SUMMARY

Beamforming Techniques for Wireless Communications in Low-Rank Channels: Analytical Models and Synthesis Algorithms

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Summary

The objective of this thesis is discussing the application of multiple antenna technology in some selected areas of wireless networks and fourth-generation telecommunication systems. The original contributions of this study involve, mainly, two research fields in the context of the emerging solutions for high-speed digital communications: the mathematical modeling of distributed wireless networks adopting advanced antenna techniques and the development of iterative algorithms for antenna array pattern synthesis. The material presented in this dissertation is the result of three-year studies performed within the Telecommunication Group of the Department of Electronic Engineering at the University of Trieste during the course of Doctorate in Information Engineering.

In recent years, an enormous increase in traffic has been experienced by wireless communication systems, due to a significant growth in the number of users as well as to the development of new high bit rate applications. It is foreseen that in the near future this trend will be confirmed. This challenging scenario involves not only the well established market of cellular systems, but also the field of emerging wireless technologies, such as WiMAX (Worldwide interoperability for Microwave Access) for wireless metropolitan area networks, and Wi-Fi (Wireless Fidelity) for wireless local area networks, mobile ad-hoc networks and wireless mesh networks. The rapid diffusion of architectures adopting an ad-hoc paradigm, in which the network infrastructure is totally or partially absent and that can be deployed using low-cost self-configuring devices, has further enlarged the number of systems that have to coexist within a limited frequency spectrum. In such evolving environment, the development of interference mitigation methods to guarantee the communication reliability, the implementation of proper radio resource allocation schemes for managing the user mobility as well as for supporting multimedia and high speed applications, represent the most relevant topics. Classic approaches are focused on the use of the time-frequency resources of the propagation channel. However, to satisfy the increasing demand of network capacity, while guaranteeing at the same time the necessary levels in the quality of the offered services, operators and manufacturers must explore new solutions.

In this scenario, the exploitation of the spatial domain of the communication channel by means of multiple antenna systems can be a key improvement for enhancing the spectral efficiency of the wireless systems. In a rich scattering environment, the use of multiple antennas enables the adoption of diversity and spatial multiplexing techniques for mitigating and, respectively, exploiting multipath fading effects. In propagation environments characterized by small angular spreads, the combination of antenna arrays and beamforming algorithms provides the possi-
ability to suppress the undesired sources and to receive the signals incoming from the desired ones. This leads to an increase of the signal to interference plus noise ratio at the receiver that can be exploited to produce relevant benefits in terms of communication reliability and/or capacity. A proper design of the medium access control layer of the wireless network can enable the simultaneous exchange of packets between different node pairs as well as the simultaneous reception of packets from multiple transmitters at a single node. Switched-beam antennas, adaptive antennas (also referred to as smart antennas), and phased-antenna arrays represent some of the available beamforming techniques that can be applied to increase the overall system capacity and to mitigate the interference, in a scenario where several different technologies must share the same frequency spectrum.

In the context of distributed wireless networks using multiple antenna systems, the core of this thesis is the development of a mathematical model to analyze the performance of the network in presence of multipath fading, with particular reference to a scenario in which the signal replicas incoming at the receiver are confined within a small angle and are characterized by small relative delays. This propagation environment, referred to as low-rank, is the typical operating scenario of smart antennas, which necessitate high spatial correlation channels to work properly. The novel aspects of this study are represented by the theoretical and numerical modeling of the sophisticated adaptive antennas in conjunction with a detailed description of the channel statistics and of the IEEE 802.11 medium access control scheme. A theoretical model providing a more realistic perspective may be desirable, considering that, at present, not only cost and competition issues, but also too optimistic expectations, as compared to the first measurements on the field, have induced the wireless operators to delay the adoption of smart antenna technology.

The presented analysis includes the most relevant elements that can influence the network behavior: the spatial channel model, the fading statistic, the network topology, the access scheme, the beamforming algorithm and the antenna array geometry. This last aspect is numerically investigated considering that the size of the user terminal represents a strict constraint on the number of antennas that can be deployed on the device, and so the maximization of the performance becomes related to the geometrical distribution of the radiators. In ad-hoc and mesh networks, the typical communication devices, such as laptops, palmtops and personal digital assistants require compact and cheap antenna structures as well as beamforming algorithms easy to implement. In particular, the low-cost characteristics have guaranteed a wide popularity to wireless mesh technology, which have encouraged the birth of a new social phenomenon, known as wireless community networks, whose objective is the reduction of the Internet access cost.

The adoption of multi-antenna systems is the purpose of the IEEE 802.11n amend-
ment, which, however, not considering modifications of the medium access control layer, provides higher bit rates for the single link, but does not allow simultaneous communications between different couples of nodes. This aspect must be taken into account together with the fact that, nowadays, IEEE 802.11x represents the leading family of standards for wireless local communications, and enhancement proposals have to pay careful attention to the backward compatibility issues. The mathematical model presented in this thesis discusses the suitable parameter settings to exploit advanced antenna techniques in 802.11-based networks when the access scheme supports multiple communications at the same time, maintaining a realistic description for the antenna patterns and the channel behavior.

The presentation of two new iterative algorithms for antenna array pattern synthesis represents the core of the last part of this dissertation. The proposed solutions are characterized by implementation simplicity, low computational burden and do not require the modification of the excitation amplitudes of the array elements. These advantages make the presented algorithms suitable for a wide range of communication systems, while matching also the inexpensiveness of mesh and ad-hoc devices. In particular, phase-only synthesis techniques allow the adoption of a cheaper hardware, including only phase shifters, which are available at a reasonable price, while avoiding the use of the more expensive power dividers. The first presented algorithm employs the spatial statistic of the channel for properly placing the pattern nulls, in order to suppress the undesired power incoming from a given angular interval. This solution exploits the improved knowledge of the spatial properties of the propagation environment for enhancing the interference suppression capabilities at the transmitter and receiver sides. The second algorithm is a phase-only technique that is able to generate multiple nulls towards the undesired directions and multiple main lobes towards the desired ones. This method provides the possibility to perform spatial multiplexing adopting low-cost electronic components.

The thesis is organized in three parts. The first one provides the background material and represents the basics of the following arguments, while the other two parts are dedicated to the original results developed during the research activity. With reference to the first part, the fundamentals of antenna array theory are briefly summarized in the first chapter. The most relevant aspects of the wireless propagation environment are described in the second chapter, focusing on the characteristics of the spatial domain in a low-rank scenario. The third chapter presents a classification of the different multiple antenna techniques according to the channel properties and provides an overview of the most common beamforming algorithms. The fourth chapter introduces the most significant aspects of the distributed wireless networks, presenting the main open issues and the current
proposals for the exploitation of the potential offered by antenna array systems. The second part describes the original results obtained in the mathematical modeling of ad-hoc and mesh networks adopting smart antennas in realistic propagation scenarios. In particular, the fifth chapter presents the theoretical analysis to evaluate the number of simultaneous communications that can be sustained by a distributed wireless network using adaptive antennas in presence of multipath. The sixth chapter extends this model to switched-beam antennas, while addressing the mobility aspects and discussing the cost-benefit tradeoff that is related to the use of multiple antenna techniques in today’s wireless networks. A detailed throughput-delay analysis is performed in the seventh chapter, where the impact of advanced antenna systems on 802.11-based networks is investigated using a Markov chain model. The influence of the antenna array geometry is examined in the eighth chapter adopting a numerical approach based on a discrete-time simulator, which is able to take into account the details of the channel and of the antenna system behavior.

The third part describes the original results obtained in the field of antenna array pattern synthesis. The ninth chapter presents the technique developed to modify the excitation phases of an antenna array in order to reject interferers spread over an angular region according to a given spatial statistic. The tenth chapter describes the iterative algorithm for phased arrays, which is able to produce low side-lobe level patterns with multiple prescribed main lobes and nulls. Finally, the eleventh chapter summarizes the thesis contributions and remarks the most important conclusions.

The intent of the work presented hereafter is to examine the benefits that derive from the employment of smart antenna techniques from a realistic perspective, as well as to provide some useful solutions to improve the reliability of the communications and to increase the network capacity.