Performance of Multi-Channel IEEE 802.11 WLANs with Bidirectional Flow Control

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***Abstract*—We investigate three ways WLANs can use two channels to carry TCP traffic. Using simulation and a simple model, we show that load balancing over both channels outperforms the others while using a single double-width channel is the worst.**

I. Introduction

Due to the prevalence of laptops and smart phones with built-in WiFi, wireless local area networks (WLANs) have become a popular means of Internet access. This places increased demand on the available capacity, and so engineers are continually seeking ways to increase the throughput while maintaining compatibility with existing standards.

One of the features in the current IEEE 802.11 standard increases throughput by allowing stations to use double the physical bandwidth when possible [1]. This allows the data rate to be doubled, which helps to increase network throughput. However, there are several techniques for using two channels concurrently while still keeping the standard medium access control (MAC) protocol. We investigate the performance of these options, which will allow designers to choose the right technique for a particular scenario.

There has been substantial research on how to use multiple channels concurrently in IEEE 802.11 wireless networks. Unlike prior work [2]–[5] which proposes multi-channel MAC protocol for wireless ad-hoc networks and focuses on the MAC layer only with simplified traffic patterns such as Poisson arrivals or saturated stations, our paper does not aim to propose a new multi-channel MAC protocol but studies the utilization of multiple channels in a single hop infrastructure WLANs with the most dominant Internet traffic (i.e. TCP traffic), where an access point (AP) is a centralized controller to inform stations of the working mode and schedule traffic over channels. For this purpose, we introduce a simple model of flow control into IEEE 802.11 models. Our model's novelty is the tractability and the ability to model networks with both uploading stations and downloading stations.

There is a considerable body of literature studying sophisticated models of TCP's congestion control operating over simple models of wireless networks [6]–[8]. However, they do not describe the interplay between TCP and the MAC protocol.

There has also been considerable work focusing on modifying the standard MAC models to capture the interaction with simple models of TCP, most notably its window flow control [9]–[13]. The standard assumptions in these models include there being no loss due to buffer overflow and TCP timeout, an ideal physical channel, long-lived flows so that the system reaches an equilibrium, and a small RTT. This means that they only consider the flow control mechanism of TCP, not its congestion control. Our model is of this second type. These models can be classified into Markov chain-based ones [9]–[11] or non Markov chain-based ones [12], [13]. Between those, Markov chain ones are much more complex due to the need to solve a Markov chain with large number of states.

Among non Markov chain models, that of [12] is simple but accurate; however, it only models a network with either TCP upload or TCP download flows. It determines the probability a station transmits in a given time slot from that of the AP. Using a similar idea, we propose a tractable non Markov chain model of IEEE 802.11 WLANs with both upload and download flows. We show that our model is accurate under a wide range of scenarios, and identify some conditions where the model's assumptions do not hold.

We then apply this model to our study of the performance of three natural modes to utilize two channels concurrently. Among those, the first mode involves using one channel with double bandwidth while the second mode balances total traffic over two separate physical channels. The third mode separates uplink transmission and downlink transmission over two separate physical channels. Based on the numerical results from the model and simulation, we find that in most scenarios, the first mode is worse than the others in terms of TCP throughput. We also find that the second mode has the best performance.

The rest of the paper is organized as follows. Three modes to use two channels concurrently are described in Section II. In Section III, we describe a model of 802.11 infrastructure WLANs with TCP upload and download flows to study these three modes. Numerical results are provided in Section IV.

II. Different modes of utilizing two channels

Given that two channels can be used concurrently as defined in the current IEEE 802.11 standard [1], there are several ways to utilize this feature. In this paper, we are interested in evaluating three natural modes which are described as follows.

A. Mode 0

Mode 0 is called "channel bonding" in the IEEE 802.11n standard. In this mode, two adjacent channels are coupled to form a single channel with double the bandwidth to be shared between upload and download TCP traffic. As a result, PHY data rate is doubled; however, this mode may have high overhead such as collision and backoff due to the full wide channel being wasted. Besides, all traffic sharing the same channel causes a bottleneck at the AP. The advantage of this mode is that it requires only one transceiver per station.

B. Mode 1

Mode 1 involves balancing upload and download traffic over two separate physical channels, each with its own MAC instance, by splitting both types of traffic equally on two channels. This reduces the number of collisions on each channel and uses the channel more efficiently due to the reduction in the cost of protocol overhead. However, this mode requires two transceivers per station.

C. Mode 2

Mode 2 separates the uplink transmissions from the downlink transmissions over two separate physical channels. (Note that "downlink" transmissions are transmissions by the AP and "uplink" transmissions are transmissions by the stations; these are not to be confused with "down*load*" transmissions, which are all transmissions associated with flows in which data packets are sent on the downlink and TCP ACKs are sent on the uplink, and "up*load*" transmissions in which data packets are sent on the uplink and TCP ACKs are sent on the downlink.) This mode eliminate collision on the downlink and solves the issue of the bottleneck at the AP. As with Mode 1, two radio front ends are required per station.

To study the performance of these three modes, we build a model of IEEE 802.11 WLANs with TCP traffic Section III.

III. Model of 802.11 WLANs with upload and download TCP flows

In this section, we will provide a brief description of our tractable model of IEEE 802.11 WLANs with $N_u \geq 1$ wireless stations (STA) uploading TCP traffic and $N_d \geq 1$ stations downloading TCP traffic through an access point (AP). See [14] for the complete model.

We focus on only the flow control mechanism of TCP traffic. Besides, the channel condition is ideal and the maximum TCP receive window size is always advertised in TCP ACK packets.

A. Model

We first describe a model with TCP upload and download stations sharing the same channel. This model can be directly used to analyze two modes 0 and 1. In Mode 0, there is only one channel with double the bandwidth shared among all stations and the AP. Similarly, each channel in Mode 1 is shared among stations and the AP; therefore, we can apply the model for each channel in Mode 1. Then, in Section III-B, we will show how this model can be modified to model Mode 2.

Like traditional IEEE 802.11 MAC models, our model is based on a set of fixed point equations between the attempt probabilities and collision probabilities of stations and the AP. We model only the flow control component of TCP. Specifically, delayed acknowledgements [15] require that one TCP ACK be sent for every D data packets.

The collision probability of a tagged station is the probability at least another station transmits when the tagged one transmits. Then, the collision probability can be straightforwardly calculated if the attempt probabilities are known.

Because all data packets and/or all TCP ACK packets flow through the AP transmit buffer, we assume that the AP transmit buffer never empties. Hence, the attempt probability of the AP can be determined as that of a saturated source. Then, the attempt probability for each type of packet (data or ACK) at the AP is proportional to the throughput of that type, since the collisions are independent of the packet type.

Similar to [12], we assume when an equilibrium state is reached, the combined effect of all upload stations yields a sequence of successfully transmitted TCP data packets with the average spacing equal to $(1/D)$ times that of the sequence of successfully transmitted TCP ACK packets at the AP. Then, the attempt probability of an upload station can be determined from that of TCP ACK packets at the AP. Similarly, the attempt probability of a download station is calculated from that of TCP data packets at the AP. However, different from [12], we take into account the collision probability of the station and delayed ACKs in its attempt probability.

To obtain the download and upload throughput, we solve the system of fixed point equations mentioned above.

B. Model for mode 2

In mode 2, uplink traffic is sent on one channel and downlink traffic is sent on another channel. To determine the total download and upload throughput, we also assume the AP is saturated. This means that the downlink channel is the bottleneck and the network throughput is determined by that obtained on the downlink channel. Then, the above model with only one saturated source (the AP) is applicable for Mode 2 when considering the downlink channel.

IV. Performance evaluation

In this section, we validate the accuracy of the proposed model and evaluate the performance of each of the three channel sharing modes described in Section II. To this end, we compare the numerical results obtained from the proposed model with the results obtained from the ns-2 simulation in each mode. We implemented in ns-2 a multi-interface support required in Mode 2 in a similar way to [16].

We simulate an infrastructure WLAN as described in Section III with N_u stations uploading and N_d stations downloading TCP traffic through the AP. All stations use TCP NewReno without delayed acknowledgements ($D = 1$). We consider the use of two consecutive 20MHz channels. The general MAC and physical layer parameters of each 20-MHz channel are shown in Table I. Note that in Mode 0, two 20MHz channels are combined into one 40-MHz channel where we set the data and control bit rates to be twice those of a 20MHz channel.

We define the "congestion level" of a channel as the ratio

$$\text{congestion level} = \frac{\text{total time when there is a collision}}{\text{total time the channel is busy}}.$$

TABLE I
MAC AND PHYS PARAMETERS FOR 802.11g SYSTEMS

Parameter	Symbol	Value
Data bit rate	R_{data}	54 Mbps
Control bit rate	R_{ctrl}	11 Mbps
PHYS header	T_{phys}	20 μs
MAC header	L_{mac}	288 bits
ACK packet	L_{ACK}	112 bits
Slot time	σ	9 μs
Short Interframe Space	SIFS	10 μs
DCF Interframe Space	DIFS	28 μs
CW_{min}	W_{min}	16
Retry limit	K	7
Doubling limit	m	5

We will use this measure to compare the performance of three modes. In the simulations, the advertised window of a TCP sender is set to 50 while the buffer size of a TCP receiver was chosen so that there is no buffer overflow at the receiver. Note that although the following results are for TCP without delayed ACKs, we observe similar qualitative results for delayed ACKs.

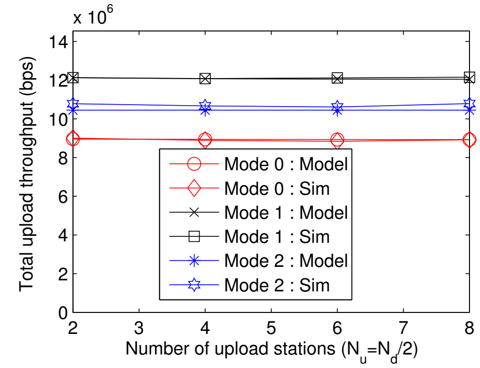
A. *Asymmetric traffic:* $N_u = N_d/2$

We first consider a network with the number of download stations being twice the number of upload stations. This reflects the fact that in practice the download traffic is typically higher than the upload traffic. The total throughput of upload and download flows under the three modes are shown in Figure 1. These figures show that the model gives an accurate estimate of the throughput under all three modes.

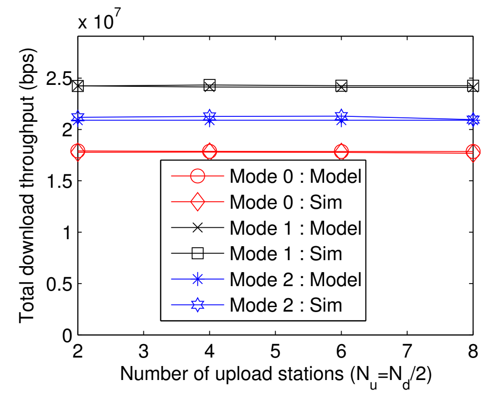
Moreover, it can be seen from Figure 1 that the best performance is obtained by Mode 1, which has two bidirectional channels. Compared with Mode 0 (a single wide channel), Mode 1 improves the upload and download throughput by 36%. In contrast, Mode 2 (two unidirectional channels) only improves the throughput over Mode 0 by 18%.

Note that when the number of stations increases, the total upload and download throughput under the three modes do not change. This can be explained through Figure 2 collected from ns-2 simulation, which shows that the congestion level of each channel under each mode does not change with the number of stations . The observation for Modes 0 and 1 is consistent with that published in prior work [9] which shows that the average number of backlogged stations at any given time does not change significantly with the number of stations and is bounded by three active stations (including the AP).

From Figures 1 and 2, one may find it counterintuitive that the throughput under Mode 1 is higher than that under Mode 2 despite the fact that the congestion level of both uplink and downlink channels under Mode 2 is smaller. This can be explained as follows. First, note that the accuracy of the model under Mode 2 implies that the assumption that AP is saturated holds in this scenario, which we have confirmed in our ns-2 simulation. This means that the throughput obtained under Mode 2 is limited by the throughput of the downlink channel where only the AP is transmitting, and the channel is never used while the AP decreases its backoff counter. This suggests that the AP in Mode 2 should use a smaller backoff level, CW_{min}. In the other two modes, each channel supports multiple stations, counting down their backoff counters in parallel, and so backoffs waste less capacity. The congestion levels are similar, since in each case the number of backlogged stations remains roughly constant in each channel.



(a) Upload throughput



(b) Download throughput

Fig. 1. Total upload and download TCP throughput in bps as a function of the number of upload stations. ($L_{\text{data}} = 1040$B, $L_{\text{ack}} = 40$B, $N_u = N_d/2 = \{2, 4, 6, 8\}$.)

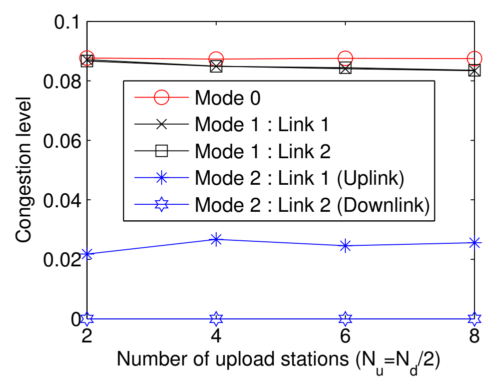
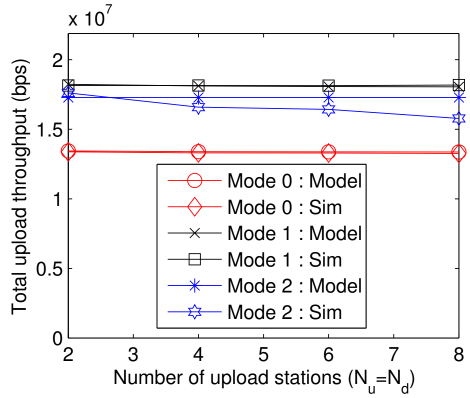


Fig. 2. Congestion level of each channel in each mode (ns-2 simulation). ($L_{\text{data}} = 1040$B, $L_{\text{ack}} = 40$B, $N_u = N_d/2 = \{2, 4, 6, 8\}$.)

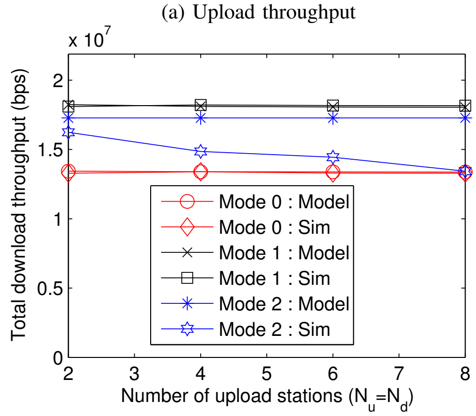
B. *Symmetric traffic:* $N_u = N_d$

We now consider a network with equal number of TCP upload and download stations. The total throughput of TCP upload and download flows in three modes are shown in Fig. 3.

From Figure 3, the model again gives an accurate estimate of the total upload and download throughput under Modes 0 and 1. However, the model fails to capture those under Mode 2.



(a) Upload throughput



(b) Download throughput

Fig. 3. Total upload and download TCP throughput in bps as a function of the number of upload stations. ($L_{\text{data}} = 1040$B, $L_{\text{ack}} = 40$B, $N_u = N_d = \{2, 4, 6, 8\}$.)

Performing further investigation, we find that this is caused by the violation of the assumption that the AP is saturated. In other words, when $N_u = N_d$, the AP is not saturated under Mode 2. To explain this, we plot the congestion level under three modes from ns-2 simulation in Figure 4. This figure shows that the congestion level of the uplink channel under Mode 2 is higher than that of each channel under Mode 0 and 1. This means that the uplink channel is the bottleneck in Mode 2, which limits the transmission of the data packets for the upload flows and TCP ACKs for download flows. Consequently, this prevents the AP from being saturated.

From Figure 3, Mode 1 again performs the best among the three modes. Mode 2 performs better than Mode 0 in terms of both total download and upload throughput for a small number of stations. When the number of stations increases, the total download throughput decreases substantially while the total uplink throughput also decreases but by a smaller amount.

V. Conclusion

In this paper, we have studied the performance of three modes which utilize two wireless channels concurrently. We have found that the default mode in IEEE 802.11 standard, which combines two channels into a channel with double the bandwidth, performs worst among those in most scenarios. Furthermore, we have also found that the load balancing mode performs well over a wide range of scenarios. To assist with this study, we proposed a tractable model of TCP traffic in IEEE 802.11 WLANs and shown that it gives accurate estimation of TCP throughput under scenarios in which TCP only performs flow control, and the AP is the bottleneck.

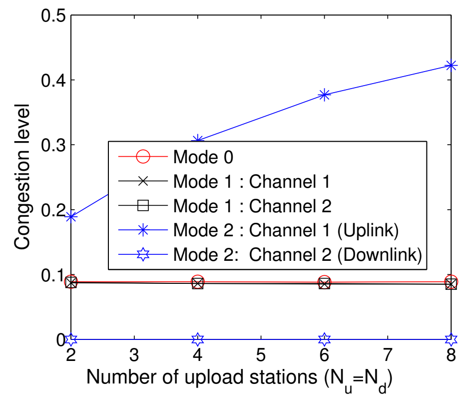


Fig. 4. Congestion level of each channel in each mode (ns-2 simulation). ($L_{\text{data}} = 1040$B, $L_{\text{ack}} = 40$B, $N_u = N_d = \{2, 4, 6, 8\}$.)

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