Providing Fairness and Maximising Throughput in

802.11 Wireless Mesh Network

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Abstract

The thesis addresses two questions: how to provide fairness in 802.11 wireless mesh networks and how to maximize the overall throughput in an distributed way. Fairness and efficiency are two fundamental issues in wireless networks, which are widely researched in both wired and wireless networks. We consider 802.11 wireless networks due to their ubiquity and practical importance. The likely trend of the wireless networks is toward the use of multi-hop wireless networks (so-called mesh networks), which provide the potential of serving the users in larger coverage with higher throughput. However, achieving fairness and efficiency remain bottleneck issues in the rollout of production-quickly mesh networks.
Chapter 1

Introduction

1.1 802.11 Wireless LAN

Over the last decades, wireless networks have become more and more popular as the last hop due to their support for mobility and flexibility. Pervasive in the workplace, the home, educational institutions, cafes, airports, and street corners, wireless LANs based on 802.11 technologies are now one of the most important access network technologies in the Internet today. There are several 802.11 standards for wireless LAN technology, including 802.11b, 802.11a and 802.11g. Table 1.1 summarizes some of the main characteristics of these standards.

1.1.1 Contention Mechanism

The IEEE 802.11 MAC defines two different access mechanisms, the mandatory Distributed Coordination Function (DCF) which provides distributed channel access based on a CSMA/CA, and the optional Point Coordination Function (PCF) which provides centrally controlled channel access through polling.

In the DCF, all stations contend for access to the medium, in a distributed manner, based on a CSMA/CA protocol. In the PCF, a Point Coordinator (PC), which is most often collocated in the AP, controls the medium access based on a polling scheme. As

<table>
<thead>
<tr>
<th>Standard</th>
<th>Frequency Range (United States)</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>2.4-2.485 GHz</td>
<td>up to 11 Mbps</td>
</tr>
<tr>
<td>802.11a</td>
<td>5.1-5.8 GHz</td>
<td>up to 54 Mbps</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4-2.485 GHz</td>
<td>up to 54 Mbps</td>
</tr>
</tbody>
</table>

Table 1.1: Summary of IEEE 802.11 standards
distributed operation is the most widely used, we focus here on the DCF scheme.

In the DCF, time is slotted and the channel states can be divided into three classes: idle slot, successful transmission and collision (two or more stations attempt to transmit at the same time). If there is no frame to transmit, a station chooses a random backoff value and it then decrements this each idle slot. While the channel is sensed busy, the counter value remains frozen until the channel has been detected idle for a period, known as the Distributed Inter-Frame Space (DIFS). When the counter reaches zero, the station transmits the entire frame and then waits for an acknowledgement which is sent by the receiver after a Short Inter-Frame Space (SIFS) after receiving the frame. If an acknowledgement is received, the transmitting station knows that its frame has been correctly received at the destination station. If the station has another frame to send, it begins a new random backoff. If the acknowledgement is not received, the transmitting station chooses a random value from a larger interval and counts it down again.

The random backoff value is uniformly chosen in the interval $[0, CW]$, called the Contention Window. At the first transmission attempt or after a successful transmission or discard, $CW$ is set to the minimum value, $CW_{\text{min}}$. $CW$ is doubled after each unsuccessful transmission until it reaches the maximum value, $CW_{\text{max}}$. An unsuccessful transmission is determined if the sender station does not receive an ACK frame within a specified ACK timeout period. After the ACK timeout period, the station assumes that a collision has occurred and enters into the backoff period again after waiting for medium to be idle for DIFS, such that the new backoff values is chosen from the doubled $CW$. A retransmit limit, referred to as the retry limit, is also specified in the DCF. A frame is discarded on an unsuccessful transmission after the retry limit is reached.

An additional mechanism, RTS/CTS, is defined to mitigate the hidden terminal problem found in wireless networks that use CSMA. With RTS/CTS, the sender and receiver perform a handshake mechanism by exchanging RTS (Request To Send) and CTS (Clear To Send) control frames. After waiting the DIFS time, prior to transmitting the data frame, the sender sends a RTS frame to the receiver, and the receiver responds with a CTS frame after waiting a SIFS time. The CTS frame indicates that the handshake is successful and ensures that the medium has been reserved for the particular sender and receiver for the subsequent data transmission.
1.1.2 802.11e

The IEEE 802.11 group also provides an enhanced extension to the 802.11 MAC, known as IEEE 802.11e, which aims to support quality of service (QoS) by introducing priority mechanisms.

IEEE 802.11e defines a new coordination function called the Hybrid Coordination Function (HCF) that combines aspects of the DCF and the PCF with enhanced QoS mechanisms. Similarly to the DCF, the Enhanced Distributed Channel Access (EDCA) is the distributed contention-based channel access mechanism of the HCF. The EDCA defines four Access Categories (ACs) for different types of traffic and a different values of MAC parameters may be used for each AC.

MAC parameters which were fixed in the previous IEEE 802.11 protocols can be adjusted in 802.11e, for example, \(CW_{\text{min}}\) and \(CW_{\text{max}}\) and additional parameters, such as AIFS and TXOP. The Arbitration Inter-Frame Space (AIFS) plays the role of DIFS in the DCF and is time the medium must be sensed idle before the transmission or backoff is started. Another new parameter is Transmission Opportunity (TXOP), the time during which the station has the right to remain transmitting once it has started a transmission. When a station wins access to the channel, it can transmit as many packets as possible such that the transmission duration does not exceed the TXOP limit. A non-zero value of TXOP Limit indicates that multiple frames might be sent in a burst and this is referred to as a Contention Free Burst (CFB). A TXOP of zero indicates that packet bursting is disabled and only one frame can be transmitted after winning channel access.

1.1.3 Rate Adaptation

The current 802.11 specification mandates the availability of multiple transmission rates at the physical layer (PHY) that use different modulation and coding schemes. For example, the 802.11b PHY supports four transmission rates (1~11Mbps), the 802.11a PHY offers eight rates (6~54Mbps), and the 802.11g PHY supports twelve rates (1~54Mbps). To exploit such multi-rate capability, a sender must select the best transmission rate and dynamically adapt its selection to the time-varying and location-dependent channel quality, without explicit information feedback from the receiver.

Rate adaptation is a link-layer mechanism critical to the system performance in IEEE 802.11-based wireless networks, yet is left unspecified by the 802.11 standards. Auto Rate Fallback (ARF)[41], the first documented bit-rate selection algorithm, has been paid much
attention because of its easy implementation. Following this research, many rate adaptation
algorithms are proposed. Among these algorithms, AMRR\[42\], ONOE\[46\], SampleRate\[43\]
are implemented in the MadWifi\[45\] Driver.

## 1.2 Mesh Networks

Wireless mesh architecture offer the potential of providing a high-bandwidth network over
a large coverage area. Wireless mesh networks are composed of wireless access points
(routers) that facilitate the connectivity and intercommunication of wireless clients through
multi-hop wireless paths. Mesh architectures sustain signal strength by breaking long
distances into a series of shorter hops. Intermediate nodes not only boost the signal,
but cooperatively make forwarding decisions based on their knowledge of the network, i.e.
perform routing. Such an architecture with careful design may provide high bandwidth,
spectral efficiency, and economic advantage over the coverage area. Wireless mesh network
are distinguished from ad hoc networks by their relatively stable topology.

### 1.2.1 Issues in Mesh Networks

Although mesh networks offer the potential for achieving large coverage and high through-
put, there are still many outstanding issues. These include channel allocation\[27\], efficient
MAC protocols\[23\], routing algorithms\[12\], and techniques for hidden terminal mitigation.

The well-known hidden terminal effects are illustrated in Fig. 1.1. The signal can
be obstructed by the buildings or other obstacles, and the signal strength is decreasing
through the medium due to fading, so that some stations can not hear the transmissions
from other stations. In mesh networks, however, the situation can be even worse. In the
example shown in Fig. 1.1(c) where station C is hidden to A, the throughput between A
and B would be zero if a same channel is used between A/B and C/D. The best solution
is to use orthogonal channels, then in the same example, the throughput between A and B
would be the same with that between C and D.

### 1.2.2 Multi-Ratio Mesh Network

As mentioned previously, one way to mitigate the hidden terminal problem in mesh network
is to use multi-radio techniques. The mesh network is formed from a series of WLANs,
each operating on an orthogonal channel from its neighbor to avoid hidden terminals. Mesh
stations equipped with multiple radios relay traffic between WLANs. This is illustrated for example in Fig. 1.2[38].

1.3 Fairness

In most networks, there are circumstances where the externally offered load is larger than can be served by the network. Then, if no measures are taken to restrict the behaviour of traffic in the network, congestion occurs and the actual network throughput may decrease as the offered load increases due to repeated retransmission of lost packets. When the offered load must be cut back, it is important to do so fairly. Unfortunately, maximizing total network throughput is often incompatible with fairness. Fairness can be defined in a number of different ways.

1.3.1 Max-Min Fairness and Proportional Fairness

Two important fairness concepts are max-min fairness and proportional fairness. Assume that each flow \( r \in S \) where \( S \) is the set of all the flows, has a data rate \( x_r \):

- Max-min Fairness[4] [44]: a feasible allocation of rates \( \{x_r\} \) is “max-min fair” if and
only if an increase of any rate within the domain of feasible allocations must be at
the cost of a decrease of some already smaller rate. Formally, for any other feasible
allocation \( \{y_r\} \), if \( y_r > x_r \) then there must exist some \( r' \) such that \( x_{r'} \leq x_r \) and
\( y_{r'} < y_r \).

- Proportional Fairness[44]: an allocation of rates \( \{x_r\} \) is “proportionally fair” if and
only if, for any other feasible allocation \( \{y_r\} \), we have:

\[
\sum_{r=1}^{S} \frac{y_r - x_r}{x_r} \leq 0
\]

In other words, any change in the allocation must have a negative average change.

Max-min fairness states that small flows receive what they demand and larger flows
share the remaining capacity equally. Bandwidth is allocated equally to all flows until one
is satisfied, then bandwidth is equally increased among the remainder and so on until all
flows are satisfied or bandwidth is exhausted. Depending on the problem, a max-min fair
allocation may or may not exist. However, if it exists, it is unique.

Proportional fairness is a compromise-based scheduling algorithm, which is based upon
maintaining a balance between two competing interests: trying to maximize total wireless
network throughput while at the same time allowing all users at least a minimal level
of service. This is done by assigning each data flow a data rate or a scheduling priority
(depending on the implementation) that is inversely proportional to its anticipated resource
consumption.

### 1.3.2 Utility Fairness

Utility fairness[44] is a general fairness concept, which subsumes proportional fairness,
minimum potential delay fairness, and max-min fairness as special cases.

Suppose that each flow \( r \) derives a utility (or benefit) of \( U_r(x_r) \) when a data rate \( x_r \) is
allocated to it. Then the utility fair approach is to allocate the network resources to solve
the following optimization problem:

\[
\max_{\{x_r, r \in S\}} \sum_{r \in S} U_r(x_r)
\]

subject to

\[
\sum_{r: l \in R_r} x_r \leq c_l, l \in L,
\]
\[ x_r \geq 0, r \in S, \]

where \( R_r \) is the set of links traversed by flow \( r \), \( c_l \) is the capacity of link \( l \), \( L \) is the set of all links and \( S \) is the set of all flows in the network.

When the utility function of flow \( r \) is of the form\[25\],

\[
U_r = \begin{cases} 
\omega_r \frac{x_r^{1-\alpha_r}}{1-\alpha_r} & \alpha_r \geq 0, \alpha_r \neq 1, \\
\omega_r \log x_r & \alpha_r = 1.
\end{cases}
\]

Then this incorporates the following objectives:

- Rate maximization when \( \alpha_r = 0 \)
- Proportional fairness when \( \alpha_r = 1 \)
- Minimum potential delay fairness when \( \alpha_r = 2 \)
- Max-min fairness when \( \alpha_r \to \infty \)

### 1.3.3 Fairness in 802.11 Wireless Mesh Networks

Fairness in wired networks has been extensively researched and globally fair rates can be attained by distributed approaches based on convex programming. However, these techniques can not be directly applied to CSMA/CA wireless networks, because the feasible rate region is nonconvex\[37\] \[19\].

Most of the literature on utility fairness in CSMA/CA networks realtes to Aloha networks rather than 802.11. It is shown in \[37\] that the Aloha rate region is log-convex and using this fact, distributed algorithm for achieving utility fair rate allocations are derived in \[?\](I guess it is not the paper about proportional fairness in aloha networks, and I don’t know the paper you mention).

Recently, it has been established in \[19\] that the 802.11 rate region is also log-convex, and this is used in \[38\] to study max-min fairness in 802.11 mesh networks. We note that these results were obtained seperately from the work reported in this thesis, and are complementary to it. In \[21\],the fairness of TCP traffic in 802.11 WLANs is addressed and the use of 802.11e is proposed to solve the problem.

As noted previously, to counteract the loss due to noise and interference from other source, multiple data rates are implemented. However, a slow station may dominate the channel in a multi-rate network. \[30\] proposes the use of time-based fairness to improve performance of multi-rate WLANs.
1.4 Contribution

In the work, two fundamental issues, fairness and efficiency in 802.11 wireless mesh networks are considered. The fairness is addressed and per-flow fairness is achieved by using TXOP. Meanwhile, the throughput efficiency is discussed by giving the theory proof and a distributed algorithm. Furthermore, part of the work is shown in [40] [39] and [38].
Chapter 2

MAC Unfairness in 802.11 Mesh Networks

2.1 Introduction

This chapter describes in more detail the MAC induced unfairness that can be found in 802.11 networks. In order to focus on MAC related issues, we consider topologies, where stations are equipped with multiple radios to avoid interference and hidden terminals. We also assume fixed routing.

2.2 Notation

Before proceeding we first describe the notation used in Fig. 2.1 and elsewhere. Client stations are marked by shadowed triangles, and mesh points (MPs) by circles. MPs are stations that relay traffic for client stations. There are 10 MPs in Fig. 2.1 where $MP_9$ acts as a gateway between the wireless multi-hop network and the wired Internet. Each MP has two radios that use channels in such a way that the channel in each hop is orthogonal to those in neighboring hops thereby avoiding interference between transmissions on different hops. Hence there are no hidden terminals. We assume that the set of routes from sources to destinations are already obtained by routing protocols such as those discussed in [11] and [12]. The routes are stable during the considered sessions’ life time. We only consider single-path routing. We use station to refer to any wireless devices (both client stations and MPs). We say client station when referring to wireless devices other than MPs. Let
\( n_i \) denote the number of client stations in channel \( i \) in the topologies in Fig. 2.1.

### 2.3 802.11 Unfairness with UDP Traffic

We begin by considering UDP traffic in the topologies in Fig. 2.1, and then extend consideration to TCP traffic.

#### 2.3.1 Without local flows

Even in the simple topology in Fig. 2.1(a), significant unfairness can exist between traffic flows. Each client station carries one upload and one download flow, and the upload and download traffic is aggregated at \( MP_9 \) which is the gateway between the wired and wireless networks. The MAC/PHY parameters are given in Table 2.1 and the rate of CBR traffic is 1 Mbps, so that all the stations are saturated. It can be seen that the throughput achieved by the upload flows is approximately an order of magnitude greater than that achieved by the download flows.

We can gain some insight into the source of this unfairness by looking at the corresponding per hop measurements shown in Fig. 2.2(b). It can be seen that on the relay hops, the aggregate throughput of the upload flows and of the download flows are approximately equal. However, at the left-hand hop, between the client stations and \( MP_0 \), the situation is very different.

Note that the 802.11 MAC ensures that roughly the same number of transmission opportunities are allocated to every station [21] [17], including the MPs. Thus, if there are \( n_0 \) client stations and all the stations (including \( MP_0 \)) are saturated, we expect each of them to obtain roughly a \( 1/(n_0 + 1) \) share of the bandwidth, and similarly for \( MP_0 \) to obtain a \( 1/(n_0 + 1) \) share. The \( n_0 \) upload flows therefore together obtain an \( n_0/(n_0 + 1) \) share whereas since all of the download flows must be transmitted via \( MP_0 \) and so they can only obtain approximately a \( 1/(n_0 + 1) \) share altogether. We can confirm this approximate reasoning by noting that the aggregate upload throughput at the left-hand hop in this
Figure 2.2: CBR results for scenario in Fig. 2.1(a). Per flow throughput is shown in Fig. 2.2(a). Per hop aggregate throughput (in Mbps) is plotted in Fig. 2.2(b).

Table 2.1: MAC/PHY parameters used in simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{SIFS}$ ($\mu$s)</td>
<td>10</td>
</tr>
<tr>
<td>Idle slot duration ($\sigma$) ($\mu$s)</td>
<td>20</td>
</tr>
<tr>
<td>$T_{DIFS}$ ($\mu$s)</td>
<td>50</td>
</tr>
<tr>
<td>$CW_{min}$</td>
<td>31</td>
</tr>
<tr>
<td>$CW_{max}$</td>
<td>1023</td>
</tr>
<tr>
<td>Retry limit</td>
<td>4</td>
</tr>
<tr>
<td>Packet size (bytes)</td>
<td>1000</td>
</tr>
<tr>
<td>PHY rate (Mbps)</td>
<td>1</td>
</tr>
<tr>
<td>PLCP rate (Mbps)</td>
<td>1</td>
</tr>
</tbody>
</table>

This type of unfairness is not new and has previously been observed in the context of single-hop WLANs (e.g., [21]). However, the impact of this unfairness can be far greater in a multi-hop context as we will see in the next section.

2.3.2 With local flows

To see the increased unfairness over multiple hops, consider the multi-hop network in Fig. 2.1(b) with one local client station at $MP_8$. End-to-end traffic from the left-hand client stations, numbered 1-10 in Fig. 2.1(b), now has to compete with the traffic from client station 11 at the $MP_8$ hop. The foregoing unfairness effect now acts multiplicatively at hops $MP_0$ and $MP_8$, greatly amplifying the level of unfairness. This effect is illustrated in Fig. 2.3(a). Here, stations 1-11 each carries one upload and one download flow, yielding 11 upload and 11 download flows in total. It can be seen from Fig. 2.3(a) that the upload flow at station 11 gains much greater throughput than the other flows.

What is happening is that at $MP_8$, each local upload flow obtains roughly a $1/(n_8 + 2)$ share of the bandwidth, where $n_8 = 1$ is the number of client stations associated with $MP_8$. An example is measured to be 0.657 Mbps while the aggregate download throughput is 0.068 Mbps. The ratio of upload to download throughput is thus 9.66, i.e. close to the value of $n_0 = 10$.

This type of unfairness is not new and has previously been observed in the context of single-hop WLANs (e.g., [21]). However, the impact of this unfairness can be far greater in a multi-hop context as we will see in the next section.
Figure 2.3: CBR results for scenario in Fig. 2.1(b). Per flow throughput is shown in Fig. 2.3(a). Per hop aggregate throughput (in Mbps) is plotted in Fig. 2.3(b). Note that 0.553 Mbps in Fig. 2.3(b) is the aggregate throughput of local upload originating from client station 11 and relay uploads from $MP_7$ to $MP_8$.

$MP_8$ and the 2 on the denominator accounts for end-to-end upload traffic from $MP_7$ and download traffic from $MP_8$. The aggregate upload traffic from client stations 1-10 also obtains a $1/(n_8+2)$ share (corresponding to the share of upload transmission opportunities allocated to $MP_7$). Thus each individual upload flow from client stations 1-10 obtains only a $1/10(n_8+2)$ share. In line with this analysis, Fig. 2.3(a) confirms that the upload flow from client station 11 obtains roughly an order of magnitude greater throughput than the upload flows from client stations 1-10.

The aggregate download traffic to client stations 1-11 also obtains a $1/(n_8+2)$ share at the $MP_8$ hop. The download traffic to client stations 1-10 then has to compete against the upload traffic from stations 1-10 for transmission opportunities at $MP_0$. This creates further unfairness. As discussed above, at the $MP_0$ hop there is approximately an order of magnitude unfairness between upload and download flows and this can been seen in Fig. 2.3(a).

The setup in Fig. 2.1(b), where download traffic must contend at two hops, is already sufficient to create a level of unfairness whereby download traffic to client stations 1-10 is almost starved of throughput. By introducing contention at further relay hops, the unfairness can evidently be amplified still further. In effect, the potential exists for almost arbitrary levels of unfairness to exist between competing traffic flows in a multi-hop setting. Note that this effect is not associated with interference or other sources of unfairness. Rather it is a direct consequence of the properties of the 802.11 MAC.

### 2.4 802.11 Unfairness with TCP Traffic

The previous section considers MAC flow unfairness with UDP traffic. However, the majority of traffic on the Internet is based on TCP. The congestion control feedback within
TCP introduces additional issues that we now consider in this section.

### 2.4.1 Overview of TCP

TCP is the Internet’s transport-layer, connection-oriented, reliable transport protocol, that is implemented on top of the unreliable (IP) network layer. To achieve reliable data transfers, TCP receivers return ACK packets to the data senders confirming the safe arrival of data packets with lost packets being retransmitted.

To achieve congestion control, TCP regulates the number of sent but unacknowledged packets (“in flight” packets) to be no more than the congestion window $cwnd$. TCP also makes use of ACK clocking, whereby data packet transmissions primarily occur on receipt of TCP ACKs. A sender reduces its $cwnd$ when a data packet loss event occurs and additively increases its $cwnd$ when it perceives that the end-to-end path is congestion free. The process of TCP congestion window adjustment is illustrated in Fig. 2.4.

### 2.4.2 Prioritising TCP ACKs Using 802.11e

To illustrate the unfairness when using TCP in 802.11 networks, we use the topology depicted in Fig. 2.5 where there are 8 flows altogether, with end-to-end flow 0 traversing three hops, flows 1 and 2 traversing the first hop, and flows 3 – 7 traversing the third hop.

In Fig. 2.6(a) we plot the results with the 802.11 DCF as the MAC layer, i.e., both TCP data and ACK packets are put into the same queue whose parameters are given in Table 2.1. It can be seen that (i) it takes a long time for the TCP flow throughput to become steady (if ever), and (ii) flows sharing the same client station achieve significantly different throughput.

We can understand this behaviour by noting that TCP flows are bidirectional, with data
packets travelling in one direction and TCP ACK packets in the reverse direction. TCP ACK packets for all of the 8 flows must be transmitted by $MP_2$. As discussed in Section 2.3 for UDP upload/download flows, this can lead to TCP ACKs becoming backlogged at $MP_2$ and so result in excessive losses of TCP ACKs due to queue overflow. This potential queuing and dropping of TCP ACKs can disrupt the TCP ACK clocking mechanism and so hinder congestion window growth and induce repeated timeouts. This is exacerbated by the sensitivity of flows with small $cwnd$ to packet loss since retransmissions can then only take place via timeouts rather than by fast retransmit, which tends to create sustained unfairness between flows with large $cwnd$ and those with smaller $cwnd$. To address this problem, we collect into a single queue the outgoing TCP ACKs and assign high priority to this queue using a small $CW_{\text{min}} = 3$, a small $CW_{\text{max}} = 7$ and a small $AIFS = 1$. The corresponding parameters for TCP data packets use the standard DCF values $CW_{\text{min}} = 31$, $CW_{\text{max}} = 1023$ and $AIFS = 2$. This ensures that TCP ACK packets effectively have unrestricted access to the wireless medium. When the wireless hop is the bottleneck, data packets will be queued for transmission and packet drops will occur there, while TCP ACKs will pass freely with minimal queuing, i.e., the standard TCP semantics are recovered.

The effectiveness of this approach is illustrated when we compare Fig. 2.6(a) (no ACK prioritisation) with Fig. 2.6(b) (with ACK prioritisation). We see that flow throughput is stabilised and that flows on the same station now have approximately the same throughput. However, denoting $x_i$ to be the throughput achieved by $MP_i$, then $x_0 = 0.39$ Mbps, $x_1 = 0.19 \times 2 = 0.38$ Mbps and $x_3 = 0.08 \times 5 = 0.40$ Mbps. However, gross unfairness still exists when we consider per-flow throughput. For example, the throughput of flow 0 is 0.4 Mbps, whereas that of flows 3 – 7 is 0.08 Mbps.

For the previous topologies in Figs. 2.1(a) and 2.1(b), we show in Figs. 2.7(a) and 2.7(b) the corresponding results for TCP flows when TCP ACKs are prioritised. It can be seen that once again the network exhibits unfairness between upload and download flows and between local and end-to-end flows.
Figure 2.6: Throughput fairness: TCP results in the topology shown in Fig. 2.5. Throughput values are average over 20s.

Figure 2.7: Measured flow throughput with prioritised TCP ACKs in Fig. 2.1(a) and 2.1(b) respectively.
Chapter 3

Restoring fairness

3.1 WLAN Throughput Model

We begin by considering modelling the throughput of 802.11 networks, taking TXOP packet bursting into account. Following [5], we divide time into MAC slots, where a slot corresponds to either a successful transmission, a collision (two or more simultaneous transmissions) or an idle slot (corresponding to a PHY idle slot). Consider a WLAN with \( n \) stations. Denote the slot transmission attempt probability of station \( i \) by \( \tau_i \). Let \( P_{s,i} \) denote the probability of a successful transmission in a given slot by station \( i \) and \( P_c \) the corresponding collision probability. We have that:

\[
P_{s,i} = \tau_i \prod_{j \neq i} (1 - \tau_j) \quad (3.1)
\]

\[
P_c = 1 - \sum_{i=1}^{n} P_{s,i} - P_i \quad (3.2)
\]

where

\[
P_i = \prod_{i=1}^{n} (1 - \tau_i), \quad (3.3)
\]

is the probability that a slot is idle.

Let \( N_i \) denote the mean TXOP burst size (in packets) at station \( i \). We can express the throughput of station \( i \) as follows:

\[17\]
\[ s_i(T, N) = \frac{E[\text{payload information transmitted in a MAC slot}]}{E[\text{length of a MAC slot}]} \]
\[ = \frac{P_{s,i} N_i L}{\sigma P_t + T_s \sum_{i=1}^{n} N_i P_{s,i} + T_c P_c} \]

where \( T = [\tau_1 \cdots \tau_n]^T \), \( N = [N_1 \cdots N_n]^T \), \( L \) is the packet size (in bits); \( T_s \) is the duration of a successful transmission (the sum of DATA frame duration and MAC ACK duration plus SIFS); \( T_c \) is the collision duration (the duration of DATA plus ACK timeout), \( \sigma \) is the duration of a PHY slot.

Letting
\[ X = [x_1 \cdots x_n]^T, \]
\[ x_i = \tau_i / 1 - \tau_i, \]
the throughput expression can be rewritten as:

\[ s_i(X, N) = x_i N_i \frac{L}{X T_c} = \frac{x_i N_i L}{X T_c} \]

where
\[ X = (\sigma/T_c - 1) + \sum_i (N_i T_s / T_c - 1)x_i + \prod_i (1 + x_i) \]

Observe that the throughput of each station is proportional to \( x_i N_i \) in Equation (3.6), and the denominator \( X \) is the same for all stations. When stations are saturated (always have a packet to send) and have the same attempt probability such that \( x_i = \bar{x} \), we have that:
\[ \frac{s_i}{s_j} = \frac{N_i}{N_j} \]

For stations which are non-saturated, we assume sufficient buffering that the throughput equals to the offered load, and that the attempt probability is the value which solves Equation (3.6) for the offered load.

Modelling of TCP over wireless is challenging due to the interactions between the TCP congestions control action, interface queue dynamics and the MAC layer channel contention mechanism. However, following [21], we note that TCP ACKs are ready for transmission shortly after the corresponding TCP DATA packet is received, creating a strong time correlation between these events when the propagation delay of the wired component of
the TCP path is small. In this case, the TCP throughput model can be modelled using Equation (3.6) but with \( T_s \) modified to be the time required to send a TCP DATA packet and receive the TCP ACK. The accuracy of the simplified model is also shown in [21]. The result of the simplified model is very close to the simulation result.

### 3.2 Per-flow Throughput Fair Allocation

Let the number of flows with packets queued at station \( i \) be \( N_i \) and let \( T_i \) denote the TXOP duration. We consider two related approaches. The first approach is to select the TXOP duration

\[
T_i = N_i \times T_s,
\]  

where \( T_s \) is the time for transmitting a packet. Using this approach, \( N_i \) packets are allowed to be transmitted once a transmission opportunity is won, and each packet transmission takes \( T_s \) time. Combining this TXOP allocation with the use of a modified queuing discipline that serves one packet per flow at each transmission opportunity, it follows from Equation (3.7) that this scheme ensures that backlogged flows in a WLAN are on average allocated the same throughput.

We illustrate the impact of this scheme under CBR traffic in Fig. 3.2(c) which shows the flow throughputs for the topologies in Fig. 2.1(a) and Fig. 2.1(b). The other parameters are shown in Table. 2.1. For the topology in Fig. 2.1(a), TXOP = 10 at all MPs according the approach in Equation (3.8). It can be seen from Fig. 3.1(a) that all flows are backlogged at the left-hand hop and achieve similar throughput. For the topology in Fig. 2.1(b), TXOP = 10 at \( MP_0, \cdots, MP_7 \), TXOP = 11 at \( MP_8, MP_9 \). All flows are backlogged at the right-hand hop and similarly achieve similar throughput in Fig. 3.1(b).

Then consider the impact of the scheme under TCP traffic. The same TXOPs are set as mentioned above. For the previous topologies in Figs. 2.1(a) and 2.1(b), we show in Figs. 2.7(a) and 2.7(b) the corresponding results when TCP ACKs are prioritised, while in Figs. 3.2(a) and 3.2(b) we show the results when in addition the proposed TXOP mechanism is used. For the topology in Fig. 2.5, flows 0 and 3 – 7 are backlogged at the right-hand hop while flows 1,2 are backlogged at the left-hand hop. The capacity at each hop is not the same since the throughput is dependent on the number of contending stations, which differs at each hop. By setting the TXOPs (TXOP=2 at client station 1, TXOP=4 at client station 2), flow 0 and flows 3 – 7 achieve almost the same throughput of 0.125 Mbps, while flows 1 and 2 achieve almost the same throughput of 0.33 Mbps. In all cases, with
the proposed TXOP scheme per-flow fairness is restored as expected.

### 3.3 The MIT Roofnet Topology

We further validate the TXOP scheme proposed in Equation (3.8) in a subset of the MIT Roofnet topology (see Fig. 3.3). In this topology, there is an Internet gateway marked as GW. Orthogonal channels are assigned in neighbouring hops so that transmissions do not interfere. The locations of the client stations and MPs are selected from data derived from the GPS coordinates of the MIT Roofnet network. There are altogether 21 TCP flows and the allocation of flows between client stations is detailed in Table 3.1. Routing for each flow is via the GW and is statically assigned as indicated by the arrows in Fig. 3.3. For example, flow 0 traverses orthogonal channels 0, 1, 3, 4 and 2 from the client station 0 to the gateway GW.

![Figure 3.1: CBR results](image1)

![Figure 3.2: TCP results](image2)

<table>
<thead>
<tr>
<th>Source station(s)</th>
<th>Number of flows on each station</th>
<th>Flow ID(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 8</td>
<td>1</td>
<td>0 – 8</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>9 – 11</td>
</tr>
<tr>
<td>10, 11</td>
<td>1</td>
<td>12, 20</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>16, 17</td>
</tr>
<tr>
<td>13 – 15</td>
<td>1</td>
<td>15 – 17</td>
</tr>
<tr>
<td>16, 17</td>
<td>1</td>
<td>13, 14</td>
</tr>
</tbody>
</table>

Table 3.1: Flows in the roofnet topology in Fig. 3.3.
In Fig. 3.4(a) we illustrate the resulting throughput when TCP ACKs are prioritised but the proposed TXOP scheme is not used. In this topology, all flows share channel 2 at the gateway GW which forms a shared bottleneck. Specifically, MPs 3, 5 and 8 act as relays between the gateway GW and the three branches of the network. With 802.11, these MPs share channel 2 equally, and receive roughly the same throughput. To see this observe that flow 20 obtains a throughput of 0.252 Mbps, flows 0 – 12 achieve 0.0188 * 12 + 0.022 = 0.247 Mbps and flows 13 – 19 achieve 0.035 * 7 = 0.245 Mbps. When the TXOP scheme proposed in Equation (3.8) is now used, it can be seen that per-flow fairness is now achieved, see Fig. 3.4(b).

### 3.4 Time-Based Fair Allocation

When multiple PHY rates are available, stations using slow PHY rates tend to dominate the channel access, resulting in fast and slow stations achieving a similar throughput[17]. For example, we select the PHY rate between client station 0 and $MP_2$, and that between client station 0 and $MP_2$ to be 11 Mbps in the topology shown in Fig. 2.5, while keeping other PHY rates at 1 Mbps. If we use the TXOP scheme in Equation (3.8), the resulting flow throughput is shown in Fig. 3.5(a) where we can see that a similar throughput allocation...
Figure 3.4: TCP flow throughputs for the topology in Fig. 3.4. Note that in Fig. 3.4(a), the throughput of flows 13 – 19, and that of flows 0 – 12 are equal, while in Fig. 3.4(b), the throughput of all flows is roughly equal.

Motivated by this, we consider modifying the TXOP scheme in Equation (3.8) to become

\[ T_i = N_i \times T_{\text{max}} \]  

(3.9)

where \( T_{\text{max}} \) is the time for transmitting a packet at the slowest PHY rate\(^1\). Again, we combine this scheme with a modified queueing discipline. Using this approach, backlogged flows at a link are on average allocated the same \textit{air time} to transmit, regardless of their actual PHY rates. Putting it another way, flows running at a higher PHY rate may send more packets than flows with lower PHY rates. Of course when all stations use the same PHY rate, the two approaches are equivalent. However, when stations have different PHY rates, the fairness properties of the two approaches are different.

Using this scheme for the topology in Fig. 2.5, \( MP_0 \) and \( MP_4 \) use a TXOP duration \( K = 9230 \text{ } \mu\text{s} \) where 9230 \( \mu\text{s} \) is the time for transmitting a 1000-byte packet at 1 Mbps, and \( MP_1 \) and \( MP_3 \) use \( T_1 = 9230 \times 2 \text{ } \mu\text{s} \) and \( T_3 = 9230 \times 5 \text{ } \mu\text{s} \). In Figs. 3.6(a) and 3.6(b) we illustrate the corresponding throughput and time results. As we can see, channel usage

\(^1\)The slowest rate of 802.11b/g is 1 Mbps, while that of 802.11a is 6 Mbps.
Figure 3.5: Throughput-fairness allocation when multiple PHY rates are available for the scenario in Fig. 2.5. The link rates between $MP_0$ and $MP_2$, and $MP_4$ and $MP_5$ are 11 Mbps, while other link rates are still 1 Mbps. Other simulation parameters listed in Table 2.1. Note that in Fig. 3.5(a), the throughput of flow 0 is similar with that of flows 3 – 7. In Fig. 3.5(b), the channel usage time of flows 3 – 7 is also similar.

Figure 3.6: Time-based fairness allocation when multiple PHY rates are available for the scenario in Fig. 2.5. The link rates between $MP_0$ and $MP_2$, and $MP_4$ and $MP_5$ are 11 Mbps, while other link rates are still 1 Mbps. Other simulation parameters listed in Table 2.1. Note that in Fig. 3.6(a), the throughput of flows 3 – 7 is roughly equal. In Fig. 3.6(b), the time of flow 0 is almost same with that of flows 3 – 7.

time is now per-flow fair with the throughput of flow 0 higher than others as expected. The difference between the throughput of flow 0 and that of flows 3 – 7 is around a factor of 7, which is the same as $9230/1303$. In comparison, using the throughput-fair allocation in Equation (3.8), $MP_0$ and $MP_4$ use a duration $T = 1303 \mu s$ where $1303 \mu s$ is the time for transmitting a packet at 11 Mbps, but $MP_1$ and $MP_3$ use $T_1 = 9230*2 \mu s$ and $T_3 = 9230*5 \mu s$.

For the MIT roofnet topology in Fig. 3.3, we illustrate the effectiveness of the time-based allocation Equation (3.9) by increasing all the link rates from station 11 to the gateway GW to be 11 Mbps, while keeping other link rates at 1 Mbps. Other simulation parameters are listed in Table 2.1. The resulting flow throughputs using the throughput-fair allocation Equation (3.8) and the time-based allocation Equation (3.9) are shown in Figs. 3.7(a) and 3.7(c) respectively. In Fig. 3.7(c), we also plot the channel usage time of
Figure 3.7: Time-based fairness allocation when multiple PHY rates are available for the scenario in Fig. 3.3. All the link rates from station 11 to the gateway GW are 11 Mbps, while other link rates are still 1 Mbps. Other simulation parameters listed in Table 2.1.

each flow over 100 seconds. It is evident that per-flow fairness in terms of channel usage time is achieved.

### 3.5 Max-Min Fairness

While the foregoing simulations consider specific topologies, we comment that it has subsequently been shown[32] that the TXOP scheme in Equation (3.8) achieves max-min fairness in general topologies. When all stations use the same PHY rates, while the TXOP scheme in Equation (3.9) achieves time-based weighted max-min fairness[13].

### 3.6 Impact of lossy channel

Now we briefly extend consideration to include losses due to channel noise. Consider the two hop network in Fig. 3.8. There are altogether 21 TCP flows in the example: 10 one-hop flows in each hop and 1 end-to-end flow (Flow 10) traversing two hops. In this topology, we expect that each flow should have the same throughput if the resulting allocation is fair, and can be seen from Fig. 3.9(a) that this is indeed this case.

Figure 3.8: Topology with lossy link.
Figures 3.9(b), 3.9(c) and 3.9(d) show the goodput allocations with lossy links. Here we think each link has the same loss rate. It can be seen that for a BER of $10^{-6}$, the noise related losses have little impact on fairness compared to the noise-free case. For 1000 Byte packets a BER of $10^{-6}$ corresponds to a packet loss rate of 0.796%, which is even negligible. This is consistent with the recent theoretical results in [34] which establish that the max-min fair allocation varies smoothly as the level of losses is increased. Thus when the loss rate is low it will have only a small impact on fairness.

At higher BERs fairness starts to degrade significantly. From the results at a BER of $10^{-5}$ ($PER \approx 7.69\%$) which is already higher that is likely to be encountered in production networks, it can be seen that a higher level of channel losses eventually leads to significant unfairness – the two-hop flow now achieves about 20% less throughput than that of the one-hop flows. When each link has a BER of $10^{-4}$ ($PER \approx 55.1\%$), the throughput of the two-hop flow is only half of that of the one-hop flows. The unfairness arises because the two-hop flow sees a greater end-to-end loss rate than the one-hop flows.
Chapter 4

Experimental measurements

We implemented the topologies shown in Figure ? and Figure ? using a testbed constructed from Soekris net4801 stations with Atheros 802.11a/b/g miniPCI cards. The NICs used support 802.11e EDCF functionality which makes adjustable the MAC parameters AIFS, CWmin and TXOP. All stations run Linux 2.6.21.1 with a version of the MADWiFi driver customised to allow the priorisations described in this paper. Otherwise, tests were performed in infrastructure mode using standard 802.11a parameters and channels with PHY rate 6Mbps. To implement dual-radio mesh relay points, we joined two net4801s at 100Mbps with a cross-over cable to form a single logical mesh point. This avoided potential interference between network cards sharing the same PCI backplane. Routing in the network was statically configured. Iperf was used to generate TCP traffic and data was collected from both iperf and tcpdump. TCP ows used SACK enabled NewReno.
Chapter 5

Improving network capacity

In this chapter we consider improving network capacity while maintaining flow fairness and decentralised operation.

5.1 Maximising WLAN throughput

5.1.1 Homogeneous Stations

We begin by considering a homogeneous network, where all stations have the same attempt probability $\overline{\tau}$ and are saturated, i.e always have a packet to send at every transmission opportunity.

The network throughput model has been given in Section 3.1. Let $\bar{x} = \frac{\overline{\tau}}{1 - \overline{\tau}}$. Equation (3.6) can be rewritten as follows:

$$s_i(\bar{x}, N) = \frac{\bar{x} N_i L}{X T_c}$$

where

$$X = (\sigma / T_c - 1) + \bar{x} \sum_i (N_i T_s / T_c - 1) + (1 + \bar{x})^n.$$ 

Setting the derivative of $s_i$ with respect to $\bar{x}$ to zero leads to:

$$\frac{ds_i}{d\bar{x}} = \frac{N_i L}{T_c} \frac{1}{X^2} (X - \bar{x} \sum_i (N_i T_s / T_c - 1) - n(1 + \bar{x})^{n-1}) = 0$$
Equation (5.2) can be rewritten as:

\[ \frac{\sigma}{T_c} - 1 + (1 + \bar{x})^n (1 - n\bar{x}/(1 + \bar{x})) = 0 \]  

(5.3)

That is

\[ 1 - n\bar{x} = \epsilon P_i. \]  

(5.4)

where \( \epsilon = 1 - \sigma/T_c \), i.e.

\[ 1 - \sum_{j=1}^{n} \tau_j = \epsilon P_i. \]  

(5.5)

Solving for \( \bar{x} \) yields the attempt probability that maximizes the stations’ (and so WLAN) throughput.

### 5.1.2 Heterogeneous Stations

Consider now a WLAN with \( n \) stations, with station \( i \) having offered load \( s_i \). We partition the WLAN into \( n - m \) stations with attempt probability \( \bar{x} \) such that \( s_j \geq \frac{\bar{x} L}{X T_c} = \bar{s}, j = m+1, \cdots, n \) and \( m \) stations with attempt probability such that \( s_j = \frac{x_j L}{X T_c} \) and \( x_j < \bar{x}, j = 1, 2, \cdots, m \). That is, we partition stations into those which are able to service their offered load and those which cannot. We seek the value of \( \bar{x} \) that maximizes the value \( \bar{x}/X \). We have that

\[ X = \frac{\sigma}{T_c} - 1 + \prod_{j=1}^{m} (1 + x_j)(1 + \bar{x})^{n-m} \]

Differentiating,

\[ \frac{d\bar{x}/X}{d\bar{x}} = \frac{d\bar{x}/X}{dX} \frac{dX}{d\bar{x}} \]

Now

\[ \frac{dX}{d\bar{x}} = (n - m) \prod_{j=1}^{m} (1 + x_j)(1 + \bar{x})^{n-m-1} > 0 \]

Hence, setting the derivative equal to zero observe that

\[ \frac{d\bar{x}/X}{d\bar{x}} = 0 \Rightarrow \frac{d\bar{x}/X}{dX} = 0 \]

We have that

\[ \frac{d\bar{x}/X}{dX} = \frac{1}{n-m} Y^{1-m-1} \left[ \frac{dX}{d\bar{x}} X - \{Y^{1-m} - 1\} \right]/X^2 \]  

(5.6)
where
\[ Y = \frac{X + \epsilon}{\prod_{j=1}^{m}(1 + Xs_j)} \]

Setting \( \frac{d\bar{x}}{dX} \) equal to 0, we obtain
\[ (n - m)\bar{\tau} + \sum_{j=1}^{m} \tau_j + \epsilon P_i = 1 \quad (5.7) \]
i.e.
\[ 1 - \sum_{j=1}^{n} \tau_j = \epsilon P_i \quad (5.8) \]
which is identical in form to equation (5.4) in the homogeneous case. Solving for \( \bar{\tau} \) yields the attempt probability that maximises throughput.

### 5.2 Decentralized Optimisation

Observe from Equation (5.8) that the optimal \( \bar{\tau} \) depends on \( \tau_j, j = 1, 2, \ldots, m \), so message-passing between stations is required in order to determine \( \bar{\tau} \). In this section we consider decentralised (i.e. no message-passing) suboptimal methods for achieving high throughput.

Motivated by the idle sense approach[18] we consider constraining the attempt probabilities such that the probability \( P_i \) that a MAC slot is idle satisfies \( P_i \geq p \) for some fixed choice of \( p \).

#### 5.2.1 \( P_i \) Constraint

We begin by considering the minimum value of \( p \) such that the \( P_i \) constraint is always active at or before the rate region boundary. This is illustrated by subset \( P_0 \) in Fig. 5.1. Along any ray from the origin, the boundary \( P_0 \) is reached at or before the boundary of the rate region. In other words, \( p \) is the smallest value such that \( P_i \leq p \) at the rate region boundary.

From the Arithmetic Mean-Geometric Mean inequality, we have that:
\[ \sum_{i} \frac{1}{1 + x_i} \geq n \sqrt[\prod_{i}(1 + x_i)^{-1}} \]
Figure 5.1: $P_0$, $P_1$, $P_2$ illustrate subsets of the rate region corresponding to different values of $p$ in constraint $P_i \geq p$. $P_0$ corresponding to the smallest value of $p$ such that $P_i \leq p$ at the rate region boundary.

Hence,

$$\sum_j \tau_j + \epsilon P_i = \sum_i \frac{x_i}{1 + x_i} + \frac{\epsilon}{\prod_i (1 + x_i)}$$

$$= \sum_i (1 - \frac{1}{1 + x_i}) + \frac{\epsilon}{\prod_i (1 + x_i)}$$

$$\leq n \{1 - \sqrt{\prod_i \left( \frac{1}{1 + x_i} \right)}\} + \frac{\epsilon}{\prod_i (1 + x_i)}$$

(5.9)

with equality when $n = 1$ or $x_1 = x_2 = \cdots = x_n, n > 1$, i.e. when moving along the 45' ray marked in Fig. 5.1.

That is,

$$n(1 - \sqrt{P_i}) + \epsilon P_i \geq \sum_i \tau_i + \epsilon P_i.$$  

(5.10)

Recall from Equation (5.8) that the rate region boundary is defined by the solution to $\sum_i \tau_i + \epsilon P_i = 1$. Now we consider the monotonicity of the following function,

$$f(n, P_i) = n(1 - \sqrt{P_i}) + \epsilon P_i,$$

which is strictly increasing with respect to $n$, and strictly decreasing with respect to $P_i$. Hence,

$$n(1 - \sqrt{P_i}) + \epsilon P_i < \lim_{n \to \infty} n(1 - \sqrt{P_i}) + \epsilon P_i = -\ln P_i + (1 - \eta)P_i$$

where $\epsilon = 1 - \eta$. Let $p$ be the solution to $1 = -\ln p + (1 - \eta)p$. Constraining the idle probability such that $P_i \geq p$ then we have from Equation (5.10) that $\sum_i \tau_i + \epsilon P_i \leq 1$. That is, the constraint on $P_i$ becomes active at or before the rate region boundary constraint.
Figure 5.2: The boundary of rate region with/without constraint on $P_i$ is shown, for $n = 2$ stations, PHY rate=11Mbps, $L=1000$ bytes, $\sigma/T_c = 67.1$ and $p = 0.8412$.

$$\sum_i \tau_i + \epsilon P_i = 1$$ as required.

Using a Taylor Series expansion we have that, $-\ln p = (1 - p) + \frac{(1 - p)^2}{2} + \frac{(1 - p)^3}{3} + \cdots \geq (1 - p) + \frac{(1 - p)^2}{2}$. Solving $(1 - p) + \frac{(1 - p)^2}{2} + (1 - \eta)p \leq 1$, we have the lower bound on $p$

$$p \geq 1 + \eta - \sqrt{2\eta} \tag{5.11}$$

to ensure that the $P_i \geq p$ constraint is always active at or before the rate region boundary is reached.

### 5.2.2 Throughput Efficiency

By constraining the idle probability such that $P_i \geq p$, there will be loss of throughput compared to the maximum possible throughput. However, it turns out that the loss is so small that it is essentially negligible. This is illustrated in Fig. 5.2 where the unconstrained and constrained rate regions are depicted and from which we can see that the constrained rate region is log-convex[19] and the gap between the two rate regions is small.

To see the difference between the achieved throughput and the maximum possible throughput in more detail, the ratio of achieved to maximum possible throughput is plotted in Fig. 5.3(a). In this figure, data is shown for three different approaches, namely for $P_i = p$ with $p$ chosen according to Equation (5.11), using the attempt probability derived by Bianchi[5] to approximately maximize throughput, and using the Idle Sense approach in [18]. Results are shown for all the available PHY rates in 802.11b (1, 2, 5.5, 11 Mbps).

It can be seen that there is at most 8 percent throughput loss, even in the worst case when only one station is transmitting. Additionally, the loss becomes extremely small (less than
1 percent lost) when there are more than 2 stations in the channel. It can be also seen that the higher the PHY rate used, the smaller the throughput loss.

![Graph showing throughput ratio vs. number of stations](image)

(a) All stations saturated  
(b) One saturated and one unsaturated station

Figure 5.3: Illustrating efficiency of approximate throughput maximisation using $P_i$ constraint. $L=1000\text{bytes};$ in Fig. 5.3(b), $\sigma T_c=67.2, \ p=0.8412, \text{PHY rate}=11\text{Mbps}$

Fig. 5.3(b) shows a second example of a network with one saturated stations and one unsaturated station. The throughput efficiency is plotted versus the offered load on the unsaturated station. The throughput ratio is again at most 8 percent, becoming smaller as the offered load increases. In Fig. 5.3(b), when the throughput of the unsaturated station is zero then only one saturated station is active and the throughput efficiency agrees with that in Fig. 5.3(a). When the throughput of unsaturated station equals that of the saturated station, two saturated stations are active and again the righthand paint in Fig. 5.3(b) can be compared with Fig. 5.3(a).

### 5.2.3 Decentralised implementation

**Algorithm**

We can see that threshold $p$ in constraint Equation (5.11) provides a design parameter that allows us to control the throughput efficiency in a WLAN. Importantly, since the channel idle probability $P_i$ is observable by all stations in a WLAN the potential exists to enforce constraint (5.11) in a decentralised manner, with no need for message passing.

We can regulate $P_i$ to satisfy constraint Equation (5.11) by adjusting the station $CW_{\min}$ values to be sufficiently large. Evidently there are many possible combinations of $CW_{\min}$ satisfying the constraint. In particular, this might be achieved in an unfair manner by having some stations with very large $CW_{\min}$ and others with small $CW_{\min}$. Such unfair solutions are not of interest in the present context. We borrow from the TCP congestion control literature the use of AIMD to provide a decentralized mechanism for achieving
Algorithm 1 Proposed ADMI tuning algorithm.

```
for Every T seconds do
    if $P_i > p$ then
        $C_{W_{min}} \leftarrow C_{W_{min}} - \alpha$
    else
        $C_{W_{min}} \leftarrow C_{W_{min}} / \beta$
    end if
end for
```

fairness. Specifically, we propose Algorithm 1. Providing all stations use the same ADMI (rather than AIMD) decrease rate $\alpha$ and increase factor $\beta$, under mild conditions we are guaranteed [33] that stations will, on average, converge to the same value of $C_{W_{min}}$ while respecting constraint $P_i \geq p$ as required.

We briefly comment that the use of channel idle probability has previously been considered in [9] in the context of measuring the link quality in a WLAN. The use of Idle Sense is also considered in [18], [16] in the context of maximizing throughput in a infrastructure mode WLAN. However, this work focusses mainly on optimising throughput in WLANs rather than achieving fairness in mesh networks.

**Design Parameters**

It can be seen that Algorithm 1 contains four design parameters $\alpha$, $\beta$, $p$ and $T$. We consider these in turn.

The choice of update interval $T$ is determined by the time required to obtain an accurate estimate of the idle probability $P_i$. As a rough guideline, if the measurement noise is roughly white and gaussian we expect that the standard deviation of our $P_i$ estimate is proportional to $1/\sqrt{N}$ where $N$ is the number of measurements available. A long update interval $T$ therefore allows more observations and so a more accurate estimate. However, this also slows convergence of Algorithm 1 (see below). In this paper, we use $T = 1$ second as a reasonable compromise. We note that this is also a common upper bound of TCP RTT on the Internet and reflects the time-scale over which network conditions are likely to change [36] (currently, WLAN users are mainly using the Internet and the main traffic type is TCP i.e. 80%–90% of traffic is TCP [31]).

From the AIMD analysis in [33], we have that the mean time between backoff events in Algorithm 1 is proportional to $\alpha/T(1 - \beta)$. The mean time to converge to the stationary distribution is proportional to $1/\log \beta$ backoff events. We have found values of $\beta = 0.75$ (corresponding to a convergence time of roughly 10 backoff events), and $\alpha = 4$ to yield good performance across a wide range of network conditions.
Simulation Results

In this section we use simulations to evaluate the fairness performance achieved when the TXOP adaptation approach of Chapter 3 is augmented with the $CW_{\text{min}}$ autotuning Algorithm 1. This yields a joint TXOP/$CW_{\text{min}}$ tuning algorithm.

We begin by revisiting the example in Section 3.6 with network topology shown in Fig. 3.8. Fig. 5.4(a) shows the throughput allocations obtained with the joint TXOP/$CW_{\text{min}}$ tuning algorithm. It can be seen that all flows, i.e. including both one-hop and two-hop flows, converge to essentially the same goodputs as required. And it is obvious that the goodput within the joint TXOP/$CW_{\text{min}}$ approach is about 10.9% higher than that with TXOP-only one.

Shown in Fig. 5.4(b) is the convergence of the throughput allocations following a change in the network load. Namely, initially the network starts with 5 flows active on each hop and one 2 hop flow. At time 500s an additional 5 flows start at each hop. It can be seen that when the traffic load is increased the network is able to quickly adapt to the new channel state.

Synchronization of $CW_{\text{min}}$ Updates

In the above figures, all stations update their $CW_{\text{min}}$ at the same time (i.e. with time synchronization.) This might be achieved in practice by synchronising updates to the access point beacons. Fig. 5.5 illustrates behaviour without time synchronization. It can be seen that throughput fairness is not achieved. This happens because the first station to increase its $CW_{\text{min}}$ when $P_i < p$ may lead to $P_i$ subsequently increasing such that $P_i \geq p$, in which case other stations may not increase their $CW_{\text{min}}$s since they do not observe the
Figure 5.5: Without time synchronization of $CW_{min}$ updates.

Figure 5.6: Goodput allocation vs BER.

temporary violation of the $P_i \geq p$ constraint, leading to unfairness. Synchronisation of $CW_{min}$ updates prevents such behaviour.

5.3 Channel Noise

In this section we briefly consider the impact of losses due to channel noise. Figures 5.6(a) and 5.6(b) show the goodput allocations for a range of channel BER values for the topology of Figure 3.8 when the joint TXOP/$CW_{min}$ algorithm is used. It can be seen that the flow fairness is still maintained for BERs up to $10^{-4}$.
Chapter 6

Conclusions

This thesis presented two TXOP algorithms that provides per-flow fairness instead of per-station fairness in the DCF and a distributed algorithm that maximises the total throughput of the mesh network. It addressed the fairness problem in 802.11 wireless mesh networks and especially the problem under TCP traffic, also discussed the impact of lossy links.

This thesis gave the boundary of the mesh networks and a feasible way to maximise the total throughput in a distributed manner. The algorithm can give about 10% more throughput and work well in lossy channels.
Bibliography


[19] Vijay S. and Douglas L. “Log Convexity of Rate Region in 802.11e WLANs”


