Achieving End-to-end Fairness in 802.11e Based Wireless Multi-hop Mesh Networks

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***Abstract*— To mitigate the damaging impacts caused by interference and hidden terminals, it has proposed to use orthogonal channels in multi-hop wireless mesh networks. We demonstrate however that even if these issues are completely eliminated with perfectly assigned channels, gross unfairness can still exist amongst competing flows which traverse multiple hops. We propose the use of 802.11e's TXOP mechanism to restore/enforce fairness. The proposed scheme is simple, implementable using off-the-shelf devices and fully decentralised (requires no message passing).**

I. INTRODUCTION

CSMA/CA based 802.11 technology is becoming increasingly pervasive as the last-hop both in office environments and in the home. Looking ahead, the next step is likely to be towards greater use of multiple wireless hops. While there exists a considerable body of related work in the literature, much of this focusses on issues related to interference and routing which are well-known difficult problems in single channel 802.11 based multi-hop networks. For example, it has been observed that due to hidden terminal effects end-to-end traffic over more than 3 hops tends to achieve rather limited throughput [8].

Recently, there has been great interest in the use of multi-radio multi-channel networks, see for example [14], [15], [11] and references therein. With this in mind, in this work we take as our starting point multi-radio multi-channel networks where the channel allocations have been chosen to avoid the damaging impacts caused by interference and hidden terminals[1]. We find that even when these issues are completely resolved in the aforementioned manner, gross unfairness can still exist amongst competing flows. This unfairness is associated with the 802.11 MAC behaviour and can be particularly problematic in the context of multi-hop networks since unfairness can become amplified over multiple hops.

In the literature, MAC-related unfairness has been studied in the context of single-hop 802.11 WLANs, e.g., see [10] [4] and references therein. However, fairness in multi-hop networks has received limited attention. In single-channel multi-hop networks, [8] illustrates that unfairness exists in parking lot deployments, and a congestion control algorithm is proposed to mitigate unfairness in [16]. However, the unfairness issue in [8] and [16] is caused by hidden terminals and interference. There has been even less work regarding the use of the TXOP (Transmission Opportunity) mechanism [1]. In [18], the authors evaluate the use of TXOP for stations with different physical rates. To the best of our knowledge, there exists no prior work on enforcing/restoring per-flow fairness using 802.11e's TXOP in multi-hop networks.

In this paper, we propose the use of 802.11e's TXOP mechanism to restore/enforce fairness. The proposed scheme is simple, implementable using off-the-shelf devices and fully decentralised (requires no message passing). We demonstrate the efficacy of this approach with both NS simulations and test-bed implementation.

II. UNFAIRNESS AT RELAY STATIONS

Before proceeding we first describe the network setup used, see Fig. 1(a). 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 among which 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 [5] and [6]. The routes are stable during the considered sessions' life time. We only consider single-path routing. We use *station* to refer to any wireless device (both client stations and MPs). We say *client station* when referring to wireless devices other than MPs.

We note that even with such a simple network setup (no interference/hidden terminals, fixed routing, standard 802.11 parameters), significant unfairness can exist between flows in a multi-hop context. To see this, consider the multi-hop network in Fig. 1(a) with one local station at MP_8. End-to-end traffic from the left-hand stations (numbered 1-10), now has to compete with the traffic from station 11 at the MP_8 hop. The unfairness effect now acts multiplicatively at hops MP_0 and MP_8, greatly amplifying the level of unfairness. 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 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 stations 1-10

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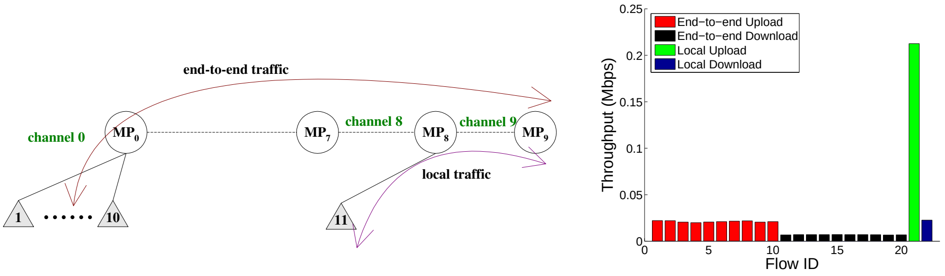
[1] Interference and hidden terminals can also cause unfairness, which is a separate question to the one we consider here, and left as future work.



T_{SIFS} (μs)	10
Idle slot duration (σ) (μs)	20
T_{DIFS} (μs)	50
CW_{min}	31
CW_{max}	1023
Retry limit	4
PLCP rate (Mbps)	1

(a) Topology (b) CBR results (c) Parameters

Fig. 1. (a) Topology used in the simulations. (b) CBR results without TXOP when there is one client station at MP_8 (i.e. $N = 11$). (c) MAC and PHY parameters used.

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 stations 1-10 obtains only a $1/10(n_8 + 2)$ share. See Fig. 1(b) for the results with packet size of 1000 bytes.

The setup in Fig. 1(a), where download traffic must contend at two hops, is already sufficient to create a level of unfairness whereby download traffic to 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 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.

III. ACHIEVING PER-FLOW FAIRNESS

Since the unfairness behaviour noted above is associated with the MAC operation, it is natural to seek to improve fairness by investigating changes at the MAC layer. In this paper, we propose the use of 802.11e's TXOP mechanism to restore/enforce fairness. We first model the functionality of TXOP, then discuss how to achieve fairness with it.

For ease of discussion, we specify the duration of a TXOP (denoted to be K) as the number of packets. That is, by saying $K_i = k$ we mean a duration during which a maximum of k packets can be transmitted by station i with a specific PHY date rate which does not change.

A. Modelling TXOP

We design a finite-load model to quantify TXOP's functionality. We use the approach proposed by Bianchi in [3] and extended in [13] to calculate the impact of TXOPs.

In multi-hop CSMA/CA based networks, modelling the relay traffic distribution from a previous hop is still an open problem. Following common practice (e.g., [9], [7]) we assume that the offered load at station i is an independent Poisson process with mean rate of λ_i bits/sec.

We therefore consider an intermediate hop between the source and the destination with relaying MP denoted as MP' and $n-1$ associated MPs/user stations. The quantity of interest is the throughput x_i of station i (recall that by station, we mean both MPs and user stations), which is defined as

$$x_i = \frac{P_{i,s} E[L_i]}{E[T]} \tag{1}$$

where $P_{i,s}$ is the probability that station i has a successful transmission, $E[L_i]$ is the expected number of bits transmitted in a transmission, and $E[T]$ is the expected slot duration.

Let τ_i be the probability that station i attempts transmission, and p_i be the probability of station i collides with others in a real slot time. Following [13], we assume that for each station i there is a constant probability $1 - q_i$ that the station's queue has no packets awaiting transmission in an expected slot. The probability q_i that one or more packets are available in $E[T]$ time is given by $q_i = 1 - e^{(-\lambda_i/K_i)E[T]}$ where K_i is the TXOP values, in packets.

Using a similar coupling technique as in [3], the probability τ_i can be modelled as a function of p_i and q_i using a Markov chain for the contention windows (see Equation (6) in [13]). A second relation relating τ_i and p_i is

$$1 - p_i = \prod_{j \neq i} (1 - \tau_j), \tag{2}$$

i.e., there is no collision for station i when all other stations are not transmitting. With n stations, $p_1, \ldots, p_n$ and $\tau_1, \ldots, \tau_n$ can be solved numerically.

Let P_{tr} be the probability that at least one station is transmitting, we then have that

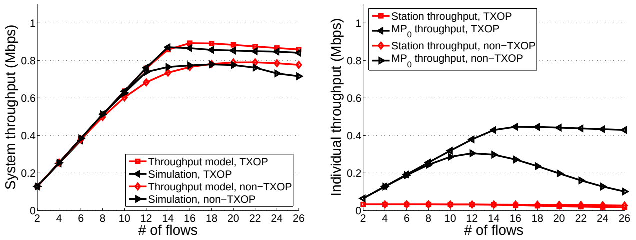
$$P_{tr} = 1 - \prod_{i=1}^{n} (1 - \tau_i). \tag{3}$$

Let $P_{i,s}$ be the probability that station i successfully wins a transmission opportunity (which may involve transmitting one or multiple packets), then

$$P_{i,s} = \tau_i \prod_{j \neq i} (1 - \tau_j), \tag{4}$$

and combining with Equation (2), we have that

$$P_{i,s} = \tau_i (1 - p_i). \tag{5}$$



(a) System throughput (b) Individual throughput

Fig. 2. Model vs. simulation for TXOP and non-TXOP cases. In the non-TXOP case, one packet (if there is) is transmitted in a transmission opportunity.

Let P_c be the probability that more than one station starts transmissions at the same time, we have that

$$P_c = P_{tr} - \sum_{i=1}^{n} P_{i,s}. \tag{6}$$

Now we can represent the expected slot duration as

$$E[T] = (1 - P_{tr})\sigma + \sum_{i=1}^{n} (P_{i,s} T_{i,s}) + P_c T_c. \tag{7}$$

where σ is the idle slot duration, T_C is the collision duration, and $T_{i,s}$ is the successful duration. In the non-TXOP (i.e., one packet is transmitted in a transmission opportunity) case, both T_C and $T_{i,s}$ correspond to a packet transmission and associated overhead, while in the TXOP case multiple packets can be transmitted.

There are two variables ($T_{i,s}$ and $E[L_i]$) in Equation (1) that are still unknown, with their relationship being that $T_{i,s} = E[L_i]/R + \Delta$ where R (bits/sec) denotes the physical rate, and Δ (in seconds) denotes the overhead including AIFS, SIFS and ACKs. For calculating $E[L_i]$, we use an approximation that station i always waits until there are enough packets to transmit in one TXOP (as we will see that analysis with this assumption matches the simulations very well), hence $E[L_i] = K_i * L$ where K_i is the TXOP duration in packets at station i and L is the packet size in bits. The aggregate overhead in one TXOP is thus $\Delta_i = DIFS/AIFS + K_i(2 * SIFS + T_{ack} + 2 * T_{phy,hdr} + T_{mac,hdr} + T_{other,hdr})$. The model is now complete.

This analysis is verified against simulations. We use two-way Poisson traffic with mean rate of 64 kbps. Each two-way traffic flow is between one associated user station and MP'. The packet size, physical data rate and physical basic rate used is 80 bytes, 11Mbps and 1Mbps, respectively. The other parameters are listed in Table 1(c). In Fig. 2(a), we illustrate the results in both TXOP and non-TXOP cases. It can be seen that (i) as the number of flows increases, in both cases the system throughput increases to a maximum level and remains thereafter, (ii) the use of TXOP allows higher throughput to be sustained compared with the non-TXOP. In Fig. 2(b), the individual throughput achieved by MP' and user stations is depicted. We can see that the throughput achieved in the non-TXOP case drops rapidly when there are more than 12 pairs of flows. With TXOP, however, MP' maintains a near constant throughput after the channel becomes saturated. In both cases, user-stations throughput decrease slightly with the number of flows. Here, MP' uses the number of flows as the TXOP value.

For stations which are backlogged, we have that the probability $q_i = 1$. According to Equations (4) and (2), we know that these saturated stations have the same transmission success probability (represented as P_s^*) in a slot. The throughput ratio between these stations is thus proportional to their TXOPs. i.e.,

$$\frac{x_i}{x_j} = \frac{P_s^* E[L_i]}{P_s^* E[L_j]} = \frac{K_i}{K_j}. \tag{8}$$

Recall that all stations are using the same parameters such as CW_{min}, CW_{max}, AIFS, etc.

In order to quantify the relationship between all stations that may or may not be saturated, we define the effective TXOP duration K_i' used by station i to be

$$K_i' = \frac{P_{i,s} E[L_i]/L}{P_s^*} \tag{9}$$

where $P_{i,s}$ is the actual successful transmission probability, L is the packet length. Observe that $K_i' = K_i$ for saturated stations, but $K_i' \leq K_i$ for stations which are not persistently saturated. That is, saturated stations can use up to the maximum assigned TXOP, but non-saturated stations can not. The advantage of working in terms of K_i' is that the throughput ratio between any stations can be written as

$$\frac{x_i}{x_j} = \frac{P_{i,s} E[L_i]}{P_{j,s} E[L_j]} = \frac{K_i'}{K_j'}, \tag{10}$$

i.e., this relationship holds for both saturated and non-saturated stations. This equation says that the ratio of throughput achieved by any two stations is equal to the ratio of their TXOPs. We can then control fairness between stations as long as proper TXOPs are chosen.

B. *The Proposed Scheme*

Let the number of flows with packets queued at MP_i on channel l be n at a transmission opportunity. We select TXOP duration $K_{l,i} = n$ and use a modified queuing discipline (e.g., [17]) that serves one packet per flow at each transmission opportunity. Note that TXOP may change from transmission opportunity to transmission opportunity as the mix of queued packets varies and so the scheme automatically adapts to changes in the number of flows carried by a station.

It follows immediately from Equation (10) that the ratio of station throughput is approximately equal to the ratio of flows carried. In practice, this dynamic TXOP allocation scheme can be simplified to select $K_{l,i}$ to equal the average number of flows carried by station i[2], and by employing FIFO

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[2] It is important to note that for a station that is assigned a long TXOP length, if during a transmission opportunity it has no packets to send (the network interface queue is empty) then that transmission opportunity is ended automatically. That is, if the offered load at a station is too low to make full use of its allocated TXOP share (or due to burstiness of the traffic, the interface queue is empty from time to time), the excess is not lost but rather becomes available on a best effort basis for use by other stations in the network.

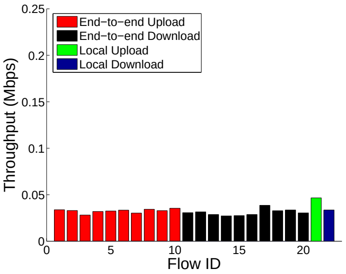
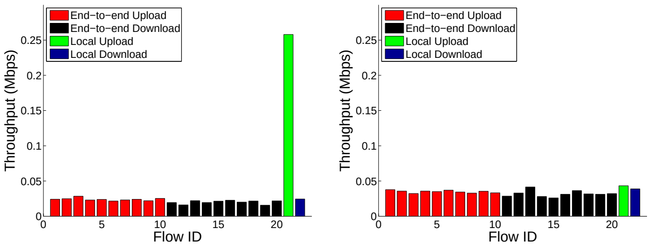


Fig. 3. CBR results with TXOP. TXOP = 10 at MP_0, TXOP = 10 at MP_7, TXOP = 11 at MP_8.



(a) Without TXOP

(b) With TXOP

Fig. 4. TCP results for topology in Fig. 1(a) (with N=11). Simulation parameters listed in Table 1(c).

queuing (rather than per-flow fair queueing) with little loss in performance – see the example below. There is no message passing required since each station is able to determine the number of flows it carries by inspection of its outgoing packet stream and thus the scheme is fully decentralised, greatly facilitating management and roll-out.

C. Remarks

We comment that with this TXOP approach a station transmits n packets in a single burst. For n large, this can result in the station occupying the channel for a substantial consolidated period of time and this may, for example, negatively impact competing delay-sensitive traffic. We can address this issue in a straightforward manner by using multiple smaller TXOPs instead of a single one. When using smaller packet TXOPs, it is necessary to ensure a corresponding increase in the number of transmission opportunities won by the station. This can be achieved by using a smaller value of CW_{min} for the prioritised traffic class at the station. It is shown in [10] that competing traffic classes gain transmission opportunities approximately in inverse proportion to their values of CW_{min}.

D. CBR Results

We revisit the earlier multi-hop examples, and illustrate the impact of the proposed TXOP assignment scheme with CBR traffic. For the topology in Fig. 1(a), Fig. 3 demonstrates the impact of this change – it can be seen that fairness is restored between upload and download flows.

E. TCP Results

Since TCP currently carries the vast majority of network traffic it is important to investigate the performance of the proposed scheme with TCP. Fig. 4(a) shows the throughput of TCP upload and download flows for the network topology in Fig. 1(a). As expected, unfairness between upload and download flows is evident. The performance with the proposed TXOP scheme is illustrated in Fig. 4(b). It can be seen that, as required, fairness is restored. Here, we assign TCP ACK packets with high priority to ensure reliable TCP ACK transmissions [10], i.e., TCP ACKs are stored in a high-priority queue with $CW_{min} = 3$, $CW_{max} = 7$ and $AIFS = 2$, and TCP data packets in a low-priority queue with $CW_{min} = 31$, $CW_{max} = 1023$ and $AIFS = 6$.

F. Experimental Implementation

The proposed scheme considers providing per-flow fairness using the TXOP mechanism of 802.11e. The resulting allocation is close to max-min fair [2] in the considered topology (as each flow achieves the same rate). This can also be seen for the parking lot topology in Fig. 5(a) which is often used to illustrate fairness of end-to-end traffic in general network setups (in both wired networks, e.g. [12] and wireless networks, e.g. [8]). According to [12], vector

$$\{\frac{c_2}{6}, \frac{(c_0 - \frac{c_2}{6})}{2}, \frac{(c_0 - \frac{c_2}{6})}{2}, \frac{c_2}{6}, \frac{c_2}{6}, \frac{c_2}{6}, \frac{c_2}{6}, \frac{c_2}{6}\}$$

is the unique max-min allocation where c_i is the current capacity of channel i.

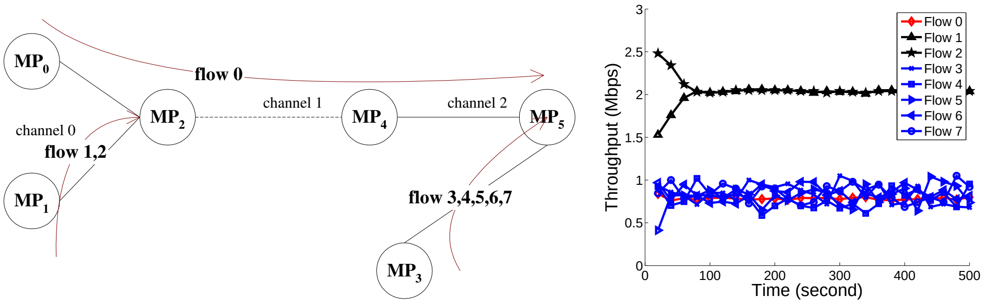
We have implemented the topology shown in Fig. 5(a) using a test-bed constructed from Soekris net4801[3] stations with Atheros 802.11a/b/g miniPCI cards. All stations run the Linux 2.6.21.1 kernel with a version of the MADWiFi[4] wireless driver which is customised to allow the prioritisation described in this paper. In order to ensure a non-interfering channel allocation at each MP and to avoid interference with neighboring WLANs, all of these tests are performed with 802.11a channels. We use channels 40, 48 and 56 of 802.11a for channels 0, 1 and 2, respectively. The channel rate is fixed at 6Mbps. To implement dual-radio MPs, we join two net4801 stations at 100 Mbps with a cross-over cable to form a single logical MP. Routing in the network is statically configured. We use iperf[5] to generate TCP traffic and data is collected from both iperf and tcpdump. All the control operations such as initializing flows, collecting statistics etc., are carried out using the wired Ethernet of net4801 stations. SACK enabled TCP NewReno with a large receiver buffers (16 MBytes) is used. The TCP data packet size is 1500 bytes. Default values of Linux Kernel 2.6.21.1 are used for all other TCP parameters. To prioritise TCP ACK packets, we put ACK packets into the highest priority queue (Queue 3) which is assigned with $CW_{min} = 3$, $CW_{max} = 7$ and $AIFS = 2$. TCP data packets are collected into lower priority queue (Queue 2) which is assigned with $CW_{min} = 31$, $CW_{max} = 1023$ and $AIFS = 6$.

With the proposed scheme, we use 0, 5000 and 12000 μs (which correspond to durations of transmitting 1, 2 and 5 pack-

[3] http://www.soekris.com/net4801.htm

[4] http://sourceforge.net/projects/madwifi/

[5] http://dast.nlanr.net/Projects/Iperf/



(a) Topology

(b) TCP results

T_{SIFS} (μs)	16
Idle slot duration (σ) (μs)	9
T_{DIFS} (μs)	34
CW_{min}	15
CW_{max}	1023
Retry limit	11
Packet size (bytes)	1500

(c) Parameters

Fig. 5. Test-bed Implementation. (a) Topology used. (b) TCP results. Note that line representing flow 0's throughput overlaps with lines for flows 3, 4, 5, 6 and 7. (c) MAC and PHY parameters used.

ets) as TXOPs for MP_0, MP_1 and MP_3. The corresponding results are shown in Fig. 5(b) where it can be seen that an approximate max-min allocation is achieved. Here, $c_2 = 4.5$ Mbps and $c_0 = 4.75$ Mbps – the capacity at each hop is not the same since 802.11 throughput is dependent on the number of contending stations, which differs at each hop. Flow 0 and flows 3, 4, 5, 6, 7 achieve the same throughput of 0.75 Mbps, while flow 1 and 2 achieve the same throughput of 2 Mbps.

IV. CONCLUSIONS AND FUTURE WORK

We have shown that gross unfairness can exist in multi-hop CSMA/CA based networks if the 802.11 DCF scheme is used at the MAC layer. We have demonstrated that the TXOP mechanism of 802.11e can be used to ensure/restore fair allocation. The proposed TXOP based scheme is implementable on standard hardware in a simple and fully distributed way without the needs of message passing.

The network setups considered are 802.11 based multi-radio multi-hop networks, where there are no packet losses due to MAC layer contention, channel noise and interference, etc. When these factors are present however, tuning TXOP alone may not be sufficient. Using static and larger that standard contention windows and retry limits may mitigate the impact of excessive MAC layer contention. However, channel capacity in CSMA/CA based networks is load-dependent. When traffic load is varied, these values should be updated accordingly. That is, dynamic solutions may be useful to enhance the proposed TXOP scheme so as to tune related parameters to minimise contention losses. Further, if losses are caused by channel noise or hidden/exposed terminals, tuning TXOP, contention window sizes and other parameters together may be necessary to ensure fairness. We leave the considerations for these cases to future work. In future work, we will also investigate the possibility of providing more general fairness criteria such as proportional fairness.

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