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A Holistic Antenna Design Paradigm for the 5G Wireless Communication System

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Abstract

The 5G wireless communication system covers a broad set of applications operating in a wide frequency spectrum, starting from the sub-GHz range to millimeterwave frequencies. The heterogeneity in requirements, which depend on the specific use case, and the pertinent radiowave propagation conditions at the operating frequency pose important challenges in terms of antenna design. Given the strict link budget margins, highly efficient antenna systems are required, often consisting of multiple antennas and tightly integrated with active transceiver hardware. In this contribution, we propose a holistic paradigm for the design of such active antenna systems, based on a full-wave/circuit co-optimization strategy. Highly efficient and autonomous solutions are obtained by directly co-designing the antenna with the transceiver circuitry that is integrated onto the antenna feed plane and the energy harvesters that are deployed on the antenna plane. The methodology is illustrated by two representative examples: a wearable wireless sensor node with integrated solar cell and a downlink remote antenna unit with integrated opto-electronic conversion circuit.

1 Introduction

Besides offering higher datarates and lower latencies, the 5G wireless communication system also encompasses low-power, low-datarate applications that operate in the Internet of Things (IoT). Therefore, antenna designers are currently developing new solutions for a wide range of products, which include wireless sensor nodes, wearables [1, 2, 3] and smart objects, besides the conventional wireless communication devices such as smartphones, tablets and laptops. A common denominator of all future antenna designs is the long list of strict design requirements, which must guarantee the desired performance, autonomy, user comfort and cost. Therefore, it becomes more and more difficult to meet the tight specifications by adopting a conventional diakoptic approach, where each component of the wireless system is designed separately and then simply concatenated. Instead, a holistic system-oriented approach is needed, co-optimizing the sensing, actuating, energy supply and wireless communication subsystems to implement a fully integrated system. This holistic co-design must be founded on all relevant system requirements and not simply on figures of merit of the separate, isolated components.

In this contribution, we outline a holistic co-design paradigm for the next-generation antenna systems for 5G wireless communication and the Internet of Things. The proposed strategy applies to both low-cost systems developed in unconventional materials, where unobtrusive integration, cost and autonomy are the main requirements, and to high-performance solutions for high datarate, low-latency wireless communication. The procedure starts by listing all design specifications relevant to the complete system. Next, a dedicated antenna topology with high antenna/platform isolation is needed to avoid parasitic coupling between the fields radiated by the antenna and the active circuits and energy harvesters that are tightly integrated onto the antenna platform. Then, the passive antenna is co-designed with the active electronic components by full-wave/circuit co-optimization. Finally, a stochastic analysis is performed to assess the variations in antenna performance due to fabrication tolerances or uncertainty on the wireless system's deployment conditions. Two representative examples showcase the proposed holistic design strategy: an autonomous 2.45 GHz wearable wireless sensor node with integrated solar cell and a fully-passive 3.5 GHz-LTE downlink remote antenna unit with integrated opto-electronic conversion circuit for analog radio-over-fiber.

2 Holistic Stochastic Design Paradigm

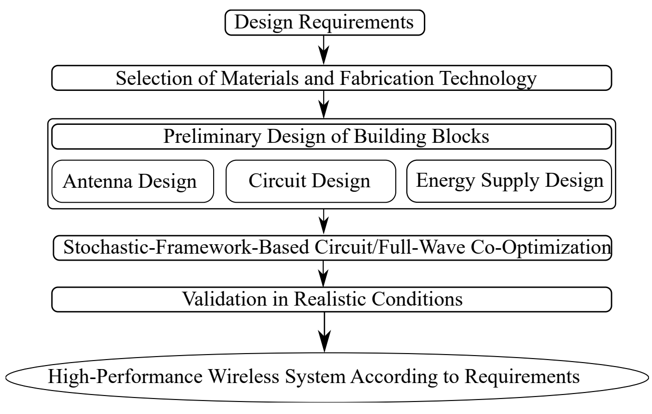

Figure 1. Proposed design flow.

We now outline the five main steps composing our holistic design strategy based on a full-wave/circuit computer-aided co-optimization procedure with integrated stochastic analysis framework as illustrated in Fig. 1.

2.1 System-Based Design Requirements

The most important user requirements concern sufficient system autonomy, which dictates power-efficient operation at low power consumption and minimal recharging, high-performance wireless functionality that remains stable under different deployment conditions, safe operation with minimal absorption of radiated waves to comply with SAR limits, and absence of dangerous, bulky batteries. In addition, reliable operation should be combined with optimal user comfort, which requires lightweight, unobtrusive and compact systems that may need to be flexible in case of wearables.

To meet all these specifications, a compact high-performance antenna system is required with very short interconnects between all subsystems. Power efficiency and reliability, both in terms of mechanical stability and signal integrity, are optimized by directly integrating as many active electronic subsystems as possible directly on the antenna platform.

2.2 Selection of Antenna Topology

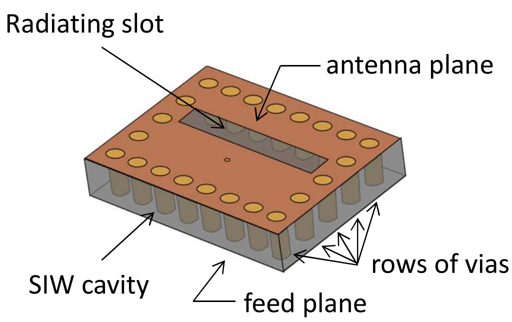

Figure 2. Substrate Integrated Waveguide (SIW) cavity-backed slot antenna.

For stability reasons, the electromagnetic fields radiated by the antenna should be kept away from the active electronic components deployed on the antenna platform. Moreover, to achieve optimal radiation efficiency, the antenna should radiate away from lossy objects, such as the human body, in close proximity of the wireless device. This may be achieved by leveraging a cavity-backed antenna topology, which may be implemented in traditional printed circuit boards or unconventional materials, such as textile [4], paper and 3D printed substrates [5], by relying on substrate integrated waveguide technology (Fig. 2). Moreover, to reduce the substrate losses in the antenna cavity, one may remove the substrate material there, creating an air-filled substrate-integrated-waveguide cavity-backed antenna [6]. In addition, the structure may be miniaturized by exploiting mode symmetry to obtain half-mode [7, 8], quarter-mode [9, 10] or even eighth-mode realizations. These may be combined to form coupled resonators that yield an antenna structure with a large impedance bandwidth. Finally, note that high isolation between antenna elements will also reduce mutual coupling in a multi-antenna system, thereby simplifying beamforming algorithms.

2.3 Full-Wave/Circuit Co-Design

The different subsystems of the wireless system will be co-designed in a unified framework, based on computer-aided full-wave/circuit co-optimization. To speed up the process, in a first step, preliminary designs will be conceived for the active circuits, the power management system including the energy harvesters and the antenna. This step also includes the layout of the antenna platform, fixing the positions of the different subcircuits on the feed plane, of the energy scavengers on the antenna plane and of the interconnections between the different building blocks [11]. Specific attention is devoted to keep the critical connections as short as possible and to avoid interference between electronic circuits and the radiating antenna. Instead of selecting standard impedance levels, we exploit the flexibility to tune the characteristic impedance of the transmission lines between subsystems, optimizing the system performance without requiring bulky and lossy matching networks [12]. After achieving acceptable performance for each separate subsystem, a global holistic optimization is performed for the complete wireless system.

2.4 Stochastic Design Analysis

After an optimal nominal design has been obtained, we must carefully verify its sensitivity to variations in dimensions and component values, and to uncertainty in deployment conditions [13]. Fabrication tolerances [14] will play an important role, both in systems for the IoT, due to cheap production processes and the use of unconventional materials, and in high-performance millimeterwave systems, because of the small dimensions. A stochastic framework may be implemented around the full-wave/circuit simulator by exploiting non-intrusive generalized polynomial chaos expansions [15] to relate the probability density functions of the wireless system's figures of merit to the statistical variations in the random design parameters.

2.5 Prototype Fabrication and Testing

Accurate knowledge about the fabrication process must be directly integrated into the design procedure. Specifically, the designer must be aware of the precise fabrication tolerances to assess their effect on system performance. After manufacturing of representative prototypes, tests must be conducted to verify whether actual tolerances are in line with the ones specified by the manufacturer. Deviations between expected figures of merit and measured ones must be explained based on these tests, or additional simulations and/or experiments must be carried out to pinpoint the reasons of these differences. This may require, among others, assessing the effect of variations in the dielectric properties of substrates or in conductivities of metals. Specific attention must be devoted to connections and soldering points, as well as to the applied passivation layers.

Finally, experiments must be conducted in situations that closely resemble all potential realistic deployment conditions. This includes studying the effect of (1) objects in close proximity of the wireless system, such a the human body, of (2) bending in case of flexible circuits and of (3) varying environmental conditions.

3 Some Representative Design Examples

3.1 Wearable Wireless Sensor Node

A 2.45 GHz ISM-band autonomous textile wireless sensor node [16] was realized based on the design formalism discussed above. The node was designed for unobtrusive integration within a garment to enable monitoring of the wearer's vital signs and for communication with smart floors, ceilings and walls [17]. Fig. 3 shows the circular microstrip patch antenna with shorting pins that serves as integration platform. On its feed plane, all necessary subsystems (schematically outlined in Fig. 5) are deployed to implement sensing, processing, controlling and powering. Moreover, a solar energy harvester is located on top of the antenna patch, whose energy is stored in a flexible battery (Fig. 4) below the feed plane by the power management system.

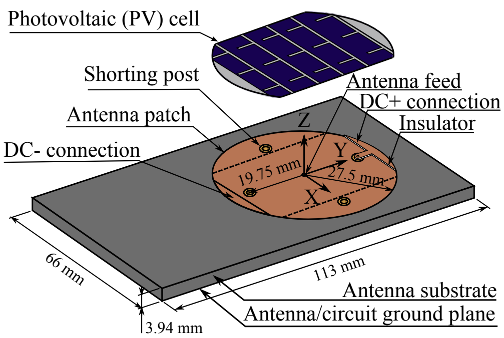

Figure 3. Antenna platform with energy harvesters deployed on the antenna plane.

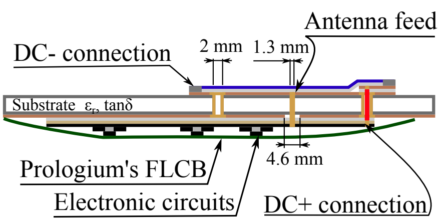

Figure 4. Cross-section of the wearable wireless node.

The antenna covers the entire 2.45 GHz ISM-band in standalone conditions, when deployed on the human body and after integration of a photo-voltaic cell, electronic circuits

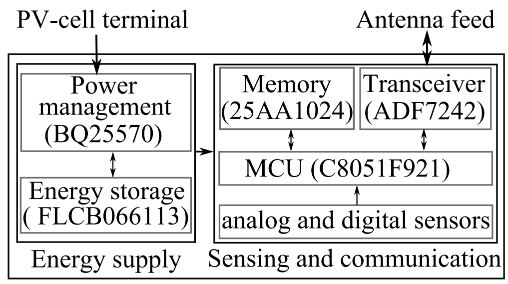

Figure 5. Active circuitry deployed on feed plane.

and a flexible battery. The node only consumes $168.3\mu W$, when sensing/processing are performed every 60 s. Its read range extends to 23 m. The maximum antenna gain equals 2.5 dBi when deployed on the human body.

3.2 Downlink Photonic-Enabled Remote Antenna Unit for Analog Radio-over-Fiber

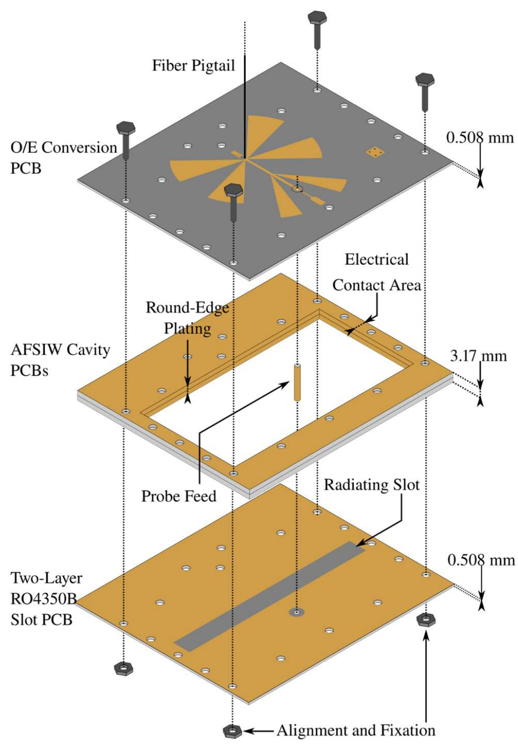

Figure 6. Downlink Photonic-Enabled Remote Antenna Unit for Analog Radio-over-Fiber

A downlink remote antenna unit (Fig. 6) for analog radio-over-fiber was designed in [18] based on an air-filled substrate-integrated-waveguide cavity-backed slot antenna platform, covering the 3.30–3.70 GHz LTE frequency bands. On the antenna feed plane, a dedicated passive impedance matching network maximizes the power transfer between the photodetector, receiving the optical signal, and the antenna. The remote antenna unit features a footprint of $1.19\lambda \times 0.66\lambda$, a -3-dB gain bandwidth of 480 MHz, a boresight gain exceeding 9 dBi (after normalization with respect to the optical source's slope efficiency), and a front-to-back-ratio of 8.8 dB at 3.50 GHz. Over a distance of 20 cm, a symbol rate of 80 MBd (64-QAM) was successfully employed in a unidirectional data link, with an RMS EVM of 2.2%, enabling transmission of data at 480 Mbps with an equivalent isotropic radiated power of -15 dBm.

4 Acknowledgements

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