TMAC: Timestamp-Ordered MAC Protocol for Wireless Mesh Networks

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ABSTRACT

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Wireless Mesh Networks (WMNs) have emerged to meet a need for a self-organized and self-configured multi-hop wireless network infrastructure. Low cost infrastructure and ease of deployment have made WMNs an attractive technology for last mile access. However, 802.11 based WMNs are subject to serious fairness issues. With backlogged TCP traffic, nodes which are two or more hops away from the gateway are subject to starvation, while the one-hop away node saturates the channel with its own local traffic. We study the interactions of TCP and IEEE 802.11 MAC in WMNs to aid us in understanding and overcoming the unfairness problem. We propose a Markov chain to capture the behavior of TCP sessions, particularly the impact on network throughput performance due to the effect of queue utilization and packet relaying. A closed form solution is derived to numerically derive 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 via a manipulative per-node scheduling mechanism which takes advantage of the age of each packet as a priority metric. Simulation is conducted to validate our model and to illustrate the fairness characteristics of TMAC. Our results show that TMAC achieves excellent resource allocation fairness while maintaining above 90% of maximum link capacity in parking lot and large grid topologies. Our work illuminates the factors affecting TCP fairness in WMNs. Our theoretical and empirical findings can be used in future research to develop more fairness-aware protocols for WMNs.

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Chapter I

Introduction and preview

I.1 Background

The past decade has witnessed an increased demand for ubiquitous anytime, anywhere Internet access. Wireless technologies provide an opportunity to satisfy these demands. The wireless revolution encompasses technologies such as Wi-Fi, cellular telephony, Global Positioning Systems (GPS), Wireless Sensor Networks (WSNs), Bluetooth, and many more. Wireless data networks in particular hold a special place in this revolution. It is one of Friedman's world flattening (*i.e.*, globalization) steroids in his visionary book, *The World is Flat* [28].

Wireless networks are under rapid deployment in public locations. Users armed with laptops, tablets, and smart phones expect to find Wi-Fi hotspots in airports, hotels, and coffee places. As a result, the utilization of such wireless networks is increasing dramatically. It is thus necessary to rethink wireless networks infrastructure in order to deliver mobility and flexibility to end-users. This must be done while maintaining ease of deployment and management, and cost effectiveness to service providers.

Wireless Mesh Networks (WMNs) mark a promising technology to help achieve anywhere/anytime connectivity. A WMN consists of *gateways* that connect the mesh

to an external network, *Mesh Points* (MPs) which form the mesh backbone, and *mesh clients* that generate the traffic in the mesh. WMNs could be deployed to provide last-mile access to end-users. WMNs can be built from simple, cheap, and widely available commodity devices. These networks are designed to be self-configuring. These properties make WMNs an attractive option for Internet providers and rural network deployments.

I.2 Overview of the research problem

WMNs have a number of open and interesting research challenges. In this thesis we focus on the fairness challenge. It was demonstrated that 802.11-based WMNs exhibit significant flow rate unfairness [31, 43, 45]. For example, it is shown in [31] that MPs one-hop away from the gateway saturate the channel, while MPs two or more hops away suffer from significant unfairness or starvation.

There has been a lot of work in the literature on the topic of resource allocation in wired networks. However, the wireless environment is substantially different from its wired counterpart. One fundamental issue that needs to be carefully considered is that the wireless channel is a shared medium between all contending neighbors. Another issue in WMNs is their multi-hop nature. These two traits of WMNs open new challenges for traditional algorithms. These challenges affect the performance of higher layers producing results such as flow rate unfairness that we address in this thesis.

I.3 Research method and goals

In this thesis we tackle the fairness problem of TCP over WMNs by proposing MAC layer modifications. We study the interaction of TCP and MAC in WMNs. A Markov chain is used to model this interaction. We show that fairness characteristics are

affected and degraded by the difference in hop count and TCP congestion window of flows. Our goal is to deliver a design of a timestamp-ordered scheduling extension to IEEE 802.11 (802.11) that overcomes starvation and unfairness, while preserving the distributed nature of 802.11.

We start with modeling the interaction of TCP and 802.11 MAC. The fairness characteristics are then analyzed and factors affecting it are extracted. After theoretically analyzing the causes of unfairness, a timestamp-ordered scheduling algorithm is designed. The idea behind our work is to achieve fairness by priority scheduling. The priority of a transmission is proportional to the age of the packet in the head of the queue. Thus, the node hosting the oldest packet (*e.g.*, with the lowest timestamp) will be eligible to transmit. We provide a detailed algorithm to achieve this type of scheduling in WMNs. Finally, we show possible ways of deploying the algorithm in the existing network stack as an extension to 802.11.

I.4 Thesis preview

The rest of the thesis is organized as follows. Chapter II provides an overview of the general background necessary for this thesis. We provide a review of WMNs, and briefly discuss various challenges in WMN design. Then, we discuss the fairness notion and the models we used to evaluate the fairness of obtained results. We then provide an overview of the history and developments of MAC protocols in the wireless domain.

Our mathematical study is presented in Chapter III. A Markov chain is proposed to model the interaction between TCP and 802.11. We use this to extract the fairness characteristics of flows in WMNs. A closed form solution of our model is then derived.

In Chapter IV we describe our scheduling algorithm. We start with discussing the motivation behind TMAC. The factors of unfairness are derived from the model and general guidelines to overcome them by a distributed MAC protocol are presented.

Then, we present an informal description of the algorithm. Afterwards, the detailed design of TMAC is presented followed by a description of extending 802.11 to support TMAC scheduling. The chapter concludes with a discussion on signaling and ordering overhead, appended with proposed optimization techniques.

Performance analysis is presented in Chapter V. Our results validate our proposed model and confirm the fairness of TMAC.

The thesis concludes in Chapter VI with a summary and directions for future research.

Chapter II

Background

In this chapter we will provide the essential background for the rest of this thesis. We discuss the concept and significance of WMNs and also provide an overview of their performance challenges. Then, we present related fairness models and metrics. A comprehensive overview of MAC layer in wireless networks is provided. The chapter concludes with an overview of the framework and assumptions used in this work.

II.1 Wireless Mesh Networks

WMNs, also known as wireless multi-hop ad-hoc networks, exhibit a hierarchical distribution of nodes based on their role in the network. WMNs encompasses only a constrained set of requirements imposed on general ad hoc networks. One key requirement of WMNs providing Internet backhaul access is efficient network performance. Existing wireless MAC schemes scale poorly in a multi-hop environment with a large number of nodes. Addressing these challenges is necessary for successful large scale deployments of WMNs.

Nodes in WMNs are classified into three types. Gateways, also called MP Portals (MPPs), provide a means for integrating WMNs with other networks, *e.g.*, the Internet. Gateways in WMNs constitute a small percentage of the whole network and

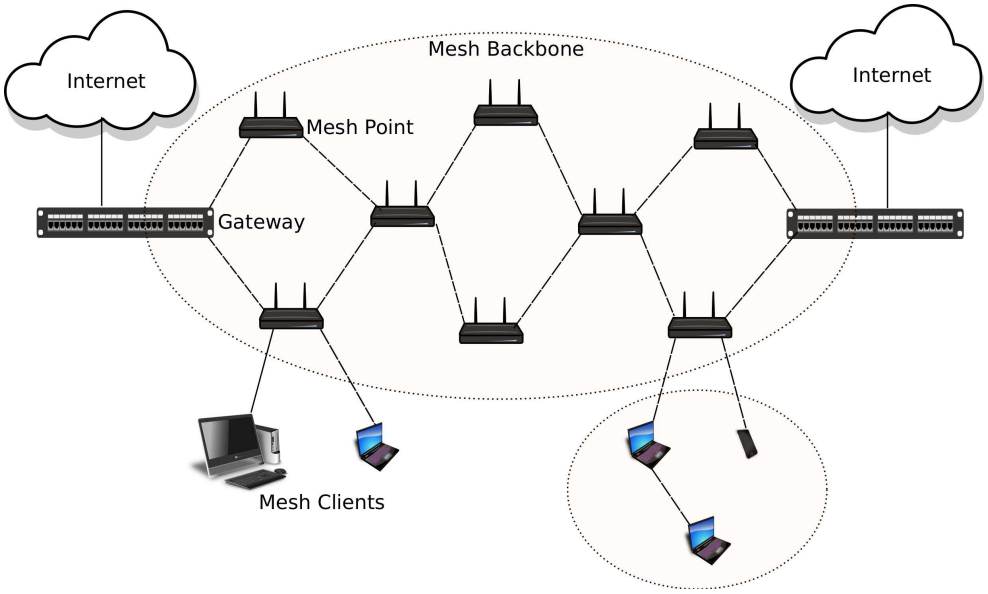

Figure II.1: An example of a WMN. Shown are two gateways, eight MPs, and five mesh clients. One mesh client has MP capabilities and is relaying another client's traffic.

act as sinks for most, if not all, traffic. Mesh routers, also called MPs, are part of WMNs backbone. MPs are responsible for relaying/forwarding traffic to and from gateways. Also, MPs are usually static and can contain enhanced hardware and operation functionality. Mesh clients are end-users of WMNs. Mesh clients can be mobile or stationary. Mesh network operators have little control on clients' devices. Some mesh clients may perform MP operations if they have the necessary capabilities. An example scenario of a WMN is depicted in Figure II.1.

II.1.1 Classification

In the literature, the functionality differentiation between MPs and mesh clients are not strictly defined. Therefore, existing WMNs can be classified into the following three architectures [12]:

- *Infrastructure WMNs*: MPs form a backbone for mesh clients, by providing the routing and self-configuration capabilities. MPs typically have advanced

hardware, *e.g.*, multi-radio MPs, where some radios are used for backhaul communication, and the other radios are used to communicate with mesh clients. With static MPs, the multi-hop backhaul operation may be further optimized using radio techniques such as directional antennas [68] and MIMO (Multiple-Input and Multiple-Output) systems [75].

- *Client WMNs*: The hierarchical structure in Figure II.1 may be simplified by removing MPs. Mobile mesh clients dynamically discover other mesh clients and relay/forward the traffic. Such network can be dynamically created without initial planning or configuration. However, this architecture has many limitations. Since no MPs exist in the WMN, end-users need to have routing and self-configuration and management capabilities.

- *Hybrid WMNs*: Hybrid WMNs combine the benefits of infrastructure and client meshing. It consists of a wireless mesh backbone. However, mesh clients can become a part of the backbone.

II.1.2 Standardization

802.11 [2] is a set of Wireless Local Area Networks (WLAN) standards. These include 802.11b and 802.11a/g which define MAC and PHY specifications for 11Mbps and 54Mbps wireless link rates respectively. More recent technologies like 802.11n can support maximum data rates up to 600Mbps. 802.11 radios are inexpensive off-the-shelf hardware. They operate in a license-exempt frequency band, allowing them to work anywhere around the world. These features made 802.11 radios an attractive framework to develop WMN solutions. Many universities use 802.11 radios for their testbeds, such as MIT's *Roofnet* [6] and Rice's *TFA* [16].

A new standardization effort is now being made by task group 802.11s [20]. The purpose of the 802.11s group is to define PHY and MAC layers for WMNs. This

includes tackling problems like QoS, security, routing protocols, etc. Support for draft 802.11s is now available in Linux kernel and BSD systems. Other task groups within IEEE are also working on WMNs enhancements, such as task groups within IEEE 802.15 (Wireless Personal Area Networks) and IEEE 802.16 (Wireless Metropolitan Area Networks) [3].

II.1.3 Applications

The main motivation behind developing any new technology is its real world applications. WMNs are no exception. Some of these applications are:

- *Community networking*: These are networks used in local communities to provide services such as free Internet access. Self-configuration and management of WMNs will help overcome the problems of traditional last-mile wireless access deployments, such as variation in wireless coverage, and overhead of network maintenance. Work in [40] is an example of a real deployment of community networking. In it, a community network was deployed in a rural area to provide better Internet connectivity. Another well known example of community networks is the *one laptop per child* project [56].

- *Transportation Systems*: An interesting application of WMNs is to extend it to transportation systems. WMNs will provide a medium for providing intelligence to transportation systems in the form of driver communications, monitoring, and information systems. Portsmouth real-time travel information system, named Portsmouth Online Real Time Traveler (PORTAL) [5], is an example of such deployment. PORTAL provides information for bus passengers in Portsmouth.

II.1.4 Challenges

It is widely known that the performance of WMNs is highly dependent on the link configuration and deployed protocols. WMN challenges appear in each layer. In this section, we focus our attention on network, transport, and MAC layers.

Network layer

User mobility-aware routing is an essential and unique feature in WMNs. Due to the stringent demand for many emerging online multimedia services such as VoIP, video conferencing, and gaming, the events of user handover and roaming are expected to appear much more frequently with a stringent delay requirement. Despite the fact that there are several proposed routing protocols for supporting mobility in WMNs such as multi-radio, multi-path, hierarchical, and geographic routing protocols, we believe that the optimal routing protocol should capture the following characteristics: it should guarantee a multi-performance metric in order to be scalable, robust, and efficient in WMN infrastructures. There are several proposed routing protocols suggested in wireless ad-hoc networks that can be slightly modified to operate in WMNs. For example, DSR [46], DSDV [65], and many others have been proposed for stateless wireless network topologies. However, none of the proposed routing protocols fully addresses the requirements of WMNs under an operational environment.

Transport layer

WMNs carry a mix of both real-time and non-real-time traffic. Thus, a number of transport protocols are required to perform well in WMNs. The Internet is dominated by TCP traffic. It is thus natural to study the behavior of TCP over wireless multi-hop networks [29, 31, 34, 50, 67, 81]. These work demonstrate the main causes of TCP's performance degradation over wireless networks. Non-congestion losses resulting from *lossy* wireless links, mobility, and link failures might trigger TCP congestion

avoidance mechanisms inopportunely. Another cause is the bias of TCP to reward connections with smaller RTT (Round Trip Time). In WMNs, nodes closer to the gateway have smaller RTT, subsequently they are favored over farther nodes. Finally, TCP cumulative acknowledgments lead to bursty traffic. These bursts may cause higher queue delays and subsequent packet drops.

Transport layer solutions can be categorized as, *end-to-end* solutions and *link-layer* solutions [15]. End-to-end solutions are in the form of modifications to existing TCP protocols. Since TCP was tuned for wired networks, these modifications try to add awareness of wireless and multi-hop links [10, 25, 26]. Link layer solutions are deployed in the wireless nodes only [13, 14, 54], hence end users in the other part of the connection are not affected. One class of solutions propose isolating the wireless network from the larger Internet [13, 14]. Thus, anomalies caused by wireless links are absorbed locally without the awareness of end hosts. In [14], for example, each connection is *split* into two connections, one between the wireless node and the gateway, and another between the gateway and the fixed end user. Another class of solutions take advantage of TCP's control exchange to change the behavior of end hosts by *spoofing* or modifying parameters of TCP packets. One way is to control TCP's congestion window (cwnd) size [54] by modifying the corresponding header parameters. Since cwnd value represents the amount of segments in transit, controlling it allows regulating queue utilization and throughput.

The interested reader is referred to [15, 60] for further discussion on TCP mechanisms for wireless networks.

MAC layer

In WMNs, MAC layer is concerned with single-hop and multi-hop links, multi-point-to-multi-point communication, and user mobility. There is a need to design a new distributed and collaborative scheme that ensures that network performance (*i.e.,*

throughput, delay, and delay jitter) is not affected by link variations and user mobility. We note that designing a scalable MAC for multi-hop WMNs is an open challenge. We further discuss MAC layer requirements in Section II.3.

II.2 Fairness

In networks, fairness refers to the problem of resource distribution between contending network entities. Fairness models differ considerably depending on the resources considered, system type, complexity, and fairness objectives. *Utility theory* may be used to model the level of satisfaction to a given resource allocation. This is usually captured using a utility function. Each user can have a different utility function. The objective is to maximize the *aggregate utility* of users, $\sum_{i=1}^{|N|} U_i(r_i)$, where N is the set of users, $U_i(r_i)$ is the utility function of node i given the resource r_i. The resource allocation is subject to the *feasibility constraints* [49] described by $\sum_{i=1}^{N} r_i \leq C$, given $r_i \geq 0, \forall i \in N$, where C is the resource's capacity.

The notion of fairness was made widely known in computer networks by research on TCP fairness [22]. The objective of the fairness model in TCP is to allocate resources *equally* among flows traversing a common bottleneck. Hence if C is the link capacity for a common bottleneck amongst $|N|$ flows, then each flow is allocated an average rate of $C/|N|$.

II.2.1 Fairness models

In this subsection we briefly describe the most widely used fairness models in computer networks literature. In these models the resource to be shared is the bottleneck link capacity C. We denote by r_i, the rate allocated to flow i, $i \in N$, where N is the set of flows.

Absolute fairness

Absolute fairness objective is to *equally* distribute the link capacity to contending flows.

$$r_i = r_j, \forall i, j \in N$$

$$r_i \leq \frac{C}{|N|}, \forall i \in N$$

This model is limited to the case when all flows require equal demand and belong to the same class, *i.e.*, have equivalent priority. In this thesis we focus on TCP flows with best effort delivery, hence flows with equivalent priority. Consequently, we employ this fairness objective in this thesis.

Max-Min fairness

This fairness model considers the case of flows with diverse demands or conditions. A set of flows is considered max-min fair if for each flow, the rate r_i cannot be increased without decreasing a flow rate $r_j \forall j \in \{r_j | r_j \leq r_i\}$. A max-min allocation may not exist for some networks. However, there is a unique max-min allocation if it exists.

Proportional fairness

Proportional fairness objective is to maximize the *aggregate utility*. Thus, an allocation $r_i \in (r_1, r_2, \ldots, r_{|N|})$ is proportionally fair if for any other allocation $r'_i \in (r'_1, r'_2, \ldots, r'_{|N|})$ the following relation holds:

$$\sum_{i=1}^{|N|} \frac{r'_i}{r_i} \leq |N|$$

II.2.2 Measuring fairness and allocation

In order to evaluate the fairness of scheduling algorithms, methods of measurement must be formalized. In this section we will overview fairness measuring techniques

used in the rest of the thesis.

Statistical measures

Using statistical measures is a natural way of describing fairness of resource allocation. *Population variance* (σ^2) is one way to describe fairness of resources allocation. However, it is dependent on the scale of measurements, which could lead to false conclusions when comparing two variance indexes of systems with different measuring metrics. Also, variance is not bounded, so normalizing the variance to get a sense of fairness bounds is not feasible. Another statistical measure is COV (*Coefficient of Variation*), $COV = \frac{\sigma}{\mu}$, where μ is the *population mean*. COV does not depend on scale like variance, but it is also not bounded.

Jain's fairness index

Jain's Fairness Index (JFI) [41] is a commonly used fairness index in computer networks literature. It is used as a measure of deviation from an equality state, *i.e.*, $r_i = r_j \forall i, j \in N$. Thus, it is commonly used with fairness models with an absolute fairness objective. However, even for models where entities have different allocation demands, JFI can be used by adjusting the measured allocated resources by the ratio of their demand. JFI is defined as the following:

$$JFI = \frac{(\sum_{i=1}^{|N|} r_i)^2}{|N|. \sum_{i=1}^{|N|} r_i^2} \tag{II.1}$$

JFI features several important properties:

- The index is bounded between 0 and 1, where a JFI of 1 denotes an absolute fair system.
- A system is totally unfair when one node saturates all resources. The fairness index of such a system is $\frac{1}{|N|}$. As the number of nodes tends to infinity, JFI of

a totally unfair system tends to 0, *i.e.*,

$$\lim_{|N|\to\infty} \frac{1}{|N|} = 0$$

This can be extended to the case with k entities fairly sharing the resources, while $(|N| - k)$ entities are starved. JFI in that case is $\frac{k}{|N|}$, which is an upper bound if the k entities were not sharing the resources equally.

- JFI is independent of scale. Any performance measure can be used.
- JFI is a continuous function, dependent on all measured allocations. Thus, any change in resource allocation affects the index.

These properties made JFI an attractive index to be used. JFI can be expressed by statistical measures presented earlier by the following transformation:

$$JFI = \frac{1}{1 + COV^2}$$

However, this transformation gives JFI the properties, we discussed above, that distinguish it from other statistical measures.

Normalized allocated resources measures

Using indexes to measure fairness by examining the distribution of *all* allocations may cause a misinterpretation of results. For example, if one node is starved in N, then JFI is $1 - \frac{1}{|N|}$. We can notice that as $|N|$ gets larger, JFI fails to describe distribution tails. For this reason, additional measures must be used to describe the tails of the distribution. The min-max ratio defined by

$$min - max = \frac{min(r_1, r_2, \ldots, r_{|N|})}{max(r_1, r_2, \ldots, r_{|N|})} = min_{i,j \in N}(\frac{r_i}{r_j})$$

describes the relation between the two extremes of the distribution. Measures that describe each extreme might be needed. Thus, each extreme could be normalized to the calculated optimal share. These measures, however, lack the continuity of JFI and statistical measures introduced earlier. A change in the population will not affect normalized allocated resources measures. In addition, the overall allocation fairness is not considered in such metric.

Effective network utilization

The indexes presented previously do not describe the overall quantity of allocated resources, *e.g.*, a rate allocation in which all flows starve is perfectly fair but practically useless. We also wish to incorporate some measure of network utilization for a given allocation. A simple sum of all flow rates or their average is not sufficient as it does not account for the fact that a multi-hop flow consumes more spectral resources than a single flow. We thus use *effective network utilization* [84] defined as:

$$U_{eff.} = \sum_{i=1}^{|N|} r_i.l_i$$

Where l_i is the number of hops traversed by flow i. In this thesis we will use JFI as a measure of fairness and effective network utilization as a measure of capacity utilization.

II.3 MAC layer

The Medium Access Control (MAC) layer is responsible for physical addressing and channel access in the network stack. It is a sublayer of the data link layer in OSI (Open Systems Interconnection) reference model [85]. Work in this field aims to provide a fair, distributed, feasible MAC protocol. Proposed protocols for solving the multiple access problem can be classified to three categories:

- *Multiplexing*: Transmissions are multiplexed over a previously partitioned shared medium. Types of multiplexing include TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access) amongst others.

- *Access by Taking Turns*: Implicit or explicit notification is used to order transmissions. Polling and token-passing protocols are examples of this category. These and channel division access protocols are also referred to as *contention-free protocols* [57].

- *Random Access*: In random access protocols, also called *contention-based protocols*, transmissions are scheduled without previous coordination between nodes. Packets might collide and when this happens collision resolution techniques are employed. Examples of random access protocols are ALOHA [9], CSMA [51], and IEEE 802.11 [2].

In this thesis we design our solution as an extension to existing, widely-deployed protocols. IEEE 802.11 is the de facto standard for wireless network implementation. Thus, we will focus on random access protocols in the rest of this section.

II.3.1 Challenges

Designing a MAC protocol for wireless networks involves many challenges. We summarize these challenges below:

Hidden and exposed terminals

Consider the network topology in Figure II.2. If node *(a)* is transmitting to node *(b)*, then node *(c)* is unable to hear its transmission. Thus, node *(c)* may interpret the channel to be idle and transmit. In this case both transmissions collide and the channel time is wasted. Thus, *(a)* and *(c)* are *hidden terminals* to each other.

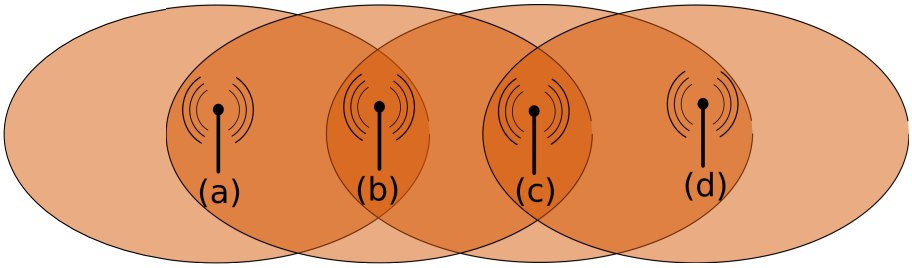

Figure II.2: This figure depicts a wireless network scenario of four nodes, namely a, b, c and d. The ellipses show transmission boundaries, hence a node transmission is receivable by nodes in its corresponding ellipse.

Another similar problem is the *exposed terminal problem* [71]. We illustrate this using Figure II.2. When *(b)* transmits to *(a)*, *(c)* cannot transmit to *(d)* because it misinterprets the channel as busy. The hidden and exposed node problems have been investigated in the literature [17, 48, 51, 79]. Since then, many techniques have been proposed to address these problems. Using control messages to communicate information about the channel state and ongoing transmissions is one of the used methods to surmount the hidden and exposed terminal problem. The work in [17, 48] is summarized in the next subsection.

Information asymmetry

In WMNs, nodes can be located many hops away from the gateway. Some of these nodes can be laying outside the carrier sense range relative to each other. This gives rise to *information asymmetry* [31] which can lead to starvation. Disadvantaged nodes, laying outside the carrier sense range, may inopportunely schedule their transmissions such that one of the receivers experiences collisions. With backlogged flows, a disadvantaged receiver experiences repeated collisions which builds-up the backoff timer for the corresponding transmitter, resulting in flow rate unfairness. An early treatment of information asymmetry is in MACAW [17], where an RRTS (Request for

Request To Send) is added to the control exchange, *i.e.*, RRTS-RTS-CTS-DS-DATA-ACK. This, however, introduces more overhead to the control exchange without eliminating information asymmetry completely [82]. The work in [31] proposed the use of sector antennas to mitigate information asymmetry. Sector antennas isolate upstream and downstream transmissions which also increases spatial reuse. Simulation results in [31] show that this eliminates information asymmetry.

Wireless link characteristics

We cannot assume a transmission to be successful in wireless networks. This is because of the following link quality characteristics. The first is *interference*, which is the modification or disturbance of the signal of an active transmission by an external source. Another is *noise*, which is random fluctuation of signal characteristics caused by the physical environment or link quality. *Fading* is the reception of multiple copies of one signal due to the *multipath effect* (*i.e.*, copies of a signal traversing the medium with different paths). The radio technology represents a performance bottleneck for WMNs. Dramatic increases in WMNs capacity require advanced physical technology that overcomes such link characteristics. OFDM (Orthogonal Frequency Division Multiplexing) is an example of such dramatic effect, where 802.11 capacity increased from 11 Mbps to 54 Mbps. Designing algorithms and protocols for existing and potential advanced physical layer solutions is an important practice. Radio technology is advancing in an unpredictable exponential manner. Some of these technologies will eventually become ubiquitous. We describe here research done on MAC techniques for two of the most promising radio technologies.

- *Multi-Channel MACs:* The use of multiple channels gives the nodes the flexibility to use different channels for various purposes. One way to use multiple channels is to dedicate one channel for signaling and one for data transmission.

RIBTMA (Receiver-Initiated Busy-Tone Multiple Access) [79] is such a protocol. It is a receiver-initiated protocol [76]; the receiver polls its neighbors for transmissions rather than waiting for allocation requests. RIBTMA uses the signaling channel to broadcast a *busy* tone when receiving a packet. Transmitters will be able to detect a reception on the intended receiver, and delay the transmission. An extension to RIBTMA is the use of two signaling channels. DBTMA (Dual Busy Tone Multiple Access) [37] uses a dedicated channel for a transmit-busy tone (BTt), used by the transmitter. In addition, another channel is dedicated for a receiver-busy tone (BTr) which is used to acknowledge an RTS, in addition to its rule as an indicator of being in a receiving state. Using BTt and BTr rid the network from collisions caused by hidden terminals. Also, It allow exposed nodes to engage in data transmissions. AMCP (Asynchronous Multi-Channel Coordination Protocol) [72] uses similar multi-channel techniques to achieve fairness.

- *Directional antennas:* These antennas allow nodes to transmit to a specific direction. This will eliminate interference with nodes in other directions in addition to increasing the range of transmission. Customizing MAC protocols for directional antennas is investigated in the literature [23, 52, 61]. One of D-MAC's (Directional MAC) [52] proposals is to employ a control handshake for transmissions. An RTS is sent to the direction of the receiver, and a CTS is replied to all directions. The work in M-MAC (Multi-hop MAC) [23] take advantage of the larger transmission range of directional antennas. Nodes in multi-hop networks can directly communicate to more neighbors compared to the omni-directional case. In [61] opportunistic scheduling mechanisms were employed to address fairness in networks with directional antennas.

Fairness and Quality of Service (QoS)

Fairness is a major challenge in designing wireless MAC protocols. The problem of unfairness gained attention since the early investigations of wireless MAC protocols [17]. MAC protocols target fairness on a local scale. Transport protocols, on the other hand, target end-to-end fairness. This conflict leads to unfairness when MAC protocols interact with transport protocols in presence of upstream and downstream, or multi-hop flows. Each transmitter gets an equal share of the medium by conventional MAC layer scheduling. However, different transmitter might carry different number of flows. The work in [67] addresses this problem. They showed that even with a simple case of one sender and one receiver communicating to a wired server through a base station using TCP, the sender achieves 1.44 times the receiver's bandwidth.

With the increasing demand on Voice over IP (VoIP) and multimedia applications in general, Quality of Service (QoS) plays a huge role in the design of MAC protocols. QoS aims to ensure a minimum boundary of resource allocation and end-to-end connection metrics. The most used metrics in QoS applications are bit rate, error rate, latency, and jitter.

Time synchronization

Many protocols require time synchronization between participating nodes. The required accuracy of time synchronization depends on the application. Some applications require loose synchronization between nodes [70]. This type of synchronization is easily achieved by the use of periodic messages. In 802.11 [2], for example, nodes broadcast periodic beacon messages that contain timing information. These are used by the Timing Synchronization Function (TSF) to achieve required synchronization. TSF is an implementation of a variant of Lamport's synchronization algorithm [58]. In addition to the lack of strict ordering, TSF is not scalable. It is shown in [39] that

using TSF in scenarios consisting of as few as 30 nodes may lead to asynchronism. Some protocols require tighter synchronization between nodes, *e.g.*, TDMA MACs. This motivated research for scalable synchronization protocols. In [39], modifications to TSF are proposed and are shown to be scalable for large networks with more than 300 nodes. Their proposal was to prioritize channel access for beacon transmissions according to the clock speed of participating stations.

Another way to achieve synchronization is by maintaining a *virtual clock*. Some protocols that use timestamps to prioritize medium access use virtual clocks. Self-Clocked Fair Queuing (SCFQ) [35] and Distributed Fair Scheduling (DFS) [78] and their variants are examples of protocols using the concept of virtual clocking. For example, SCFQ maintains a central virtual clock that starts with time 0. Each transmission is stamped with a start tag and a finish tag. The start tag is the greater of the current virtual clock reading or the previous finish tag. The finish tag is the sum of the start tag and the ratio of the packet size to the link weight. The virtual clock is updated by the beginning of each transmission with the finish tag of the packet.

Message multicasting and broadcasting

Many protocols need multicasting and broadcasting functionality. By broadcasting we refer to the transfer of a message to all neighbors, and by multicasting we refer to the transfer of a message to a select subset of neighbors. Notable applications are broadcasting beacon messages in 802.11 [2], and multicasting AODV (Ad-hoc On-demand Distance Vector) routing protocol packets [66]. In 802.11, broadcast and multicast frames are not acknowledged by the receivers. Thus, additional mechanisms are needed to provide reliable broadcast and multicast operation.

MAC layer multicasting was treated rigorously by Jain *et al* [42] as part of the AODV project. They propose modifications to the control message exchange in 802.11

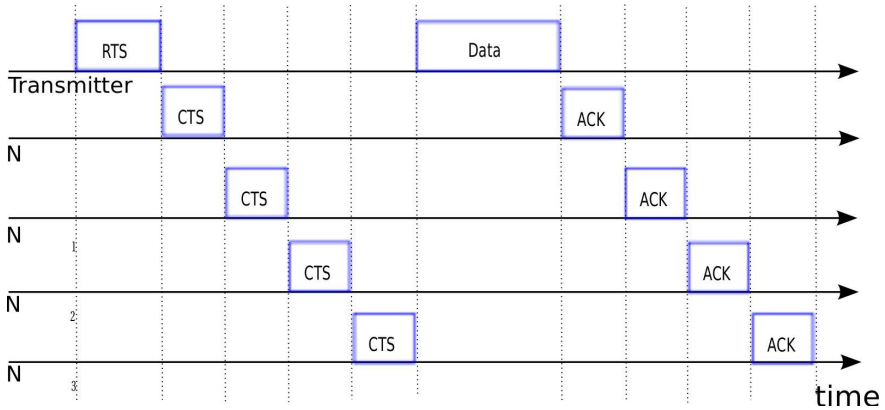

Figure II.3: Jain's reliable multicasting extension to 802.11.

to achieve reliable multicast frame exchange. RTS packets are modified to include the addresses of a select subset of neighbors. If a node is in this subset, upon receiving the RTS message it replies with a CTS message according to the conventional unicast conditions. CTS messages are modified to include the CTS transmitter's address, thus enabling the RTS transmitter to track the received CTS messages. To avoid collisions of CTS messages, neighbors schedule their transmissions according to a position index inferred from the RTS message. After receiving CTS messages from all neighbors, the multicast frame is transmitted. Afterwards, frame acknowledgments are transmitted in a fashion similar to that of CTS messages. A depiction of the dynamics of this mechanism is shown in Figure II.3.

II.3.2 Wireless MAC protocols

In this section we will overview the evolution of wireless MAC protocols.

ALOHA protocols

ALOHA protocols [9] are pioneering protocols designed for ALOHAnet, the first operational wireless network. ALOHA is a random access protocol where the transmitter transmits immediately when a packet is passed to the MAC layer. However, when a transmission fails, a retransmission is performed with probability p. Otherwise,

the node defer its transmission for a period equal to the transmission time, *i.e.*, $\frac{packet\_length}{transmission\_rate}$. ALOHA does not perform carrier sensing. Therefore, for a node A to transmit successfully, all neighbors must be idle for the duration of transmission.

Carrier sensing protocols

Carrier sensing protocols improve upon ALOHA protocols by incorporating channel sensing capabilities. Thus, a node can defer its transmission when it senses a busy channel. Carrier Sense Multiple Access (CSMA) protocol is an example of this category. It should be noted that Collision Detection (CD) techniques are not feasible in wireless hardware. Thus, CSMA/CD protocols, such as traditional Ethernet, cannot be migrated to wireless MAC protocols.

Collision resolution protocols

CSMA protocols still suffer from the hidden and exposed terminal problems. Thus, collision resolution protocols were proposed to alleviate these issues. One of the techniques is the use of extra signaling to prevent collisions. Multiple Access Collision Avoidance (MACA) [48], for example, uses a three-way handshake to inform the neighbors of both the transmitter and the receiver of the data transmission. MACA uses the following communication sequence. First, the transmitter sends a Request-To-Send (RTS) control message. Then, the receiver replies with a Clear-To-Send (CTS) control message. The sender finally transmits the data packet. Furthermore, Multiple Access Collision Avoidance for Wireless (MACAW) [17] proposed an addition of two extra control messages to the ones used in MACA: *(1)* a Data Sending (DS) control message is sent before the data packet to inform the transmitter's neighbors that the RTS-CTS exchange was successful *(2)* an ACK is sent by the receiver to confirm the reception of the data packet, allowing the sender to retransmit lost packets.

Multiple protocols emerged from MACAW by modifying the handshake and incorporating carrier sensing techniques inherited from CSMA protocols. Examples for such protocols include FAMA [30], and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

IEEE 802.11

802.11 [2] is a PHY and MAC layer standard for Wireless Local Area Networks (WLANs). 802.11 is responsible for many functionalities such as channel access, association, security, etc. However, in this section we will concentrate on channel access management. 802.11 defines three access modes:

- *Distributed Coordination Function (DCF)*: It is a contention-based protocol that uses CSMA/CA for contention resolution.
- *Point Coordination Function (PCF)*: It assumes the presence of a coordinator that can communicate directly to all the nodes. It is a contention-free protocol resembling a token based protocol where the coordinator, *i.e.*, access point, possesses the token.
- *Hybrid Control Function (HCF)*: It is part of the 802.11e protocol. It aims to provide a framework for QoS by maintaining multiple queues and balance access to the channel.

The rest of the section will focus on the DCF mode since it is suitable for the distributed, multi-hop nature of WMNs. 802.11 DCF mode is a collision avoidance protocol. It uses two types of collision avoidance techniques. A physical carrier sensing technique is used which senses the medium before transmission. A virtual carrier sensing technique is also incorporated using NAV (Network Allocation Vector). It uses a duration field embedded in transmitted packets to indicate the time required for completing the ongoing transmission. NAV maintains

a timer to defer transmissions. When the channel is idle, the timer decreases until it reaches zero, then it can transmit. When a packet is sensed, NAV timer is set to be $max(NAV_{current}, duration_{sensed\ packet})$. 802.11 uses a simple differentiation between different types of messages. This is done by varying IFS (Interframe Spaces), which are waiting periods used before the transmission of a message. Varying the lengths of these periods provides different priorities for transmissions. IFS periods defined in 802.11 are as follows:

- *Short IFS (SIFS)*: This is the shortest space time, *i.e.*, for highest priority. It is used for CTS and ACK transmissions.

- *DCF IFS (DIFS)*: This period is used as a waiting time before a transmission in the DCF mode. A node senses the channel for a DIFS period before it is allowed to transmit. Otherwise, it defers its transmission. It is defined by the following relation $DIFS = SIFS + (2.Slot\ Time)$.

- *PCF IFS (PIFS)*: This is the DIFS equivalent for the PCF mode. It is defined by $PIFS = SIFS + (Slot\ Time)$.

- *Extended IFS (EIFS)*: This space is used in the same way as DIFS and PIFS if the last received packet contained errors, hence the duration field was not obtained. It allows for enough time for an ACK message to be transmitted. It is defined as $EIFS = ACK_{transmission\ time} + SIFS + DIFS$.

A node with a packet to transmit first senses the medium idle for a DIFS interval. It then enters the *contention period*, also called the *backoff period*. The contention period equals *cw* slot times, where *cw* is the MAC *contention window*. For the first attempt, transmission starts at the beginning of a randomly chosen slot between $[0, cw_{min}]$. For 802.11b, the standard defines $cw_{min} = 31$. Cw increases exponentially with every failed transmission, up to a value of 1023, following which the packet is dropped.

II.3.3 Fair MAC protocols

In this subsection, we will overview the main directions taken to overcome unfairness using MAC layer solutions.

Distributed contention-based solutions

The main factor affecting channel access in contention-based protocols is backoff periods. We will see that most contention-based protocols perform access scheduling by manipulating the backoff period. Early investigations on the unfairness problem in wireless networks assumed a single-hop network. The general fairness objective for such cases is to converge MAC contention windows of all nodes to a similar value, while maximizing network throughput. This treatment to the unfairness problem is found in ALOHA [9], CSMA [51] and MACAW [17].

A number of proposals modify the conventional backoff scheme to incorporate fairness or other objectives [38, 62, 78]. For example, some work modify the backoff scheme to achieve service differentiation and prioritization [7, 24]. In general, a transmission with a higher priority is assigned a lower MAC contention window and *vice versa*. DFS [78] 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 [35]. The priority of a transmission is dependent on a 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 [38]. In it, the authors propose a distributed algorithm that performs two tasks: it first estimates the fair share of medium access without global knowledge. Later it 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 in protocols to achieve prioritization and service differentiation [1, 73]. Translating these prioritization and differentiation objectives to lead to fairness can be done in a similar fashion to the case of backoff procedures.

Distributed contention-free solutions

Contention-free schemes refer to protocols that avoid contention through previous assignment or scheduling. They employ methods such as resource division multiplexing, access by turns, and token passing. An example of their use is in 802.11 PCF, where TDMA is used. PCF is centralized and can only be used for single-hop WLANs. The centralization, complexity, and synchronization required for such protocols limits their use in a multi-hop network. Nonetheless, there is some effort in addressing this challenge in the literature [11,33,59,70,80]. Some work [70,80] propose implementing a virtual *overlay* on top of the MAC layer to simulate contention-free methods. OML (Overlay MAC Layer) [70], for example, divide the time into equal size slots. Nodes are allowed access to the channel only in allocated slots that are assigned using a distributed algorithm. OML require loose synchronization between nodes' clocks.

Innovative MAC protocols that achieve contention-free behavior are available in the literature [11,33,59]. [33] proposes a distributed algorithm to organize nodes into clusters. Channel access is scheduled by *clusterheads* which divide time into slots and synchronize nodes for transmission. However, global synchronization is required. A contention-free protocol that does not require such global synchronization, yet achieves contention-free behavior is presented in [59]. An interesting hybrid solution

to remove synchronization constraints is presented in SRMA/PA (Self Reservation Multiple Access with Priority Assignment) [11]. In SRMA/PA a control handshake is used to reserve channel access to nodes in a contention-free manner. Furthermore, it supports service differentiation through priority assignments. Channel access scheduling is performed by *soft* reservations, in the sense that nodes with higher priority packets can hijack other nodes' reservations.

Centralized MAC solutions

Centralized MAC protocols are not favored in wireless ad hoc networks for reasons of scalability. They generally require global information and signaling to control the overall behavior. In WMNs, however, such solutions are attractive because of its traffic patterns. With the majority of flows passing through the gateway this makes the process of collecting information and controlling behavior more feasible. One common method of achieving fairness is rate control [21, 43, 44, 74]. In [43] a rate-based scheduler, Feedback Rate Controller (FBRC), is proposed to achieve fairness. They demonstrate that max-min fairness can be achieved by limiting the *aggregate capacity* of the network at gateways. Other centralized solutions achieve fairness by explicit or implicit signaling to participating nodes [27, 69, 83]. RED (Random Early Detection) [27] performs queue management in gateways. Upon reaching a queue size threshold, the gateway informs nodes of the congestion status. This can be done explicitly through feedback or implicitly through packet drops.

II.4 Framework

In this section we discuss the framework of our research. We begin with a terminology section to identify the necessary components and entities of our framework. Then, we discuss the interference, communication, and capacity models used in our work.

II.4.1 Terminology

- A *host*, or an *end-user*, is the device that generates the network traffic. We assume that MPs connect to end-users using a different network interface than the one used for relaying traffic to the gateway.

- We denote by a *wireless link* the possibility of two nodes communicating through the wireless medium.

- A wireless link is *active* if packets are routed through it.

- A *source* is used to denote the higher layer traffic generator, and a *destination* is used for the higher layer traffic sink. On the other hand, a *transmitter/sender* is the physical device that transmits/relays data to the wireless medium to be received by a *receiver*.

- A *transmission* is the process of sending data through the physical medium between a transmitter and a receiver. A *flow/stream* denotes the higher layer exchange of data between a source and a destination.

- In WMNs the term *uplink streams* is used to describe connections directed from mesh clients to the Gateway (GW). *Downlink streams* describe connections from the GW to mesh clients.

II.4.2 Communication model

The interactions between nodes in our scenarios are determined by the distance separating them. We use the following distance definitions and the interactions possible in them:

- The *transmission area* is the area around the transmitter, covering the nodes sharing a wireless link with it.

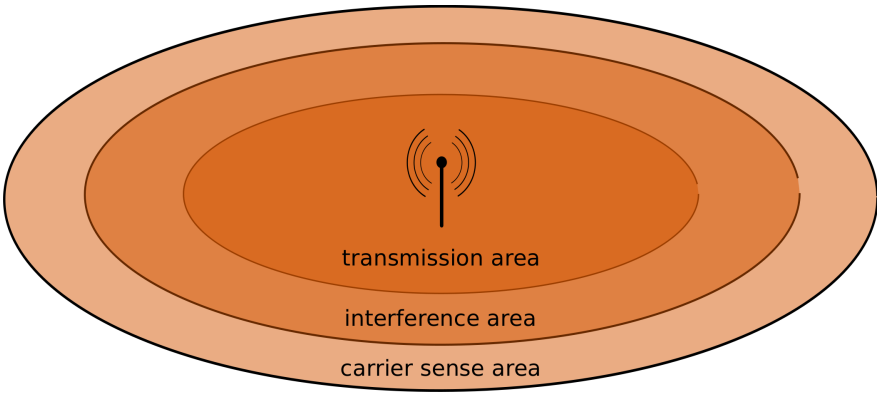

Figure II.4: The figure depicts the relationship between the various radio range parameters used in our communication model.

- The *interference area* is the boundary around a receiver, where a transmission from another transmitter will interfere, and corrupt, any other active transmission for this receiver.

- The *carrier sense area* contains the nodes that can sense a transmission from the node.

The relationship between the ranges are depicted in Figure II.4. It should be noted that this relationship is not strict, hence two areas can overlap completely.

II.4.3 WMN model

We now present our assumptions on WMNs:

- In our simulations and study we assume the existence of one gateway. However, extending our results can be done by representing multi-gateway WMNs as multiple single-gateway WMNs.

- For simplicity we only consider uplink streams. Downlink transmissions are for TCP ACKs only. This assumption can be relaxed by implementing the proposed mechanisms separately for uplink and downlink flows.

- The solution design is directed to 802.11-based WMNs. Simulation implementation is an extension of 802.11 modules. However, the general idea of our solution is applicable to other WMNs.

- We also assume that TCP is the dominant protocol for most of the traffic in the network. We base our study and most of the simulations under this assumption.

- The traffic of end-users is modeled as flows generated from MPs. In the simulation study, each MP initiates a flow to the gateway. Flows generated from one node act as a single flow constituting the aggregate of them.

- MPs are assumed to be static throughout the simulation. This is a feasible assumption since we are considering the WMN backbone. Thus, there are no link failures in our experiments.

- Our study assumes single channel, omnidirectional radios.

II.4.4 Capacity model

In order to evaluate our results, we need to study the capacity utilization in addition to fairness characteristics. The calculated optimal capacity will serve as a reference to measure the efficiency of the proposed work. Much work has been done to estimate the capacity of wireless networks [36, 47, 55]. [47] tackles the problem of capacity estimation by examining the *bottleneck collision domain*; this domain bounds the throughput of the network. In the calculation of collision domains they only consider active wireless links, so a graph representation of the network where the vertices (V) are the nodes, and the edges (E) are the active wireless links is used. The edges are directed by making the transmitter as the source of the edge and the receiver as the edge's destination. The weight of each edge is the amount of traffic relayed or generated by the source vertex. A collision domain of a wireless link contains the

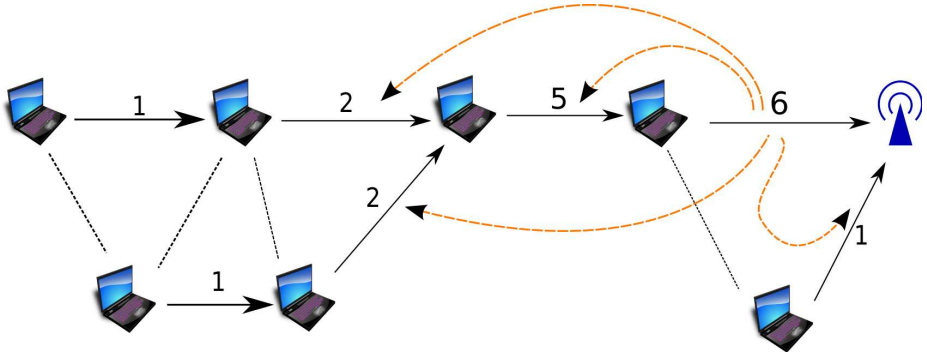

Figure II.5: This figure depicts an example of a link constraint graph. Seven nodes are all transmitting to the gateway. The solid arrows show active wireless links. Dotted lines show inactive wireless links. The number above each edge is the weight of the edge, hence the number of flows relayed or generated by the source node. The orange curvy arrows show the link constraints of the edge with a weight of 6.

other links that cannot transmit with it simultaneously. Such graph is supplied in Figure II.5. Each collision domain cannot transfer traffic higher than

$$\frac{C}{\sum_{i \in E_{domain}} w_i}$$

where E_{domain} is the set of edges in the collision domain, and w_i is the weight of edge i. After calculating the bounds of all the collision domains, the bottleneck collision domain is the one that deliver the lowest throughput bound. In Figure II.5 for example, the sum of edge weights in the bottleneck collision domain is 17. Therefore, the throughput of each node is bounded by $\frac{C}{17}$.

In this thesis we use the model in [47] because of the following reasons:

- It provides an exact network capacity, opposed to other work that provide an asymptotic estimation of the capacity.
- The assumptions made in [47] are similar to those in our work. We summarize these below.
  - Networks with a single gateway are considered.
  - Each node is backlogged with infinite traffic.

- Absolute fairness is assumed to be enforced on all nodes.
- A symmetric MAC protocol is used, hence a protocol where the sender and receiver exchange messages in each transmission.
- All the traffic of the network are uplink streams.
- Node mobility is not considered.

It should be noted that this model is not generic for all MAC protocols [12]. TDMA protocols and 802.11e are able to achieve higher capacities than those estimated by the model.

Chapter III

Modeling TCP flows over WMNs

III.1 Introduction

TCP is well known for allocating fair shares of network resources. However, the problem of fairness in WMNs domain is observed even with TCP flows. A better understanding of the interaction between TCP congestion control mechanism and 802.11 MAC in a WMN is important to address the fairness problem. An analytical model that 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 also lead to network performance degradation and node starvation.

In this chapter we propose an analytical model that captures the behavior of competing TCP flows in a 802.11-based WMN [64]. 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. We will denote this parameter as the number of *transmission steps*. Since transmissions beyond the carrier sense range of the gateway can be made concurrently while the gateway is transmitting, the number of transmission steps for the nodes in a network varies between 1 and 3 (depending on links carrier sense range).

III.2 Related models

There has been a significant amount of research done for modeling wireless link characteristics. This includes models for describing the detailed behavior of random access protocols in wireless networks [8, 18]. 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 [19,31] and [32]. 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 [50, 67]. We are mainly interested in the objective of [50], where the effect of multi-hop relaying and TCP data/ACK packets exchange are explicitly modeled. However, the work in [50] only considers a simple two-hop chain topology with a single flow with a conservative choice of TCP congestion window. Intractability, caused by its complexity, limits its use to unreasonably simple scenarios. We, on the other hand, focus on larger WMNs topologies with a larger number of flows. Thus, we maintain the objective of the work in [50] with a more tractable model that is applicable to more complex scenarios.

III.3 Cumulative Network Queue (CNQ) model

In this section we model TCP flows over 802.11-based WMNs. An investigation of the necessary parameters to capture the TCP flow's characteristics is presented followed by a methodology for constructing a Markov chain to model these parameters. Derivation of performance characteristics is shown.

The causes of TCP unfairness are highlighted and further analyzed.

III.3.1 Overview

We model TCP flows in WMNs while focusing on the fairness characteristics. Without loss of generality, our model considers a single mesh gateway. We assume that all nodes have backlogged TCP traffic destined to the gateway and the TCP streams are in a state of equilibrium (*i.e.,* the flow rate characteristics are stable over time). Similar to [50], we start by fixing TCP's congestion window size. Later in this section, we investigate the effect of varying this limit on the rate of a flow.

Given the assumptions above, the parameters necessary for modeling TCP throughput are the utilization of the network queues at various nodes and the order of packets in the queues (relative to their source and destination) for both data and ACK packets. However, deriving a closed form solution would be hard in the presence of topologies with a larger number of nodes and active flows. Thus, the following two assumptions are raised to simplify the problem. First, we model the queue utilization without considering the order of the packets; in other words, only the number of packets for each flow is taking into account, while the order is then considered by calculating possible permutations and assigning the transition probabilities accordingly. Second, by observing the behavior of single sink networks, we found that the queue belonging to the closest node to the gateway exhibits significant utilization. Thus, we can model all queues as one cumulative network queue, which represents an aggregate of

all queues in the network. The multi-hop effect is modeled by assigning the transition probabilities according to the number of necessary transmission steps in the network.

III.3.2 Model description

A Markov chain is used to model the TCP behavior. The system state is represented by the cumulative network queue utilization. Each state represents the number of data packets for each flow in the cumulative network queue. Thus, for a 2-hop parking lot topology (PLT) we describe the network as the process $\{P_1, P_2\}$, where P_n indicate the number of data packets belonging to the nth flow that exist in the network (*i.e.,* P_1 and P_2 represent the number of packets queued for the 1 and 2-hop flows). The model is a Markov chain with n-dimensions, where n is the number of flows. We use W_n to denote the TCP congestion window of the nth flow. Thus an equivalent state description of the network is the number of ACK packets in the network, *i.e.,* the process $\{W_1 - P_1, W_2 - P_2\}$. State transitions are governed by three aspects: (1) the number of nodes competing for channel access; (2) the relative number of data and ACK packets in the network; and (3) the multi-hop effect, which is modeled as additional self loops with an equal share of the transition probability of the original link. These self loops lower the probability of transitions to another state to capture the effect of the necessary number of transmission steps. We assume that all nodes have an equal chance to access the channel. This assumption holds given that we only model the cumulative network queue. Note that the number of self loops corresponds to the number of transmission steps which in turn affects the cumulative network queues. For example, in a 2-hop PLT a data transmission of a packet belonging to flow 2 is represented as a transition from state $\{P_1, P_2\}$ to state $\{P_1, P_2 - 1\}$ with probability

$$\frac{P_2}{k_2.l_{\{P_1,P_2\}}.(P_1 + P_2)}$$

where l_η is the number of stations competing for the channel for a given state, *e.g.*, $\eta = \{P_1, P_2\}$. k_j is the number of transmission steps needed for flow j.

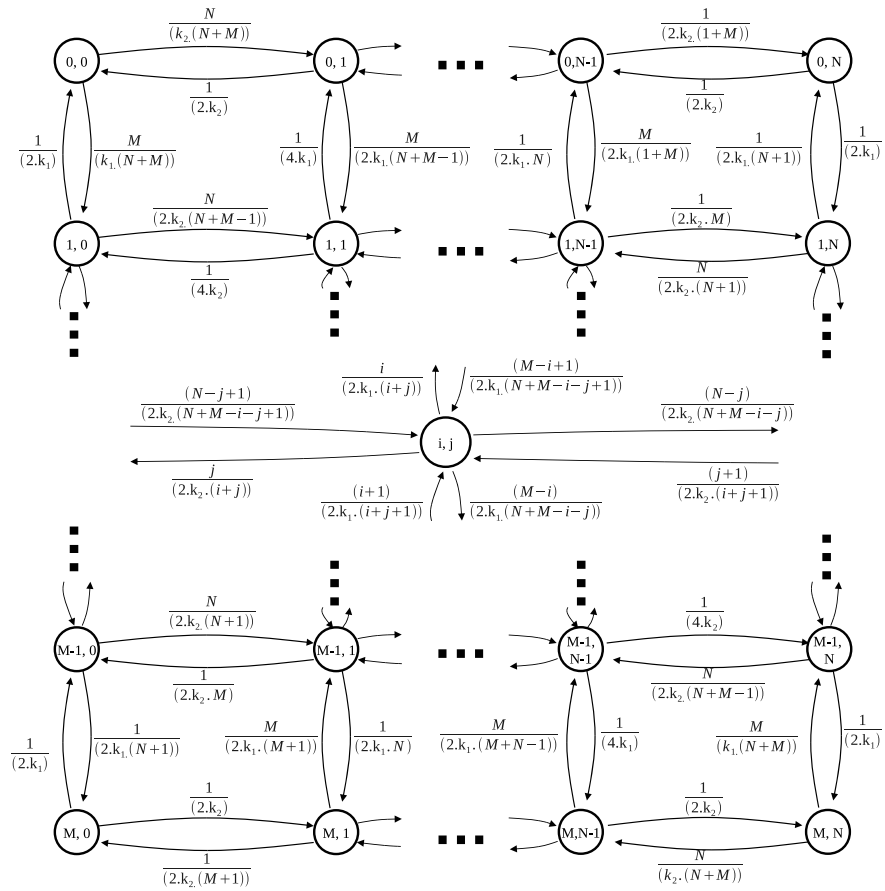

Figure III.1: Transition diagram for two-hop PLT. Congestion windows for the farthest and closest flows are M and N respectively. The state (P_1, P_2) denotes that the network has P_1 data packets for flow 1 and P_2 data packets for flow 2, where an upward transition corresponds to the transmission of a data packet of flow 1, a downward transition is for an ACK transmission of flow 1, a leftward transition is for the transmission of a data packet of flow 2, and a rightward transition corresponds to an ACK transmission of flow 2.

We summarize the possible transmissions for a packet belonging to flow i as follows,

- *Data Packet:* Transition from state $\{P_1, \ldots, P_i, \ldots\}$ to $\{P_1, \ldots, P_i - 1, \ldots\}$ with probability $\frac{P_i}{k_i . l_\eta . (\sum_j^n P_j)}$, given that $P_i > 0$.

- *ACK Packet:* Transition from state $\{P_1, \ldots, P_i, \ldots\}$ to $\{P_1, \ldots, P_i+1, \ldots\}$ with probability $\frac{W_i - P_i}{k_i . l_\eta . (\sum_j^n (W_j - P_j))}$, given that $(W_i - P_i) > 0$.

The assignment of the number of competing nodes is as follows,

- $l_\eta = 1$, given that $\sum_j^n P_j = 0$ or $\sum_j^n P_j = \sum_j^n W_j$. These two conditions correspond to the cumulative network queue or gateway being empty.

- $l_\eta = 2$, otherwise.

From the above we observe that the number of competing nodes is determined by the existence of data/ACK packets in the cumulative network queue and gateway. The number of transmissions necessary for a packet (*i.e.*, k_j) determines the number of transmission steps affecting the modeled queues. In other words, transmissions that do not contribute to the relative utilization of the cumulative network queue do not affect network performance. This is as a result of our earlier observation that the queues closer to the gateway have significantly higher utilization than that of the other queues. The value of k_j always equals to 1 for flows originating from any one-hop away node. Otherwise, it is a function of the hop count and interference range of wireless links. An example of a state transmission diagram of CNQ model is depicted in III.1.

III.3.3 Model analysis

Relative throughput of participating flows is an important performance metric for our study. We examine a network with n flows, *i.e.*, $J = 1,\ldots,j,\ldots,n$. The local symmetry exhibited in the model allows us to calculate the probability of a state by traversing from state $P_{0,\ldots,0}$ to the desired state through each dimension. We assume that state $I = \{i_1, \ldots, i_j, \ldots, i_n\}$ is where we want to reach. First, we introduce the following formula to calculate the intensities of traversal in dimension j,

$$\phi_{j,i_j} = \prod_{X=0}^{i_j-1} [(\frac{(W_j - X)}{l_{\eta_a}.(\sum_w^n W_w - X - \alpha_j)})/(\frac{(X+1)}{l_{\eta_d}.(X+1+\alpha_j)})] \tag{III.1}$$

The first term corresponds to the probability of an ACK transmission from state $\{\ldots, P_j = X, \ldots\}$, divided by the probability of a data transmission from state $\{\ldots, P_j = X+1, \ldots\}$. l_{η_t} represents the number of competing nodes on the transition probability, where the subscript a refers to the ACK transmission and d refers to the data transmission. The α in Equation (III.1) corresponds to state changes from previous traversals in other dimensions. Assuming that we traverse dimensions in ascending order it will be given by

$$\alpha_j = (\sum_w^{j-1} i_w)$$

Using Equation (III.1) we obtain the state probabilities as follows,

$$\pi(I) = (\prod_{j=1}^{n} \phi_{j,i_j})\pi(0,\ldots,0) = \beta_I \pi(0,\ldots,0) \tag{III.2}$$

The total probability must equal to one,

$$\pi(0,\ldots,0) = \frac{1}{\sum_{w_1=0}^{W_1} \cdots \sum_{w_n=0}^{W_n} \beta_{\{w1,\ldots,w_n\}}} \tag{III.3}$$

Using Equations (III.2) and (III.3) we show a closed form solution of $\pi(I)$ as follows,

$$\pi(I) = \frac{\beta_I}{\sum_{w_1=0}^{W_1} \cdots \sum_{w_n=0}^{W_n} \beta_{\{w1,\ldots,w_n\}}} \tag{III.4}$$

From Equation (III.4) the throughput (T_j) of flow j can be calculated as follows,

$$T_j = \sum_{w_1=0}^{W_1} \cdots \sum_{w_j=1}^{W_j} \cdots \sum_{w_n=0}^{W_n} [\frac{w_j}{l_\eta.k_j.\sum_{y=1}^{n} w_y} \pi(w_1,\ldots,w_n)] \tag{III.5}$$

Obtaining the fairness measure is straightforward by applying Equation (III.5) to the desired fairness model.

An interesting observation can be obtained from the analysis as follows. The number of transmission steps does not affect the state probabilities obtained by Equation (III.4). This leads to a special symmetry between the model's states that can be intuitively predicted from the aforementioned observation that the process can be represented by either the number of data or ACK packets. This symmetry is represented by

$$\pi(P_1, \ldots, P_i, \ldots) = \pi(W_1 - P_1, \ldots, W_i - P_i, \ldots) \tag{III.6}$$

We examine the case where flows have identical congestion windows. This introduces an additional symmetry in our model. Examining Equation (III.4) for the case of identical congestion windows leads to the identity

$$\begin{aligned} P(\{i_1, \ldots, i_n\}) = P(\{y_1, \ldots, y_n\}) \\ , \forall_{i,y \in S}(freq_I(s_j) = freq_Y(s_j); s_j \in S) \end{aligned} \tag{III.7}$$

The term $freq_S(e)$ denotes the frequency of element e in S. The identity in Equation (III.7) can further simplify studying the throughput relationship between different flows. Examining Equation (III.5) for the case of identical congestion windows we notice that all flows have the same number of states that lead to a data transmission. Using the identity in Equation (III.7) we know that each state has other *mirroring* states with the same probability. The number of these mirroring states is a multiple of the number of flows. Furthermore, we notice that for these mirroring states, the factors affecting the contribution to throughput is the number of data packets of the flow under consideration and the number of transmission steps (*i.e.,* k_j). The number of transmission steps is independent from the summations and only affect the throughput linearly. Given our identity, the sum of the contribution

of any set of *mirroring* states is the same for all participating flows. Thus, the relative throughput of two flows with the same congestion window can be calculated as follows,

$$\frac{T_i}{T_y} = \frac{\frac{\lambda_i}{k_i}}{\frac{\lambda_y}{k_y}} = \frac{k_y}{k_i} \tag{III.8}$$

Where λ_j is Equation III.5 while taking the transmission steps (k_j) outside the summations. Equation (III.8) shows that if two flows with the same congestion window compete for channel access, their relative throughput depends only on k.

Chapter IV

Timestamp-ordered Medium Access Control protocol (TMAC)

In this chapter we propose TMAC, a timestamp-ordered MAC [63]. The mathematical study presented in Chapter III highlighted the necessary objectives to overcome fairness. We translate these objectives to design goals of a distributed MAC layer protocol. First, we introduce TMAC. Then, discuss its motivation and design objectives followed by the proposed design.

IV.1 Introduction

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 [58]. Lamport algorithm uses request timestamps to ensure that the node with the earliest request is the node that will be 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., older). This can be related to the *aging* process in task scheduling, in which tasks priority increase proportionally to waiting time [77]. We show that for backlogged TCP flows, scheduling packets according to their age when coupled with a specialized queuing discipline results in absolute flow rate fairness.

IV.2 Motivation

From our discussion in Chapter III we conclude that fairness is affected by two factors, namely values of congestion windows, and the number of transmission steps for each flow. Observing these factors, there are two ways to achieve fairness. One way is to tune flows' congestion windows to values that will lead to fair allocations. This can be done by formulating Equation III.5 as an optimization problem to derive suitable congestion window values. Afterwards, congestion window tuning techniques can be used to achieve fairness. However, it is necessary to obtain real-time information and perform the optimization on the fly. The other way to achieve fairness is by an observation of Equation III.8. The relative throughput of flows with identical congestion window values is dependent on the number of transmission steps only. Achieving identical congestion windows while making the number of transmission steps equal will lead to absolute fairness.

In this work, we take the later strategy. We propose a MAC-layer solution to minimize the difference in the congestion window between various flows and to make the number of transmission steps equal. For minimizing the difference in congestion windows, a round-robin queuing of TCP acknowledgments is used. This will penalize flows with larger congestion windows relative to other flows. The number of transmission steps is dependent on the flow's hop count to the gateway. We need to remove

this dependence, hence force a transmitted packet to reach its destination before younger packets regardless of the flow's hop count. In our model this will translate into an identical number of transmission steps for all flows, and consequently leads to fairness. Our scheduling algorithm to achieve this priority scheduling is influenced by Lamport's mutual exclusion algorithm [58]. Lamport algorithm uses request time and ensures that the node with the earliest request is the node that will be served the next. The algorithm uses an explicit exchange of control messages in order to ensure that all nodes are fully aware of the network state. This algorithm is suited for fully-connected wired networks. However, implementing Lamport algorithm in WMNs introduces new challenges. TMAC can be seen as a distributed variant of Lamport algorithm that overcomes wireless multi-hop challenges. A node prioritizes packets according to their ages.

IV.3 TMAC operation

We illustrate the dynamics of TMAC in Figure IV.1 using a simple 4-node chain topology where nodes N_0 and N_2 transmit one data packet each to N_3. We consider the transmission of two data packets, D_1 from node N_0 and D_2 from node N_2.

1. N_0 schedules its packet for transmission first. It assigns a timestamp of 1 to packet D_1. Since N_0 has no child nodes, D_1 is transmitted to N_1.

2. N_2 schedules its packet, D_2, for transmission after N_1 reception of D_1. It assigns a timestamp of 2 to it. N_2 now sends a request message to its child node, N_1. N_1 will not issue a grant message as its queue holds a packet of a higher priority. Instead, it sends a request message to its child node N_0. N_0 replies with a grant message as it does not have any pending transmissions. Thus, N_1 transmits D_1 to N_2.

3. Both packets are in N_2's queue. Since D_1 has a higher priority, it is scheduled

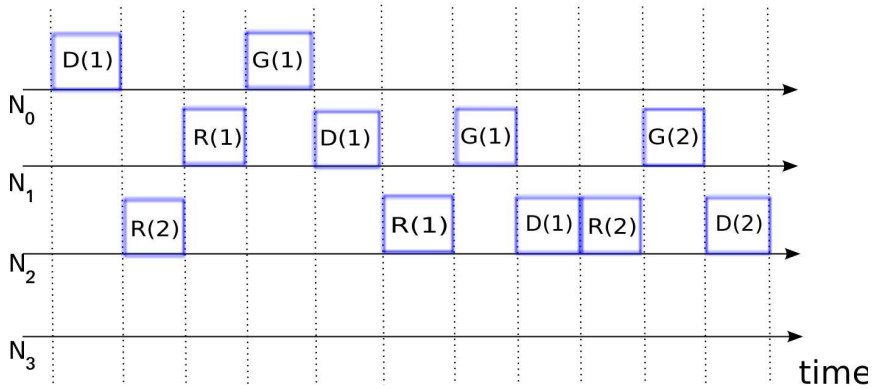

Figure IV.1: TMAC operation in a WMN

for transmission first. A request is sent to N_1, and a grant is replied due to the lack of pending transmissions. D_1 is sent to its destination.

4. The propagation of D_2 from N_2 to N_3 continues in a similar fashion.

IV.4 Design

We start by describing the scheduling algorithm of TMAC. Afterwards, the queuing discipline used to compliment the scheduling algorithm is presented. Then, we show different ways to implement TMAC over 802.11 radios. Finally, we discuss causes of overhead and possible optimization techniques to alleviate them.

IV.4.1 MAC scheduling

The fundamental idea behind TMAC is to schedule packets based on their age as identified in their timestamps. In wired networks, control messages can be used to achieve consensus between nodes. However, any message exchange requiring global co-ordination incurs a significant overhead in multi-hop WMNs. Our proposed TMAC protocol addresses this by limiting the exchange of control messages to a subset of direct neighboring nodes only, (*i.e.,* one-hop away). We argue that the single-sink

property of WMNs allows us to limit ordering enforcement on nodes with a parent-child relationship[1]. This local ordering can be achieved by an explicit exchange of control messages between nodes. Each node maintains a table of its child nodes. Whenever a node has a packet to send, it advertises the priority (*i.e.,* age) of the packet in the head of the transmission queue by multicasting a *request* message to its child nodes. When a child receives this message it responds with a *grant* message only if the requesting node has a higher priority than any packet pending transmission at the child node. When grant messages are received from all child nodes, the packet is transmitted.

TMAC uses timestamps to measure the packet age and influence its scheduling priority. These timestamps enforce a local ordering between neighboring nodes. For example, a node cannot transmit a packet until the packet has a higher priority (*i.e.,* a lowest timestamp) than the packets of its child nodes. The mechanics of TMAC require a transmitter to poll its child nodes and seek confirmation that they do not have older packets awaiting transmission. This explicit polling ensures that a node cannot starve its child nodes at the cost of its own transmission.

The local ordering enforced by TMAC creates a backpressure that translates into global ordering in WMNs with a single gateway. Since all flows traverse this gateway, the local ordering enforced on one-hop neighbors of the gateway propagates to all flows traversing them. For example, suppose nodes N_1 and N_2 are one-hop away from the gateway and nodes N_3 and N_4 are two or more hops away. Suppose that there exist flows f_3 and f_4 originated from nodes N_3 and N_4 respectively. The local ordering between N_1 and N_2 creates a backpressure such that packets of f_3 and f_4 are relayed according to their priorities. The time for backpressure to propagate within the network is a function of the node depth. This determines the latency incurred in converging distant nodes to their fair rate. We evaluate these flow rate convergence

[1] A parent node is the next node on the route towards the gateway.

characteristics of TMAC in Chapter V.

IV.4.2 Queuing discipline

TCP flow rate is clocked with its Round Trip Time (RTT). With a faster feedback loop, nodes closer to the gateway can quickly build up larger TCP congestion windows compared to distant flows. Thus, the buffers at one-hop and two-hop nodes are largely populated with packets originating locally. If we use a simple DropTail queue (the packet in the tail of the queue is dropped in case of overflow) with a FIFO (First In, First out) discipline, distant flows will experience packet drops from queue overflows when they reach these two-hop and one-hop nodes. Thus, the queueing discipline is integral in improving the fairness of TCP streams in WMNs.

TMAC uses a variant of Fair Queueing (FQ) by separating data packets from ACKs. Since TCP ACKs are cumulative, its congestion control mechanisms may not be triggered even when some ACKs are lost as long as long as an ACK with a higher sequence number gets delivered. Both data and ACK queues are sorted by timestamps such that the packets at the head of the respective queues are the oldest packets that are next scheduled for transmission. It should be noted that we prioritize packets transmissions from their original nodes to reach the gateway before younger transmissions, hence the priority of a packet corresponds to the point of first transmission, not generation. Thus, a locally generated packet is assigned a timestamp when it reaches the head of queue. This, however, leaves the locally generated traffic vulnerable to indefinite preemption by relay packets that have already been assigned a timestamp by their source nodes. We prevent this by partitioning our queue space into *rounds*, where each round corresponds to packets received relative to locally generated packets. To avoid indefinite preemption, relay packets from a round k cannot preempt packets generated locally in round $k + 1$.

IV.4.3 Implementation over IEEE 802.11 radios

TMAC can be implemented through minor modifications to the IEEE 802.11 protocol. The modifications include the design of request/grant messages, as well as associating a timestamp with a data frame through its journey in the network.

Request/grant messages: A TMAC node requires request/grant messages to poll its neighbors about the state of packets pending for transmission. Our TMAC implementation uses modified RTS/CTS control frames to build this request/grant messaging framework. We introduce two modifications in the way RTS/CTS control frames are exchanged. First, the RTS frame is delivered to selected child nodes rather than a single designated receiver. This can be achieved either by transmitting RTS as a broadcast frame or by making the neighbors promiscuously capture the frame. Second, all neighbors receiving an RTS message should respond with a CTS message as long as the received RTS has a lower timestamp than any pending local transmission. The initial sender triggers data transmission only after receiving CTS frames from a sufficient number of child nodes.

The proposed scheme may result in collision among CTS frames when multiple child nodes respond to an RTS. Therefore, these child nodes need to schedule their transmissions. We have implemented the scheme proposed in [42] using broadcasting and multicasting wireless transmissions and adapted it to control messages. The main idea is to append the neighbor addresses in the RTS in the order which they are expected to transmit CTS. Thus, a node responding to an RTS waits for a predefined amount of time T before launching the CTS message as follows:

$$T = (order - 1) \times (CTS\ transmission\ time)$$

These modification to the RTS frame structure not only supports the scheduling

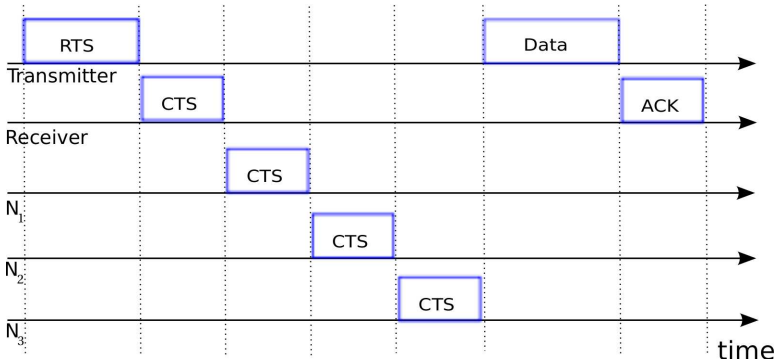

Figure IV.2: Multicasting control frames in IEEE 802.11 radios

of CTS transmissions, but also enables the polling of specific neighbors for their CTS messages. Figure IV.2 shows the exchange of these control frames between a transmitter and a receiver with three neighboring nodes N_1, N_2, and N_3.

Timestamp generation: 802.11 radios achieve time synchronization by periodically exchanging timestamp-carrying beacons between neighboring nodes. We have implemented timestamps based on the synchronized clock among nodes. Our results in Chapter V show that such synchronization is sufficient to ensure the ordering of packet transmissions required for the proposed TMAC protocol.

Revised RTS/CTS and Data frames format: We modified the 802.11 RTS/CTS and data frames to support TMAC protocol as shown in Figure IV.3.

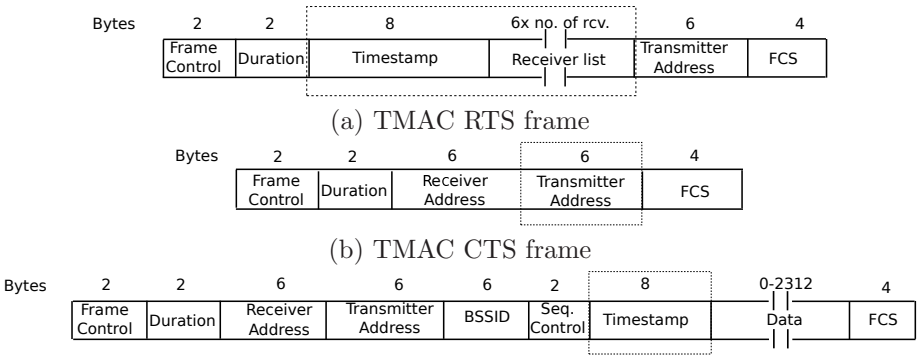

Figure IV.3: 802.11 modified frame structure as used in our TMAC implementation

RTS frames have been modified as follows: a Timestamp field is appended (8 Bytes); this corresponds to the Timestamp field included in the Beacon frames per

the 802.11 standard specifications. The Receiver address list (6 Bytes × no. of receivers) specifies the list of child nodes that are required to respond with a CTS. The Duration field is updated such that it reflects the time required for completing the transactions, including the additional CTS transmissions from selected child nodes.

CTS frames are appended with a Transmitter Address field (6 Bytes). This allows the RTS transmitter to differentiate between CTS frames from various child nodes.

Data frames are appended with a Timestamp field (8 Bytes). This allows the receiver to sort its transmit queue based on the age of the data packet.

IV.4.4 Interface queue design

An interface queue design satisfying the fairness requirements discussed earlier is implemented as follows: packets arriving to a certain queue are either *fresh* (*i.e.,* locally generated) or timestamped packets (data or ACK). A *fresh* packet is placed at the tail of the queue. A timestamped packet is inserted in the queue sorted according to its timestamp. Note that *fresh* packets in the queue have not been assigned a timestamp yet. At this stage, *fresh* packets should first be placed between rounds of transmissions to prevent preemption by other flows packets. Consequently, if the tail of the queue has a *fresh* packet and a timestamped packet arrived with a timestamp larger than all the other timestamped packets, then it is placed in the tail of the queue. It is then scheduled in the next round of transmissions.

IV.4.5 Mitigating TMAC control message overhead

The control message exchange required for TMAC may cause significant performance penalty. Recall, each RTS frame triggers CTS frames from child nodes. By default, these control frames are transmitted at the base rate, further increasing the impact of this overhead. We now propose an optimization technique to alleviate this overhead.

We propose using data bursts to amortize the overhead associated with the control

message exchange. This allows a node to forfeit requesting grant messages from its neighbors for a fraction of the transmissions, allowing the grants to be effective for more than one transmission. For example, a burst length of five indicates that each received grant is effective for five transmissions. Selecting the proper burst size is an important configuration parameter. Larger bursts can significantly reduce the control frame overhead, yet it may introduce short-term unfairness between flows.

Chapter V

Simulation evaluation

This chapter presents simulation experiments used to confirm CNQ model validity and TMAC's efficacy. For validating CNQ model we simulated different scenarios while changing the congestion window assignments for some experiments. We are interested in the fairness characteristics of TMAC in addition to the channel utilization and speed of convergence. The simulator used for these experiments is ns-3 [4].

V.1 Simulation Environment

The parameters used in our simulations are shown in Table V.1. We started collecting the results after the first 20sec of simulation trace as the initial transients spent for establishing routes and populating ARP tables.

Parameter	Value
Link rate	12 Mb/s
MAC protocol	IEEE 802.11a
Packet size	1500 B
Interface queue size	500 packets
Routing protocol	OLSR
Traffic source	Backlogged TCP Tahoe

Table V.1: Simulation parameters

Link rate	CSMA (Mb/s)
12 Mb/s	8.5

Table V.2: Measured 'Optimal' goodput for a TCP flow in a 1-hop network

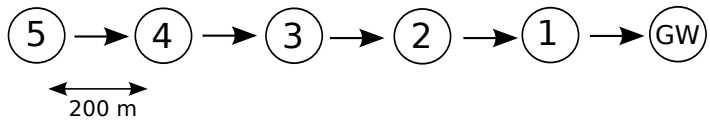

Figure V.1: A 5-hops PLT. All five nodes are participating in a connection with the Gateway (GW). Node numbers denote the number of necessary transmissions (*i.e.*, hop count to the gateway) for a data packet, initiated in that node, to reach the gateway.

We use *Jain's Fairness Index* (JFI) [41] to quantify the fairness of our measured rate allocation. We normalize the simulation results to the *optimally fair* flow rate distribution obtained with the collision domain network capacity model proposed by Jun and Sichitiu [47]. For 802.11 radios, the PHY and MAC layers overhead reduces the nominal MAC layer capacity to be much less than the corresponding link rate. TCP ACK overhead incurs an additional penalty. The achievable goodput (application level throughput) of a single-hop TCP flow is used as a baseline for the 'optimal' (*i.e.,* no collisions) link capacity with the collision model is shown in Table V.2.

V.2 Data burst size optimization

In this section, an analysis of the effect of data bursts (Section IV.4.5) in mitigating control messages overhead is presented. We performed a set of experiments on a 4x4 grid topology while varying the burst size from 0 to 30. Results are presented in Table V.3. From the table we note that without data bursts or with a small burst size (*i.e.*, 0 and 1) maintains a high JFI, albeit with a low utilization. Burst sizes of 5 or higher show a utilization of over 90%. Moderate burst sizes (lower than 30) still achieve high JFI, albeit a little lower than small bursts. Our experiments in the rest

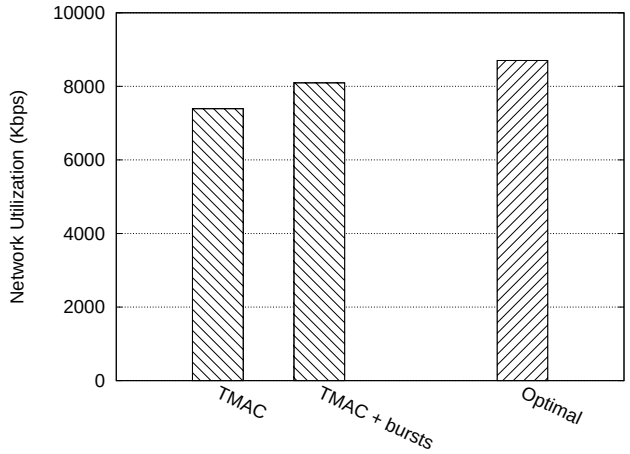

Figure V.2: Impact of TMAC optimizations on the utilization of a 5-hop chain

of the chapter uses TMAC with a burst size of 5. This value shows a high utilization while maintaining fairness. Furthermore, increasing the burst size to 20 exhibits little impact on fairness and utilization relative to a burst size of 5. Thus, a burst size of 5 is selected as a conservative choice. For completeness we also show the effect of bursts on network utilization in a 5-hop PLT. Figure V.2 shows that a burst size of 5 can increase the network utilization by 9.5% in such a topology.

Burst Size	Norm. Net. Util.	JFI
0	74.93%	0.9996
1	77.72%	0.9995
5	90.14%	0.9967
10	92.50%	0.9965
20	92.40%	0.9948
30	92.00%	0.9366

Table V.3: Examining the effect of burst size in a 4x4 grid topology with 12 Mb/s links

V.3 CNQ model validation

We performed a set of experiments on several PLTs (Figure V.1) to validate the CNQ (Cumulative Network Queue) model. The spacing between nodes is 200m. Using

the default NS-3 radio parameters, only the adjacent nodes in the chain are within transmission range and the two-hop nodes away are within interference range. Each node initiates an uplink TCP flow to the gateway. We used our model to numerically calculate the expected rate of each flow. This rate is then scaled by the maximum achievable throughput for a single flow over a one-hop network.

Our first set of experiments is performed on a two-hop PLT. In the following depicted results, nodes are numbered from 0 to $n-1$, where node 0 is the farthest node from the gateway and n is the number of nodes. The maximum congestion window of each flow is varied in both the simulation and model. Our results are shown in Figure V.3. The model predicts the experimental results closely. We performed an additional set of experiments without limiting the congestion window. These results were approximately identical to those obtained by limiting the maximum congestion window size for the two flows to the same value.

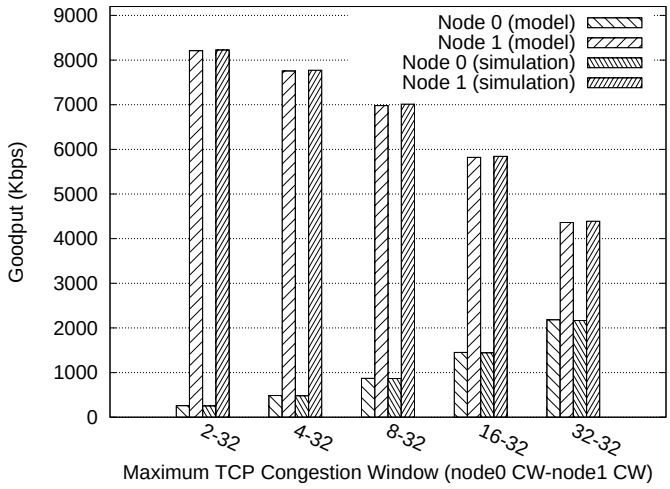

Figure V.3: Results comparing the model with simulation results for a 2-hop PLT

The next experiment has larger topologies, including three-hops and four-hops PLTs. The results are shown in Figures V.4 and V.5. The numerical results derived from our model while limiting the maximum congestion window size of different flows are compared to simulation results where no such limit is imposed. Despite this

difference, we found that the model can closely predict the behavior of the network.

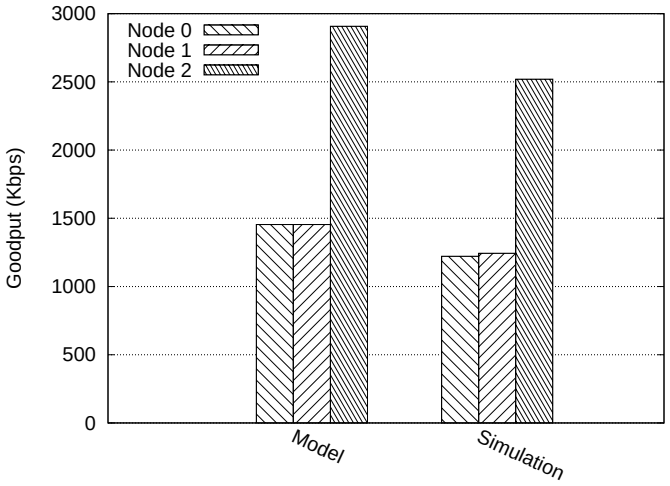

Figure V.4: Numerical results obtained from the model vs. simulation results for a 3-hops PLT

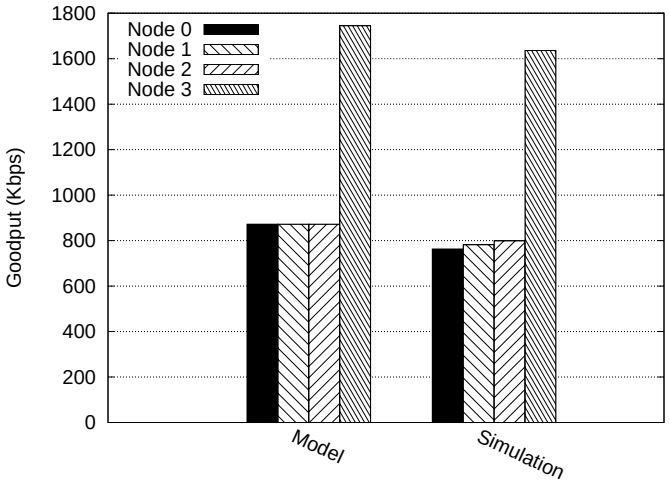

Figure V.5: Numerical results obtained from the model vs. simulation results for a 4-hops PLT

V.4 TMAC evaluation

In this section, TMAC performance is examined for PLTs and grid topologies. As a performance benchmark, we compare our results to the optimal results achieved by

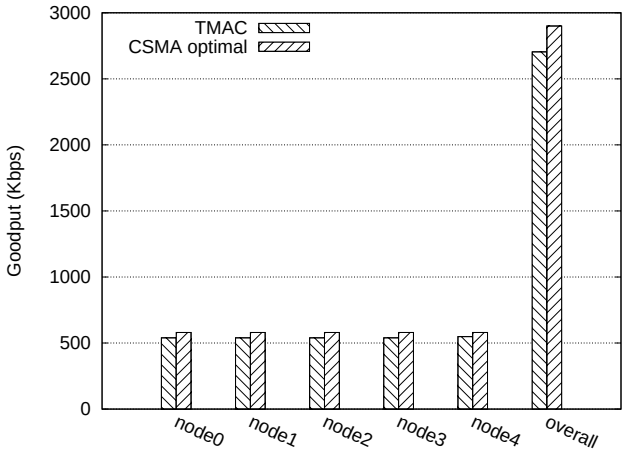

Figure V.6: Per-node goodput for a 5-hop PLT

a perfect scheduler.

V.4.1 Parking lot topologies

We evaluated TMAC with several variations of PLTs (Figure V.1). We present below a discussion on the fairness and convergence characteristics of TMAC.

TMAC fairness: First, we analyze flow rate fairness characteristics of TMAC. We first describe our results for a 5-hop chain. Figure V.6 shows the throughput obtained by TMAC compared to the reference optimal results discussed earlier. TMAC registers a utilization drop of approximately 7% compared to these reference results.

We have extensively evaluated TMAC over a number of additional PLTs, varying the size from 2-hops up to 6-hops. Our results are tabulated in Table V.4. For network utilization, we list the values normalized to the reference optimal results. TMAC achieves a minimum JFI of 0.99 and an average network utilization of around 93%.

TMAC convergence rate:

We use a 4-hop PLT to characterize the convergence time for various TCP flows. This experiment aims to obtain the time required for a new flow to converge to its fair rate allocation. At the beginning of the simulation, all flows are inactive. At time

Scenario	Norm. Net. Util.	JFI
2-hops	93.38%	0.999
3-hops	93.35%	0.999
4-hops	94.20%	0.999
5-hops	93.04%	0.999
6-hops	93.80%	0.998

Table V.4: TMAC over PLTs with 12 Mb/s links

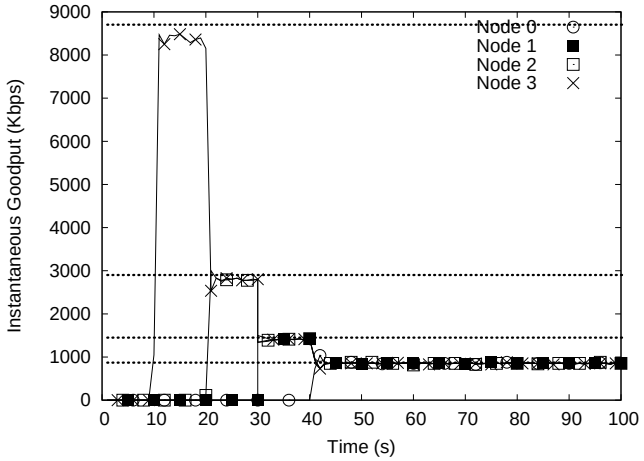

Figure V.7: The instantaneous goodput of a 4-hop PLT. New flows are initiated every 10 s. starting with the 1-hop flow from (node 3) at time 10 s. Dotted lines show the optimal throughput.

10 sec. the 1-hop node (node 3) initiates a flow destined to the gateway. Every 10 sec, each of the other nodes initiates a new flow destined to the gateway. Figure V.7 shows the instantaneous throughput of each flow (averaged over a 1 sec. interval). We observe that all flows successfully converge to their fair share assignments within 1 sec. from initiation.

V.4.2 Grid topologies

We extend our experiments to grid topologies as shown in Figure V.8. The vertical and horizontal spacing between nodes is 200 m; thus, nodes in a 4x4 grid topology have up to four neighbors in the transmission range and up to 11 neighbors in the

interference range. The number inside a node indicates its hop-count number along the shortest path to the gateway. All nodes in the network have an active TCP connection with the gateway.

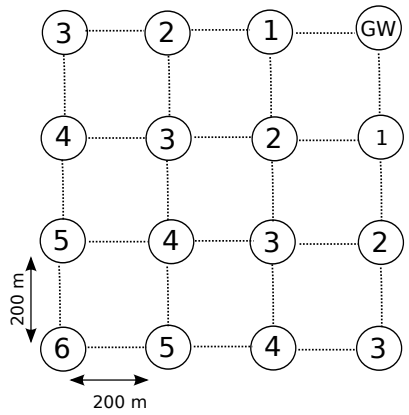

Figure V.8: A 4x4 grid topology. Node numbers represent the number of hops along the shortest path to the gateway. Dotted lines connect nodes that are within communication range relative to each other

Grid size	Norm. Net. Util.	JFI
2x2	92.42%	0.999
3x3	91.17%	0.992
4x4	90.18%	0.993

Table V.5: TMAC results for grid topologies with 12 Mb/s links

We performed several simulations while varying the grid size from 2x2 to 4x4. Our results are shown in Table V.5. TMAC achieves a network utilization higher than 90% while maintaining a JFI fairness of at least 0.99. Figure V.9 shows detailed results for TMAC compared to CSMA and CSMA/CA for the 4x4 grid. Both CSMA and CSMA/CA have nodes experiencing unfairness and starvation; approximately 45% and 65% of the nodes starve with CSMA and CSMA/CA, respectively. TMAC (both with and without data bursts) improves fairness amongst nodes. Using data bursts further increases average flow rate by approximately 15–20%. Thus our conservative choice of burst size parameters maintains a balance between the throughput and fairness requirements of this network.

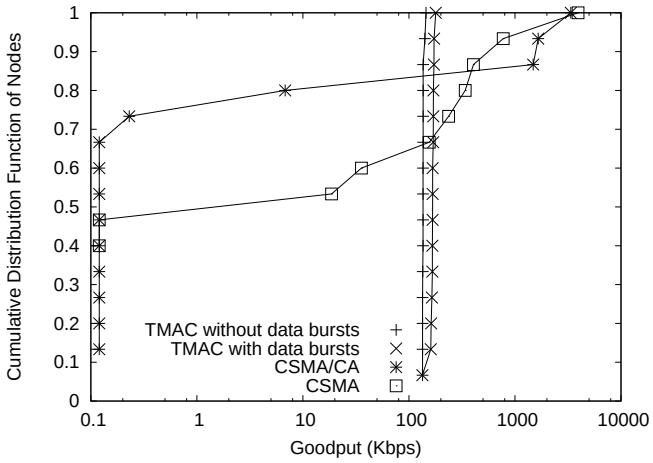

Figure V.9: The CDF of goodputs in a 4x4 grid topology

The TMAC convergence time, which is the time where the instantaneous throughput (we use granularity of 1 sec.) reaches its fair share, for the presented grid topologies is shown in Figure V.10. We observe that all nodes converge to their fair allocation within 7 sec. of the simulation run.

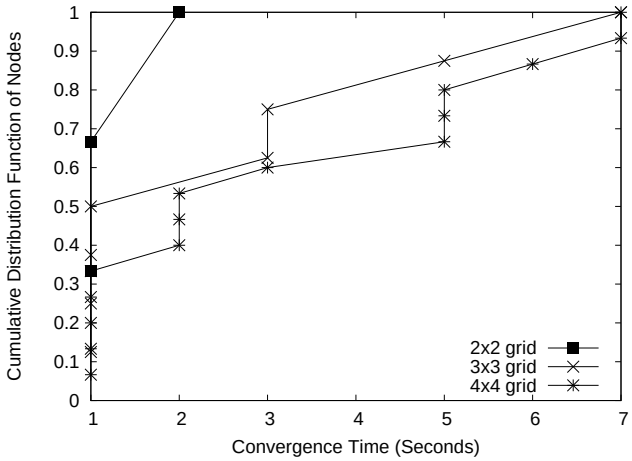

Figure V.10: The CDF of convergence time in grid topologies

V.4.3 Performance comparison with a centralized scheduler

We now report reference results obtained from a recently proposed centralized protocol, namely FBRC [43], introduced earlier in Section II.3.3. We will examine how

the distributed TMAC compares to a centralized solution. FBRC's results are obtained from a reference implementation over ns-2, which is an earlier version of the simulator used for TMAC's implementation. There are minor differences between the simulation environment of FBRC and TMAC. First, wireless link characteristic and interference models of both implementations correspond to the default values in their respective simulators. Moreover, ns-2 implements an interference model that allows for *Physical Layer Capture* (PLC)[2]. However, the capacity model used in this thesis assumes a static interference model, where PLC is not considered. Second, link capacities are 1 Mb/s and 12 Mb/s for FBRC and TMAC respectively. Thus, FBRC's reported results are normalized for comparison purposes. Third, used TCP implementations are NewReno and Tahoe for FBRC and TMAC respectively. However, these are minor differences and do not conflict with our purpose of using FBRC as a benchmark for comparison.

Performance results of FBRC are shown in Table V.6. We notice that for PLTs, FBRC achieves a higher utilization compared to TMAC. However, TMAC shows better fairness characteristics. FBRC achieves more than 100% network utilization for 5-hops and 6-hops PLTs, when normalized to the results obtained with the capacity model. This is due PLC. On the other hand, grid topologies show around 1-2% increase in utilization compared to TMAC, while showing a better JFI for a 3x3 grid and lower JFI for a 4x4 grid.

We conclude that a fully distributed protocol, TMAC, can achieve a more fair allocation than centralized schemes such as FBRC. For topologies with a large number of nodes, TMAC achieves a comparable capacity utilization. We believe these results demonstrate that a protocol that maintains the distributed nature of 802.11

[2]PLC [53] refers to successfully receiving a packet even in the event of a collision. Ns-2's model of PLC is to allow capturing the earlier packet, of multiple collided packets, if its received signal power exceeds others by a certain threshold.

Scenario	Norm. Net. Util.	JFI
4-hops PLT	96.60%	0.999
5-hops PLT	105.97%	0.995
6-hops PLT	108.14%	0.985
3x3 grid	91.96%	0.997
4x4 grid	91.67%	0.990

Table V.6: FBRC on PLTs and grid topologies with 1 Mb/s links

is capable of competing with centralized solutions. These improved fairness characteristics encourage us to continue investigating additional techniques to mitigate the difference in utilization for networks with a small number of nodes.

Chapter VI

Conclusions and future directions

We presented an analytical model to evaluate TCP throughput fairness over 802.11-based WMNs. Our model captures the interaction between multiple TCP streams and 802.11 MAC protocol. This is done by focusing on the relative flow utilization of the cumulative network queue. The multi-hop effect on TCP performance is modeled by embedding the number of transmission steps affecting the modeled queues. We then propose TMAC, a distributed MAC protocol to overcome the unfairness characteristics of 802.11 in multi-hop networks. TMAC effectively addresses the various causes of unfairness as observed in our model. We performed a simulation evaluation to validate the model and found that it can accurately predict flow throughput. Further experiments were performed on TMAC to confirm its fairness. TMAC is found to achieve resource allocation fairness in PLTs and large grid topologies while maintaining over 90% of maximum link capacity.

We are further investigating optimizing the performance of TMAC by inverting the use of grants. For example, in response to a request message from a sender S, a neighbor N instead responds with a deny message if it has a packet with an older timestamp pending for transmission. This can also suppress further transmission of messages from neighbors which have pending transmissions with a lower timestamp than S but higher than N. However, the challenge is how to act when a deny-message

is lost? The loss of deny-messages can inherently interpreted as a grant. This is problematic for wireless networks with high loss rates and being further investigated.

Currently, we are investigating extending the use of CNQ model to propose WMN-aware protocols in other layers of the protocol stack. Transport-layer protocols are a potential candidate for such work, *e.g.,* TCP's congestion control mechanism may be adapted to support the fairness requirements. The proposed model and the derived throughput equations can be formulated as an optimization problem to achieve fairness by limiting the congestion windows. This will enable us to achieve fairness by applying modifications to the gateway only. However, it is necessary to obtain real-time information and perform the optimization on the fly.

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