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Performance modeling of next-generation WiFi networks☆

Antonios Michaloliakos*, Ryan Rogalin, Yonglong Zhang, Konstantinos Psounis, Giuseppe Caire

University of Southern California, Los Angeles, CA 90089 United States

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ABSTRACT

The industry is satisfying the increasing demand for wireless bandwidth by densely deploying a large number of access points which are centrally managed, e.g. enterprise WiFi networks deployed in university campuses, companies, airports etc. This “small cell” architecture is gaining traction in the cellular world as well, as witnessed by the direction in which 4G+ and 5G standardization is moving. Prior academic work in analyzing such large-scale wireless networks either uses oversimplified models for the physical layer, or ignores other important, real-world aspects of the problem, like MAC layer considerations, topology characteristics, and protocol overhead. On the other hand, for deployment purposes the industry is using on-site surveys and simulation tools which do not scale, cannot efficiently optimize the design of such a network, and do not explain why one design choice is better than another.

In this paper we introduce an analytical model which combines the realism and practicality of industrial simulation tools with the ability to scale, analyze the effect of various design parameters, and optimize the performance of real-world deployments. The model takes into account all central system parameters, including channelization, power allocation, user scheduling, load balancing, MAC, advanced PHY techniques (single and multi user MIMO as well as cooperative transmission from multiple access points), topological characteristics and protocol overhead. The accuracy of the model is verified via extensive simulations and the model is used to study a wide range of real world scenarios, providing design guidelines on the effect of various design parameters on performance.

1. Introduction

Modern wireless devices such as tablets and smartphones are pushing the demand for higher and higher wireless data rates while causing significant stress to existing wireless networks. While successive generations of wireless standards achieve continuous improvement, it is the general understanding of both academic research and the industry that a significant increase in wireless traffic demand can be met only by a dramatically denser spectrum reuse, i.e., by deploying more base stations/access points per square kilometer, coupled with advanced physical (PHY) layer techniques to reduce inter-cell interference.

Enterprise WiFi networks have been deployed following this paradigm for years. As a matter of fact, the density of access points (APs) has increased to a point where inter-cell interference is canceling any additional gains from even denser deployments. At the same time, advanced physical layer techniques have been incorporated into the standards, most notably single-user MIMO in 802.11n and multi-user MIMO in 802.11ac. Cellular networks, unable to satisfy the bandwidth demand of data plans, resort to WiFi offloading, i.e. they deploy WiFi networks to offload traffic from the cellular network. Future cellular network architectures will most likely follow a similar pattern, that is, they will consist of many small cells densely deployed and use advanced physical layer techniques, e.g. massive MIMO.

The industry has responded to the need to efficiently manage such networks with tools that are mostly based on on-site measurements, simulations, and over-simplistic analytical models. Based on the available public information about such tools in the enterprise WiFi market [1,2], these tools perform three main operations: (i) user load balancing among APs, (ii) interference management between APs by channel allocation and power control, and (iii) optimization of the Clear Channel Assessment (CCA) CSMA threshold to allow for concurrent transmissions which can tolerate interference from nearby APs. While such network management tools have increased the performance of enterprise WiFi networks, they do not scale well, cannot be used to efficiently optimize the

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* Corresponding author.
E-mail address: michalol@usc.edu (A. Michaloliakos).

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system, and do not incorporate the effects of advanced physical layer techniques.

In this paper, we introduce an accurate and practical analytical model which takes into consideration all the important parameters affecting the performance of present and future wireless networks, and can be efficiently used in real-world setups. Specifically, we model and investigate the performance impact of physical layer features such as channelization, power allocation, topological characteristics (e.g. user density and AP distribution in various buildings/structures) and physical layer techniques like single-user (SU), multi-user (MU), and coordinated MU-MIMO [3,4] (where a number of remote APs coordinate and transmit concurrently and jointly to multiple users). Additionally, we model the performance impact of MAC and higher layer features such as user-AP association, MAC parametrization and adaptive coding/modulation.

Our main contributions are the following. We introduce and validate through simulations the first (to the best of our knowledge) analytical model which can be applied in real-world scenarios while taking into account all the important design parameters in the PHY, MAC and higher layers. Second, we include in the model next generation wireless networking technologies such as MU-MIMO and coordinated MU-MIMO for which there is currently no clear understanding of large scale network performance. Third, we apply the model to a variety of real world scenarios, including conference halls, office buildings, open spaces, large stadiums, etc., and study a number of important phenomena (see Section 5 for a detailed discussion). It is important to note that as of today there are no existing 3rd party simulators which support advanced PHY layer techniques like MU-MIMO and coordinated MU-MIMO, and no software defined radio testbeds supporting both MU-MIMO and WiFi, neither in the industry nor in academia.[1] Thus, our analytical model is, at the moment, the only way to study the performance of large scale WiFi networks utilizing advanced PHY layer techniques.

The outline of the paper is as follows. In the next section we discuss related work. Section 3 motivates and describes a unified analytic treatment of wireless network deployments consisting of an analytical model for various current and next generation PHY layer schemes as well as for the CSMA MAC. The validation and limitations of our model are studied via extensive simulations for tractable scenarios of interest in Section 4. Finally Section 5 applies the analytic model in various deployment scenarios of interest like conference halls, open and closed office floor plans and stadiums.

2. Related work

Traditional 802.11 analysis. When it comes to analyzing wireless network deployments, the wireless networking community has focused on the MAC layer and has generally ignored the PHY layer. Specifically, early work of Bianchi [5] on 802.11 MAC layer proposed an analytical model to analyze CSMA/CA overhead and performance. Meanwhile in [6] the authors investigated the performance of exponential backoff mechanism in terms of throughput and delay. In [7–10] similar Markov Chain models of CSMA/CA have been developed and employed to develop algorithms optimizing various performance metrics. Stochastic geometry approaches have been also used to model CSMA networks, using appropriate point processes (see [11,12] and references therein). Finally, in our own previous works [13,14], a full analytic model for computing the achievable rate region of CSMA in multi hop wireless networks has been presented. These works are mostly based on pure upper layer modeling and do not take the advances of physical layer into account.

Random matrix theory approaches. There are two main trends the wireless communication literature follows in analyzing wireless network deployments. The first makes use of techniques based on random matrix theory to extract performance measures (such as achievable rates, SINRs etc.) that are used with combinatorial and convex optimization methods to solve problems that appear in multi-cell wireless networks. Such problems include but are not limited to: finding the optimal achievable rates under power control, massive MIMO system asymptotics, base station cooperation towards a coordinated MU-MIMO solution and more as can be found in prior work of ours [15–17] and others [18–23]. These works exhibit similarities to our work on the basis that we also adopt random matrix theory results and techniques to come up with analytically tractable PHY layer performance models. On the other hand our work differs from the aforementioned approaches because we use the analytically tractable models in combination with an accurate MAC layer approximation, to compare the various forthcoming WiFi technologies, and examine their applicability and efficiency under various use cases and MAC layer parameters.

Stochastic geometry approaches. The second approach is based on stochastic geometry and focuses on the random placement of APs and users according to some stochastic point process (see for example [24,25] and references therein). Most of these works do not consider advanced interference management schemes at the PHY layer since they introduce statistical dependence between the nodes, and this would break the independence on which most of these results are based. Recent progress has been made to model more advanced PHY schemes such as MU-MIMO [26,27], AP cooperation [28,29] and multi-cell coordination [30,31] using a stochastic geometry analysis, however these works are limited to non-coherent AP cooperation (also called single-user joint transmission) [29] or pairwise only coherent joint transmission [28]. In other words, the performance of full coherent coordination of a large number of APs serving concurrently users is not being captured in these works, although it is one of the most promising forthcoming PHY layer technologies. In contrast, our approach applies also to large coherent cooperative clusters of APs and that can serve multiple users simultaneously. Moreover, although stochastic geometry methodologies can give important insights for the average behavior of a network, they cannot encompass a specific AP/user placement topology since they analyze performance over network ensembles with certain distributions and densities.

Advanced PHY layer comparisons. Recent papers have taken steps towards comparing advanced PHY layer techniques, but lack the analytic simplicity of the model we proposed in this work. In [32] the authors compare a traditional Wi-Fi network with advanced cooperative cellular networks (coordinated MU-MIMO), they resort however to standard Monte Carlo simulation based approaches and fail to address the adoption of MU-MIMO in future Wi-Fi networks. In [33] the authors compare dense station deployments against coordinated approaches but only incorporate PHY layer characteristic and no MAC is included in the model. Moreover, they also rely on Monte Carlo Simulations over both the topology and the channels. In contrast, we propose a simple analytic approach based on random matrix theory that incorporates PHY layer advances in a single PHY/MAC layer model and accounts for a variety of network design choices. This approach allows for very accurate deterministic approximations of the users' peak link rates for a given geometry of the network.

Industry tools. Lastly, there are a number of tools that the industry currently uses for wireless network deployment guidance. For example, Fluke Networks has developed a product [34] which creates a model for the wireless environment so that an

[1] MU-MIMO enabled WiFi chipsets are expected to become available soon, but such chipsets can't be used in a coordinated MU-MIMO setup and come with the usual limitations of non-programmable hardware when it comes to experimentation.