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Wireless resource sharing for multiple operators: Generalization, fairness, and the value of prediction

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ABSTRACT

Sharing wireless channel resources among cellular network operators saves cost by efficiently utilizing hardware, sites, and spectrum. To achieve high spectral efficiency, resource sharing has to adapt to the instantaneous load and channel state. However, before operators accept such dynamic scheduling policies, a solid understanding of their reliability and performance is required. In this paper, we present a consistent theoretical framework for Multi-Operator Scheduling (MOS). This formulation allows to analyze sharing guarantees and spectral efficiency for a large number of parameters and covers various fixed and dynamic resource sharing policies as special cases. Extending our study to the complete knowledge of the future channel state allows us to study the complete performance region of MOS. The proofs, analysis and simulation results in this work provide a profound understanding of the fundamental tradeoff between sharing guarantees and performance in multi-operator sharing. This insight will enable reliable yet efficient infrastructure sharing in 5G Radio Access Networks.

1. Introduction

Sharing wireless channel resources is an effective approach to reduce the costs of deployment and operation [1]. Resource sharing enables operators to increase utilization and revenue by lending parts of their spectrum to service providers. Alternatively, an infrastructure provider can lease spectrum to multiple operators, which enables statistical multiplexing gains by moderating peak load among different operators [2]. New business models may emerge, where spectrum will be traded by infrastructure providers and operators on time scales of minutes, seconds or even milliseconds [3].

Most of the sharing agreements that are in place today are static, which gives strict guarantees on the shared resource but does not allow fast renegotiation and high spectral efficiency [1,4]. To overcome this gap, resource sharing must be performed in both a controlled and efficient manner. Therefore, we introduce the concept of *dynamic sharing guarantees* to refer to the fraction of channel resources that has to be guaranteed to the users of a specific network operator over a specific time window. Defining the sharing guarantees in terms of physical resource ratio allows the system to provide definite guarantees to operators a-priori, giving them the freedom to decide how to distribute the assigned resources among their own users. In particular, sharing guarantees among operators and infrastructure providers must be held at a minimum reduction of spectral efficiency, while the high performance of dynamic resource allocation schemes with exclusive spectrum access must be kept. Moreover, the effect of resource

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sharing needs to be well understood before operators can accept this new technology. This requires approaches that are not only efficient but have a solid foundation.

To this end, we propose a concise theoretical framework for *Multi-Operator Scheduling (MOS)* in this paper. By dynamically adapting to channel and load, our centralized approach maximizes the spectral efficiency for multiple operators with full control over the agreed sharing guarantees. An interesting novelty of our approach is that it can trade off sharing guarantees versus spectral efficiency. By choosing how much and for how long the sharing guarantee of an individual operator is kept, the infrastructure provider can serve operators with the guarantees and performance they need. For instance, operators serving industrial networks may require strict guarantees in terms of a fixed fraction of the wireless channel resources. On the other side, operators with best effort services may choose higher average spectral efficiency at the cost of occasionally receiving no wireless resources. While flexibly adapting to different policies, our rigorous mathematical framework assures that the degree and duration of such violation is under full control at the Base Station (BS) scheduler.

1.1. Contributions

Following the approach of centralized resource allocation, we propose a Multi-Operator Scheduling (MOS) framework that allows to trade off sharing guarantees versus spectral efficiency at the BS. Furthermore, we extend this to the more general *Anticipatory Multi-Operator Scheduling (AMOS)* problem. In particular, the contributions of the paper are:

(1) An MOS formulation that allows operators to control their sharing guarantees in terms of maximum deviation and duration for which the guarantee holds. The MOS is formulated as a convex optimization problem that can be used to implement any scheduling policy between the lower performance bound (at strict sharing guarantees) and the upper performance bound (at no guarantees).
(2) A profound understanding of how the proposed framework reacts to important parameters for infrastructure sharing: we prove monotonic behavior between the maximum deviation from an agreed sharing guarantee and the spectral efficiency, and prove that relaxing the duration constraint of sharing guarantees leads to a higher spectral efficiency with a certain probability that depends on the users' rate distribution.
(3) An extension to the more general AMOS problem: assuming perfect knowledge of future channel states allows to study the complete performance region of MOS. We prove that AMOS always improves the performance of MOS and highlight how sharing and channel prediction will affect each other.

1.2. Applications

This analysis provides us with a theoretically sound approach, which gives a deep insight in the effect of important sharing parameters on the performance. This understanding allows formulating more flexible and more efficient service agreements between infrastructure provider and operators.

Nevertheless, our approach is also practical. Based on BS schedulers, MOS can be already adopted to existing Radio Access Networks (RANs) without major architectural changes. We expect large benefits in Heterogeneous Networks (HetNets) where trading off sharing guarantees versus utility allows to cope with the highly diverse operational parameters and service requirements [5]. Although the full channel knowledge of AMOS represents a hypothetical case to study the complete performance region of MOS, limited knowledge of future channel states is known to be practical [6,7] and considered as a promising feature in future systems [8]. Recent work on this topic has shown reasonable prediction errors in the estimated channel quality [9] and performance gains in terms of spectral efficiency and packet loss [10,11]. In addition to the channel coherence time, an important factor of anticipatory channel adaptation is the time for which the prediction is assumed to stay within an acceptable error bound. We will study the requirements of MOS on this *prediction horizon* in Section 5.

An important application of MOS and AMOS with limited channel knowledge is the so-called Virtual RAN or CloudRAN. In such centralized architectures, a single "cloud" scheduler manages the wireless channel resources of multiple cells. Once resource allocation for multiple cells has been moved to "the Cloud", it is a logical next step to share these resources among multiple operators. Such joint resource management over multiple cells and multiple operators is expected to be a key driver behind cutting the costs of small cell deployments [3].

1.3. Structure

We continue our paper by summarizing related work in Section 2 and by providing a description of system model and integration in Section 3. Section 4 formalizes the MOS problem, proves its performance bounds and provides a probabilistic analysis of its utility. Section 5 introduces AMOS and extends the above analysis to this new approach. After providing detailed system models in Section 6, we verify the analytical studies for a wider range of scenarios by simulation. The paper is concluded in Section 7.

2. Related work

The centralized allocation of channel resources to multiple operators is raising more and more attention in the wireless communications community. Compared to auctioning [12] or game-theoretic approaches [13], the traditional centralized perspective provides lower computational complexity, higher analytical tractability, higher spectral efficiency, and a simpler integration into existing RAN architectures. It is, therefore, not surprising that centralized resource sharing promises a substantial reduction on operating expenses [1,14] and has been adopted for