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Cell-level modeling of IEEE 802.11 WLANs ☆,☆☆

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ABSTRACT

We develop a scalable *cell-level* analytical model for multi-cell infrastructure IEEE 802.11 WLANs under a so-called Pairwise Binary Dependence (PBD) condition. The PBD condition is a geometric property under which the relative locations of the nodes inside a cell do not matter and the network is free of *hidden nodes*. For a given number of cells, the computational complexity of our cell-level model remains constant even if the number of nodes per cell increases. For the cases of saturated nodes and TCP-controlled long-file downloads, we provide accurate predictions of cell throughputs. Similar to Bonald et al. (Sigmetrics, 2008), we model a multi-cell WLAN under short-file downloads as "a network of processor-sharing queues with state-dependent service rates." Whereas the state-dependent service rates proposed by Bonald et al. are based only on the *number* of contending neighbors, we employ state-dependent service rates that incorporate the impact of the overall *topology* of the network. We propose an *effective service rate approximation* technique and obtain good approximations for the *mean flow transfer delay* in each cell. For TCP-controlled downloads where the Access Points (APs) transmit for a much larger fraction of time than the stations (STAs), we consider the case when the APs can sense all the nodes in the neighboring cell, but ≈50% of the STAs in each cell can sense only a subset of STAs in the other cell. Our cell-level model can predict the throughputs quite accurately in this case as well even though the PBD condition does not strictly hold.

1. Introduction

With widespread deployment of WiFi networks (or, more formally, IEEE 802.11 networks) in office buildings, university campuses, homes, hotels, airports and other public places, it has become very important to understand the performance of Wireless Local Area Networks (WLANs) that are based on the IEEE 802.11 standard, and also to know how to effectively design, deploy and manage them.

The IEEE 802.11 standard [2] provides two modes of operation, namely, the ad hoc mode and the *infrastructure* mode. Commercial and enterprise WLANs usually operate in the infrastructure mode. An infrastructure WLAN contains one or more Access Points (APs) which provide service to a set of users or client stations (STAs). Every STA in the WLAN associates iself with exactly one AP. Each AP, along with its associated STAs, constitutes a so-called *cell*. Each cell operates on a specific channel. Cells that operate on the same channel are called *co-channel*. We call a WLAN containing multiple APs a *multi-cell* WLAN.

☆ This paper is an extended version of our earlier work [1]. In this paper, we extend our analytical model in [1] to TCP-controlled short-file downloads, characterize the associated service process, and provide approximations for the mean flow-transfer delays. We also demonstrate the applicability of our analytical model when the "PBD condition" does not strictly hold.

☆☆ Much of the research work for this paper was carried out when the first author was affiliated with the Indian Institute of Science Bangalore.

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In a multi-cell infrastructure WLAN, the APs are usually connected among themselves and to the Internet by a high-speed *wireline* Local Area Network (LAN), e.g., a Gigabit Ethernet. The STAs, on the other hand, access the Internet *only through their respective APs*. Thus, the 802.11 MAC protocol is employed only for *single-hop intra-cell* frame exchanges between an AP and its associated STAs (and not among the APs and/or STAs belonging to different cells). Fig. 1 depicts an example of such a multi-cell WLAN.

This paper is concerned with analytical modeling of infrastructure WLANs (such as in Fig. 1) that are based on the Distributed Coordination Function (DCF) Medium Access Control (MAC) protocol as defined in the IEEE 802.11 standard [2]. Analytical modeling can provide important insights to effectively design, deploy and manage the WLANs. However, accurate analytical modeling of multi-cell WLANs is a challenging problem. Nodes (i.e. AP or STA) in two closely located co-channel cells can suppress each other's transmissions via carrier sensing and interfere with each other's receptions causing packet losses. Thus, the activities of the nodes in proximal co-channel cells are essentially coupled, which makes the analytical modeling difficult.

1.1. Literature survey

The seminal analytical model for *single cell* WLANs was developed in [3], and later generalized in [4]. In a single cell, nodes can sense and decode each other's transmissions. Thus, nodes in a single cell have the same *global* view of the activities on the common medium. Nodes in a multi-cell WLAN, however, can have different *local* views of the network activity around themselves, and their own activity is determined by this local view.

In the context of multi-hop ad hoc networks (see Fig. 2), *node-* and *link-level* models have been proposed to capture

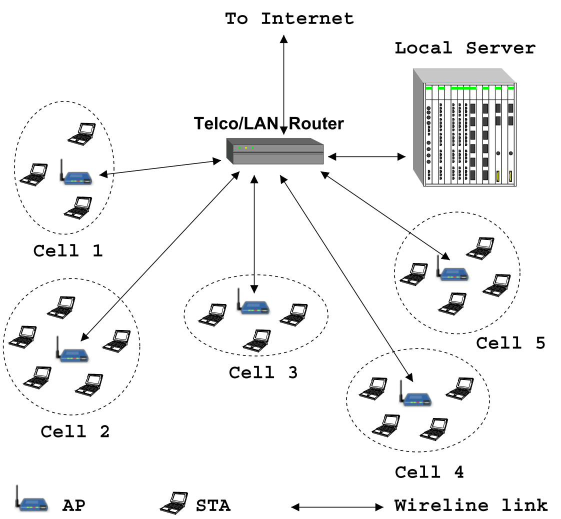

Fig. 1. A multi-cell infrastructure WLAN: The 802.11 MAC protocol is employed only for single-hop intra-cell frame exchanges within the cells (shown by dashed ovals). A high-speed wireline LAN connects the APs and provides access to the Internet.

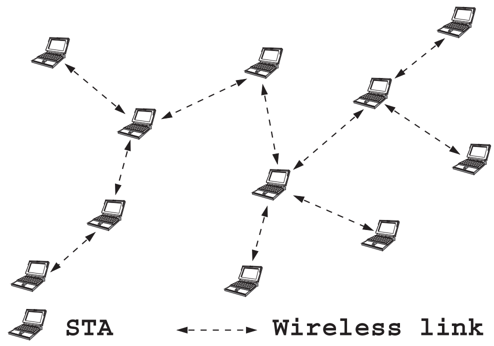

Fig. 2. A multi-hop ad hoc WLAN.

the *local* characteristics of network activities [5–7]. However, for networks of realistic size, a node- or link-level model is intractable, since its complexity increases exponentially with the number of nodes or links [8].

Since a node- or link-level model is often intractable and provides little insight, several simplifying assumptions have been made in order to gain insights. A common simplification is to ignore collisions due to *hidden nodes* by assuming that hidden nodes are suppressed either via RTS/CTS handshaking [9,10], or via a so-called "hidden-node-free design" [11–14]. Another simplification is to assume an infinite number of nodes placed according to either some regular topology [9] or a regular point process [15]. The performance analysis of a single-AP WLAN in presence of hidden nodes has been reported in [16–18].

TCP-controlled data transfers are usually classified into two types: (i) *long-lived* flows (e.g., file transfer), and (ii) *short-lived* flows (e.g., web browsing). The case of long-lived flows in a single isolated cell has been analyzed in [19,20]. A single isolated cell with short-lived flows was modeled as "a processor-sharing queue with state-dependent service rates" in [21,22]. The seminal papers by Bonald et al. provide the most comprehensive treatment of multi-cell networks with short-lived flows, both for cellular data networks [23] as well as for 802.11-based WLANs [10]. In [10] the authors model a multi-cell infrastructure WLAN under short-lived downloads as a "network of *multi-class* processor-sharing queues with state-dependent service rates."

1.2. Our contributions

To accurately model a multi-cell infrastructure WLAN, one needs to account for the node- and link-level interactions, as in the case of multi-hop ad hoc networks. However, comparing Figs. 1 and 2, we observe the following key differences:

- The ad hoc WLAN does not possess any specific structure (topology). However, the infrastructure WLAN has a nice *cellular* structure. Let R denote the *cell radius* (i.e., the maximum distance between an AP and its associated STAs) and D denote the distance between two nearest co-channel APs. For communication at high Physical layer (PHY) rate to be possible between an AP