The Impact of Link Adaptation on WiFi 802.11n

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Abstract—**WiFi networks based on the IEEE 802.11 standard are currently penetrating into our daily life in many ways. With increasing demand for higher data rates by mobile applications, better network performance is required. Since link adaptation algorithms can play a key role in improving performance, they have been extensively investigated in the last decade. However, the relative impact of different approaches has not been thoroughly investigated. In this paper, we evaluate the impact of three link adaptation algorithms on WiFi's 802.11n networks in the 2.4 and 5GHz bands. Network performance has been evaluated in terms of network throughput, WLAN delay and medium access delay. Simulation results show that the three link adaptation algorithms have greatly varying improvements on network performance, improvements that are also influenced by which frequency band the network is operating in.**

Keywords—WiFi network; 802.11n; link adaptation algorithm; data rate adaptation; power adaptation; channel adaptation; OPNET; network performance.

I. INTRODUCTION

With the ever increasing demand for wireless bandwidth, some parts of the available spectrum are becoming overcrowded, such as the unlicensed industrial, scientific and medical (ISM) bands. This makes spectrum availability a bottle-neck for technological evolution. Finding how to improve spectrum efficiency is becoming crucial for improved wireless communications.

WiFi is a popular example of a Wireless Local Area Network (WLAN) technology. It is based on the IEEE 802.11 standard [1]; current variants are a/b/g/n/ac/ad/s. WLANs based on this standard have become a part of peoples' daily lives due to its attractive features such as low cost, fast deployment, and network performance, which can meet the average client's requirements. In the family of 802.11 standards, each variant has an associated set of frequency bands, transmission data rates and ranges.

Link adaptation can play a key role in improving spectrum efficiency. The purpose of a link adaptation algorithm is to react to physical channel conditions by changing link parameters such as the modulation scheme, coding scheme or transmission power in order to achieve better network performance. In WiFi networks, link adaptation algorithms can change all three of these parameters. Rate adaptation has been well studied for the past decade since it can significantly improve network performance, especially network throughput. Some rate adaptation algorithms are based on frame loss; for example, Auto Rate Fallback (ARF) [2], Adaptive Auto Rate Fallback (AARF) [3], Collision-Aware Rate Adaptation (CARA) [8] and the Robust Rate Adaptation Algorithm (RRAA) [9]. Other rate adaptation algorithms are based on signal strength, such as Receiver Based Auto Rate (RBAR) [4], Opportunistic Auto Rate (OAR) [5], Full Auto Rate (FAR) [6] or Beacon Assisted Rate Adaptation (BARA) [7]. All these algorithms attempt to improve network performance through link adaptation. Channel and power adaptation algorithms are not as widely studied in the literature since rate adaptation has a more significant impact on overall network throughput.

In order to better understand the relative impact of different types of link adaptation, the work described in this paper has simulated a data rate adaptation algorithm on an 802.11n WLAN. At the same time we simulated power and channel adaptation algorithms to better understand how much each technique improves the network's delay and throughput. The simulation results show that the link adaptation algorithms, especially rate adaptation, can greatly improve WiFi network performance.

This paper is organized as follows. In section II, the simulation environment is introduced and the link adaptation algorithms, which include data rate adaptation, transmission power adaptation and channel adaptation, are described. In section III, we first define our baseline simulation scenario and parameter configurations. We then introduce the link adaptation scenario that was simulated. In section IV, the OPNET simulation results and analysis are presented and discussed. Section V provides a conclusion and future work.

II. SIMULATION ENVIRONMENT AND ALGORITHMS

A. Simulation Environment

OPNET [10] is a commercial software package that is specialized for network level simulation. It can be flexibly used to study communication networks, devices, protocols, and applications. Unfortunately, in the latest version of OPNET (2015), the WiFi module does not include link adaptation algorithms. For this work, we implemented power, channel and data rate adaptation algorithms in OPNET. The resulting simulation testbed has been used to evaluate WiFi network performance and show the relative advantages of different link adaptation algorithms in 802.11n networks.

B. Link Adaptation Algorithms

For this work, we implemented three link adaptation algorithms in OPNET. The algorithms are transmit power adaptation, channel adaptation, and data rate adaptation. Currently we use time as the trigger for all of the link adaptation algorithms, i.e., they are applied at a fixed time in the simulation. In the future it will be possible to develop more advanced algorithms using other metrics with respect to system requirements. The implemented algorithms function as follows: for power adaptation, when clients are too far away from the Access Point (AP) with which they are associated, or the received power level is too weak due to interference, the transmitter increases the power level in order to recover the communication. For channel adaptation, when too many users are crowded in the same WiFi channel, and the number of packets dropped due to collision or to co-channel interference passes a threshold, then the AP and its associated clients switch to another less congested channel to get better network performance. For data rate adaptation, when the AP senses that the physical channel condition is good, in other words, when there is less interference and the signal to noise level is high, it will switch to another modulation and coding combination available in the 802.11n standard that offers a higher data rate, thus improved throughput.

All three adaptation algorithms can work either alone or in concert in order to improve spectrum efficiency, which may help alleviate the congestion in the crowded ISM bands.

III. Scenario Description

First we introduce the baseline scenario. Then we will compare the network performance of the link adaptation algorithms with the baseline scenario to show the improvements achieved.

A. Baseline Scenario and Parameters

a) Network Topology

In the baseline simulation, we use the extended service set network topology which includes top level network and a sub network. The top-level network structure includes several APs. All APs are connected to an Internet Service Provider (ISP) by a reliable wired link. The number of APs is configurable.

Fig. 1 shows the subnet topology. There are several laptop Work Stations (WST) which are associated with each AP via wireless links. They are all fixed, i.e. mobility is not enabled in baseline scenario. The number of WST is configurable.

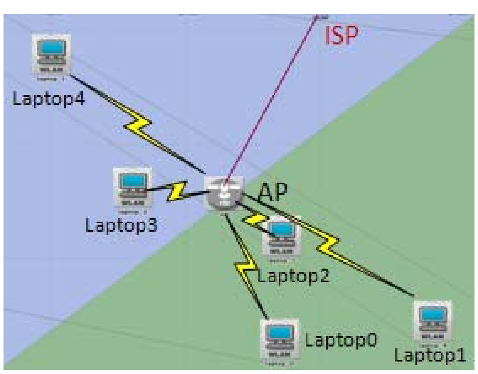

Fig. 1. Sub-network Topology

b) Traffic Profile

OPNET (version 18.0.2) offers a number of standard traffic generation models that generate different types of network traffic such as email, ftp, on-line banking, web-surfing, video conferencing and voice with different source coding schemes. We defined a user profile that included business users and leisure users. Business users were given a combination of applications such as Email, FTP, web surfing and voice. Leisure users were given a combination of email, on-line banking, web surfing, voice and video traffic. These traffic models were applied to both the uplink and downlink channels at each WST.

c) Physical Layer Parameter Configuration

We used two baseline scenarios. In the low density scenario, a low density of users is operating at both 2.4 and 5 GHz in at 802.11n WLAN; the second scenario has a high user density and operated only at 5 GHz. Physical layer parameter configurations as well as the network topologies and traffic models are summarized in Table 1.

TABLE I. Baseline Scenario Summary

Technical Configuration \ **Scenario name**		**Baseline 802.11n-Low density**	**Baseline 802.11n-High density**	**Adapta-tion Algori-thm**
Network Topology	***Network Type***	Infrastructure BSS	Infrastructure BSS	
	No. of AP	11	15	
	No. of fixed WST/AP	6	266	
	WST location distribution	random	random	
	Subnet Range	300m	300m	
Traffic type	***UL/DL***	UL/DL	UL/DL	
	Email	yes	yes	
	FTP	yes	yes	
	Online banking	yes	yes	
	Web surfing	yes	yes	
	Voice	yes	yes	
	Video	yes	yes	
PHY	***Standard***	802.11n	802.11n	
	Freq. band	2.4GHz and 5GHz	5GHz	
	Bandwidth	22MHz	20MHz	
	Channel	Auto-assign	Auto-assign	**yes**
	Modulation & coding scheme	BPSK 1/2	BPSK 1/2	
	Guard interval (ns)	800	800	
	Spatial stream	1	1	
	Data rate	6.5Mbps	6.5Mbps	**yes**
	Tx power (W)	0.005	0.01	**yes**
	Antenna Gain (Tx / Rx)	0 dB	0 dB	
	Propagation	Free Space	Free Space	
	Path loss	N/A	N/A	
	Power reception threshold	-95 dBm	-95 dBm	

B. Scenario with Link Adaptation

In the 5 GHz band low-density scenario, the data rate adaptation algorithm was used to vary the data rate from 6.5 to

13 Mbps at the t=4 minute mark on all links and it was kept at the 13 Mbps rate for the remaining simulation time. This is the rate step available in 802.11n standard and it is defined by the coding and modulation combination scheme. Similarly, for power adaptation, the power level was changed from 0.01 W to 0.9 W at the t=4 minute mark in a separate set of simulations. For channel adaptation, the high-density scenario was used since the small number of users in the low-density scenario was insufficient to fully load the network with its traffic load. This made it impossible to see the impact of the channel-switching algorithm. In other words, channel adaptation algorithms can offer advantages only for higher density networks where the spectrum is heavily loaded. Therefore, to study the exact impact of link adaptation algorithms, we needed to expand the network.

As shown in Table I for the high-density scenario, 15 APs are used with 266 fixed work-stations associated to each AP. For the current phase of our work, we compare the performance of all WSTs operating in channel No. 52 to the baseline scenario with the OPNET default auto-assignment, wherein the simulator sets the channel number according to the Basic Service Set (BSS) ID and available bandwidth. For example, in 802.11n operating in the 5 GHz band, and if there are only 20 MHz BSSs in the network (as we use in simulation), then the channel assignment is [10]:

C = BSS_index % 12;

Channel_num = 36+C * 4 (if C<8)

149+(C-8) * 4 (if C>=8)

If there are only 40MHz BSSs in the network, the channel_num is the same as the above formula, except that

C = (BSS_index * 2) % 12

If there are combinations of 20 MHz and 40 MHz BSSs, the OPNET channel number calculation will be based on the number of 40 MHz channels and also the number of 20 MHz channels. Detailed calculation methods can be found in [10].

IV. Performance Evaluation

In this paper, network performance was evaluated in terms of WLAN delay, individual network throughput, and data traffic dropped. Results for other performance metrics were collected but not shown here due to space limitations.

A. *Link Adaptation Algorithms Performance Comparison*

For this work, each of the link adaptation algorithms has been simulated using the high-density scenario operating at 5 GHz as described above. They are compared based on two metrics, throughput and WLAN delay, i.e. the end-to-end packet delay. The following graphs measure performance over time with the adaptation algorithm activated after 4 minutes of simulated time using the baseline scenario.

a) *Data Rate Adaptation*

The results of the data rate adaptation (DRA) algorithm give the most significant results. Figure 2 shows that each network (red), or individual subnetwork (green, cyan and blue), has an approximately three times increase in their throughput at 4 minutes, once the DRA has been activated.

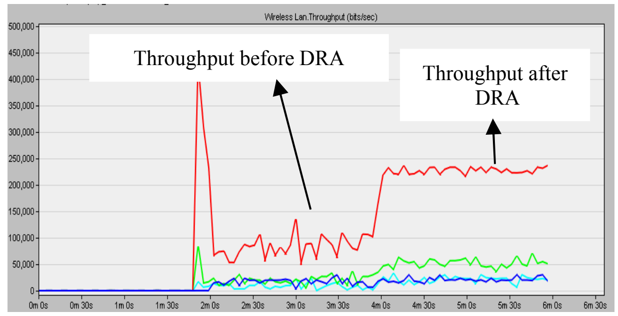

Fig. 2. Subnetwork Throughput before/after Data Rate Adaptation (DRA)

Similarly, as shown in Figure 3, once the data rate adaptation algorithm has been activated, the WLAN delay drops significantly, by 60% in this case.

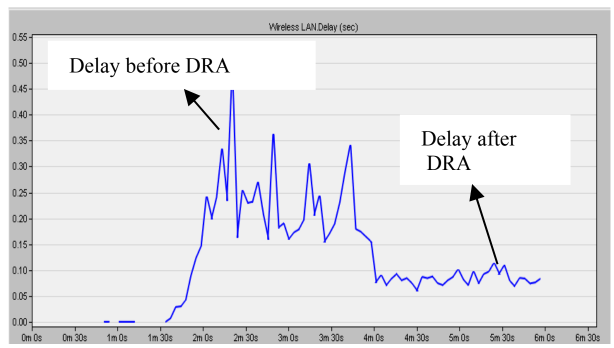

Fig. 3. WLAN Delay before/after Data Rate Adaptation (DRA)

b) *Power Adaptation*

The improvement given by the power adaptation (PA) algorithm is shown in Figures 4 and 5. It is interesting to note that in Figure 4 the WLAN was initially incapable of communicating with any workstations before power adaptation begins at 4 minutes.

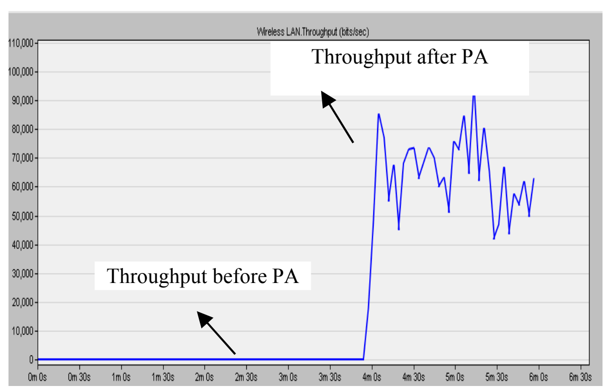

Fig. 4. WLAN Throughput before/after Power Adaptation (PA)

In Figure 5, we similarly note that before 4 minutes, even though there is traffic being sent, nothing can be received as is shown by the extremely long delays. Afterwards, when the transmission power has been increased by the PA algorithm, traffic has significantly lower delays.

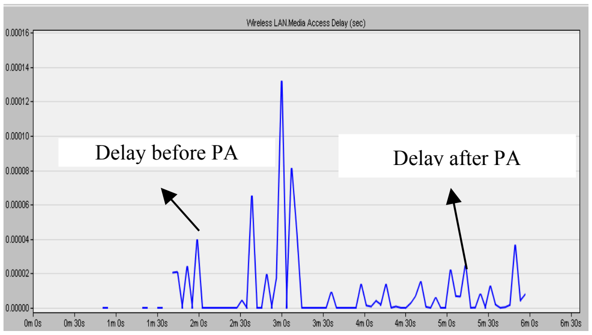

Fig. 5. WLAN Delay before/after Power Adaptation (PA)

c) Channel Adaptation

Figures 6 and 7 show the impact of the channel adaptation (CA) algorithm on WLAN throughput and medium access delay, respectively. In Figure 6, individual WiFi networks begin with CA disabled. At t=6.6 minute, all users are forced to use the same channel. When each individual WiFi is operating in a different channel, the overall network throughput is higher as shown in the left part of the plot. When forced onto the same channel, the throughput decreases.

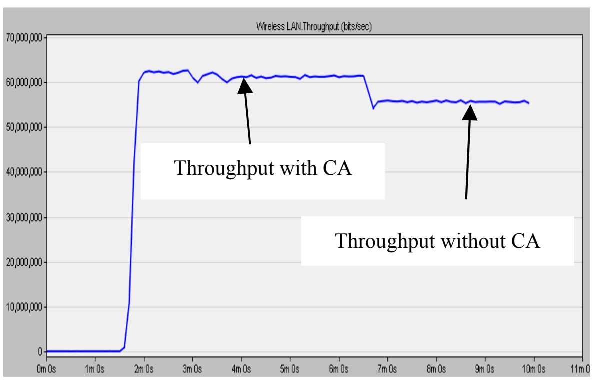

Fig. 6. WLAN Throughput before/after Channel Adaptation (CA)

Figure 7 reveals a similar positive impact of channel adaptation as in Figure 6 but in terms of WLAN medium access delay. It is the delay introduced by the MAC layer and WLAN delay is the end-to-end delay.

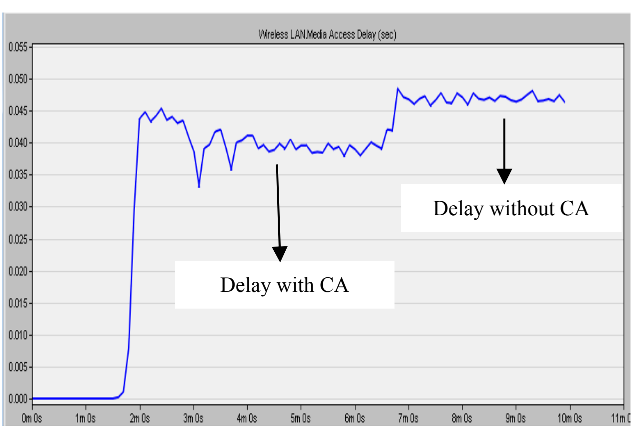

Fig. 7. Medium Access Delay before/after Channel Adaptation (CA)

d) Discussion

As can be seen, data rate adaptation has the largest impact, with an approximately threefold increase in throughput and a 60% reduction in average delay. Power adaptation was more difficult to quantify, as in this scenario it enabled the network to connect and thus no communication was possible without it. Finally, channel adaptation showed a measurable but only incremental improvement to throughput and delay. While it is expected that these results will be generalizable to other scenarios, it should be noted that the impact of these algorithms is dependent on the details of the use case chosen.

B. Link Adaptation Algorithms Performance Comparison between 2.4 and 5 GHz band

A comparison of the performance of link adaptation algorithms between 802.11n at 2.4 GHz and 5 GHz is of interest since different network behaviours when using the same algorithms would give a better understanding of the technology and its features. Here we provide a brief performance comparison.

Using the low-density scenario of Table I, the performance in the 5 GHz band does not change after the link adaptation algorithms are activated, while the performance at 2.4 GHz does, despite the fact that both use 20 MHz channels. Figures 8-10 provide simulation results where the blue and red plots represent performance at 2.4 GHz and 5 GHz respectively.

Figure 8 shows the WLAN throughput. It can be seen that there is a throughput change when the channel adaptation algorithm is applied for 2.4 GHz, it is the same as in fig. 6, but the throughput remains unchanged for 5 GHz. However, Fig. 8 shows the overall system throughput is higher when operating at 5 GHz. The key reason that channel adaptation has no impact for 5 GHz is that at 5 GHz there are 12 non-overlapping 20 MHz bands available, while at 2.4 GHz, there are only 3 non-overlapping channels. It implies that at 5GHz there was no need to change channels to find a clean channel in the scenario simulated. Given a more crowded network scenario, for example, the high density scenario as shown in figure 6, it is possible that CA would have an impact on 5GHz.

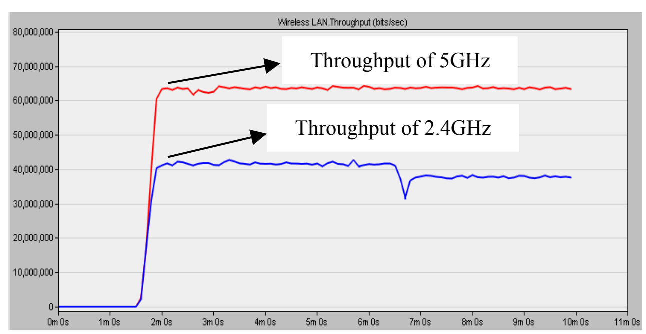

Fig. 8. Throughput Comparison at 2.4GHz and 5GHz before/after Channel Adaptation (CA)

In Figure 9, the amount of data dropped is plotted to show the impact of the channel adaptation algorithm. It can be seen from the figure that at around 6.7 minutes, when channel adaptation is applied, the number of dropped packets substantially increases in the 2.4 GHz band. This shows that the network performance decreases when all users are operating in the same channel. Meanwhile the amount of data dropped remains the same for the 5 GHz band.

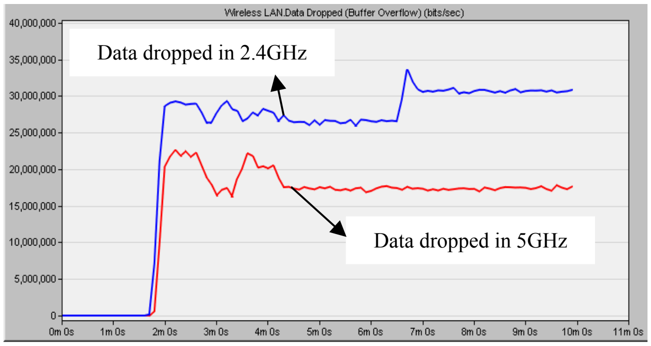

Fig. 9. Comparison of WLAN Data Droped before/after Channel Adaptation in 2.4 and 5GHz band

In Figure 10, we use the WLAN delay to show the performance change before and after we enable the channel adaptation algorithm in the low-density scenario. It shows a big increase in delay when all users are packed in the same channel in 2.4 GHz band while there is no change in 5 GHz.

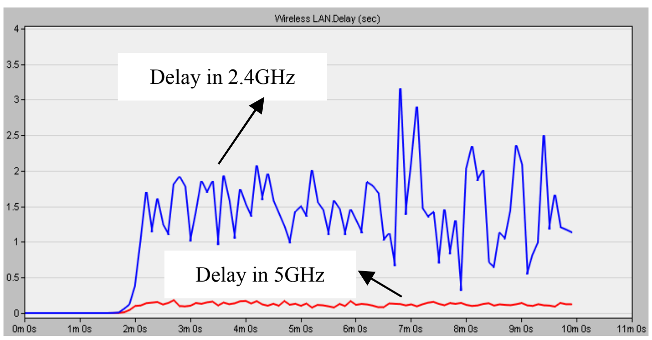

Fig. 10. Comparison of WLAN Delay before/After Channel Adaptation in 2.4 and 5 GHz

Figures 8-10 all imply that the 5 GHz band has a better network capability, including less interference, compared to the 2.4 GHz band. We have collected other simulation results available for both the 2.4 GHz and 5 GHz bands based on metrics other than delay and throughput. While there isn't room to include them in this paper, they show a similar positive impact from link adaptation algorithms that improve network performance.

V. Conclusions and Future Work

With the ever-increasing demand for wireless communications, WiFi networks based on the IEEE 802.11 standard, with its low cost, fast deployment, and comparatively high performance, have become more and more important to our daily lives. Link adaptation algorithms can play a key role in improving network performance and remain an active research area. Popular network simulators, such as OPNET, do not currently have link adaptation models available. In this work, we implemented three simple link adaptation algorithm models including data rate adaptation, power adaptation, and channel adaptation into the OPNET 802.11n model (for both 2.4 and 5 GHz bands). We investigated the relative network performance of the adaptation algorithms. Performance was evaluated in terms of network throughput, delay and packets dropped. The simulation results showed that the link adaptation algorithms, especially rate adaptation, can greatly improve WiFi network performance. Significantly, this is the case for heavily loaded networks with a high user density and high traffic load.

Currently, the trigger for the implemented link adaptation algorithms is time. This is a preliminary implementation step to allow for future improvements to the algorithms with other triggers such as SINR, channel utilization, or other more comprehensive metrics. For future work, we plan to explore such advanced techniques. With further development of link adaptation algorithms, spectrum efficiency can be greatly improved.

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