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A scalable delay based analytical framework for CSMA/CA wireless mesh networks

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ABSTRACT

We present an analytical framework for the performance analysis of CSMA/CA based wireless mesh networks. This framework can provide an accurate throughput-delay evaluation for both saturated and unsaturated cases. An efficient algorithm that determines the collision domain for each node based on both the interference range and routing in the network is presented. As another important application of this framework, we develop an analytic model that enables us to obtain closed form expressions for delay in terms of multipath routing variables. A flow-deviation algorithm is used to derive the optimal flow over a given set of routes for any number of classes. The model takes into account the effects of neighbor interference and hidden terminals, and tools are provided to make it feasible for the performance analysis and optimization of large-scale networks. Numerical results are presented for different network topologies and compared with simulation studies.

1. Introduction

Wireless mesh networks are multi-hop access networks used to extend the coverage range of current wireless networks [1]. They are composed of mesh routers and mesh clients, and generally require gateways to access the backhaul links.

High performance, including high throughput and low delay, is required for mesh networks because they are mainly used to serve commercial and residential customers. In this paper we aim to provide a scalable analytical framework for throughput-delay analysis in wireless mesh networks and explore possible ways to improve their performance.

Like most work in this field [5,7–10,14], we focus on the effects of the medium access control (MAC) layer, the layer that has the largest difference between wired and wireless packet networks. Factors from the upper protocol layers that affect the performance are beyond the scope of this study and are not considered.

The medium access control of mesh routers can be either centrally controlled by the base station (e.g. TDMA/FDMA/CDMA), or distributively controlled by each mesh router, typically using some form of CSMA/CA protocol. Despite its inefficiencies, the CSMA/CA based IEEE 802.11 protocol dominates in mesh network applications because it is economical. For this reason, IEEE 802.11 and the more fundamental CSMA/CA protocol are the main MAC protocols studied in mesh networks, and our work presented in this paper is also based on CSMA/CA. In more detail, it is based on non-persistent CSMA studied by Kleinrock and Tobagi [12], which is the basis for current IEEE 802.11 type protocols.

Most implementations of CSMA/CA based wireless networks, including IEEE 802.11, are slotted systems with fixed size data frames. This would indicate the use of discrete models. However, an important observation made by Kleinrock and Tobagi [12] was that only the first moment of the retransmission delay distribution has an effect on the throughput-delay performance. This property allows for accurate continuous time models to be developed that avoid the difficulties of modeling cyclical behavior and synchronization found in discrete models.

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Recently, Medepalli and Tobagi [9], go so far as to show that a simple M/M/1 model can give a reasonable approximation for the throughput-delay analysis of IEEE 802.11 networks.

As pointed out by Tobagi [2], the exact throughput-delay analysis for multi-hop networks requires a large state space. For large topologies, an exact analysis is almost impossible, leading us to consider an approximate analysis. The most common approximation methods are single node based models, where each node has a view of the neighborhood characterized by a number of parameters representing the average behavior of the neighboring nodes. Parameters for all nodes are then found through an iterative process. Representative work of this type include Leiner [3], Silvester and Lee [4], Bianchi [10], Medepalli and Tobagi [9], and Garetto et al. [8]. In this paper, the analytical model we introduce is also based on a single node analysis. Interfering nodes and hidden terminals are taken into account when computing the probability that a node successfully transmits frames. However, with our analytical framework we not only provide both throughput and delay based performance evaluation, but also provide ways to improve the performance of the network, for example, by choosing the best routing paths, including multipath routing.

Multipath routing, also known as alternate path routing (APR), is an efficient way for avoiding congestion and loss in mesh networks and achieving higher capacity. By distributing traffic using different paths alternatively, the load in the network can have better balance, and thus achieve better performance [19–21].

The main contributions of this paper include: (1) A scalable model for the throughput-delay analysis of wireless mesh networks that is accurate at both saturated and unsaturated loads. The performance of each node can be analyzed in isolation based on the knowledge of interfering neighbors and hidden terminals, which has much lower complexity than methods that maintain state of the complete network. The algorithm for deciding the hidden terminals also guarantees that our method can be easily applied for networks with large topologies. (2) Under an infinite buffer assumption, the Pollaczek–Khinchin (P–K) formula is used to derive closed form expressions for the mean waiting time in terms of path flow variables, which makes it possible for optimizing the network based on multipath routing. The biggest advantage of this optimization is that the network can achieve better load balance and accommodate more traffic. A two step method is presented to provide reliable QoS for high priority traffic while guaranteeing the performance of the whole network.

The rest of this paper is organized as follows: In Section 2, we discuss related work; in Section 3 we describe the basic model and exploit the neighbor relationships to derive solutions using iterative algorithms. In Section 4, the closed form representation of delay at each node is derived and a corresponding optimization model is introduced, both for a single class and multiple classes of traffic. Examples using our method for the analysis and optimization of wireless mesh networks are shown in Section 5. Section 6 concludes this paper.

2. Related work

In the work by Leiner [3], a model of the neighborhood around each node is developed and characterized by a number of parameters representing average behavior. Parameters for all nodes are then found through an iterative process. However, in Leiner's work, single-hop models are used for the neighborhood around each node, which means that all of the interfering nodes of a certain node interfere with each other. This makes the model relatively simple, but is generally not applicable for most multi-hop networks.

In a more recent work, Carvalho and Garcia-Luna-Aceves [6] present a single node based model that takes into consideration the effects of the physical layer parameters, MAC protocol, and connectivity. However, they mainly focus on the throughput of nodes for the saturated case, and no delay based analysis is addressed. Garetto et al. [8] address fairness and starvation issues by using a single node view of the network that identifies dominating and starving flows, and accurately predicts per-flow throughput in a large-scale network. Although they also address the unsaturated load case, a delay based analysis is not included. Cali et al. [14] used a *p*-persistent CSMA mechanism instead of binary exponential backoff (BEB) to model the backoff behavior in IEEE 802.11 LANs. They discovered ways to maximize the throughput by finding the optimal contention window size for backoff.

The work of Medepalli and Tobagi [9] is based on the framework of Bianchi's work [10] with IEEE 802.11 Distributed Coordination Function (DCF). They extend Bianchi's work to include multi-hop networks, attacking the unsaturated load situation, and providing a delay based analysis using an *M/M/1* assumption. Their computing complexity is also low due to the use of a single node based analysis. However, no closed form about delay is presented in their work, thus making delay based optimization impossible.

The work of Boorstyn et al. on node group based decomposition [5] is another representative approach for the performance analysis of CSMA/CA based multi-hop networks. Wang and Kar [7] basically use the same framework, but extend it to more complex MAC protocols by considering RTS/CTS exchange, and study fairness issues. Their main contribution is that large networks can be decomposed into smaller groups, called "independent sets", consisting of nodes that can transmit simultaneously. Markov chains are then built for those "independent sets" and product form solutions for steady state are obtained. The need to compute all possible independent sets in the network makes the complexity of the algorithm prohibitive. Furthermore, this method can only be used for throughput and fairness analysis when the system is saturated, so a delay analysis is not provided.

It is worthy to mention that, although applying the idea of "independent set" to the analysis of the whole network is formidable, it is profitable to use it for neighboring nodes around a certain node. This technique was used by Garetto et al. [8].

With respect to multipath routing in multi-hop networks, work appearing in the literature include Hass