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On the scheduling, multiplexing and diversity trade-off in MIMO ad hoc networks: A unified framework

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ABSTRACT

In this paper we study the fundamental scheduling, multiplexing and diversity trade-off in MIMO ad hoc networks. In particular, we propose a unified framework for the scheduling-multiplexing and scheduling-diversity sub-problems that constitutes a major step towards solving the overall problem. The two sub-problems are motivated by a fundamental trade-off between scheduling full multiplexing (diversity) gain non-interfering links and scheduling interfering links using lower multiplexing (diversity) gain in conjunction with interference nulling. First, we cast each sub-problem as a cross-layer optimization problem that jointly decides the scheduling and MIMO stream allocation, subject to signal-to-interference-and-noise-ratio (SINR) constraints. Second, we characterize the problem as non-convex integer programming which is quite challenging to solve. Hence, we shift our focus to characterize the optimal for the simple case of two links. The main result of this paper is that the two fundamentally different sub-problems give rise to structurally similar SINR-based decision rules which constitute the basis for a resource allocation algorithm with *linear* complexity in the number of links, namely Iterative MIMO Link Scheduling (IMLS), that solves the two sub-problems and achieves significant gains for any number of links. Numerical results exhibit more than twofold/quadratic improvement over scheduling non-interfering links with full multiplexing/diversity gain, for plausible scenarios. IMLS and its variants reveal an important throughput-fairness trade-off which is an interesting topic for future research.

1. Introduction

Multiple-input multiple-output (MIMO) [16] is a major breakthrough in wireless communications that received considerable attention in the point-to-point literature due to its substantial spectral efficiency and diversity advantages for the same power and bandwidth resources. Exploring the benefits of different MIMO schemes, namely interference mitigation, spatial multiplexing (SM) and diversity, in multi-user settings has started to receive attention. Thus, we focus in this paper on the MIMO-MAC resource allocation problem in ad hoc networks.

Multiuser MIMO is envisioned to bring multiple benefits to mobile ad hoc and vehicular networks as key extensions to state-of-the-art mobile broadband networks. For instance, it provides a capacity boost to mobile ad hoc networks (MANETs) in rich multi-path environment [2]. Furthermore, it is projected to provide resource-efficient and reliable support to diverse applications with stringent quality of service (QoS) requirements, e.g., vehicular safety applications as well as bandwidth-hungry multimedia streaming applications on the move. For example, it is envisioned that, by 2015, mobile video will contribute 68.5% of the Internet traffic worldwide. Finally, the versatile nature of MIMO radios opens ample room to serve multiple purposes (interference mitigation, maximize data rate, minimize bit error rate) as the scenario and application QoS dictate.

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The problem of networking MIMO radios has received considerable attention in the literature [21,10,18,15,1,20,29,14,2,9,11]. Exploiting the interference reduction advantages of smart antennas and reducing the MAC overhead constitute major thrusts. However, optimally allocating MIMO streams in network settings has not received sufficient attention. This problem is motivated by a fundamental trade-off between scheduling, multiplexing and diversity. In this paper, we propose a unified framework for balancing the scheduling-multiplexing and scheduling-diversity trade-offs which constitutes a significant step towards addressing the generalized trade-off. Our prime focus in this paper is on the fundamental trade-off, problem formulation, and solution approach which eventually yields the unified framework. MAC Protocol design, inspired by the proposed framework, lies out of the scope of this work and is a subject of future research.

Our contribution in this paper is threefold:

- Introducing a unified mathematical framework, exhibited by the SINR-based decision rules and the Iterative MIMO Link Scheduling (IMLS) algorithm, for the generalized scheduling, multiplexing and diversity trade-off under the SINR (physical layer) interference model.
- Characterizing the optimal solution for two links which yields SINR-based decision rules that constitute the basis for solving arbitrary number of links.
- Introducing a linear complexity IMLS algorithm which leverages the SINR-based decision rules to efficiently pack the MIMO links. Hence, it demonstrates significant improvement over scheduling non-interfering links with full spatial multiplexing (diversity) gain.

The paper commences with different formulations having fundamentally different objectives for two disparate sub-problems, namely scheduling-multiplexing and scheduling-diversity. We cast each sub-problem as a cross-layer optimization problem that addresses resource allocation and fundamental trade-offs spanning two layers, namely link scheduling (layer 2) and MIMO stream allocation (layer 1), under the physical model of interference (i.e. SINR constraints). Inspired by the optimal solution for the two-link case, the two sub-problems eventually lend themselves to structurally similar SINR-based decision rules which constitute the basis for the same cross-layer link scheduling algorithm, namely IMLS. To the best of the author's knowledge, this paper is the first to point out the remarkable synergy between the two sub-problems and their solution approaches which gives rise to a unified framework for balancing the generalized trade-off.

In the first part of the paper, we consider the scheduling-multiplexing sub-problem which maximizes the average sum link rate, F, subject to SINR constraints. We characterize it as a non-convex integer programming problem. Motivated by the sheer complexity of the problem, we shift our attention to the two link scenario which reveals decision rules characterizing the optimum.

In the second part of the paper, we consider the fundamentally different scheduling-diversity sub-problem. Given the objective of minimizing link i probability of error over K slots, denoted ζ_i, subject to SINR constraints and motivated by problem complexity, we adopt a solution approach inspired by the first sub-problem. This, in turn, gives rise to a *unified* framework, manifested by the SINR-based decision rules and the IMLS algorithm, which holds great promise for balancing the, rather challenging, generalized scheduling, multiplexing and diversity trade-off in MIMO ad hoc networks. Finally, we present numerical results for plausible scenarios that not only capture the trade-offs but also show the considerable performance gains attributed to IMLS.

The rest of the paper is organized as follows: In Section 2, we review related work in the literature. We introduce the system model in Section 3. In Sections 4 and 5, we formulate the optimization problems for the scheduling-multiplexing and scheduling-diversity sub-problems, respectively, characterize the optimal policy for two links and distill decision rules for arbitrary number of links. Afterwards, we introduce the IMLS algorithm that solves the two sub-problems for arbitrary number of links in Section 6. In Section 7, we present performance results that confirm the trade-offs and demonstrate the key role the SINR-based decision rules and IMLS play in designing MAC protocols for MIMO networks. Finally, conclusions are drawn in Section 8.

2. Related work

Space–time signal processing has undergone major developments over the past decade. For instance, spatial multiplexing [7] and space–time coding [22] have been introduced as candidate schemes for exploiting multi-path fading to increase the wireless link capacity and reliability, respectively. A fundamental trade-off between diversity and multiplexing has been characterized for point-to-point links [28] and later for multiple access channels [25] and group detection [19]. In this paper, we focus on the interference channel for which the general information-theoretic capacity region is still an open problem, even for two single-input single-output (SISO) links.

Recent work has focused on the design of MAC protocols that exploit the unique capabilities offered by networking MIMO nodes [21,10,18,15,1,20,29,14,2,9,11]. Redi et al.[18] focuses on handling the non-negligible encoding and decoding delays caused by Lucent's V-BLAST [26]. It introduces mechanisms for reducing the MAC overhead (e.g., RTS/CTS) as well as parallel stop-and-wait automatic repeat request (ARQ) scheme to remedy the per packet ACK. SPACE-MAC [15] enables denser spatial reuse patterns with the aid of transmitter and receiver beam forming. However, it does not explore the role of multiplexing or diversity and their tradeoffs with beamforming. Hu and Zhang explore in [10] the role of spatial diversity (e.g., space–time coding (STC)) to exploit fading and achieve robustness in MIMO ad hoc networks. Casari et al. introduce distributed scheduling for MIMO ad hoc networks (DSMA) within the CSMA/CA paradigm where SM stream allocation depends on the transmitter–receiver distance [1]. A power-controlled MAC protocol (CMAC) for a wireless network with two antennas per node is proposed in [20]. Unlike this work, CMAC is inspired by a