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Fair packet scheduling in Wireless Mesh Networks

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ABSTRACT

In this paper we study the interactions of TCP and IEEE 802.11 MAC in Wireless Mesh Networks (WMNs). We use a Markov chain to capture the behavior of TCP sessions, particularly the impact on network throughput due to the effect of queue utilization and packet relaying. A closed form solution is derived to numerically determine the throughput. Based on the developed model, we propose a distributed MAC protocol called Timestamp-ordered MAC (TMAC), aiming to alleviate the unfairness problem in WMNs. TMAC extends CSMA/CA by scheduling data packets based on their age. Prior to transmitting a data packet, a transmitter broadcasts a request control message appended with a timestamp to a selected list of neighbors. It can proceed with the transmission only if it receives a sufficient number of grant control messages from these neighbors. A grant message indicates that the associated data packet has the lowest timestamp of all the packets pending transmission at the local transmit queue. We demonstrate that a loose ordering of timestamps among neighboring nodes is sufficient for enforcing local fairness, subsequently leading to flow rate fairness in a multi-hop WMN. We show that TMAC can be implemented using the control frames in IEEE 802.11, and thus can be easily integrated in existing 802.11-based WMNs. Our simulation results show that TMAC achieves excellent resource allocation fairness while maintaining over 90% of maximum link capacity across a large number of topologies.

1. Introduction

Wireless Mesh Networks (WMNs) have been proposed as a low-cost alternative for last mile access [1]. These dynamic, multi-hop networks can be built with commodity hardware (including off-the-shelf IEEE 802.11 radios) and open source software. A typical WMN is composed of distributed Mesh Points (MPs) that form a multi-hop backhaul. MPs may connect with multiple other MPs within their radio range. Some MPs have a wired back-channel to the public Internet; these act as gateway nodes and bridge traffic between the WMN and the Internet. End-users often communicate with their closest MP to access the Internet.

Multi-hop wireless networks, including WMNs, exhibit flow rate unfairness among competing nodes [2–4]. With backlogged traffic, the impact of flow unfairness can be significant and can lead to starvation for flows two or more hops away from the gateway. This problem is observed even with TCP, which is designed for fair allocation of network resources. A better understanding of the interaction between TCP congestion control algorithm and IEEE 802.11 MAC in a WMN is important to address the fairness problem. An analytical model that successfully predicts TCP flow characteristics can isolate the causes of such performance degradation. However, this is a challenging task since multi-hop wireless networks are subject to losses from collisions as well as random channel noise, which may eventually degenerate to the point of starvation.

In this paper we propose an analytical model that captures the behavior of competing TCP flows in a

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802.11-based WMN. Our model uses the cumulative number of TCP data packets in the network for a given TCP flow. These are the packets generated by that flow but not yet delivered to the destination. At any given time, these packets are distributed over various queues along the path between the source and destination. For simplicity, we model the network as a closed system where the state of a flow is represented by the cumulative number of data packets existing in the network for a particular flow (called the cumulative network queue). Furthermore, our model uses the number of transmissions required by a particular flow from the perspective of the gateway (called the transmission step). Since transmissions beyond the carrier sense range of the gateway can be made concurrently while the gateway is transmitting, the transmission step for the majority of the nodes in a network varies between 1 and 3.

In this paper we improve flow rate fairness by proposing a new MAC scheduling protocol, called Timestamp-ordered MAC (TMAC). TMAC addresses the fairness and throughput degradation in WMNs using the age of a packet as a metric for prioritizing its scheduling. TMAC is based on the mutual exclusion algorithm of Lamport [5]. Lamport algorithm uses request timestamps to ensure that the node with the earliest request is served next. The algorithm relies on an explicit exchange of control messages to make all nodes aware of the network state. These communication requirements are more suited for fully-connected wired networks, but may scale poorly in large WMNs. TMAC addresses these challenges by limiting the exchange of these control messages to a set of neighboring nodes that contend for channel access. It improves fairness by prioritizing the transmission of packets that are generated before others (i.e., have a larger age). We show that for backlogged TCP flows, scheduling packets according to their age when coupled with a specialized queuing discipline results in absolute[1] flow rate fairness.

The remainder of this paper is organized as follows: We provide an overview of the related work in Section 2. Our proposed model is described in Section 3, including a discussion of the causes of unfairness. In Section 4, we introduce TMAC and describe its various functional blocks. In Section 5, we describe the design challenges in implementing TMAC over 802.11 radios and propose optimizations for improving its behavior. We validate our model in Section 6. Furthermore, we present a simulation study of performance analysis of TMAC. We conclude with a discussion and a summary in Section 7.

2. Related work

There has been a significant amount of research on modeling wireless links characteristics. This includes models for describing the detailed behavior of random access protocols in wireless networks [6,7]. These studies, however, assume that all nodes are fully aware of the network state, which is only feasible in the presence of additional signaling mechanisms on top of a distributed 802.11 WMN. Multi-hop wireless network models have also been proposed in [8,9,2]. These models capture the MAC protocol interactions by assuming a connection-less backlogged traffic. Other models account for TCP traffic by considering the impact of an extra flow caused by the acknowledgment (ACK) packets. However, rather than capturing the interaction of TCP and MAC, these studies model the aftermath of these interactions. Some previously proposed models capture the interaction of MAC and TCP in wireless networks [10,11]. We are mainly interested in the objective of [11], where the effect of multi-hop relaying and TCP data/ACK packets exchange are explicitly modeled. However, the work in [11] only considers a two-hop chain topology with a single flow with a conservative choice of TCP congestion window. The intractability of this limits its analysis to more reasonable multi-hop scenarios. However, in this paper, we focus on larger WMNs topologies with a larger number of flows. Thus, we maintain the objective of the work in [11–13] with a more tractable model that is applicable to complex scenarios.

A number of proposals modify the conventional backoff scheme to incorporate fairness or other objectives [14–16]. For example, some work modify the backoff scheme to achieve service differentiation and prioritization [17,18]. In general, a transmission with a higher priority is assigned a lower MAC contention window, and vice versa. DFS [16] is an example of a protocol using backoff prioritization with a fairness objective. It is a fully distributed protocol that tries to emulate the centralized SCFQ [19]. The priority of a transmission is dependent on a timestamp associated with the corresponding packet. The authors postulate that giving higher priorities to lower finish timestamps will lead to SCFQ fairness. To translate that objective to an appropriate backoff assignment mechanism, they proposed several schemes to map finish timestamps to backoff intervals. The simplest one is a linear scheme that is inversely proportional to the flow weight and transmission priority. Linear mapping can lead to large backoff intervals, thus leading to lower utilization of the channel. To overcome this limitation they also proposed exponential and adaptive mappings. Another example of achieving a fairness objective through backoff manipulation is in [14]. The authors propose a distributed algorithm that first estimates the fair share of medium access without global knowledge, and then assigns backoff intervals according to the estimated fair share. Manipulating parameters other than backoff interval can also be used as means to achieve fairness objectives. Such parameters are the inter-frame spacing periods (IFS), slot size, etc. These parameters are used to achieve prioritization and service differentiation [20], and can further be manipulated to lead to fairness.

There are many distributed protocols designed to achieve fairness in wireless networks [16,21–23,14], including WMNs [2,24]. Most of the proposed schemes achieve fairness by limiting flow rates to the fair share of the network capacity. This requires actively maintaining network global state and flow synchronization among distributed nodes. The proposed TMAC protocol, on the other hand, does not estimate the fair rate for each flow. Instead, it establishes priority scheduling for transmitting data packets at each node according to the local condition.

[1] Absolute fairness is the equal distribution of resources among competing nodes.