Intelligent Channel Bonding in 802.11n WLANs

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Abstract—The IEEE 802.11n standard defines channel bonding that allows wireless devices to operate on 40MHz channels by doubling their bandwidth from standard 20MHz channels. Increasing channel width increases capacity, but it comes at the cost of decreased transmission range and greater susceptibility to interference. However, with the incorporation of Multiple-Input Multiple-Output (MIMO) technology in 802.11n, devices can now exploit the increased transmission rates from wider channels with minimal sacrifice to signal quality and range. The goal of our work is to identify the network factors that influence the performance of channel bonding in 802.11n networks and make intelligent channel bonding decisions. We discover that channel width selection should consider not only a link's signal quality, but also the strength of neighboring links, their physical rates, and interferer load. We use our findings to design and implement a network detector that successfully identifies interference conditions that affect channel bonding decisions in 100% of our test cases. Our detector can form the foundation for more robust and accurate algorithms that can adapt bandwidth to variations in channel conditions. Our findings allows us to predict the impact of network conditions on performance and make channel bonding decisions that maximize throughput.

Index Terms—IEEE 802.11n, Channel Bonding, Measurement, Performance, Experimentation.

1 Introduction

With the wide deployment of the IEEE 802.11n standard and with the upcoming 802.11ac, WLANs now have the option to operate over wider channels that achieve higher capacity. The standardized 802.11n technology supports up to 40MHz channels through channel bonding, where two 20MHz channels are combined into a single 40MHz channel. Although transmissions over 40MHz channels should provide advantages over 20MHz channels, performance benefits are largely influenced by the adopted antenna technology. With the incorporation of MIMO smart-antenna technology in 802.11n devices, problems faced by traditional Single-Input Single-Output (SISO) systems from channel bonding [1], [2] can now be mitigated [3], [4]. MIMO technologies in 802.11n promise new potential for channel bonding and higher transmission rates.

Wider bandwidths are also faced with challenges. The IEEE 802.11n standard imposes a fixed maximum transmission power on devices. By doubling the channel width, SNR is effectively decreased by 3dB [5], and thus, reception errors increase [6]. Furthermore, wider bandwidths are more likely to suffer from frequency selective fading. A 40MHz channel, therefore, not only requires a stronger transmission power to achieve the same SNR but also a higher SNR to provide the same PER. That is, transmissions using channel bonding require a slightly stronger signal strength to provide the same reliability as that of a single 20MHz channel. This tradeoff between higher transmission rates and susceptibility to interference must be carefully understood in order to improve performance. The 802.11n standard itself gives no guidelines or recommendations on how to benefit from channel bonding [7].

Previous experimental studies on 802.11n provide valuable insights into 802.11n features [5], [6], [8], [9], but fall short in effectively characterizing the opportunities for channel bonding in real-world WLAN settings, where interfering links co-exist. Furthermore, most existing work operates within the 2.4GHz ISM band [6], [8], [9], where channel constraints are too tight to effectively gauge the performance of channel bonding. In fact, it was shown that channel bonding in the 2.4GHz range poses more harm than benefits [1], [8], [10]. There is therefore a clear need to evaluate the behavior of and opportunities for channel bonding under a broader range of circumstances, where the benefits of channel bonding can truly be exploited: the 5GHz range. In fact, the emerging 802.11ac standard operates only on the 5GHz band for this very reason.

Our previous work identified the usage conditions for channel bonding in 802.11n WLANs [11]. These usage terms allow for intelligent channel bonding decisions and efficient utilization of available spectrum. To this end, we first characterized the behavior of channel bonding through experimental studies. Experiments were performed in the 5GHz frequency range over a stationary 802.11n testbed deployed in a semi-open office environment. These experiments demonstrated the impact of network conditions and interference patterns on throughput performance with channel bonding. From our experiments, we discovered that naïve channel bonding decisions degrade performance.

Intelligent channel bonding decisions require knowledge of not only a link's signal quality, but also of the strength of neighboring link's transmissions, their channel distance, and their physical rates.

We improve on our previous work by considering additional information that improves the performance of channel bonding. Our first contribution is identifying the load of interferers as another key factor in channel bonding decisions and evaluating its impact on performance. By considering the impact of load in a real network setting, we achieve up to a $1.75x$ increase in network throughput compared to our previous work, and up to a $6x$ increase compared to a naïve and uninformed solution.

In our previous work, we identified a metric, called *normalized throughput*, that alerts us to interference patterns in the network. Normalized throughput is the ratio of the achieved throughput over the expected throughput. We believe that normalized throughput can be used in the design of an interference detector; this detector can form the foundation to more robust and accurate algorithms that can adapt bandwidth to variations in network conditions. Our second contribution in this paper is in the actual design and implementation of this interference detector. Our proposed detector successfully identifies interference conditions in 100% of test cases.

In our previous work, we evaluated the performance of channel bonding using UDP traffic. We restricted flows in the network to UDP in order to isolate the impact of transport layer parameters on performance and to evaluate the behavior of channel bonding alone. We believe that with the added constraints imposed by TCP, the benefits of channel bonding will be limited to a narrower range of opportunities, given the intolerance of TCP to packet error rates and the susceptibility of a 40MHz channel to interference. Our third contribution in this work is to develop a better understanding of how channel bonding performs using TCP, and whether our conclusions from our earlier work [11] hold. Contrary to our expectations, we found that the performance benefits of wider channels apply to both TCP and UDP.

This paper is organized as follows. We discuss background and related work in Section 2. In Section 3, we describe the details of our testbed environment and experimentation. We present experimental results in Section 4 and discuss observed patterns in channel bonding behavior. Based on our findings, we discuss methods of assessing a network for channel bonding opportunities in Section 5. To verify the correctness of our assessment, we provide a proof of concept in Section 6, where we show that our recommendations for exploiting channel bonding improve network throughput. Finally, we conclude in Section 7.

2 Background and Related Work

We now present the related body of work. We discuss how channel bonding in the 802.11n standard, unlike in 802.11a/b/g, presents a compelling research direction in the context of wireless LANs. In particular, we focus on how existing work has fallen short in studying the utilization of channel bonding in 802.11n environments.

The 5GHz Frequency Range: Channel bonding in 802.11n combines two adjacent 20MHz channels to form a single 40MHz channel. Ideally, this feature should double the PHY layer data rate. One tradeoff of channel bonding is that fewer channels remain for other devices [1]. In traditional 2.4GHz Wi-Fi deployments where there are only three non-overlapping 20MHz channels, channel bonding has been found to be harmful due to both the limited channel availability and the resulting throughput degradation [8], [10]. There are more opportunities to exploit channel bonding in the 5GHz range where there are 24 non-overlapping 20MHz channels and up to 12 non-overlapping 40MHz channels. Furthermore, unlike the 2.4GHz band which shares its frequency with commonly used consumer products, such as Bluetooth and microwave ovens, the 5GHz band typically suffers less interference.[1] Our work therefore focuses on operation within the 5GHz band.

MIMO: IEEE 802.11 networks have operated on the 5GHz band since the emergence of the 802.11a standard in 1999. Although 802.11a networks have benefited from the increased number of non-overlapping channels in the 5GHz band, the benefit was not widely realized due to the decrease in transmission range caused by operating at higher frequencies. Furthermore, if an access point (AP) were to take advantage of wider channels to increase the data rate, for example by channel bonding, the AP would consequentially suffer an additional decrease in transmission range as well as greater sensitivity to interference [1].

With the introduction of MIMO smart antenna technology in the 802.11n standard [7], adoption of wider channels is now an appealing concept. Problems that are faced using wider channels in traditional 802.11 SISO networks can be mitigated with MIMO. MIMO utilizes multiple discrete antennas to transmit multiple data streams simultaneously along the same channel [12], [13], [14].[2] MIMO takes advantage of this multiplicity of data streams to improve either the signal-to-noise ratio (SNR) or the data rate at the same distance by using one of its two modes of operation: *spatial diversity* and *spatial multiplexing*, respectively. *Spatial diversity* transmits the same signal over multiple antennas simultaneously, while *spatial multiplexing* transmits different signals over multiple antennas.

Previous work has looked at the impact of MIMO on 802.11n testbed environments [2], [4]. Compared to traditional SISO systems, MIMO is shown to improve the transmission range, reliability, and data rate. Some work has focused on the impact of MIMO on the design of rate adaptation solutions [15], [16]. These studies show that traditional methods of determining the best operating rate in a SISO environment no longer apply with MIMO.

Although existing research has uncovered the unique

1. WLANs vacate the 5GHz band in the presence of weather and military radar signals. This is called Dynamic Frequency Selection (DFS).
2. The IEEE 802.11n specification allows up to four spatial data streams; current products in the market support up to three streams.

behavior of MIMO systems in 802.11n environments, we have yet to understand the implications of these findings on the performance of channel bonding in 802.11n WLAN settings. We build on these findings to accurately assess the performance of channel bonding in 802.11n WLANs.

Channel Management: The ability of channel bonding to increase data rate can be leveraged to allow more flexibility in distributing the load. This flexibility has defined the recent direction in bandwidth management solutions that advocate adapting channel width in wireless networks to accommodate changes in load conditions [1], [17], [18], [19]. These studies rely on the assumption that increasing the channel width should theoretically increase the data rate, since more data is being transmitted over a wider bandwidth. Recent studies, however, have shown that the benefits of channel bonding in 802.11n are influenced by network factors, such as interference and loss [5], [6], [8]. Therefore, it is clear that channel management solutions in 802.11n WLANs must first understand the behavior of channel bonding in order to make intelligent decisions as to how to assign bandwidth in the network.

Experimental Studies of 802.11n: Experimental studies on 802.11n have provided valuable insights into its features [6], [8]. Work most related to ours proposes a framework to incorporate channel bonding in WLANs [5]. Yet, although much has been contributed, research still falls short on accurately analyzing and characterizing the behavior of and opportunities for channel bonding in real-world WLAN settings, where interfering links co-exist. Most prior work has evaluated operation on the busy 2.4GHz range [6], [8], [20], which has a limited number of non-overlapping channels; performance constraints are thus tighter to be able to properly gauge performance benefits [1], [8], [10]. As such, a complete picture that demonstrates the opportunities for channel bonding and the effect of varying network conditions on performance has not yet been achieved in wireless networks.

3 Test Environment

We set out to understand the characteristics of channel bonding in 802.11n WLANs and the network factors that influence its behavior to ultimately predict how to maximize performance. To achieve this goal, we set up a configurable testbed that gives us the flexibility to evaluate channel bonding in a variety of network conditions. Below, we describe our testbed environment while focusing on node configuration, measurement tools and the general measurement setup. Configurations that are specific to particular experimental scenarios are discussed when the findings of those experiments are presented.

3.1 Node Configuration

We conduct our experiments using a stationary testbed deployed in a semi-open office environment. The testbed consists of 12 laptops. All the laptops are equipped with an 802.11n AirMagnet 2×3 MIMO PC card with a dual-band Atheros AR5416/AR5133 chipset. The AR5416 baseband and MAC processor supports modulation and coding scheme (MCS) indices 0 to 15 (see Table 1 for a detailed list of supported PHY modes). The Linux device driver is based on the Atheros ath9k that supports 802.11n [21].

We vary the locations of transmitter and receiver pairs to obtain a rich set of link conditions, where the transmitter operates in AP mode. Our experiments consist of 20 different links. We set the symbol guard interval to the short guard interval (SGI) of $400ns$.[3] Our goal in configuring the network is to select link settings that yield the highest PHY data rates supported by the 802.11n standard.

TABLE 1
Tested Modulation and Coding Schemes (MCS).

MCS index	Spatial Streams	Modulation	Coding Rate	Data Rate (Mb/s) 20 MHz	Data Rate (Mb/s) 40 MHz
0	1	BPSK	1/2	6.5	15.0
1		QPSK	1/2	13.0	30.0
2			3/4	19.5	45.0
3		16QAM	1/2	26.0	60.0
4			3/4	39.0	90.0
5		64QAM	2/3	52.0	120.0
6			3/4	58.5	135.0
7			5/6	65.0	150.0
8	2	BPSK	1/2	13.0	30.0
9		QPSK	1/2	26.0	60.0
10			3/4	38.0	90.0
11		16QAM	1/2	52.0	120.0
12			3/4	78.0	180.0
13		64QAM	2/3	104.0	240.0
14			3/4	117.0	270.0
15			5/6	130.0	300.0

3.2 Measurement Environment

In our experiments, we generate constant bit-rate UDP traffic between the transmitter and receiver pairs using the *iperf* tool, with fixed packet sizes of 1500 bytes. We monitor UDP flows, and evaluate their performance in terms of MAC layer throughput and packet reception rate (*PRR*). All our reported performance metrics are averaged over 10 runs. We restrict flows to UDP in order to measure the performance gains of channel bonding without having to account for the performance effects of transport layer parameters, such as TCP's congestion control. Furthermore, to provide accurate measurements of the packet delivery rate at the MAC layer, we disable both link layer retransmissions and frame aggregation (A-MPDU). By disabling aggregation, we also avoid software-driven retransmissions. This system setup constrains the maximum throughput to less than 45Mb/s, even for MCS 15.[4]

We run our experiments for all supported MCS (see Table 1) and identify the best MCS for each tested link and channel width configuration. In so doing, we mimic

3. The chipset does not allow SGI to be used with 20MHz channels.

4. Compliance to the 802.11 standard imposes an irreducible MAC overhead, independent of bandwidth, on every transmitted packet; even with an infinite PHY rate, the maximum throughput will be bound to 50Mb/s. With aggregation, the fixed overhead is shared by multiple frames, reducing the relative overhead, thus allowing higher throughput.

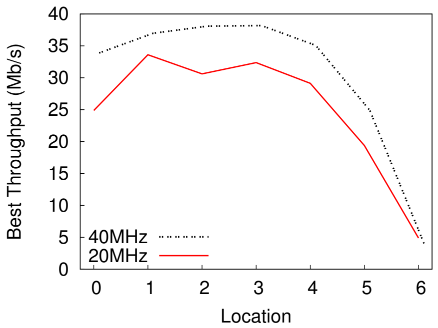


Fig. 1. Throughput achieved between single transmitter and receiver pairs at varying locations. The locations are sorted in order of decreasing RSSI.

the behavior of an ideal rate adaptation mechanism that selects the MCS that maximizes link performance. We henceforth use the term *best throughput* to reflect the highest application layer throughput yielded by the best MCS for the link under study. We thus present a fair evaluation of the performance of 40MHz versus 20MHz channels under varying network scenarios. We categorize MCS indices into two groups based on their corresponding MIMO mode and refer to these groups as *sets*: a set for MCS 0 to 7, which exploits *spatial diversity*, and a set for MCS 8 to 15, which achieves *spatial multiplexing*.

We conduct experiments exclusively on the 5GHz band and at night when potential for interfering traffic is minimal.

4 Empirical Study of Channel Bonding

The purpose of our study is to examine the performance of an IEEE 802.11n WLAN with channel bonding in response to particular network characteristics. Our findings give us guidance into how to build 802.11n networks that maximize the performance gains available from channel bonding. In the following subsections, we use experimentation to answer questions that are critical to understand the use of 40MHz channels in 802.11n WLAN environments.

4.1 What parameters affect the performance of channel bonding between a transmitter and receiver pair?

In this section, we take a close look at the parameters between a transmitter and receiver pair that affect the performance of channel bonding.

4.1.1 Is performance always monotonic with RSSI?

Ideally, we expect performance to decrease monotonically as the received signal strength indicator (RSSI) decreases. However, we find that RSSI does not accurately reflect performance, as shown in Fig. 1. Fig. 1 plots the best throughput between single transmitter and receiver pairs at varying locations, sorted in decreasing order of RSSI of each node pair, from strongest to weakest. Regardless of channel width, locations 1 to 4 in Fig. 1 outperform location 0, even though the latter receives the strongest signal. This fact is also observed in Figs. 3(a) and (b), which show the PRR and throughput of a link with strong (above −40dBm) and moderate (above −50dBm) RSSI, respectively; the link with moderate RSSI outperforms that with strong RSSI. We can thus affirm that RSSI alone is not an adequate link quality metric, especially at high data rates, where performance with MIMO is further influenced by propagation characteristics. As further discussed in Section 4.1.2, MIMO transmissions can take advantage of different propagation phenomena. These phenomena depend on particular characteristics of the path between a transmitter and receiver, which can be highly unpredictable.

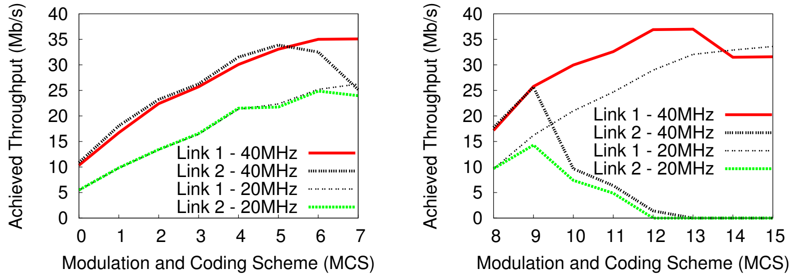
Although RSSI does not directly reflect performance, we find that it is necessary, but not sufficient, information to determine when a 40MHz channel outperforms a 20MHz channel. For RSSI values that are close to the current MCS's sensitivity (which is higher for faster modulations), channel bonding degrades performance. In Fig. 1, we observe that only for location 6, which has an average RSSI[5] of −82dBm, a 20MHz channel yields a higher throughput. Since the minimum receiver sensitivity of a 40MHz channel is −79dBm while that of a 20MHz channel is −82dBm, operating on a 40MHz channel at location 6 degrades performance because RSSI falls below the sensitivity range of a 40MHz channel. When the RSSI lies above the minimum sensitivity, channel bonding always improves performance. However, with low RSSI values, the sacrifice in available spectrum to channel bond may not be worthwhile, given the low level of improvement. Section 4.2 gives more insight into this matter.

4.1.2 How does rich scattering affect performance?

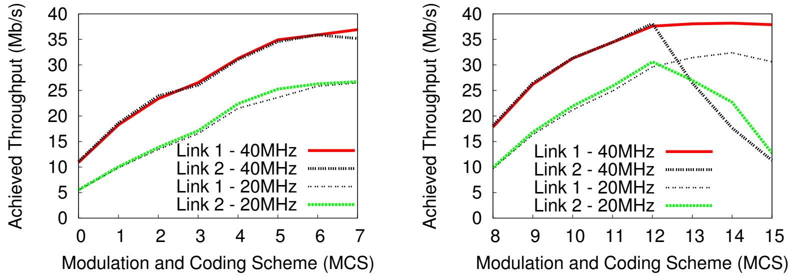
As shown in Section 4.1.1, RSSI alone is not a good predictor of 802.11n performance. In this section, we demonstrate how rich scattering contributes to this behavior.

Multi-path diversity has traditionally had a negative impact on performance. However, with the incorporation of MIMO technology in 802.11n networks, multi-path diversity is now used to overcome fading effects and instead improve signal quality [13]. We evaluate the impact of MIMO by comparing the throughput achieved between links with similar signal quality. In Fig. 2(a), we compare two links with good signal quality (> −30dBm), where the client for Link 2 is in direct line-of-sight of the transmitter while the client of Link 1 is separated by obstacles. In Fig. 2(b), we compare two links with moderate signal quality (between −43 and −46dBm), where the receivers are placed at different locations and are separated by different obstacles. The behavior of the links is representative of the behavior observed in our experiments. For the *spatial diversity set* (MCS 0–7), we observe little difference between links of similar strength. However, for the *spatial multiplexing set* (MCS 8–15), we observe considerable differences in throughput. In Fig. 2(a), Link 1 and Link 2 achieve similar throughput values for low MCS indices, but for MCS

5. The average RSSI is the per-packet RSSI averaged over multiple received beacon packets, where per-packet RSSI is the RSSI averaged over all MIMO antennas.



(a) Good signal quality (> -30dBm)



(b) Moderate signal quality (between -43 and -46dBm)

Fig. 2. Throughput achieved between the transmitter and receiver pairs with similar signal qualities.

greater than 8, Link 2's performance drops while Link 1 maintains or improves its performance with higher MCSs.

As mentioned in Section 2, *spatial multiplexing* transmits multiple independent data streams over different transmit antennas on the same channel. In order for the signals to be correctly decoded, they should arrive at the receiver across independent spatial paths with sufficiently different spatial signatures [14]. Although there is no existing method that can accurately characterize multipath diversity, we attribute the performance differences in Fig. 2 to the extent to which an environment is rich in scattering. The impact of poor scattering is observed more accurately for strong links where the transmitter and receiver are likely to be in close range with each other, as seen in Link 2 in Fig. 2(a), where both nodes are in line-of-sight. In such cases, performance varies considerably due to the potential scarcity of independent spatial paths between transmitter and receiver pairs. Yet, regardless of the scattering environment, a 40MHz channel consistently outperforms a 20MHz channel, provided that the link's RSSI is above minimum sensitivity, and the link is configured to its best MCS.

4.1.3 *What patterns do we observe between varying MCS values?*

We now evaluate our performance metrics, namely PRR and achieved throughput, for all possible MCS values in a variety of link qualities, as shown in Fig. 3. The results of our experimentation expose distinct patterns in the behavior of our performance metrics with respect to different MCSs.

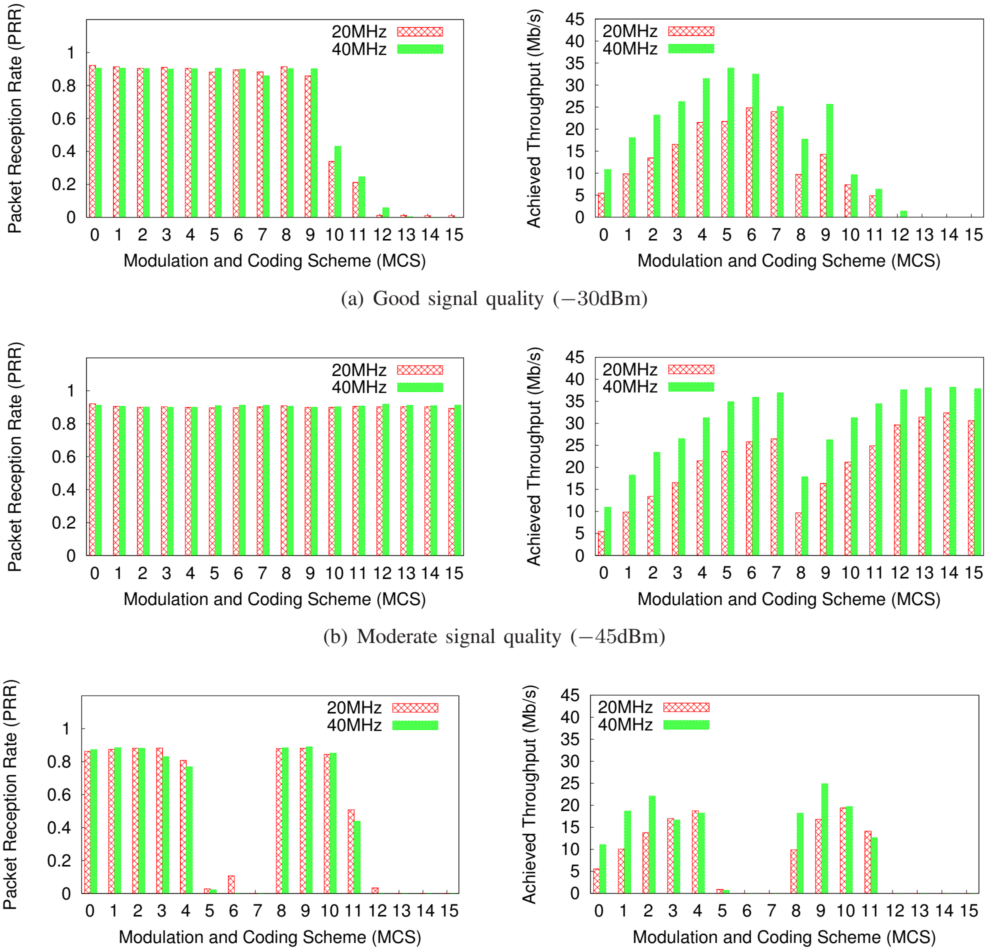
As expected, independent of the signal strength, throughput either monotonically increases or decreases as we move from low to higher transmission rates within each MCS set. Recall that MCS values are divided into two sets based on the MIMO mode used (MCS 0 to 7 and 8 to 15). In other words, when throughput begins to decrease at a particular MCS, any higher MCS *in that set* will not perform better.

PRR gives clearer insight into the quality of a link than RSSI or throughput. PRR remains relatively constant and then drops when conditions cannot support the required transmission rate at a particular MIMO mode; this behavior is consistent among all links. Fig. 3(c) depicts how weak links perform poorly at high transmission rates, irrespective of the MCS set. On the other hand, for strong links that suffer from scarcity of multipath diversity, PRR drops at MCS values that sacrifice data redundancy for higher rates using *spatial multiplexing*, as shown in the PRR plot of Fig. 3(a) for MCS above 9. In general, by comparing the behavior of a 40MHz versus a 20MHz channel in Fig. 3, it is clear that channel bonding outperforms a 20MHz channel, particularly when the correct MCS is chosen. Doubling the physical rate compensates for the increased error rate provided that, roughly, $\text{PRR}_{20MHz} < 2\text{PRR}_{40MHz}$.

4.2 How should bandwidth be assigned between neighboring nodes?

Our evaluation of the behavior of channel bonding in isolation revealed that it improved performance provided that signal quality is greater than receiver sensitivity. We now evaluate how channel bonding behaves in more realistic settings with neighboring and potentially interfering links.

The impact of neighboring links depends on the amount of spectral overlap. This phenomenon has been studied extensively, particularly in the 2.4GHz band, in the context of partially overlapping channels [22]. We now evaluate how neighboring links with varying bandwidth impact performance, in order to be able to assign channels efficiently. To do so, we examine two constituent subproblems: how

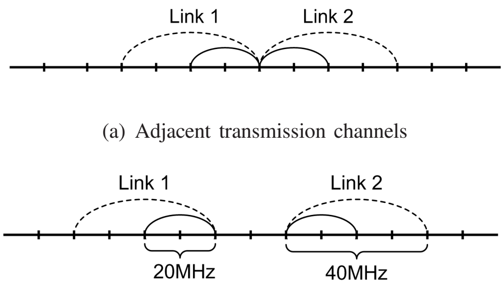


(a) Good signal quality (−30dBm)

(b) Moderate signal quality (−45dBm)

(c) Poor signal quality (−75dBm)

Fig. 3. PRR and throughput between transmitter and receiver pairs with good, moderate, and low signal qualities.



(a) Adjacent transmission channels

(b) Transmission channels separated by 20MHz

Fig. 4. Separation cases between non-overlapping channels: (a) adjacent channels, and (b) 20MHz channel width apart.

to assign non-overlapping channels between neighboring nodes, and how to deal with co-channel interference.

4.2.1 *What is the impact of channel leakage?*

To maximize throughput, simultaneously transmitting neighboring nodes should operate on non-overlapping channels in order to avoid contention and interference for the wireless medium. However, nodes that operate on non-overlapping, yet adjacent, channels, as depicted in Fig. 4(a), still suffer interference from channel leakage when power from transmissions on adjacent channels spills to neighboring channels [23].

In Table 2, we evaluate the impact of channel leakage on the performance of links with strong, moderate, and poor signal quality. We test channel leakage under conditions where the interferer has both a strong and weak signal quality to the transmitter and receiver of the studied link, as well as when the interferer is operating on either a 20MHz or 40MHz channel. We vary the separation between the non-overlapping channels from being adjacent (*adj*), shown in Fig. 4(a), to being separated by a 20MHz channel (*sep*), as in Fig. 4(b). We also include the case where the transmission channels are far enough apart (40MHz or more) to be considered interference-free. Table 2 shows how these conditions affect the studied link's best throughput, its corresponding best MCS and PRR. These performance values summarize the methodology we use to conclude patterns in the behavior of non-overlapping channels.

Even in the presence of a weak interferer, performance is still negatively impacted, as shown in Table 2, row 2 for a 20MHz link. As the interferer's signal strength increases[6], the performance of the studied link further deteriorates,

6. The RSSI of the interferer link is measured at the studied link from beacon packets, which are sent at a constant bit rate on a 20MHz channel.

TABLE 2
Effects of channel leakage on performance.

Row	Link Conditions	Link Metrics	Bandwidth of Studied Link									
			20MHz					40MHz				
			interference-free	20 MHz adj	20 MHz sep	40 MHz adj	40 MHz sep	interference-free	20 MHz adj	20 MHz sep	40 MHz adj	40 MHz sep
1	Strong Signal Quality and Strong Interferer	Mb/s*	33.60	23.86	30.70	14.18	22.35	36.98	18.74	35.98	20.56	32.69
		MCS	15	13	13	14	6	13	9	6	13	5
		PRR	0.92	0.90	0.90	0.88	0.90	0.91	0.90	0.91	0.91	0.91
2	Moderate Signal Quality and Weak Interferer	Mb/s*	30.61	20.49	26.02	25.12	25.99	38.09	37.42	38.11	37.68	38.44
		MCS	12	4	12	12	12	12	12	12	12	12
		PRR	0.93	0.96	0.95	0.94	0.95	0.95	0.96	0.95	0.96	0.95
3	Moderate Signal Quality and Strong Interferer	Mb/s*	32.27	24.49	29.57	15.08	25.33	38.17	25.21	34.83	29.62	34.00
		MCS	14	15	15	4	12	14	7	12	5	12
		PRR	0.90	0.86	0.88	0.91	0.86	0.91	0.86	0.91	0.92	0.90
4	Weak Signal Quality and Strong Interferer	Mb/s*	19.38	11.34	16.45	12.31	15.51	24.89	11.91	21.58	15.35	23.35
		MCS	10	9	3	3	3	9	2	9	9	9
		PRR	0.84	0.90	0.90	0.90	0.90	0.89	0.90	0.82	0.90	0.89

*: Best Throughput (Mb/s)

even when channels are non-adjacent, as shown in Table 2 row 1, 3, and 4 for strong interferers. To achieve interference-free conditions, links with strong to moderate signal strength should thus be separated by at least 40MHz.

Typically, power leakage from neighboring transmissions produces reception errors due to the decreased SINR (Signal to Interference-plus-Noise Ratio). The increased error rate can be compensated by using a more reliable (but slower) modulation. Furthermore, when interfering transmissions on adjacent channels are from physically close nodes, power leakage could be strong enough to activate carrier sensing at the transmitter's MAC layer [24], [23]. By activating carrier sensing, collisions are avoided, and the transmitter can use more aggressive modulations, which compensates for the negative impact of deferred transmissions. As mentioned earlier, for the same interferer, a 20MHz transmission has more energy than a 40MHz transmission and, thus, a 20MHz transmission is more easily detected. Therefore, for sufficiently strong interferers that activate carrier sensing, performance is better with a 20MHz interferer than with a 40MHz interferer, as shown in Table 2 row 1, 3, and 4[7]. However, if the studied link channel bonds, its best MCS is generally less aggressive and thus more robust to interference. In such cases, collisions will not significantly impact performance and *40MHz adj* performs better than *20MHz adj*. On the other hand, if the interferer is weak, as shown in Table 2 row 2, and the power leakage is seldom above the carrier sensing threshold, a 40MHz interferer produces fewer reception errors since it is received with less energy.

Table 2 demonstrates that channel bonding must be intelligently executed to improve performance. In some cases, even if a free 40MHz channel is available, leakage from adjacent channels can degrade performance compared to that of a single 20MHz channel. For example, in Table 2 row 1, although the studied link is strong, if the interferer is strong and operates on an adjacent 20MHz channel (*20MHz adj*), then channel bonding degrades performance. On the other hand, if the interferer operates on an adjacent 40MHz channel (*40MHz adj*), channel bonding improves performance. This observation applies independent of the signal strength of the interferer, as shown in all cases in Table 2. Further, if the interfering channel is separated by 20MHz, channel bonding always improves performance.

7. In Table 2 row 4, there is little difference between *40MHz adj* and *20MHz adj* for a 20MHz channel, since the studied link operates using low, reliable MCS. This link is thus more resilient to interference caused by a lower-energy *40MHz adj* leakage.

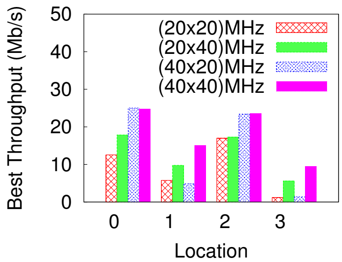


Fig. 5. Best throughput for different links suffering from co-channel interference. The legend is defined as *(transmitter's bandwidth* $\times$ *interferer bandwidth)MHz*. The locations are sorted in order of decreasing RSSI.

4.2.2 *What are the effects of sharing the channel?*

In densely populated networks, devices share channels, since the number of available non-overlapping channels may not be enough to avoid co-channel interference. Cells may in fact share a channel without being aware due to the known hidden terminal problem, which is a difficult to detect without client-side modifications [25]. We now investigate the hidden terminal problem that occurs when transmitters are not in transmission range of each other, but in carrier sensing range. We evaluate the impact of channel bonding on the performance of such shared channels.

We configure the network such that two transmitters share the wireless medium. We vary the channel width of each transmitter and evaluate the throughput when the channels completely overlap in Fig. 5. The 802.11n specification for channel bonding pairs in the 5GHz range states that 40MHz transmissions cannot partially overlap with each

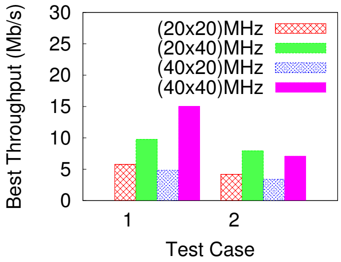


Fig. 6. Best throughput for a link (location 1 in Fig. 5) suffering from co-channel interference. In Test Case 1, the overlapping transmitter has good link quality to its receiver and operates at MCS 10. In Test Case 2, the overlapping transmitter has poor link quality to its receiver, and thus operates at MCS 0.

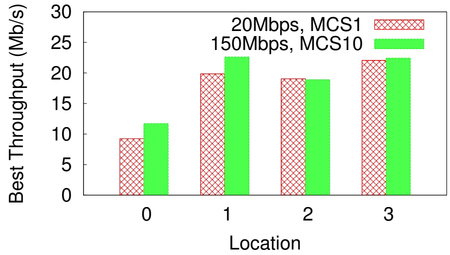


Fig. 7. Best throughput for different links suffering from a 40MHz co-channel interferer and fairness constraints. The locations are sorted in order of decreasing RSSI.

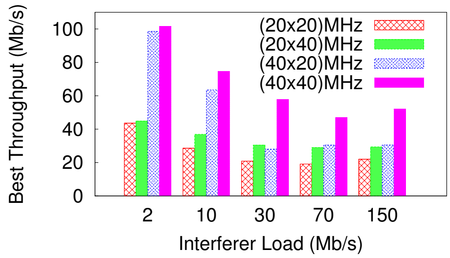


Fig. 8. Best throughput for a link suffering from co-channel interference with varying interferer load. We define the legend: *(transmitter's bandwidth* $\times$ *interferer bandwidth)MHz*.

other [7]. For simplicity, we refer to the transmitter under question as T and the transmitter sharing the channel with T as S. We define the legend in Fig. 5 as: *(T channel-width* $\times$ *S channel-width)MHz*. We vary the signal strength between T and its corresponding receiver and order the locations by decreasing signal quality. S always has good signal quality to its receiver and operates at high transmission rates.

The best performance in Fig. 5 occurs when both T and S operate on a 40MHz channel (*40$\times$40 MHz*). In most cases, T's operation on a 40MHz channel, independent of the bandwidth of S, improves performance compared with a 20MHz channel; however, this condition is not guaranteed and depends on how effectively a link can take advantage of signal strength to increase data rate, as discussed in Section 4.1. For example in Location 1, T's performance degrades with channel bonding when it competes for the medium with a 20MHz interferer (*40$\times$20 MHz*). In this case, performance degrades due to the combined effects of interference and channel sharing, resulting from S being a weak interferer. When sharing a channel with a weak interferer, not all transmissions can be detected, and thus the "effective" noise on the shared channel will increase; the increased errors in 40MHz forces T to use slower MCS.

In situations where multi-rate CSMA nodes share the medium, since all transmitters have the same access rights, low data rate nodes have been found to capture the medium for longer periods of time, thus penalizing fast stations [26]. Therefore, we also evaluate the scenario where, instead of operating at high data rates, S operates at low data rates, shown in Fig. 6. Test cases 1 and 2 correspond to the scenario in location 1 of Fig. 5; however, in Test case 2, S now operates at the lowest data rate of MCS 0. As we can see, when S operates at low rates, T does not improve performance by channel bonding.

Our findings on channel sharing show that, regardless of the bandwidth of T, it is more advantageous for T to compete for the channel with an interferer who transmits at 40MHz: 40MHz interferers attain higher transmission rates and alleviate fairness issues in multi-rate scenarios, leading to better performance. However, the decision to channel bond relies on the accurate characterization of T's potential to take advantage of channel bonding, as described in Section 4.1, as well as knowledge of the transmission rate of S with its corresponding receiver.

4.3 How does channel utilization affect performance?

In channel sharing conditions, a station's medium access opportunities depend on the load imposed on the network by other interferers operating on the same or overlapping channels. We now evaluate the impact of different load levels on the performance of channel bonding. We configure the network with two transmitters sharing the wireless medium, and use a configuration identical to the one in Section 4.2.2. We again refer to the studied transmitter as T and the transmitter sharing the channel with T as S.

In order to isolate the effect of channel utilization on performance, we enable packet aggregation in these experiments so that transmitters with a high MCS are allowed a higher degree of aggregation. This means that fast STAs can send more aggregated frames per transmission opportunity than slow STAs, enabling airtime fairness [27]. As we show in Fig. 7, packet aggregation mitigates the impact of fairness issues caused in such multi-rate scenarios and allows us to evaluate the impact of channel utilization alone. Under the same channel utilization conditions for the interferer S, S at MCS 1 impacts the performance of T similarly to when S operates at MCS 10.

We make two key observations as we evaluate the impact of load on performance in Fig. 8. Our first observation is that the benefit of channel bonding decreases with increased load. For the same interferer bandwidth and rate, the benefit of channel bonding decreases as the load imposed by the

TABLE 3
Comparison of TCP and UDP performance.

Link Metric	Link Strength	UDP 20 MHz	UDP 40 MHz	TCP 20 MHz	TCP 40 MHz
Achieved Throughput (Mbps)	Strong	29.66	32.35	21.72	24.26
	Moderate	22.94	27.46	17.44	21.22
	Weak	16.50	25.66	12.00	20.22
Best MCS	Strong	15	13	13	13
	Moderate	12	12	12	11
	Weak	5	11	10	11
Throughput Gain (%)	Strong	9		12	
	Moderate	20		22	
	Weak	56		69	

interferer increases and the link approaches saturation. In saturation, there is high contention for the shared medium and little time to exploit the benefits of channel bonding.

Our second observation is that, with increased load, it is still better for stations to compete for the medium with a 40MHz interferer, until saturation, at which point performance differences are minimal. As discussed in Section 4.2.2, competing with a 40MHz interferer reduces fairness issues due to higher PHY rates achieved by channel bonding. The highest throughput is achieved when both *T* and *S* operate on completely overlapping 40MHz channels (*40x40 MHz*).

Our findings reveal that our channel bonding decisions will differ depending on the channel utilization of the overlapping channel. For example, a transmitter might choose to compete with a 20MHz interferer with low load instead of a 40MHz interferer with higher load.

4.4 What are the performance benefits of channel bonding using TCP traffic?

We now evaluate the performance of channel bonding under TCP traffic. TCP is more sensitive to packet losses, and we therefore evaluate the impact of varying PRR levels on performance. In Table 3, we show a representative sample of our performance measurements from 15 different links using TCP traffic. We compute the achieved throughput of each link, the corresponding MCS that achieves that throughput value, which we refer to as the *Best MCS*, as well as the channel bonding throughput gain. We also include UDP results for the same links to compare against.

As expected, we find that for varying link strengths, and for the same transmission bandwidth, TCP throughput values are lower than UDP throughput values. This result is due to TCP's increased overhead and higher sensitivity to packet losses. However, if we look at the throughput gains from channel bonding, we find that the performance benefits under UDP traffic are also observed under TCP traffic. Though a 40MHz channel is more susceptible to loss [5], channel bonding is capable of achieving higher throughput values for all link strengths. Furthermore, we observe that the performance improvements achieved by UDP over TCP are similar for both 20MHz and 40MHz channels, provided that a more conservative MCS is used to counteract both the increased errors caused by channel bonding as well as TCP's sensitivity to errors. As such, channel bonding does not appear to particularly affect TCP.

Along the same lines, we also observe that, regardless of the traffic type, the MCS chosen by a 20MHz channel is generally more aggressive than that chosen by a 40MHz channel[8]. Since a 40MHz channel is more susceptible to interference, it utilizes more reliable (*i.e.*, low) MCS rates in order to maximize performance.

Though a 40MHz channel is more susceptible to noise and interference, and TCP traffic suffers from greater sensitivity to loss, the combination of TCP and channel bonding still provides performance benefits as compared to a 20MHz channel. This result demonstrates that the performance improvements of channel bonding are not restricted to a particular traffic type. Hence, 40MHz channels can be exploited in WLANs for both UDP and TCP traffic in order to achieve higher data rates.

5 Identifying Channel Bonding Opportunities

Through our investigations in Section 4, we identified the network characteristics that are either conducive or detrimental to the performance of channel bonding. With this knowledge, we now answer some questions that allow us to evaluate a network to determine channel bonding opportunities and to make recommendations of when channel bonding improves the performance. This information could be used as valuable input to a channel management scheme.

5.1 How can unfavorable network conditions be determined from performance metrics?

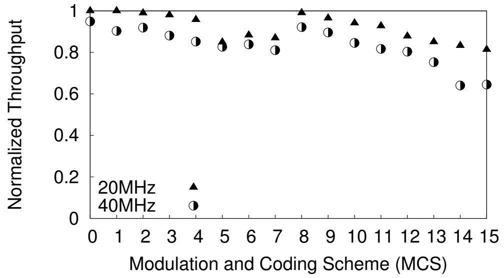
There are multiple conditions in WLANs that contribute to performance variations. Of these conditions, some can be mitigated through intelligent channel management solutions without readjustments to the network topology nor client-side modifications; we refer to these conditions as *unfavorable network conditions*. In our work, we identify two possible unfavorable conditions. One condition is the presence of nodes that operate on overlapping channels. The second condition is interference caused by channel leakage from nodes operating on adjacent channels. As shown in previous sections, both conditions lead to degradations in performance if left unidentified and unresolved.

In the evaluation of our results, we define *normalized throughput*, an accurate indicator for unfavorable network conditions. Based on *normalized throughput*, we design and implement a MAC-layer anomaly detector that successfully alerts to the presence of unfavorable network conditions in 100% of the test cases. This detector can form the foundations of future channel management algorithms.

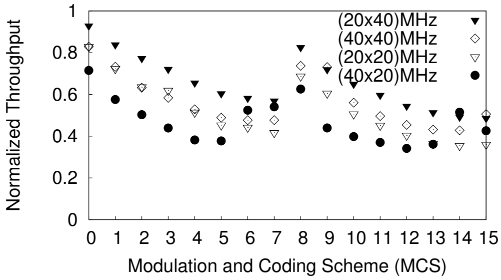
5.1.1 Normalized Throughput

Normalized throughput is the ratio of the achieved throughput over the expected throughput. Expected throughput is the throughput that would be achieved in an ideal

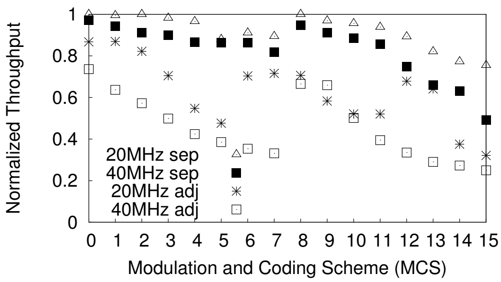
8. MCS 8–15 apply the same modulation and coding as MCS 0–7.



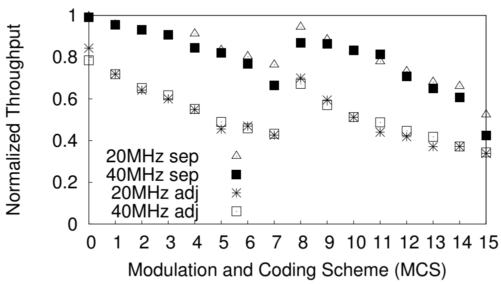
(a) Interference-free environment



(b) Channel overlap with another transmission



(c) Channel leakage from a neighboring 20MHz transmission



(d) Channel leakage from a neighboring 40MHz transmission

Fig. 9. Normalized throughput of a moderate strength link.

environment. We measure achieved throughput at the MAC layer. Similar to [28], we calculate expected throughput (E_{Th}) in terms of delay per packet:

$$E_{Th} = \frac{K \cdot L_{data} \cdot PRR}{DIFS + T_{BO}(PRR) + T_{Kdata} + SIFS + T_{ACK}} \quad (1)$$

where K is the number of aggregated frames, which is equal to 1 with disabled aggregation; L_{data} is the payload carried per frame (in bits); $DIFS$ is the time interval a wireless medium should be idle before a station can transmit; T_{BO} is the average backoff time, which is a function of the PRR; T_{Kdata} is the total time required to send the A-MPDU (including preamble and headers) at a given PHY rate; $SIFS$ is the constant time interval between a data frame and its ACK; and T_{ACK} is the time required to send an ACK frame (or Block ACK).

We observe from our results that normalized throughput is a good indicator of unfavorable network conditions; the greater the impact an unfavorable condition has on performance, the more clearly the impact is reflected in the computed normalized throughput at each MCS.

Fig. 9 depicts the typical behavior of normalized throughput for all MCS under varying network conditions. Fig. 9(a) computes normalized throughput for a single link in an interference-free environment. For that link, Fig. 9(b) represents values when a second link operates on an overlapping channel, while Figs. 9(c) and (d) show values when a second link operates on a non-overlapping, yet adjacent, channel. We find that the behavior of a link in an interference-free environment is consistent, independent of the strength and conditions of that link. This observation allows us to identify and characterize situations where performance is affected by unfavorable network conditions. We now explain our observation and reasoning.

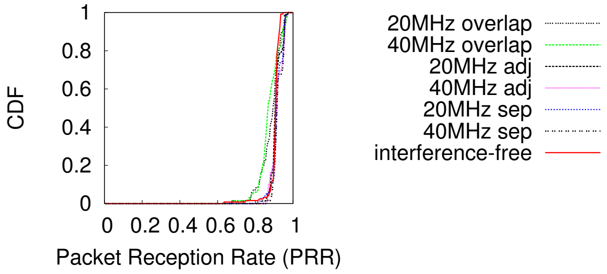
Fig. 9(a) depicts the behavior we observe in an interference-free environment. We note a gradual drop in normalized throughput as transmission rates increase. For low MCS, particularly for MCS values of $0, 1, 2$ and $8, 9, 10$, the achieved throughput very closely approximates the expected throughput with ratios between 90% and 100%. This condition holds as long as the RSSI of the link in question is greater than the receiver's minimum input sensitivity. However, as rates increase, ratios monotonically drop. Furthermore, we observe that 20MHz channels achieve higher ratios than 40MHz channels for all MCS. Therefore, we believe that the distance of the achieved throughput from the expected throughput is due to the strict SNR requirements necessary to achieve those rates.

The difference between achieved and expected throughput increases depending on the severity of the aforementioned penalty imposed on fast stations due to sharing a medium with slow stations. Therefore, even with a high PRR, the achieved throughput will be lower than expected. If we look at Figs. 9(b), (c), and (d), we notice a consistent pattern, which is the drop in normalized throughput for low MCS, which we do not observe in interference-free settings. This drop is reflected in the higher transmission rates where normalized throughput drops more steeply.

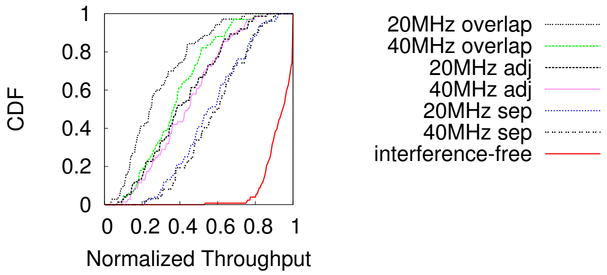
Next, we test the effectiveness of using normalized throughput in the design of a MAC-layer anomaly detector.

5.1.2 Network Anomaly Detector

We now discuss our network anomaly detector. We start by describing how normalized throughput forms the foundations of our detection mechanism, using results shown in Fig. 10. We plot the CDFs of the PRR and the corresponding normalized throughput values for multiple links of varying strength, channel width, and MCS. We further subject our links to the different network conditions investigated in this work, namely channel sharing, leakage, and interference-free conditions. To emulate an intelligent



(a) CDF of packet reception rate (PRR)



(b) CDF of normalized throughput

Fig. 10. CDF of PRR and the corresponding normalized throughput values for multiple links of varying strength, channel width, and MCS.

rate adaptation solution that reacts to changes in PRR [21], [29], [30], Fig. 10 only includes the results from MCS values that provide reasonable PRR levels for each link.

As we can see from Fig. 10(a), the PRR achieved by these links under varying network conditions show little difference compared to the interference-free scenario. However, although a successful rate adaptation solution can maintain an acceptable PRR despite changes in network conditions, the corresponding CDF of normalized throughput values for the given PRR values depicts considerable differences in behavior, as shown in Fig. 10(b). In interference-free conditions, around 80% of the links have normalized throughput values greater than 0.9, and almost all links have values greater than 0.8. This means that the achieved throughput closely approximates the expected throughput in interference-free conditions. However, in the presence of interference, normalized throughput is distributed over a wider range of values and, in the best case, less than 10% of links attain values greater than 0.8. This increasing difference between achieved and expected throughput reveals the presence of an interferer.

We use this insight to implement a MAC-layer detector that monitors changes in normalized throughput. To compute the expected throughput in time, we used the per-packet transmission and reception statistics from Eq. 1. The achieved throughput is computed as the total number of bytes received in a given time, divided by that time. By averaging the achieved throughput over time, we avoid rapid reconfigurations due to non-persistent interfering sources, thus preventing unnecessary and costly channel migrations. Such highly dynamic interference conditions can be efficiently handled by a fine-grained per-packet rate adaptation mechanism [30].

By subjecting our MAC-layer detector to changing network conditions, we find that it successfully identifies unfavorable network conditions, or anomalies, in the environment in 100% of the test cases. With such high success rates, this detector can form the foundations of future channel management algorithms.

It is worth noting that monitoring changes in normalized throughput to detect anomalies is a useful tool in cases where T is fully saturated. For unsaturated transmitters, the detector could be adapted to consider other metrics, for example medium access delay.

5.2 Which parameters characterize a network to determine opportunities for channel bonding?

We compile a list of parameters that facilitate network characterization. This characterization can be applied in both centrally managed and distributed network environments.

Signal strength at receiver (RSSI): Our results show that RSSI is a prerequisite to determining whether 40MHz transmission could improve performance. If RSSI is above the minimum input sensitivity of a 40MHz channel (depends on MCS) in an ideal environment with minimum interference, a 40MHz channel always outperforms a 20MHz channel.

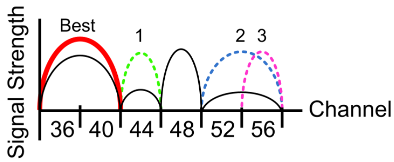
MCS in use: Since the minimum receiver sensitivity varies according to the MCS in use (higher for faster modulations), a proper selection of the MCS helps to maximize the benefits of channel bonding. In other words, to get the most from channel bonding, it should be set jointly with rate adaptation.

Strength of interfering transmissions: This metric is crucial to determine whether to bond. For example, neighboring links with strong signal strengths to each other will benefit from operating on non-overlapping channels separated by at least 20MHz, to avoid interference from channel leakage.

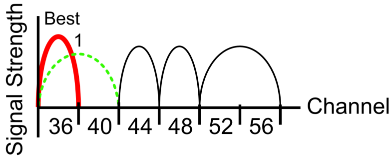
Physical rates of links in CS range: Beyond the increased contention, links that operate on the same or on overlapping channels, are susceptible to fairness issues in multi-rate scenarios. Knowing the PHY rate of neighboring links is required not only to make good decisions on when to channel bond, but also on which channel should be used.

5.3 Can performance on a 40MHz channel be inferred from performance on a 20MHz channel?

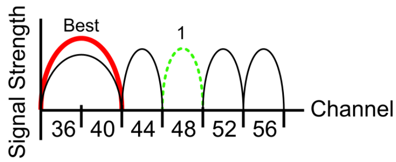
Due to multipath diversity in wireless environments, transmissions are susceptible to frequency-selective fading. Frequency-selective fading occurs when signals from different paths combine destructively at the receiver and the effect of signal-cancellation is deepest only at particular frequencies. Frequency-selective fading is an unpredictable factor in network environments and degrades performance [31]. Wider channels are thus more susceptible to frequency-selective fading. For the above mentioned reasons, performance from a 20MHz channel cannot be used to infer performance on a 40MHz channel, and we have further confirmed this behavior through experimentation.



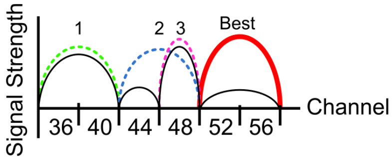
(a) Test Case 1



(b) Test Case 2



(c) Test Case 3



(d) Test Case 4

Fig. 11. Scenarios to demonstrate the impact of intelligent channel bonding decisions on network performance. In each case, a node *T* requests bandwidth. The amplitude of signals represents their strength at *T*. The bold lines represent our suggested channel configurations for *T*, while the numbered dotted lines indicate possibilities for naïve channel assignments.

5.4 Should we increase channel width to 40MHz with incomplete knowledge of the neighboring 20MHz channel?

Based on the data presented so far, the answer is clearly *no*. Not only information on the status of the adjacent channel is required due to channel leakage (cf. Section 4.2.1), but even interfering transmissions on separate channels could potentially affect channel management decisions. If channel bonding is performed under unfavorable conditions, performance will degrade. Particularly, if a 20MHz channel bonds with a channel that is used by a transmitter in carrier sensing range, the medium would then be shared by both transmitters. If the transmitter in carrier sensing range operates at a low physical rate, then performance suffers further due to fairness issues in multi-rate scenarios. As discussed in Section 5.2, there are network parameters that should be identified to perform an intelligent assignment of channel widths to improve network throughput.

6 Evaluation of Intelligent Channel Bonding

To demonstrate the impact of intelligent channel bonding decisions on network performance, we create network scenarios where naïve uninformed solutions to channel management lead to incorrect and detrimental decisions.

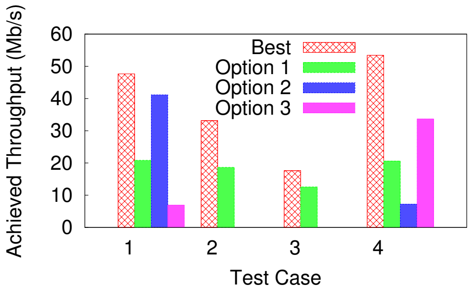


Fig. 12. Comparison of *T*'s performance using intelligent channel bonding decisions versus naïve approaches.

We show that our understanding of channel bonding allows us to make intelligent decisions that leverage the benefits of channel bonding in typical 802.11n environments. We present four different test case scenarios, depicted in Fig. 11. In each test case, we characterize the network environment and, accordingly, decide on a channel assignment for a single node *T*. We then evaluate *T*'s performance using our intelligent approach and compare it with *T*'s performance from naïve channel management decisions. It is worth noting that the same logic we apply for a single node can also be applied in the context of a centrally-managed network. We restrict our analysis to one link since our aim is to demonstrate a proof-of-concept.

For each test case scenario, we depict the corresponding assignment of channels to links in the network, and indicate the possible assignments for *T* using our intelligent approach (in bold) and a possible set of naïve alternatives (dashed). The strength of the active links with respect to *T* is represented by the amplitude of the signal. All transmitters are driven to saturation to gauge the capacity of each link. We limit the number of available channels to recreate contention for bandwidth in a large-scale testbed. In all links, RSSI is above the minimum receiver sensitivity (cf. Section 4.1.1). Furthermore, in these experiments, we enable frame aggregation and automatic rate selection to replicate the behavior of typical off-the-shelf devices. The performance results from each possible channel selection for *T*, for each test case, are shown in Fig. 12.

Case 1, Fig. 11(a): All available channels are occupied. To minimize interference, a naïve approach would scan the available channels and assign *T* the channel on which the weakest interfering signal is received. In this case, *T* can be assigned a single 20MHz channel at either channels 44 or 56: *Option 1* or *Option 3*, respectively. *T* could also be assigned bonded channels 52 and 56: *Option 2*. On the other hand, our intelligent solution identifies an opportunity to maximize performance by channel bonding on channels 36 and 40, where the existing transmitter also operates with a 40MHz channel: *Best*. Intelligent channel bonding will eliminate *Option 2* because the strong adjacent 20MHz transmission at channel 48 will cause interference from channel leakage. *Option 1* is disregarded for the same reason. As for *Option 3*, we do not distinguish any added benefit over *Best*; knowledge of the MCS used by the interfering transmitters would be a key factor for deciding between both options (cf. Section 4.2.2). As shown in Fig. 12, our intelligent solution maximizes performance considerably, with up to 7 factor increase in achieved throughput compared to the naïve solutions.

Case 2, Fig. 11(b): Two channels are free. A naïve decision would assign *T* the free 40MHz channel: *Option 1*. However, our study indicates that interference from channel leakage from the neighboring 20MHz transmitter on channel 44, which has a strong signal strength to *T*, can degrade performance. Therefore, our intelligent channel bonding solution assigns channel 36 to *T*: *Best*. As shown in Fig. 12, our intelligent solution improves performance by a factor of 83%, from 18Mb/s to 33Mb/s.

Case 3, Fig. 11(c): Only one unoccupied 20MHz channel. Similar to Case 2, a naïve approach would assign the free 20MHz channel 48 to *T*: *Option 1*. In this case as well, performance can degrade due to interference from channel leakage from the two neighboring 20MHz transmissions, on channels 44 and 52, with strong signal strength to *T*. The alternative identified by our intelligent approach is to transmit on a 40MHz-width channel, on channels 36 and 40, in parallel with an existing 40MHz transmission operating at a high physical rate: *Best*. As shown in Fig. 12, by identifying the opportunity for channel bonding, we increase the performance by 38%, from 13Mb/s to 18Mb/s.

Case 4, Fig. 11(d): We now evaluate the impact of channel utilization. This test case scenario is identical to the one used in Case 1, except we now vary the channel utilization of each interferer. A naïve approach would ignore the impact of channel utilization; thus, its assignment decisions would not differ from those in Test Case 1. In this test case, the interferer on channels 36 and 40 operates at 80% channel utilization, the interferer on channel 44 at 60%, on channel 48 at 50%, and on channel 52 and 56 at 80%.

The decision we made in Case 1, which is operation on channels 36 and 40, no longer achieves the best performance, as shown in Fig. 12. *T* now competes for about 20% of the channel with a 40MHz interferer with low MCS, which starves *T*. Similarly, *T* in *Option 3* competes for around 50% of the channel with a 20MHz interferer, which we have shown creates fairness issues. We also evaluate *Option 2*, where *T* operates on a 40MHz channel and contends for the medium with two unsynchronized 20MHz interferers; in such cases, it has been shown that the 40MHz channel will starve [32]. Our intelligent solution identifies an opportunity to maximize throughput by competing with the transmitter on channels 52 and 56, which operates at average MCS with high load: *Best*. As shown in Fig. 12, we provide up to a 6 fold increase in throughput by also considering the impact of channel utilization on performance.

7 Conclusion

Channel bonding in 802.11n networks promises increased data rates and improved performance. In this work, we identify a key set of network factors that allow us to accurately assess the impact of network conditions and channel bonding choices on performance, specifically under 5GHz operation. We find that intelligent channel bonding decisions rely on the knowledge of a transmitter's surroundings, particularly the signal strength of links, interference patterns, and channel utilization. Such findings serve as usage-terms for intelligently incorporating 40MHz operation in network deployments to maximize performance and efficiency. We further analyze the behavior of channel bonding under TCP traffic loads, and find that the performance values are diminished compared to performance under UDP. However the benefits of wider bandwidths still hold. Our work serves as a solid foundation on which channel management solutions for 802.11n networks can be built, calling on channel management design principles from existing literature [5], [19]. Our findings can be applied both at a network scale to improve channel management of the whole WLAN, and also at a link scale to aid per-packet rate adaptation mechanisms aimed at optimizing individual transmitter and receiver pairs [30]. We believe our work will also apply to the upcoming 802.11ac standard that allows up to 160MHz bonding channels in the 5GHz band.

8 Acknowledgments

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