Energy-Geometry-Entropy Bounds aware Analysis of Stochastic Field-Field Correlations for Emerging Wireless Communication Technologies

Sidina Wane[1], Damienne Bajon[2], Johannes Russer[3], Peter Russer[3], Gabriele Gradoni[4]
[1]NXP-Semiconductors, Caen-France, [2]ISAE-SUPAERO Toulouse-France
[3]Institute for Nanoelectronics, Technische Universität München, Germany,
[4]School of Mathematical Sciences, University of Nottingham, UK

Abstract— **Exponentially increasing demands for higher data rates and quality of service cannot be satisfied by delivering more power as higher power levels may reduce Signal-to-Interference-plus-Noise Ratio (SINR) with negative impact on overall system performances. Simultaneously, the continuous shrinking in transistors size for denser circuits integration, following Moore's law, will be constrained by the physical limits while the switching energy is approaching the thermal noise spectral density. The resulting thermal cooling capacity in terms of energy per unit time for given area will lead to a bottleneck.**

This paper calls for *Energy-Geometry-Entropy* Co-design tradeoffs for addressing the challenges of emerging technologies and for driving innovative applications relative to interactions of humans with smart devices in randomly changing environments.

Index Terms —Energy-Geometry-Entropy Co-design, Field-Field Correlations, MIMO, Phased-Arrays, Energy Harvesting, Built-In-Self-Test.

I. INTRODUCTION

Emerging wireless communication systems are envisioned to undergo revolutionary changes for supporting non-uniformly distributed heterogeneous cells in dense network nodes with massive numbers of devices. In the practical situation of 5G evolution, cellular networks are evolving towards infrastructure and ad-hoc based networking for enabling direct device-to-device (D2D) and machine-to-machine (M2M) communications beyond the legacy device-to-BS (Base Station) links. The resulting architectures impose Stochastic Geometry (SG) partitioning as illustrated in Fig.1. As a consequence, innovative methodologies are required in order to bridge the gap between the underlying theoretical concepts and the practical technological implementations. The use of Stochastic Geometry for modeling communication networks is recent following the work relative to Random Plane Network (RPN) and Poisson-Voronoi Tessellations (PVT) discussed in the Gilbert's papers of 1961 [1] and 1962 [2]. The SG analysis [3] developed in [1] on continuum and Boolean percolation of the connectivity in large wireless networks can be linked to Markov chains [4] and queueing theories installed by the work of Erlang [5] on the notion of statistical equilibrium and the method of writing down balance of state equations (known as Chapman-Kolmogorov equations). However, available SG-based methodologies remain mainly based on simplified spatio-temporal correlations approach where Electromagnetic Field-based interferences are approximated by node-based behavioral models. These behavioral models are built using different statistical techniques such as Random-Walk [6], Brownian-Motion [7], Random-Waypoint [6] for describing

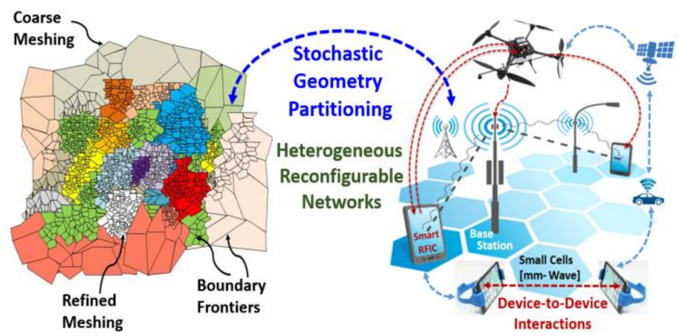

Fig.1: Stochastic-Geometry Partitioning (SGP) of emerging heterogeneous network connections for reconfigurable wireless mobile communication systems including Device-to-Device, Device-to-Machine and Device-to-Human interactions.

the random pattern of mobile nodes as a Point Process (PP) [8] at each time instant. Furthermore, dynamic time-space averages are not supported by most of existing predictive modeling analysis only operational for limited scenarii where statistics of interferences are assumed identical at every time instant. Beyond the use of time-correlation based behavioral models for the estimation of aggregate interference and outage probability, it is essential to bring the accuracy of SG to the level of computational Electro-magnetic (EM) fields.

In [9] Russer has established an elegant and powerful link between Electromagnetic field-based Differential Geometry (DG) calculus [10] of Hermann Grassmann [11] and Elie Cartan [12-13] with Network Methods (NM) [14-15]. This link provides the required theoretical framework for tackling the challenges of coupled Geometry-Network vision of randomly distributed wireless devices and systems.

In this paper, a holistic *Energy-Geometry-Entropy* Co-design approach is proposed for addressing the challenges of emerging applications based on identified key technology enablers. *Energy-Geometry-Entropy* Co-design will open new possibilities in communication theory for properly coupling Information-Signal Theory (IT) and Physical-Information Theory (PT) into a unified framework [16].

II. MAIN RESULTS, ANALYSIS AND PERSPECTIVES

A. *Energy-Geometry-Entropy Bounds aware Analysis*

The International Technology Roadmap for Semiconductors (ITRS) identifies [17] the management of system power and energy as the main critical challenge. Beyond the ITRS near-term projections, overcoming the challenge of Power-Energy constraints requires a holistic approach accounting for Energy-Geometry-Entropy Co-design. 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. The use of microscopic correlations to obtain the macroscopic entropy for an equilibrium system was studied by Lindgren in [18]. 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 [19]:

$$\mathbf{H(z) = S(U,N,V)/k\ln(2) = -\sum_s P_z(s)\log_2 P_z(s)} \quad (1)$$

In (1), 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 (1) 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. These conceptual difficulties reveal the dependence of entropy on the scale [19] of analysis. The concept of a scale dependent entropy dates back to the ε-entropy of Kolmogorov [20], which can be linked to Shannon noisy-channel information theory [21]. Multi-scale analysis of the structure of the state space relates the energy, entropy and geometry at different levels of resolution for both equilibrium and non-equilibrium conditions. For dynamic systems in non-equilibrium conditions, use of entropy-based [22] metrics for evaluating the attributes of chaotic regimes will open new possibilities. In [23] it is suggested that for any bounded system with entropy $\mathbf{S_{Entropy}}$ and rest energy $\mathbf{E_{Rest}}$ there exists a universal upper limit on the entropy-to-energy ratio which leads to the following inequality:

$$\mathbf{S_{Entropy}/E_{Rest}} \leq 2\pi\mathbf{R} \quad (2)$$

where **R** represents the radius of the sphere circumscribing the system. For topologically compact systems, **R** is to be defined in terms of the system's volume. In the derivation of (2) we have assumed $h/2\pi = k = G = 1$ without loss of generality.

In [24] the implications of the entropy-to-energy ratio on an upper bound of the entropy-to-surface-area ratio are discussed. The resulting entropy-to-surface-area ratio is expressed in the form:

$$\mathbf{S_{Entropy}/A_{Surface}} \leq \frac{1}{4} \quad (3)$$

The limit of (2) leads to the equality $\mathbf{S_{Entropy=}A_{Surface}/4}$ which is consistent with the expression for black holes.

The derived Entropy-to-Energy and Entropy-to-Surface-Area bounds open new possibilities in communication theory for properly coupling IT and PT into a unified approach.

In reference to computational energy dissipation, Landauer, in 1961, has stated the principle that erasing one bit of information entails an energy loss of kTln(2) (the thermodynamic threshold), where k is the Boltzmann constant and T is the temperature in Kelvin. This principle has generated rich comments [25] and motivated new directions of research ambitioning solutions (e.g., applied superconductivity [26]) with less dissipation than the Landauer limit.

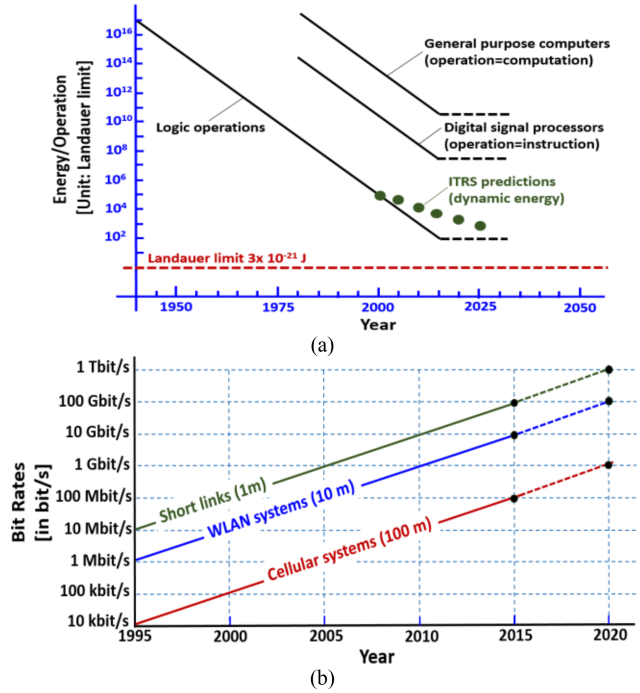

Fig.2: Technology trend (a) of dissipated energy per operation expressed in reference to Landauer limit against evolution over years showing saturation effects. Bit rates in wireless systems (b): e.g., evolution of short links (1m), WLAN systems (10m) and cellular systems (100m).

Fig.2(a) shows technology trends [27-31] expressed in terms of dissipated energy per operation in reference to Landauer limit. The overall evolution indicates a saturation effect starting around 2000.

In Fig.2(b), the trends [32] and projections of bit rates are presented for short links, WLAN and cellular systems. It is observed that bit rates at fixed link distance has been increasing 100 times per decade. The dot-lines reported in Fig.2(b) are expected to undergo some saturation beyond the performances of 100 Mbit/s, 10Gbit/s and 100 Gbit/s at link distances of 100m, 10m and 1m respectively.

In the perspectives of emerging technologies including 5G applications where high throughput and low latency are important requirements, Fig.3 presents the power consumption as function of bit rates and computing power versus dissipated energy in J/bit. Following Moore's exponential trend, the energy efficiency of a transistor and a logic gate has improved by a factor of one hundred in ten years, corresponding to a factor of two each 18 months. In Fig.3(b), 1 billion transistors integrated in a chip is expected to consume an average power between 100 and 200W while a human brain (about 2% of the total mass of the body) consumes about 20W (20% of the total power consumed by an adult human body in the order of 100W). The trends of Moore's prediction is starting to show some saturation as exponential decrease in the physical size of the transistor is constrained by the physical limits. At the lower scales, the switching energy is approaching the thermal noise spectral density. In addition, the cooling capacity (*limited to the range from 1 to 150W/cm²)* in terms of energy per unit time for given area will lead to a bottleneck imposing *Energy-Geometry-Entropy* trade-offs.

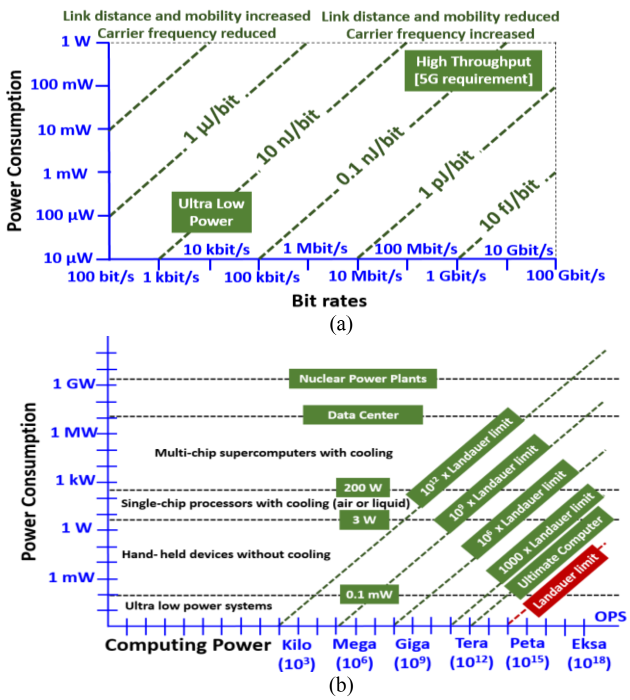

Fig.3: Power consumption versus bit rate (a) and versus computing power (b).

B. *Energy-Geometry-Entropy Co-Design: Perspectives for Emerging Wireless Technologies*

Energy-Geometry-Entropy co-design will offer a unified holistic approach for pushing emerging applications to their ultimate performances by taking benefit of the following key technological enablers:

- Use of 3D material engineering for designing conformal antennas with optimal EM-Thermal-Mechanical performances. Fig.4 shows prototypes of 3D antenna patterning realized using Liquid Crystal Polymer (LCP) anisotropic substrates experimentally evaluated in MIMO configurations [33].
- Implementation of hybrid (Fig.5(a)) Analog-Digital beamforming (single & multi-beam focus) and beam-steering for full-control of EM energy spatial distribution using Built-In-Self-Test (BIST) with cognitive functionality. Beyond the cognitive functionality, BIST-assisted smart detections will create new applications for improved performances through awareness and exploitation of multiple scattering through obstacles (including controlled reactive loading [34]) with *trackable motions* following random trajectories (*Stochastic Geometries*).
- Power management in the perspective of Multi-physics Energy harvesting for improved system-level efficiency. In [35] perspectives for EM-Thermal harvesting are drawn.

In Fig.5(b) the concept of Multi-Cell cooperative networks is illustrated for the mitigation of fading and interference effects. *Energy-Geometry-Entropy* co-design vision is expected to transform what is perceived as problems (e.g., fading, interference) into opportunities for performance improvement.

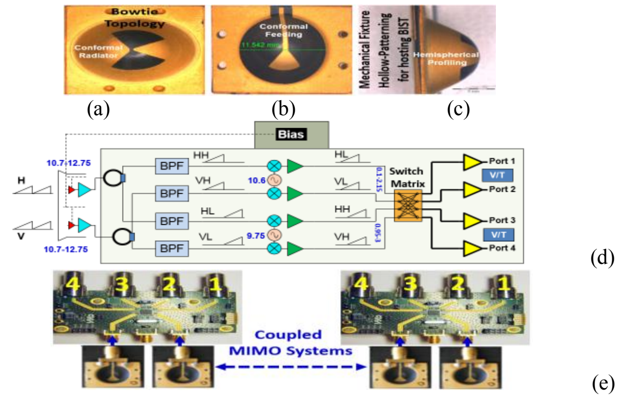

Fig.4: views of fabricated 3D conformal antennas for MIMO and Phased-Array systems: Top (a), bottom (b) and side (c). MIMO single Chip solution including calibration path and polarization controls (d). Coupled MIMO system (e) for evaluating Near-Field and Far-Field couplings and interferences.

Exponentially increasing demands for seamless connectivity with higher data rate and quality of service cannot be satisfied by delivering more power as higher power levels may reduce Signal-to-Interference-plus-Noise Ratio (SINR) with negative impact on overall system performance at the end-user.

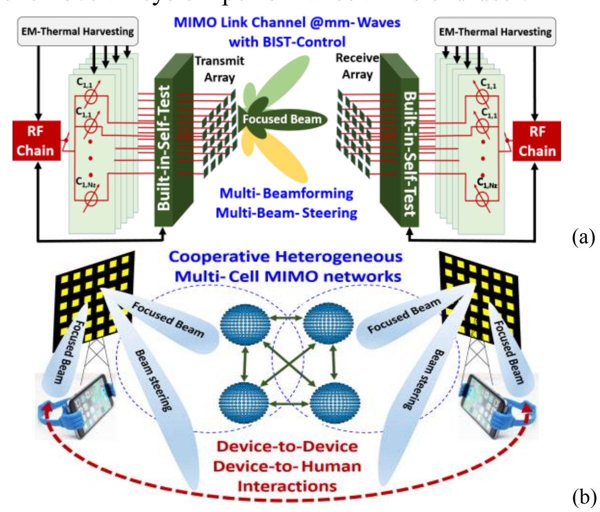

Fig.5: Hybrid Analog-Digital beamforming with BIST-assisted control of MIMO links at mm-Wave frequencies (a) including cooperative (b) Multi-Cell MIMO systems (*Device-to-Human interactions*).

Thus, one critical challenge for next-generation communication systems is to be able to contain the predicted increase in the information traffic in a sustainable manner (beyond the economic and environmental cost of the resulting Carbon footprint). In this prospect, the *GreenTouch* consortium recently initiated studies [36] on the Green Meter Research that claims that it is feasible through a combination of changes in technologies [37], architectures, components, algorithms and protocols to decrease the net energy consumption in end-to-end communication networks by up to 98% by 2020 compared to the 2010 reference scenario based on projection assumptions formulated by *GreenTouch*. Available approaches such as the recently standardized IEEE 802.11ad will provide basic building blocks for testing Time Reversal [38] processing, foreseen as a green PHY/MAC technique [39], with millimeter-wave hotspot transmissions in the perspectives of mobile EM-based computing [40].

III. Conclusion & Perspectives

This paper calls for a holistic *Energy-Geometry-Entropy* Co-design approach in the perspectives of pushing the performances of emerging applications to their ultimate thermodynamic limits based on identified key technology enablers. Combination of these key technology enablers with *Energy-Entropy* confinement in Stochastic-Geometries and Random Fields will create new paradigms relative to interactions of humans with smart devices and systems in randomly changing environments. *Energy-Geometry-Entropy* Co-design will open new possibilities in communication theory for properly coupling Information-Signal Theory (*Shannon information-based Entropy*) and Physical-Information Theory (*Statistical-Physics based Entropy*) into a unified framework.

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