Frequency and Spatial Filtering Antennas for Energy Efficient Wireless Networks

PhD Research Proposal - LABEX UCN@Sophia

Involved Teams: CMA/LEAT- APICS/INRIA

LABEX Research Axes: Infrastructures: Heterogeneity and Efficiency / Energy Efficiency

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1. Project Relevance and Strategic Importance

The interest in wireless sensor networks and connected objects is continuously increasing thanks to their use in applications such as the monitoring of environmental or biomedical parameters. However, some important constraints like power consumption or miniaturization can limit their deployment. At the system level, several works concerning the smart power management of the network nodes to reduce their energy consumption can be found in literature, especially when dealing with nodes that are equipped with energy harvesting systems [1], [2]. However, the overall network consumption can be further decreased by enhancing the design of the radio frequency (RF) front-ends, in particular the antennas of the network nodes.

The electrical and radiating properties of the employed antennas basically define how the available energy is spread in the frequency and spatial domains. Consequently, nodes of radiating systems must be carefully optimized in order to increase the global system efficiency.

In the frequency domain, the RF front-end transfer function indicates the frequency range in which radiation is allowed. The correct synthesis of this function is essential, not only to avoid interference with neighbouring RF systems, but also to meet the transmission masks prescribed by the standards. This point is becoming more and more important considering the exponential increase of communicating objects in close proximity.

Concerning the spatial domain, the radiation pattern of the antenna defines the directions where the radiation gets maximized or minimized. The classical approach consists in adopting for each node an omnidirectional antenna identically covering all directions [3]. However, in multi-hop wireless sensor networks, data are always transmitted in fixed directions. In this framework, the proper synthesis of the antenna radiation pattern would allow one to profitably focus the radiated energy, thereby optimizing the link budget thanks to the reduction of power consumption, the increase of range and the minimization of interferences.

The objective of the present PhD research proposal is to design innovative antenna systems providing filtering characteristics in the frequency as well as in the spatial domain so as to improve the overall system energy efficiency. More specifically, both the antenna impedance matching and the radiation characteristics will be optimized in order to better exploit the limited energy available on the nodes.

In this respect, the present proposal pertains to the scientific directions “Infrastructures: Heterogeneity and Efficiency” and “Energy Efficiency” of the LABEX. As a matter of fact, the proposed antenna systems will be a valuable support to design novel infrastructures offering high performance, autonomous operation and extended lifetime. Such “green” solutions have the potential to enable new services for the user, confirming the "user at the heart of the network" vision of the LABEX.

2. Scientific Challenges and Approach

In order to design energy efficient antennas with frequency and spatial filtering capabilities, the PhD candidate will be required to address several scientifically challenging issues.

In terms of frequency characteristics, the antenna systems will be optimized to efficiently operate over the requested operating band. Dealing with wireless sensor networks, the frequency band around 2.4 GHz is often used. However, sub-GHz bands such as the 868 MHz band in Europe and the 915 MHz band in the USA are now gaining momentum because of their more reliable propagation characteristics, and will also be considered during the research work. In order to better exploit the energy available at the RF front-end, the research activity will focus on the co-design of the antenna and the pass-band filter. This will be obtained by combining antenna design techniques with mathematical approaches for the synthesis of frequency filters. As opposed to classical filter synthesis, the one we need here should not just match a pure resistive load, but the frequency-varying impedance of the antenna. This type of question is intrinsically difficult, in that it entails approximating an anti-analytic function, locally in frequency, by an analytic one. Specifically, a rational approximation problem with norm-constraint in the hyperbolic metric has to be solved on the bandwidth of the antenna, which resorts to Schur analysis and Nevanlinna-Pick interpolation. As regards antennas, such a combined approach will require studying different antenna structures and considering non-standard antenna input impedances.

Concerning the radiation behaviour, the spatial filtering will be obtained by designing directive antennas.

This promising research direction relies on the use of arrays of parasitic elements, comprising reconfigurable components, to dynamically steer the radiation pattern [4]. However, in order to develop original solutions with compact size, it will be interesting to design small-scale elements, which already possess high directivity. Starting from an initial system, antenna solutions based on one or several associated elements aimed at realizing the desired radiation pattern will be proposed. Such solutions could be based, for example, on a proper modal combination of the currents flowing through the elements to enable spatial filtering. Consequently, new geometries capable of correctly supporting these modes will be needed. Subsequently, new research paths based, for example, on superdirectivity concepts, will be studied [5], [6]. To our knowledge, the design of compact (as compared to the operating wavelength) and superdirective antennas with proper combination of different current modes obtained by filtering circuits designed using advanced mathematical techniques has not yet been demonstrated. It constitutes a serious scientific and technical challenge especially for communication systems which have several MHz of bandwidth.

Superdirectivity is in fact intrinsically narrowband and is often achieved at the expense of radiation efficiency. To compensate for this, a next step in the thesis work will be aimed at integrating the optimization of the radiation behaviour with the fulfilment of impedance matching requirements. The simultaneous optimization of both radiation and matching characteristics will represent a step forward with respect to classical approaches, usually addressing these two issues separately. The problem of matching frequency-varying loads is a classical one (so-called broadband matching) whose study goes back to the work by Fano and Youla. Function-theoretic and operator-theoretic approaches were inaugurated in [7], shedding light on the best achievable gain, but they cannot account for degree constraints on the filter and thus have limited impact. Recently developed techniques, dwelling on generalizations of Nevanlinna-Pick interpolation with boundary data and prescribed zeros of the spectral factor [8], appear to offer a promising path to tackle such problems.

Finally, it is worth noting that, when dealing with wireless sensor network applications, antenna structures and associated circuits of small size will be preferred. This will further increase the complexity of the research objectives of this proposal, since miniaturization usually comes at the cost of performance degradation (e.g., decrease of antenna radiation efficiency, reduction of the covered frequency band, etc.).

3. Project Consistency

The multidisciplinary aspect of the project requires high level competences in different domains, such as Electromagnetics, antenna design, filtering design, etc. This can be ensured by the combination of two laboratories having recognized expertise in their own domains.

LEAT, and in particular the CMA (Modelling and Design of Antennas) group will bring expertise in the study and design of innovative antenna solutions and the development of new methodologies for the integration and miniaturization of the antenna and the associated circuits. Moreover, the presence in LEAT of the MCSOC (Modelling and System Design of Communicating Objects) group will be useful for the definition of the specifications of antennas suitable for wireless sensor networks.

The APICS project-team (Analysis and Problems of Inverse type in Control and Signal Processing) at INRIA Sophia-Antipolis, has expertise on mathematical filter synthesis and frequency optimization of microwave devices. It owns a long record of collaborating with companies, agencies, and research laboratories in microwave design (THALES, Flextronics, CNES, Xlim...). It will bring expertise in the mathematical aspects of this co-design problem, in particular the constructive and algorithmic aspects of matching filter design.

The combination of compact and directive antenna design techniques with mathematical filter modeling makes the proposed research project strongly innovative, pushing both the involved laboratories towards new research activities.

The project and the PhD candidate will be equally hosted by LEAT and INRIA. The plan for the thesis work development is as follows:

1. Bibliography:
   - Study of existing filter and antenna design approaches.
   - Getting familiar with filter design tools.
2. Frequency filtering
   - Matching filter design for high quality factor single band antennas.
   - Co-design of the filter and the antenna in the single-band case.
3. Frequency and spatial filtering
   - Co-design in the multi-port and multi-mode case.
   - Co-design in the single-port multi-mode case.

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