b)

Fig.7: Hybrid Analog-Digital Multiphysics BIST [6-7] controllable beamforming with EM-Thermal energy harvesting for V2V communication (a). Illustrative view, in TX mode, of stochastic load matching compensation (b).

By steering the phased-array beam through digital control using electronically steered antenna arrays, the system can track not only distance but also the obstacle or target's location in range and azimuth. Steering techniques have been applied to recover target shape, thus the straightforward approach to gesture tracking would suppose designing a narrow pencil beam and scanning it across the hand to spatially resolve its skeletal structure and individual finger motion. Fig.8 (a) shows data fusion in unified 3D maps for analysis of ADAS systems. The prototype demonstrator in Fig.8(b),(c) developed with *ESIGELEC-IRSEEM* will benefit from the hybridization of optical sensors with agile mm-Wave MIMO and Phased-Array technologies offering the possibility of compact radar Chip-Package-PCB-antennas co-design to achieve the necessary angular resolution for both target's localization, objects avoidance and gesture recognition in stochastic environments.



(a)

(b)

(c)

Fig.8: Data fusion in unified 3D maps (a). Prototype demonstrator of connected vehicle (b)-(c) toward autonomous driving solution following P. Merriaux, R. Boutteau, R. Rosii, G. Coru, V. Vauchey, and X. Savatier, "*Synchronization and calibration between a 3D Lidar and an inertial measurement unit for the accurate localization of an autonomous vehicle*", in JS18 URSI France.

III. Conclusion

This paper proposes hybridizing static-dynamic classical multiphysics detectors (including ultrasonic and optical sensors) with smart RF and mm-Wave technology solutions for operating the unification of C*ontact-driven* actions and contactless *Gesture-driven* interactions in the realisation of emerging technologies relative to environmental perceptions and ubiquitous interactions. The development of stochastic *Field-Field Correlation* techniques backed-up by innovative modeling and measurement techniques will provide the required design and verification platforms for properly coupling Information-Signal Theory (*Shannon information-based Entropy*) and Physical-Information Theory (*Statistical-Physics based Entropy*) into a unified [7] framework. Such unification will benefit to wide range of applications relative to interactions of humans with smart devices and systems in randomly changing environments. Practical applications relative to autonomous vehicles with ADAS and *gesture-recognition* functionalities including machine learning and cognitive signal processing are addressed. Perspectives for RFIC photonics are drawn for optical MIMO and Phased-Array technologies implementing adaptive BIST [5] techniques with EM-Thermal harvesting [12].

Acknowledgment

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