Experimental Characterization of Wide and Dynamic Channel Widths in 802.11ac

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Contents

Abstract

802.11ac is the latest in the series of 802.11 standards that have evolved mainly with the goal of providing increased speeds. Of the new features 802.11ac offers, wider channel width of up to 160 MHz is the major contributor to per-user throughput gains. Because wider channels in practice are likely to suffer from spectrum congestion and starve for channel access, 802.11ac offers another feature called the *dynamic channel width*. We find that spectrum sharing and congestion is inevitable in the 5 GHz band due to spectrum regulations and device capabilities, thereby making *dynamic channel width* indispensable for the use of wider channels. Despite its importance, dynamic channel width has received little attention in the literature. Specifically, its implications for spectrum management and link-layer rate adaptation are not fully understood. In this work, using commodity hardware we conduct a systematic measurement study for better understanding the functioning of dynamic channel width in practice and its implications for other 802.11 functions. We uncover novel findings which we believe are useful for designing better spectrum management and link-layer rate adaptation schemes for 802.11ac.

1 Introduction

It is no secret that WiFi is ubiquitous today. The amount of data traffic carried by WiFi has only increased over the years, thanks to the smartphone and social media revolution. By 2018, WiFi is predicted to carry 85% of the global mobile data traffic with video comprising 69% of it [10]. We must note that the growth in WiFi usage is not only in terms of the number of devices or users, but also in terms of per-user bandwidth. The latest high resolution 4K videos demand up to 68 Mbps per video stream [12]. Since today's fibre-based consumer broadband access networks can provide up to 1 Gbps speeds, the last mile WiFi connectivity has become a bottleneck concern. In this light, *speed* has been one of the primary factors that has driven the evolution of WiFi technologies with IEEE 802.11ac [9] being the latest. Unlike its predecessor 802.11n [7], 802.11ac is an evolutionary standard. It only builds upon 802.11n to add the dense 256-QAM modulation (MCS 8 and 9), wider channel widths up to 160 MHz and MU-MIMO [11]. It also simplifies (standardizes) existing features in 802.11n such as frame aggregation and beamforming for better vendor interoperability. Among the additions in 802.11ac, it is only the wider channel width that is expected to provide throughput gains in terms of per user bandwidth in real world deployments. The 256-QAM modulation requires very high quality links which are rare in real world deployments. On the other hand, the per-user throughput gains from MU-MIMO are small compared to those from using wider channels. This is because MU-MIMO only enables simultaneous transmissions to multiple clients in the downstream direction. However, the corresponding ACKs in the upstream direction are still serialized [18]. Therefore, given the higher gains from operating wider channels (80 MHz or 160 MHz) compared to 256-QAM modulation or MU-MIMO, this work is focused on the wide channel aspect of 802.11ac.

While wider channels provide high throughput gains, the use of wider channels in practice is mired by the congestion present in the unlicensed spectrum. It is not difficult to imagine that when there are several competing narrow links overlapping with a wider channel link, the wider link would be starved for channel access. In order to alleviate this *starvation problem*, 802.11ac includes a new feature called the **dynamic channel width**. The dynamic channel width mechanism divides the wider channel (80 MHz or 160 MHz) into smaller 20 MHz channels. One of the 20 MHz channel functions as the primary or the control channel and the remaining function as the secondary channels. Whenever a 802.11ac transmitter is about to transmit a wider frame (say 80 MHz), if all channels are found to be free, then it transmits the frame with 80 MHz width. On the other hand, if some or all of the secondary channels are busy, then it transmits the frame with 40 MHz or 20 MHz by appropriately bonding the primary channel with one or no secondary channel. Essentially, the dynamic channel width mechanism avoids the *starvation problem* by transmitting at reduced channel widths when the secondary channels are not free.

As the 802.11 standards evolve, new features get added and they often have implications for other 802.11 functions. This sometimes gives rise to new research problems or adds new dimensions to already solved problems, thereby making existing solutions invalid or inefficient. For example, MIMO spatial streams was a major feature introduced in 802.11n which added a new dimension to the problem of link-layer rate adaptation. Consequently, Pefkianakis et al. [22] pointed out that the existing rate adaptation schemes are inefficient in the wake of this new dimension and proposed a new rate adaptation scheme called MiRA that takes into account the MIMO spatial streams. The motivation behind our work is also similar. We believe that the wide and dynamic channel width is a major feature introduced by 802.11ac and is likely to have implications for spectrum management and link-layer rate adaptation. Therefore, our work is focused on experimentally evaluating the dynamic channel width feature to uncover its implications for other 802.11 functions. However, before we do that it is important for us to confirm the prevalence of dynamic channel width when using 802.11ac in practice. This is important because if the dynamic channel width is rarely used in practice, then doing its deep evaluation is probably not worth the effort. Now the use of dynamic channel width would be prevalent as long as the problem of starvation is also prevalent. Since 802.11ac is specified to operate only in the 5 GHz band, we conducted a small study to investigate if the problem of starvation exists in the 5 GHz band. The 5 GHz band offers 500 MHz of spectrum for unlicensed use compared to only 85 MHz available in the 2.4 GHz band. However, in our study we found that due to spectrum regulations, a large portion (64%) of the available spectrum can be used by 802.11 devices only if the devices are capable of Dynamic Frequency Selection (DFS) [5]. Further investigation into 802.11 device capabilities revealed that implementing DFS is hard and thus currently almost no commodity 802.11 device is authorized to use the portion of the spectrum requiring DFS. Therefore, without DFS, all 802.11 devices operating in the 5 GHz band are confined to only 180 MHz (36%) of the available spectrum. As a result, 802.11ac is faced with the same problem of spectrum congestion in the 5 GHz band as its predecessors have been facing in the 2.4 GHz band. In summary, with only 180 MHz of spectrum in hand, spectrum sharing and congestion are inevitable. Therefore, *dynamic channel width is indispensable for operating wider channels in practice and its usage is thus prevalent.*

Dynamic channel width is not a new idea, although 802.11ac [9] standardized it. Chandra et al. [14] were the first to propose the idea of variable channel width for a single link which was later extended by FLUID [24] to a centrally managed WLAN. This was followed by several works [26, 15, 29, 27] which improved upon the basic idea in different ways – doing dynamic channel width on a per-frame basis, enabling asynchronous transmissions, handling overlapping transmissions and enabling heterogeneous channel widths. The dynamic channel width mechanism in 802.11ac is similar to these works in terms of the broad functionality it offers. However, its design differs significantly in two aspects: (i) 802.11ac uses much coarse granularity for channel widths (either 20/40/80 MHz) instead of individual subcarriers which are 312.5 kHz wide; (ii) For reduced width transmissions, 802.11ac is less flexible as each transmission is required to use the primary channel. Due to these differences, 802.11ac's spectrum sharing dynamics diverge from that of the previous schemes. But, the particular dynamic channel width mechanism of 802.11ac has received little attention in the literature and thus its implications for spectrum management as well as link-layer rate adaptation are not fully understood. While Park [21] conducted a simulation-based study of 802.11ac's dynamic channel width, their study pre-dates the ratification of the 802.11ac specification [9] and thus suffers from several inaccuracies. Additionally, Zeng et al. [28] conducted an experimental evaluation of the dynamic channel width using commodity 802.11ac hardware. However, we found several issues in their experimental methodology, data presentation as well as inference. Moreover, their work provides very limited understanding as they did not exhaustively evaluate all possible cases. While few other works [19, 13] propose improvements to 802.11ac's spectrum sharing mechanisms, they do not help us understand the standardized dynamic channel width mechanism that is already working in commodity 802.11ac hardware.

In this light, we try to fill the gap by conducting a systematic measurement study focused only on the dynamic channel width feature of 802.11ac. Since the behavior of dynamic channel width mechanism depends on detecting (sensing) transmissions from other senders, our study needs to consider two cases: (i) *Symmetric Sensing:* where spectrum sharing transmitters can perfectly detect each other's transmissions; (ii) *Asymmetric Sensing:* where one of the spectrum sharing transmitters cannot detect the other transmitter but is detected by the other transmitter. At the time of this writing, we have only completed the symmetric sensing case while the asymmetric sensing case is in progress. For the symmetric sensing case, we construct a simple testbed using a custom-built commodity 802.11ac platform. We conduct several experiments using exhaustive combinations of channel widths and positions of the primary channel. Our results help us uncover new findings about the behavior of the dynamic channel width mechanism in 802.11ac. Some of our key findings are summarized as below:

- When a narrow link overlaps the secondary channels of a wide link, the narrow link has an advantage for channel access but no exclusive access i.e. the wide link can still get some airtime share. Also, if the narrow link is slower in terms of PHY rate, the wide link has lower chances to transmit across its entire width.
- When a 40 MHz wide link overlaps with the secondary channels of a 80 MHz wide link, it results in two links that are *effectively* 40 MHz wide. Such two links are more efficient in spectrum sharing as they yield higher total throughput than a single 80 MHz wide link.
- The dynamic channel width mechanism comes into play only when links of heterogeneous channel widths overlap and it enables width-based spectrum sharing. For overlapping links of same channel widths, the spectrum is always shared in a time-based manner even if changing to width-based spectrum sharing yields higher throughput per individual link. This is a deficiency of the link-layer rate adaptation (RA) as it can always preemptively reduce the channel width for possible throughput gains.

We believe that the above observations have implications for spectrum management and link-layer rate adaptation. For example, while setting up a 80 MHz wide 802.11ac home network, a channel selection scheme can prefer to overlap its secondary channels with other overlapping networks having faster PHY rates (802.11ac/n) than those having slower PHY rates (802.11a). Doing so, the home network would have higher chances to use the entire 80 MHz channel width. Also, enterprise WLANs now have a new possibility of having two overlapping BSSs (OBSSs) that are *effectively* 40 MHz wide and share the spectrum more efficiently than a single 80 MHz wide BSS. Finally, the said deficiency of the link-layer rate adaptation (RA) arises because, traditionally, the design of the RA schemes does not take into account the channel access time. This has been so because higher channel access time does not change the *best* PHY rate chosen by the RA schemes and the RA schemes could not do anything to reduce the channel access time and increase the throughput. However, now by reducing the channel width, the RA schemes could possibly reduce the channel access time which can lead to potential throughput gains. This suggests an opportunity to re-think the design of existing RA schemes and make fundamental changes by taking into consideration the channel access time and the dynamic channel width mechanism.

The remainder of the paper is organized as following. In §2 we describe our study to investigate if the problem of *starvation* exists in the 5 GHz band. §3 provides an overview of the dynamic channel width mechanism. A thorough summary of the related works is presented in §4. §5 provides details of our testbed and hardware platform and also describes the various experiments and their results. Finally, we conclude in §6 along with discussion on future work.

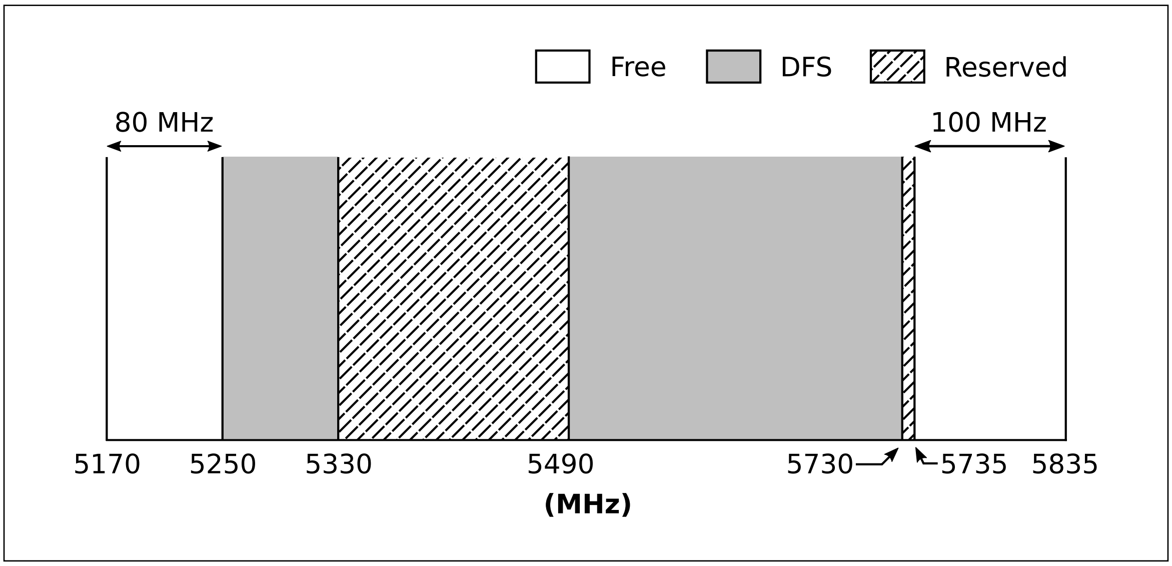


Figure 1: Free, DFS and reserved portions of the 5 GHz spectrum as designated in most regulatory regions in the world.

2 Problem of Starvation in 5 GHz band?

In this section we investigate the possibility of spectrum congestion in the 5 GHz band and thereby check if the wider channels of 802.11ac would indeed face the *starvation problem*. While the 5 GHz band is much wide compared to the 2.4 GHz band, it can still accommodate a maximum of 6 non-overlapping[1] channels that are 80 MHz wide (considering only the unlicensed spectrum width). However, the actual number of channels that could be used for 80 MHz or 160 MHz operation depends on: (i) local spectrum regulations for unlicensed use of the 5 GHz spectrum, and (ii) capability of WiFi devices to support Dynamic Frequency Selection (DFS) as per IEEE 802.11h [6]. DFS allows WiFi devices to detect military, weather and civilian radar transmissions and immediately change their operating channel.

2.1 Spectrum Regulations

The DFS standard is a requirement by the International Telecommunications Union (ITU) which is further specified by the local regulations of each country. Most spectrum regulations in the world allow unconditional use of certain frequencies in the 5 GHz unlicensed band while for certain other frequencies, they require the devices to support DFS. The Linux Wireless Regulatory Database [3] maintains up-to-date information on global regulations for unlicensed spectrum use. Singapore's regulation (similar to the US/FCC) enables the use of maximum five 80 MHz channels, of which only two can be freely used and the rest three require DFS capabilities. China's regulation on the other hand enables a maximum of three 80 MHz channels, two of which can be used freely and the remaining one requires DFS capabilities on part of the oper-

[1]Note as per the 802.11n specification, all channels, irrespective of their widths, are non-overlapping in the 5 GHz band. Only non-partial overlaps can occur due to heterogeneous channel widths.

ating devices. A careful look at the regulatory database [3] reveals two particular sets of 5 GHz channels that are allowed for non-DFS use in majority of regulatory regions: (i) channels 36, 40, 44, 48 (5170-5250 MHz), and (ii) channels 149, 153, 157, 161 (5735-5815 MHz). On the other hand, majority of regulatory regions require DFS capabilities to operate on channels that fall in the frequency ranges of 5250-5330 MHz and 5490-5730 MHz. These DFS, non-DFS, as well as reserved parts of the 5 GHz spectrum designated by majority of regulatory regions are shown in Figure 1. The usable unlicensed spectrum consists of free and DFS portions. We can see that the free portion constitutes only 36% of the usable unlicensed spectrum. Moreover, the free portion is fragmented. This translates to only two 80 MHz channels and no 160 MHz channel without DFS. Thus the spectrum regulations make it necessary for the operating devices to have DFS capabilities in order to fully exploit the 5 GHz unlicensed band.

2.2 DFS Capabilities

In the light of the spectrum regulations allocating a larger chunk for DFS-enabled usage, we investigated the DFS capabilities of commodity WiFi devices. First off we found that implementing DFS is hard [8]. DFS requires detecting radar patterns precisely which means that WiFi systems should know the radar patterns beforehand. They should also have sufficient listening air-time to be able to hear the radar and the RF noise level should be low enough to correctly identify the radar transmission. This is exacerbated by the fact that the radar patterns change as the technology evolves and different countries have different radar patterns which also depend on the type of the radar (military, weather, etc.). It is thus not feasible for a WiFi vendor targeting a global market to be aware of all radar patterns and to correctly implement them all in their WiFi access point devices. We surveyed a number of commodity WiFi access points capable of 5 GHz operation to find out the channels that they support. The results of the survey are shown in Table 1. We see that most of the access points only support channels in the non-DFS frequency ranges. A few that support the DFS frequency range of 5250-5330 MHz only do so because of the corresponding regulation allowing non-DFS use for lower-than-usual transmission power. Further conversations with access point vendors revealed that if an access point has to operate on DFS channel frequencies, it not only has to implement radar pattern detection particular to each regulatory region, but also has to get region specific regulatory approval for selling devices in that particular region.

For these reasons, DFS is not widely supported and the 802.11a/n/ac WiFi devices operating in the 5 GHz band are confined to operating in the non-DFS channels. Figure 2 shows a snapshot of BBSs operating in the 5 GHz band in an enterprise environment. One can clearly see that the BSSs are clustered together in the two non-DFS (free) segments of the spectrum.

Table 1: Supported channels by different commodity access points

Access Point Model	802.11 Standard	Supported 5 GHz channel frequencies (MHz)				Regulatory Region
		5170 - 5250	5250 - 5330*	5490 - 5730*	5735 - 5835	
Apple Time Capsule (2009)	802.11n	✔	✘	✘	✔	US
Apple Time Capsule (2011)	802.11n	✔	✘	✘	✔	US
Apple Time Capsule (2013)	802.11ac	✔	✔	✘	✔	AU
Arris DG1670A	802.11n	✘	✔	✘	✘	US
Asus RT-AC5300	802.11ac	✔	✘	✘	✔	SG
Asus RT-AC55UHP	802.11ac	✔	✘	✘	✔	SG
Asus RT-AC56S	802.11ac	✔	✘	✘	✔	SG
Asus RT-AC66U	802.11ac	✔	✘	✘	✔	SG
Asus RT-AC68U	802.11ac	✔	✘	✘	✔	SG
Asus RT-N56U	802.11n	✔	✘	✘	✔	SG
Asus RT-N66U	802.11n	✔	✔	✘	✘	SG
Belkin AC1200FE	802.11ac	✔	✘	✘	✔	US
D-Link DIR-865L	802.11ac	✔	✘	✘	✔	SG
D-Link DIR-868L	802.11ac	✔	✘	✘	✔	SG
NetGear C3700 N600	802.11n	✔	✘	✘	✔	US
Singtel AC1900	802.11ac	✔	✘	✘	✔	SG
TP-Link Archer C7	802.11ac	✔	✘	✘	✔	SG
Xiaomi Mi WiFi Router	802.11ac	✔	✔	✘	✔	CN

* indicates DFS channel frequencies

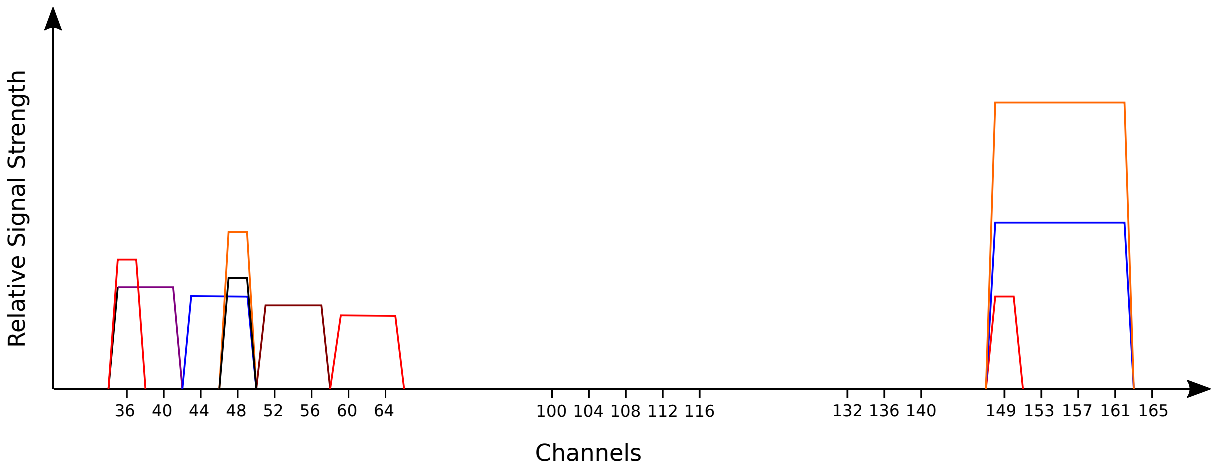


Figure 2: A snapshot of BSSs operating in the 5 GHz band in an enterprise setting. The two non-DFS pieces of the spectrum can be clearly seen to be occupied.

2.3 Study Conclusion

What all this means is that if we were to operate 80 MHz channel widths to deliver high per-user speeds, overlapping BSSs (OBSSs) are inevitable as we simply do not have enough free spectrum. In other words, spectrum congestion exists even in the so called *wide* 5 GHz band and there is no way that the wide channels of 802.11ac can avoid the *starvation problem*. This underscores the importance of the dynamic channel width mechanism of 802.11ac.

3 Dynamic Channel Width Overview

In principle, for any dynamic channel width scheme to work correctly, the following three requirements should be fulfilled: (i) The sender should be able to sense other 802.11 transmissions across the maximum channel width that it can transmit. Also, other 802.11 devices in the vicinity should be able to sense the sender's wide transmissions. (ii) The sender should be able to change its channel width on a per-frame basis thereby enabling dynamic spectrum access. (iii) The receiver should be able to adapt its RF frontend to transmissions of changing channel widths and decode them correctly on a per-frame basis. Note that these requirements stem from the fundamentals of wireless channel access and RF transmission. In this section we provide an overview of the various mechanisms specified in 802.11ac [9] that fulfill the above requirements. In the rest of this section, we limit our discussion to a maximum channel width of 80 MHz, as 80 MHz is the maximum width supported by commonly available commodity hardware. Nevertheless, the mechanisms for 160 MHz width work in the same fashion as that for 80 MHz.

3.1 Channel Width Granularity

802.11ac allows changing of channel widths at a very coarse granularity. A 802.11ac transmitter can transmit frames with either 20, 40, or 80 MHz channel width. For that purpose, the 80 MHz channel width is divided into four channels of 20 MHz each as shown in Figure 3. Any one of the four channels can be designated as the primary channel while starting up a managed WiFi network (BSS). The primary channel functions as the control channel of the BSS thereby transmitting and receiving 20 MHz wide management frames such as Beacon, Probe Request, Probe Response, Association Request, Association Response, etc. For sending data frames of varying widths, a 802.11ac transmitter utilizes the channels in the following way. If the data frame to be sent is 20 MHz wide, then it is sent using only the primary channel. In case of a 40 MHz wide data frame, it is sent by bonding together the primary and secondary-1 channels. Finally, for a 80 MHz wide data frame all the channels are bonded together. Note that the primary channel has to be a part of the transmission irrespective of the width. Also note that this procedure of bonding the channels remains the same irrespective of the position of the primary channel, provided the convention for labelling the secondary channels is as per Figure 3.

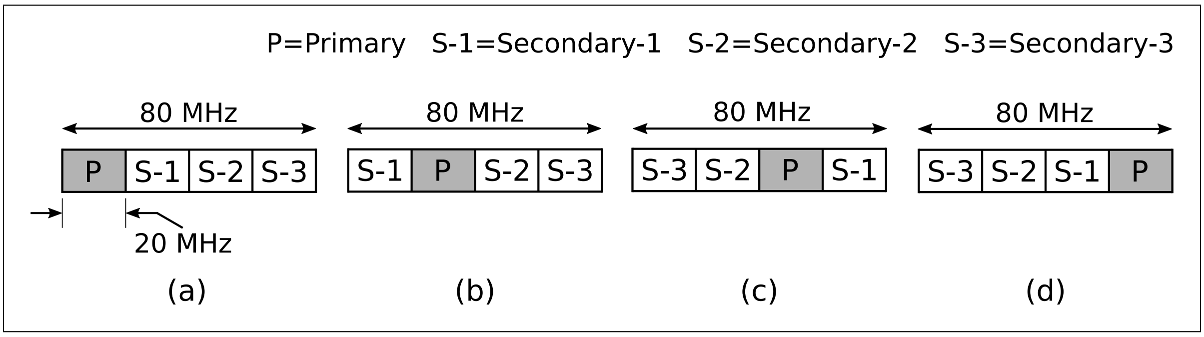


Figure 3: 802.11ac divides the 80 MHz channel width into four channels of 20 MHz. Any one channel can be the primary channel and the remaining channels function as the secondary channels.

3.2 Channel Sensing

All 802.11 devices are capable of performing Clear Channel Assessment (CCA) in two ways – (i) **Signal Detect (SD):** In SD, a 802.11 device detects the PHY header (Preamble + PLCP header) of a 802.11 transmission and thus holds the medium to be busy. (ii) **Energy Detect (ED):** If a 802.11 device misses to detect the PHY header in SD, it can still sense the raw energy in the medium and hold the medium to be busy. ED is thus also helpful in detecting non-Wifi interference. Traditionally a 802.11 channel has been 20 MHz wide and it can signal detect any 802.11 transmission whose signal strength is above -82 dBm as well as energy detect any RF transmission whose signal strength is above -62 dBm. These CCA thresholds are specified by the original 802.11 specification and we can see that SD is more sensitive than ED. When 802.11n [7] introduced 40 MHz wide channels, it retained the SD and ED thresholds for the primary channel and specified only the ED threshold for the secondary channel. In our prior experience of working with 802.11n, we observed that this ED threshold for the secondary channel was not low enough. As a result, a 40 MHz wide 802.11n transmitter couldn't reliably detect any 20 MHz 802.11 transmission on its secondary channel leading to frame collisions. 802.11ac improves over 802.11n precisely in this aspect. It specifies a SD threshold of -72 dBm to reliably detect any 20 MHz or 40 MHz 802.11 transmissions on the secondary channels. This 10 dBm lower CCA threshold enables a 802.11ac transmitter to reliably perform channel sensing across the entire 80 MHz width.

On the flip-side, it is also required that other 802.11 devices in the vicinity are able to sense the wider transmissions of a 802.11ac transmitter. For backward compatibility, 802.11ac uses the same PHY header as 802.11a which is naturally 20 MHz wide and uses the legacy OFDM modulation. However, 802.11ac duplicates the PHY header across all the 20 MHz channels. For example, a 80 MHz wide transmission that encompasses the channels 149 (primary), 153, 157 and 161, duplicates and transmits the 20 MHz wide OFDM modulated legacy PHY header on each of the 20 MHz channels followed by the 80 MHz wide VHT modulated PLCP payload (see Figure 4(a) for illustration). This duplication of the legacy PHY header enables other

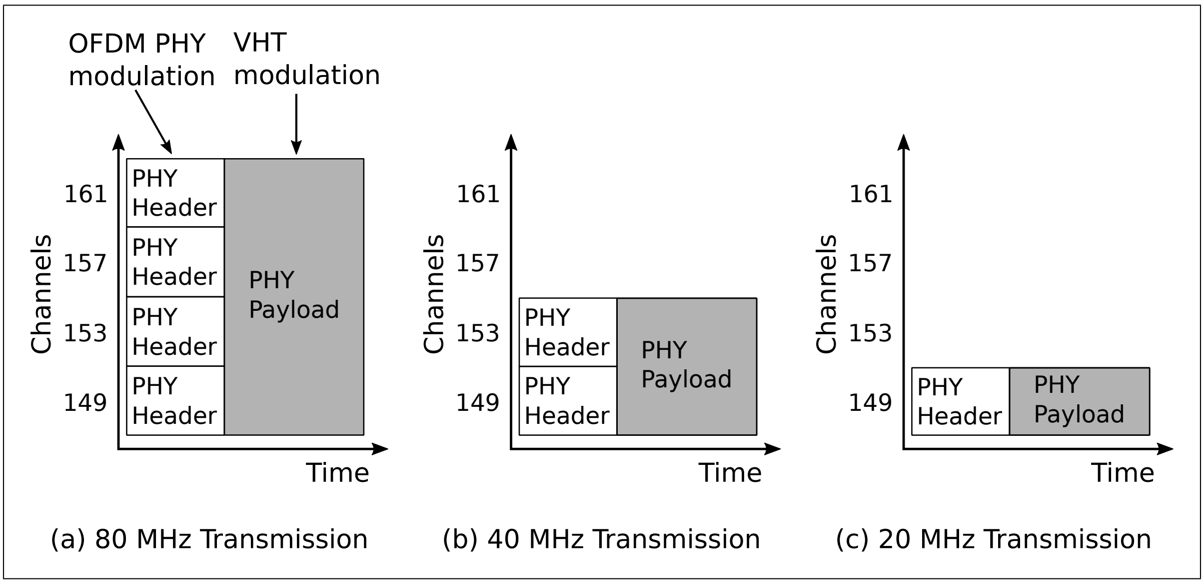


Figure 4: 802.11ac transmissions of different widths with channel 149 as the primary channel. The 20 MHz wide OFDM modulated legacy PHY header is duplicated across all the 20 MHz channels for wider transmissions.

802.11 devices to signal detect the wider transmission irrespective of their operating widths and choice of primary channel.

3.3 Dynamic Spectrum Access

For allowing dynamic spectrum access on a per-frame basis, 802.11ac slightly modifies the traditional CSMA/CA procedure. This modified procedure is summarized in Algorithm 1. Step 1 and Step 2 are the same as traditional CSMA/CA in which the CCA and the backoff counter mechanism only consider the primary channel. In Step 3, CCA is performed simultaneously on all the secondary channels for PIFS interval just before the end of the backoff counter. Depending on busy/free state of the secondary channels, the final transmission width either remains 80 MHz or is reduced to 40 MHz or 20 MHz.

3.4 Channel Width Negotiation

As seen from Figure 4, the PHY payload would be VHT modulated and would have varying widths depending on the secondary channels being free or busy at the time of transmission. It is necessary for a 802.11ac receiver to know the width and other rate parameters in order to correctly decode the PHY payload. The required decoding information is provided by the sender via the VHT-SIG-A field of the PHY header. The VHT-SIG-A field indicates the channel width (20/40/80 MHz) and other rate information such as the number of MIMO spatial streams, the guard interval (long or short) and the VHT MCS. Since the PHY header is OFDM modulated, it is decodable by any 802.11 receiver. However, the VHT-SIG-A field is understood only by

Algorithm 1: Dynamic Spectrum Access Procedure in 802.11ac

Step 1: Perform Clear Channel Assessment (CCA) on the primary channel
    if *primary channel is idle for DIFS time* **then**
        Choose a random backoff counter from the current contention window
    else
        Repeat Step 1
    end

Step 2: During the countdown of the backoff counter, if the primary channel is sensed to be busy, freeze the backoff counter. When the primary channel becomes idle again, resume the backoff counter

Step 3: Sense all the secondary channels simultaneously for PIFS interval just before the backoff counter becomes zero
    if *all secondary channels are free* **then**
        Transmit using 80 MHz width
    else if *secondary-2 or secondary-3 are busy* **then**
        Transmit using 40 MHz width
    else if *secondary-1 is busy* **then**
        Transmit using 20 MHz width
    end

802.11ac receivers. Having known the decoding parameters from the PHY header, a 802.11ac receiver can decode the corresponding PHY payload. In summary, the channel width is negotiated between the sender and the receiver through the PHY header along with other rate parameters. There is thus no need for an explicit handshake protocol or a RTS/CTS frame exchange to negotiate the channel width.

4 Related Work

4.1 Dynamic Channel Width

Dynamic channel width or dynamic spectrum access is not a new idea. Chandra et al. [14] first made the case for adapting channel width in 802.11 networks. Their motivation behind adapting channel width was to trade-off physical range for higher throughput and vice-versa. Through software modifications to a 802.11a chipset driver, they were able to vary the channel width from 5 MHz to 40 MHz around the same center frequency for a single isolated pair of nodes. Because of being a custom change, their scheme (SampleWidth) required modification to the client and also implementation of a handshake protocol to negotiate the change of channel widths. This work was followed up by FLUID [24] which is an enterprise WLAN system that centrally performs downlink packet scheduling and channel width adaptation of all the access points and their clients in the WLAN. FLUID follows similar implementation as of SampleWidth [14] to adapt the channel width. However, for coordinating channel frequency and width switching, FLUID employs 802.11 Beacon Information Element (BIE). In FLUID, the packet scheduling and the assignment of center frequencies and channel widths is done at the time granularity of an *epoch* which is set to 6 ms in their implementation. Taking a step further, FICA [26] proposed a fine-grained channel access scheme that uses subchannels to adapt channel width on a per-frame basis. Using a custom PHY-MAC design, their scheme mainly addressed the MAC inefficiencies involved in the use of wider channels but required tight synchronization between the transmitters using different subchannels. The requirement of tight synchronization between the transmitters was a limitation of FICA which was addressed by WiFi-NC [15] by enabling fully asynchronous transmissions. The focus of the above works was mainly performance and coordination and thus none of them considered the problem of channel access *starvation*. Zhang et al. [29] were the first to adapt the channel width on a per-frame basis while simultaneously avoiding the problem of partial-channel blocking (essentially *starvation*) that severely affects the performance of wider channels in the presence of uncontrolled overlapping BSSs (asynchronous overlapping transmissions). Their custom solution, *Adaptive Subcarrier Nulling (ASN)* redesigns the preamble structure, packet detection and decoding algorithms of the PHY and also extends the CSMA/CA mechanism of the MAC. Finally, Fine-grained Spectrum Adaptation (FSA) [27] is similar to ASN [29] but it leverages the existing preamble in IEEE 802.11a and unlike ASN it doesn't assume that all nodes use the same RF channel width i.e. it can work with heterogeneous channel widths.

The dynamic channel width feature in 802.11ac [9] is similar to the above schemes in terms of the broad functionality that it offers. It adapts channel width on a per-frame basis, handles asynchronous transmissions with heterogeneous channel widths and most importantly avoids channel access *starvation*. However, its design differs in a few key aspects – **(i)** It uses a very coarse granularity to change the width. The channel width could be either 20, 40 or 80 MHz, while the previous works used sub-20 MHz channel widths. **(ii)** For a transmission of reduced width, the primary channel must be involved and it could be bonded with only adjacent secondary channels. Unlike some of the previous proposals, any arbitrary portion of the maximum width cannot be used for reduced width transmissions. **(iii)** It uses legacy 802.11a PHY header and duplicates it across all the 20 MHz channels (as explained in §3.2). In contrast, previous schemes proposed custom PHY designs to address the challenges of using sub-20 MHz channel widths. **(iv)** Finally, for negotiating the channel width between the sender and the receiver, previous schemes had to develop sophisticated techniques. In 802.11ac, however, the width of a transmission is communicated via the 'bandwidth' parameter in the VHT-SIG-A field of the PHY header along with other rate information (§3.4). Now since the PHY header is transmitted with 20 MHz width using a conservative modulation and is duplicated across all the 20 MHz channels, the receiver requires no special mechanisms to negotiate the channel width with the sender[2]. **(v)** Trivially, 802.11ac's dynamic channel width mechanism enjoys the benefits of

[2] FSA [27] incorrectly mentions that 802.11ac requires a RTS/CTS exchange to negotiate the channel width. However as detailed in §3.4 and sanity checked later in §5.2, we show that this is not the case.

standardization as it requires no changes to the 802.11ac client and works with commodity devices.

While the above design choices greatly simplify the dynamic channel width mechanism of 802.11ac and also provide backward compatibility with 802.11a/n PHY, they do so at the cost of reduced flexibility and performance compared to some of the previous approaches. Note that due to the above design differences, the dynamics of spectrum sharing using 802.11ac's dynamic channel width mechanism are substantially different from any of the previous approaches; and hence the need to study them.

4.2 Evaluation of dynamic channel width in 802.11ac

There are not many works that study the spectrum sharing dynamics of 802.11ac's dynamic channel width mechanism. Park [21] was one of the first to evaluate (via simulation) the dynamic channel width mechanism of 802.11ac. They simulated the scenarios when the interfering transmissions on the secondary channels of 802.11ac have signal strengths less than the secondary channel CCA sensitivity. However, this work pre-dates the ratification of 802.11ac [9] and as a result incorrectly assumes the secondary channel CCA sensitivity of 802.11ac by simply extending 802.11n. In reality, the ratified 802.11ac specification defines much higher secondary channel CCA sensitivity than 802.11n. Also, if an incoming transmission has signal strength more than the CCA sensitivity, the signal detection is not guaranteed. In fact, the very definition of CCA sensitivity states that if the signal strength is above the sensitivity threshold, it would be detected with greater than 90% probability. It is unclear if their simulation considers this detection probability. They also incorrectly assume that when one of the two middle 20 MHz channels is chosen as the primary channel (see Figure 3b/c), the 802.11ac transmitter has two options to transmit a 40 MHz frame. However, the middle 20 MHz channel can only bond with the 20 MHz channel that is at the start or end of the 80 MHz channel and not the other middle 20 MHz channel. This is in accordance with the 802.11n specification [7] that doesn't allow partially overlapping 40 MHz channels in the 5 GHz band. Also it is unclear if their simulation setup considered channel leakage from adjacent channels given the physical separation and transmit power of the two transmitters in their setup. In contrast, our approach uses commodity 802.11ac hardware which implicitly ensures correct CCA sensitivities and signal detection probability. Also as we describe in §5.3, we take special care that adjacent channel interference due to channel leakage doesn't affect our experiments.

With regards to experimental characterization of 802.11ac in general (not specific to dynamic channel width), [28] is claimed to be the first work. In [28], Zeng et al. first evaluate the coexistence of heterogeneous channels widths when a 80 MHz wide link operates in a static mode, i.e. it does not dynamically change its width and instead contends for the entire 80 MHz spectrum. We find that there are several issues in their experimental methodology as well as the inferences drawn from their presented results. But, from the observations that we make in §2, we argue that the use of a static 80 MHz channel width is impractical in the first place. When the authors of [28] evaluate the dynamic channel width mechanism, they incorrectly assume that dynamic channel width in 802.11ac requires RTS/CTS exchange to negotiate the channel width. As detailed in §3.4 such is not the case. What is further wrong with their analysis is that they show experimental data showing CTS frames from two sharing links at intervals of more than 1 ms. As we show in §5.2, RTS/CTS exchanges would be present due to retransmissions of A-MPDUs. However, a mere presence of RTS/CTS frames doesn't imply that they are being used for channel width negotiation. The interval of more than 1 ms between the CTS frames is too large to justify that each transmission is being accompanied by a RTS/CTS exchange. With dynamic channel width, Zeng et al. do not consider the cases when the overlapping link is 20 MHz or 40 MHz. While they do consider the case when the overlapping link is 80 MHz, they do not consider all the primary channel overlap cases between the two links. In summary, although [28] is the first attempt to experimentally evaluate dynamic channel width in 802.11ac, several issues in the experimental methodology, data presentation as well as inference render this work to be far from correct. Besides, by not considering the exhaustive combinations of channel widths and positions of the primary channel, it is also incomplete in terms of understanding the implications of dynamic channel width for other 802.11 functions. Dianu et al. [17] also conducted a measurement-study of the performance of 802.11ac. However, in their experiments they did not evaluate the dynamic channel width and instead used static 80 MHz channel width. We suspect this is because they used 802.11ac draft 2.0 chipset which may not implement the dynamic channel width mechanism.

4.3 Studies from 802.11n

Prior to 802.11ac, the use of channels wider than 20 MHz was first standardized by 802.11n [7]. Consequently there exist works such as [25, 16] that have tried to experimentally study the co-channel interference scenarios when links of heterogeneous widths overlap. However, both these studies being focused on 802.11n do not consider the issue of primary channels overlapping with secondary channels. This is because 802.11n provided no signal detect capabilities on the secondary channels. As a result, the 802.11n specification's channel selection rules mandate that if an existing BSS is found to be operating in the desired 40 MHz region, then an access point that is starting a new BSS *shall* ensure that the primary channels of the new BSS and the existing BSS overlap. However, in 802.11ac, because of signal detect capabilities on the secondary channels, primary channels can overlap on secondary channels giving rise to several more co-channel interference scenarios. Further, dynamically changing the channel width is a feature unique to 802.11ac and thus its effects cannot be known from studies pertaining to 802.11n.

4.4 Other related works

Gong et al. [19] explained the enhanced RTS/CTS (e-RTS/CTS) mechanism and via simulations compared the performance of dynamic channel width with e-RTS/CTS against dynamic channel width without e-RTS/CTS in a hidden node scenario. They also showed that in a scenario without hidden nodes, dynamic channel width in general is more helpful than static channel width when there are more contending streams in the OBSSs. Byeon et al. [13] proposed improvements to the e-RTS/CTS mechanism in terms of dynamically determining the duration field in the CTS frames. They also proposed a heuristic-based approach to determine the presence of hidden node interference and dynamically turn ON or OFF the e-RTS/CTS mechanism. These works contribute in their own ways towards a better spectrum management in 802.11ac and thus are related to our effort. However, they do not contribute to understanding the implications of dynamic channel width for spectrum management and link-layer rate adaptation.

4.5 Related Work – Summary

In summary, dynamic channel width is not a new idea in 802.11ac and several proposals in the literature such as [14, 24, 26, 15, 29, 27] have already proposed different schemes to dynamically vary the channel width. However, 802.11ac's design of dynamic channel width differs in several key aspects from these schemes. As a result, the dynamics of spectrum sharing using 802.11ac's dynamic channel width mechanism are substantially different than any of the previous approaches. In terms of evaluating the 802.11ac's dynamic channel width mechanism for its spectrum sharing characteristics, Park et al. [21] presented a simulation study which suffers from inaccuracies and several key parameters in their simulation setup are unclear. The only experimental evaluation of dynamic channel width is done by Zeng et al. [28], which we found to be incorrect on several aspects and is also incomplete. Because 802.11n had wider channels but no dynamic channel width, studies such as [25, 16] are not helpful. While other works such as [19] and [13] propose improvements (via simulations) to 802.11ac's spectrum sharing mechanisms, they do not study the implications of dynamic channel width on other 802.11 functions.

The bottom-line is that the practical working of 802.11ac's dynamic channel width mechanism and its implications for other 802.11 functions is still not fully understood. Our work is thus an attempt to fill this gap.

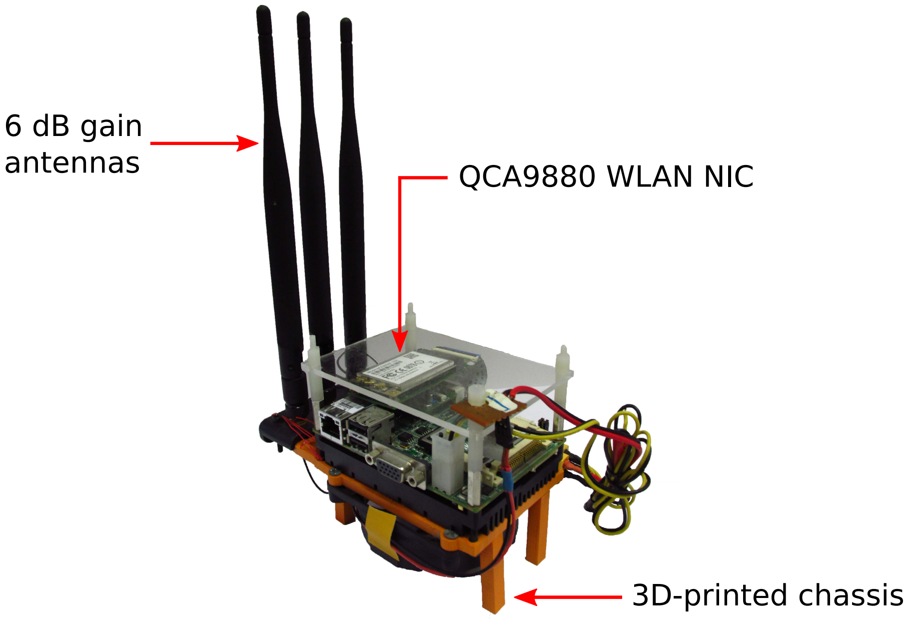


Figure 5: Our custom-built 802.11ac platform with 6 dB gain omni-directional antennas and custom 3D-printed chassis.

5 Experimental Characterization

5.1 System Setup

For our experiments, we have put together four pieces of 802.11ac platform. These four custom-built nodes use commodity 802.11ac hardware – QCA9880 (Compex WLE900VX) 802.11ac wave-1 chipset with 6 dB gain dual-band omni-directional antennas – and are equipped with either single, dual or quad core x86_64 CPUs and 1-2 GB RAM. The software stack consists of QCA 10.2.4.70.9-2 firmware [23] and ath10k open-source driver [1] running on Linux kernel 4.7-rc4. We were required to make minor changes to the kernel configuration, the mac80211 module of the kernel as well as the ath10k driver to suite the requirements of our experiments. We chose a x86_64 platform over an embedded platform as it allows easy installation of required tools using pre-compiled distribution binaries. It also saves us the trouble of cross-compiling the Linux kernel, its modules as well as the ath10k driver. We are able to compile them on powerful x86_64 server class machines and then simply transfer the compiled binaries to our 802.11ac platform. Figure 5 shows one of our custom-built 802.11ac platform.

During the experiments, we use `hostapd` [2] to run the required access point in each BSS. `iperf` [2] is used to generate saturating UDP traffic. Unless otherwise stated, the throughput reported is average per-second application-level throughput measured by the `iperf` receiver. `tcpdump` [4] is used on the receiver to capture received packets via monitor-mode interface for further analysis.

Table 2: Sender-Receiver combinations

Index	Sender		Receiver	
	Operating System	WLAN NIC	Operating System	WLAN NIC
A	Linux 4.7	Qualcomm Atheros 9880	Linux 4.7	Qualcomm Atheros 9880
B	Linux 4.7	Qualcomm Atheros 9880	Linux 4.2	Intel 3160
C	Linux 4.2	Intel 3160	Linux 4.7	Qualcomm Atheros 9880
D	Linux 4.7	Qualcomm Atheros 9880	Windows 10	Intel 3160
E	Windows 10	Intel 3160	Linux 4.7	Qualcomm Atheros 9880
F	Linux 4.7	Qualcomm Atheros 9880	iOS 9	USI 339S00043

5.2 RTS/CTS exchange needed for channel width negotiation?

Before we perform the experimental characterization of 802.11ac's dynamic channel width feature, we first perform a sanity check to verify that RTS/CTS exchange is indeed not required for negotiating the channel width. As explained in §3.4, the channel width is negotiated via the VHT-SIG-A field of the PHY header. However, in view of the related works [27] and [28] claiming that 802.11ac uses RTS/CTS exchange for channel width negotiation, we believe that such a sanity check would do no harm.

Experiment Methodology. We want to ensure that the VHT-SIG-A based channel width negotiation is not specific to a 802.11ac WLAN NIC or the NIC driver or the operating system. Thus we first list out different combinations of heterogeneous sender-receiver pairs in Table 2. For the ease of referring to these combinations, they are indexed alphabetically as A, B, C, etc. Then for each combination we establish a 80 MHz wide test link and send saturated UDP traffic for 30 seconds. We repeat the experiment 5 times. In order to introduce more channel width transitions, we also start an interference link that coincides with the secondary-3 channel of the test link. For example if the test link operates on channels 149 (Primary), 153, 157 and 161, the interference link operates on channel 161. The interference link transmits approximately 300 frames per second at the basic rate of 6 Mbps. To further increase the number of transitions, we introduce relative mobility between the sender and the receiver. Mobility results into fast changes in the test link quality which causes the link-layer rate adaptation at the sender to try different channel widths in order to improve the packet delivery ratio. We use `tcpdump` [4] on one of our custom built 802.11ac platforms to sniff and capture the packets on the 80 MHz sender-receiver link. We then analyze the captured traces for channel width transitions and RTS/CTS exchanges.

Experiment Results. For each sender-receiver combination we consider the channel width transitions across all the experiment runs. Figure 6 shows the fraction of channel width transitions that were accompanied by a RTS/CTS exchange. We can clearly see that for none of the sender-receiver combinations, the fraction is 1; which re-affirms the fact that *a RTS/CTS*

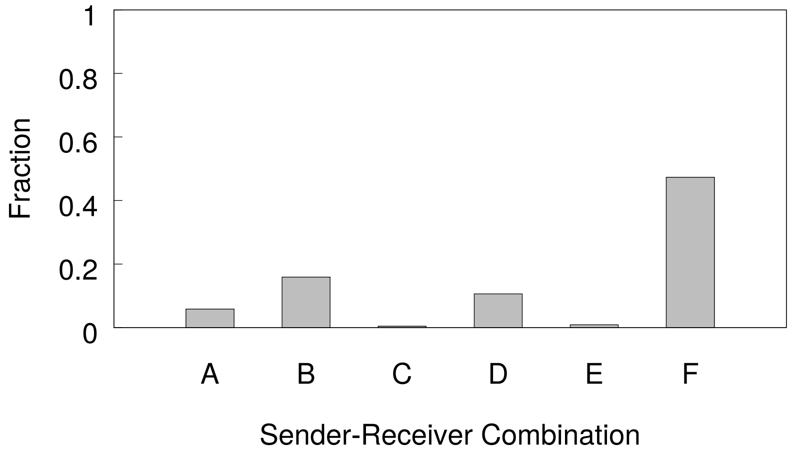


Figure 6: Fraction of channel width transitions accompanied by RTS/CTS exchange

exchange is not required to negotiate a channel width transition. We also go a step further to investigate the cause behind the RTS/CTS exchanges. Our traces reveal that whenever a channel width transition is accompanied by a RTS/CTS exchange, the transition was being made to retransmit an A-MPDU. In other words, the default link-layer rate adaptation (RA) of our chipset does a RTS/CTS exchange before every retransmission and the retransmission is done with a change of channel width. We suspect this behaviour of the RA is because it assumes the presence of hidden terminals on loss of an A-MPDU and thus sends the next A-MPDU under RTS/CTS protection.

5.3 Spectrum Sharing – symmetric sensing case

In this subsection, we experimentally evaluate different cases when a 80 MHz wide *link-1* with dynamic channel width shares the spectrum with an interfering link *link-2* in a symmetric sensing case. By symmetric sensing we mean that the senders of both the links can perfectly sense each other i.e. they are within strong CSMA range of each other. We consider different widths (20/40/80 MHz) of link-2 and for each width of link-2, we consider different overlap cases that differ in the relative positions of the primary channels of the two links. The goal is to study the impact of co-channel interference on the throughput of both the links for different channel width and overlap combinations when dynamic channel width is in action.

Experimental Setup. For all the experiments described below we use a simple testbed setup in our lab as shown in Figure 7. The nodes in the testbed are connected via a wired ethernet network (not shown in Figure 7) that serves as the control channel. For both the links, the sender and the receiver are in clear line-of-sight. Moreover, the sender of link-1 and the sender of link-2 are also in clear line-of-sight and about 5 m away. We set the Tx power for both the senders to 21 dBm. This Tx power setting along with the physical arrangement of the two senders ensures that their transmissions are strong enough to be sensed by each other under all combinations of channel widths and channel overlaps. At the same time it also

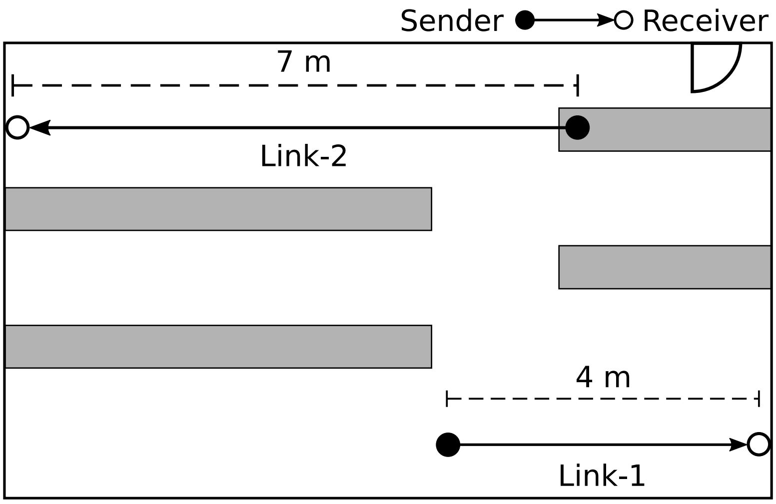


Figure 7: Simple testbed setup in our lab for studying spectrum sharing by two links which are in strong CSMA range of each other.

ensures that the transmissions from the two senders are not too strong so as to cause adjacent channel interference to each other. We conducted a few sanity check experiments to get this symmetric sensing setup right. Because in this subsection we are studying spectrum sharing under CSMA, such a careful setup helps us eliminate other factors such as asymmetric sensing, hidden terminals and their consequences such as collisions, ACK corruption, etc.

For the following experiments, we fix the primary channel of link-1 to be the leftmost of the four channels (Figure 3a). We understand that another set of combinations is possible when the primary channel is either of the two middle channels (Figure 3b/c). We consider this separately in §5.3.5.

5.3.1 20 MHz Link-2

With link-1's primary channel fixed to be the leftmost of the four channels, we have 4 possible overlaps with a 20 MHz link-2 as shown in Figure 8.

Experiment Methodology. For each overlap, we measure the no interference and co-channel interference (i.e. spectrum sharing) throughput of both the links. The measured throughput is a per-second throughput and is averaged over 6 runs of 120 seconds each. This gives us 720 samples of per-second throughput measurements. Through several trial runs we found that 720 samples are sufficient so that the standard deviation of the measured per-second throughput is below 2%. Since both the links have their default link-layer rate-adaptation running, it is not surprising that we need such large number of samples. To avoid any external interference, the experiment was carried out during midnight hours (00:00 to 08:00) and on channels where there was no other user or access point running.

Experiment Results. In Figure 9a, we plot the spectrum sharing (interference) throughput of both the links as a fraction of their no interference throughput. This fraction captures how much less loss in throughput each link suffers while sharing the spectrum – higher the fraction,

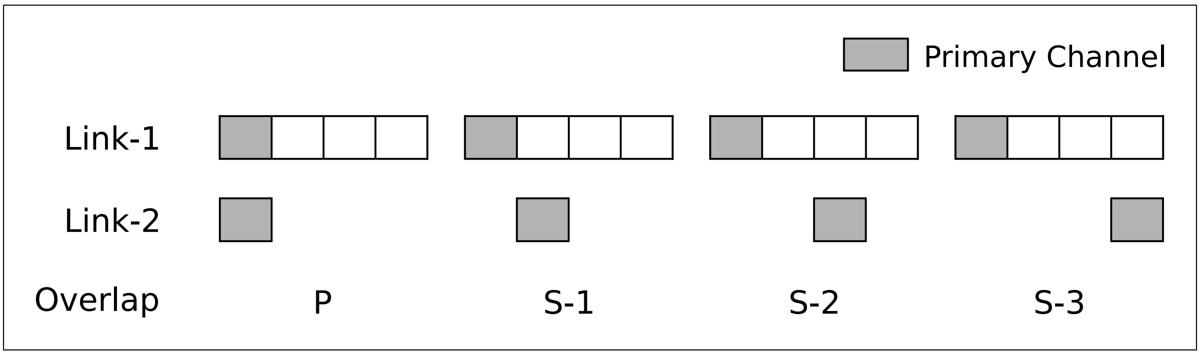
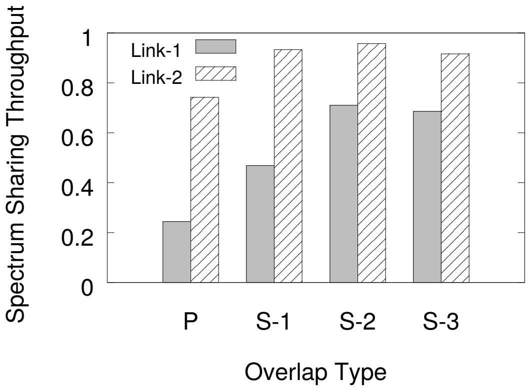
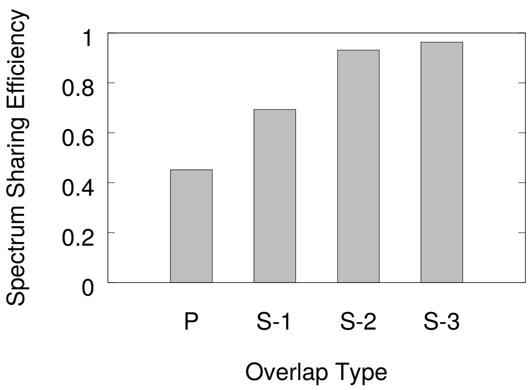


Figure 8: Different overlap combinations when 80 MHz link-1 shares spectrum with 20 MHz link-2.



(a) Spectrum sharing throughput as a fraction of no interference throughput.



(b) Spectrum sharing efficiency.

Figure 9: Spectrum sharing with 20 MHz link-2

lower the loss. Further we define *spectrum sharing efficiency* as the ratio of total throughput achieved by both the links when sharing the 80 MHz spectrum to the no interference throughput achieved by the 80 MHz wide link-1 (equation 1). Spectrum sharing efficiency essentially captures how efficiently the spectrum is shared by the two links while considering the no interference throughput of link-1 as the baseline. For each overlap case, we plot the spectrum sharing efficiency in Figure 9b.

$$\text{Spectrum Sharing Efficiency} = \frac{\text{Sum of link-1 and link-2 interference throughput}}{\text{link-1 no interference throughput}} \tag{1}$$

From Figures 9a and 9b, we make the following observations: (i) S-2 and S-3 overlap cases are similar since in both the cases link-1 dynamically falls back to 40 MHz and thus also affects link-2 in similar ways. This suggests that in a symmetric sensing case, the relative position of the primary channels of the two links do not matter, as long as they result in similar channel width reduction (in this case from 80 MHz to 40 MHz). (ii) From link-1's perspective, we see maximum degradation in the P overlap case and it is even worse than the S-1 case. Note that in P overlap, link-1 is operating at 80 MHz and is sharing the spectrum in a time-based manner. On the other hand in S-1 overlap, link-1 is operating at 20 MHz and is sharing the spectrum in a width-based manner. This suggests that even though with 80 MHz width link-1 can transmit data much faster than with 20 MHz width, the gain with 80 MHz width is not sufficient enough to offset the throughput degradation suffered from time-sharing in P overlap. As a result, the spectrum sharing efficiency is also the least in the P overlap case. (iii) From Link-2's perspective, it suffers negligible degradation in S-1, S-2 and S-3 overlap cases as is evident from its spectrum sharing throughput being more than 90% of its no interference throughput. This is because link-2 has an advantage over link-1 in gaining channel access to S-1, S-2 and S-3 parts of the spectrum. A careful observation of Algorithm 1 reveals that this is because link-1 simply does not contend for channel access to S-1, S-2 and S-3. This is in fact the crux of dynamic channel width mechanism and the key enabler for avoiding the problem of *starvation*. In an otherwise case if link-1 would have contended for S-1, S-2 and S-3, it would have met the same fate as that of P overlap; and with multiple competing narrow links, link-1 would have starved for channel access.

5.3.2 40 MHz Link-2

With link-1's primary channel fixed to be the leftmost of the four channels, we have 4 possible overlaps with a 40 MHz link-2 as shown in Figure 10. Note that the overlaps P and S1 as well as S2 and S3 are the same in term of occupying the spectrum; the only difference being the position of link-2's primary channel.

We follow the same experiment methodology as in §5.3.1 and plot the spectrum sharing throughput and the spectrum sharing efficiency in Figures 11a and 11b respectively. We make the following observations: (i) The overlap cases P and S-1 as well as S-2 and S-3 are similar indicating that even in this case the position of link-2's primary doesn't make a difference as long as link-1 can sense link-2's transmissions correctly (which is the case in our setup) (ii) From link-1's perspective, more degradation is observed in time-based spectrum sharing (P or S-1 overlap) compared to width-based spectrum sharing (S-2 or S-3 overlap). This is similar to the 20 MHz link-2 case in §5.3.1. However, it is relatively less worse than the P overlap case of 20 MHz link-2 because a 40 MHz link-2 is much faster and that helps alleviate the well-known performance anomaly [20]. (iii) From link-2's perspective, it suffers less degradation in S-2 or S-3 overlap because it has an advantage over link-1 for channel access for the same reasons as explained in §5.3.1. However, the degradation in this case is higher compared to S-1, S-2, and S-3 overlap cases of 20 MHz link-2. This suggests that a 40 MHz link being faster than a 20 MHz link has reduced advantage of channel access to the secondary channels thereby allowing greater chances for link-1 to use the whole 80 MHz spectrum. (iv) The spectrum sharing efficiency for S-2 or S-3 overlaps is greater than 1. On investigating, we found that this is because the no interference throughput of the 80 MHz wide link-1 is much less than two times its no interference throughput with 40 MHz width. What this suggests is that, in practice, two links that are *effectively* 40 MHz wide would lead to a higher total throughout compared to a single 80 MHz wide link.

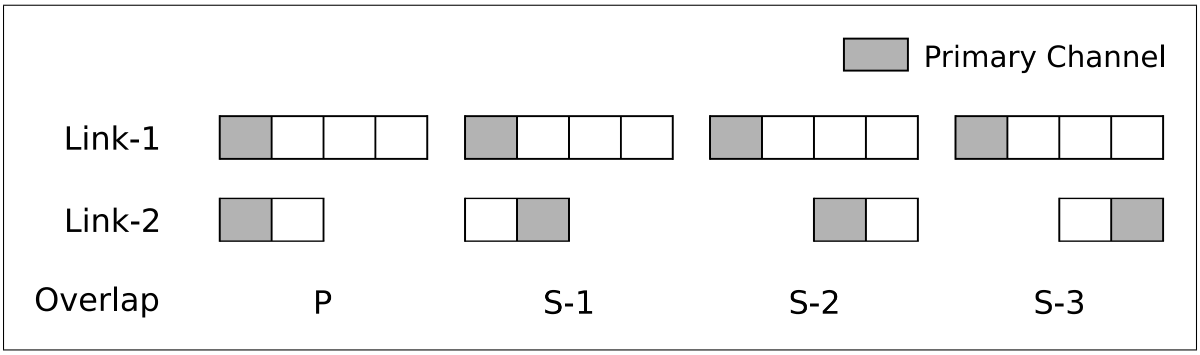
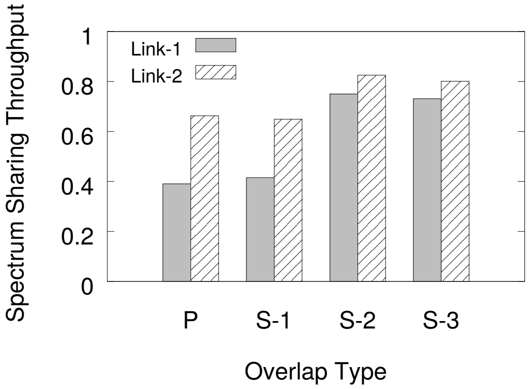
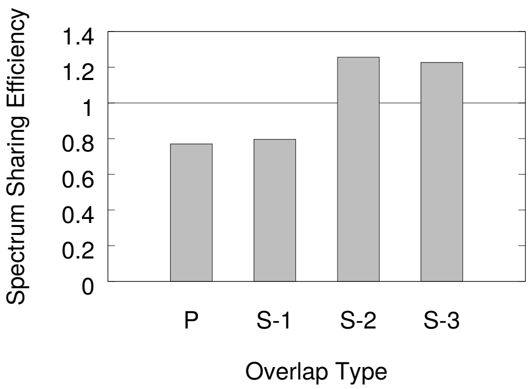


Figure 10: Different overlap combinations when 80 MHz link-1 shares spectrum with 40 MHz link-2.



(a) Spectrum sharing throughput as a fraction of no interference throughput.



(b) Spectrum sharing efficiency.

Figure 11: Spectrum sharing with 40 MHz link-2

5.3.3 80 MHz Link-2

With link-1's primary channel fixed to be the leftmost of the four channels, we have 4 possible overlaps with a 80 MHz link-2 as shown in Figure 12.

We follow the same experiment methodology as in §5.3.1 and plot the spectrum sharing throughput and the spectrum sharing efficiency in Figures 13a and 13b respectively. We see that irrespective of the overlap, the spectrum sharing throughput of both the links is roughly half of their no interference throughput. On investigating, we found that both the links are doing time-based spectrum sharing by transmitting 80 MHz wide frames each time. The reason for this behavior also traces back to Algorithm 1 according to which both the links contend for channel access only on their respective primary channels and not the secondary channels. However, since the maximum channel width for both the links is 80 MHz and there is no other link with lesser width, the channel condition across the 80 MHz spectrum is correlated with the channel condition of the primary channel i.e. if the primary channel is busy/free, then the secondary channels are busy/free as well. Thus both the links effectively end-up contending for the entire 80 MHz width. Since the two links perfectly time-share the spectrum, the spectrum sharing efficiency is 100% in all the overlap cases. The key take-away here is that the dynamic channel width mechanism would come to play only when the spectrum is shared between links of heterogeneous channel widths.

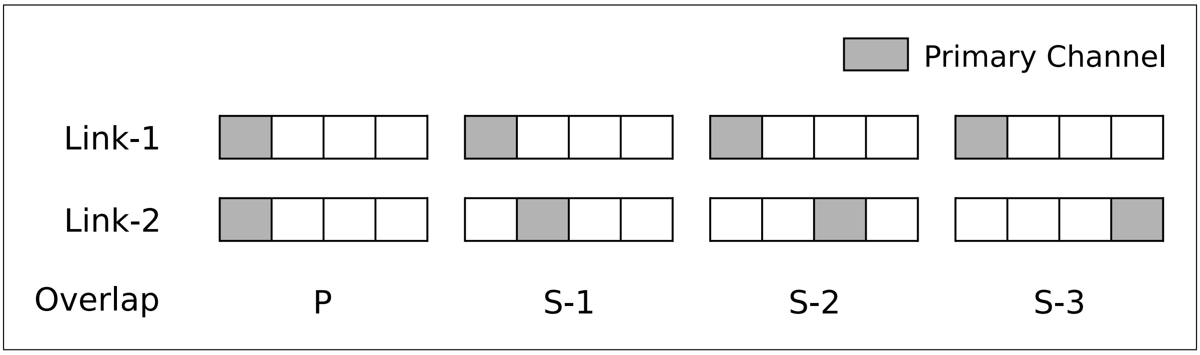
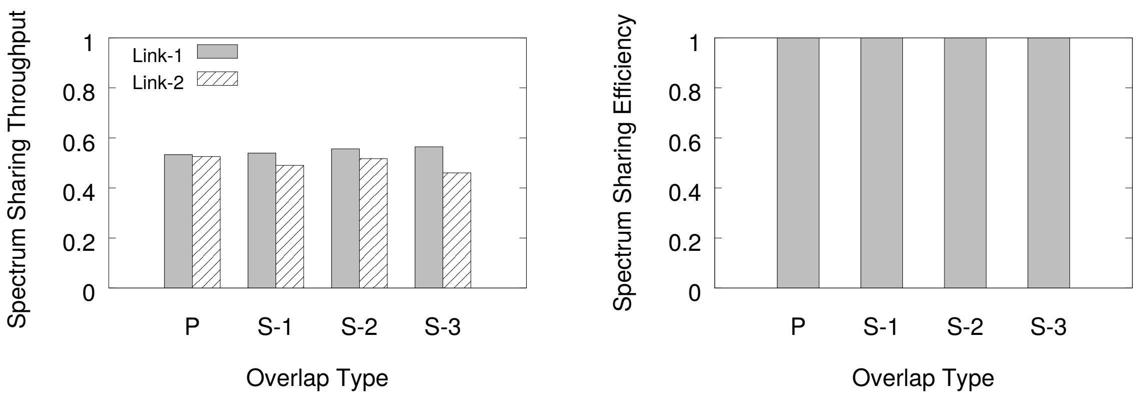


Figure 12: Different overlap combinations when 80 MHz link-1 shares spectrum with 80 MHz link-2.



(a) Spectrum sharing throughput as a fraction of no interference throughput.

(b) Spectrum sharing efficiency.

Figure 13: Spectrum sharing with 80 MHz link-2

5.3.4 80 MHz Link-2 – Alternative Overlaps

In above section, we saw that due to the lack of heterogeneous channel widths, two 80 MHz wide links always do time-based spectrum sharing irrespective of the type of overlap. However it is always possible for the link-layer rate adaptation algorithm (RA) to preemptively reduce the channel width of an individual link. Such a preemptive change by the RA in the channel width of an individual link can change the way the spectrum is shared – from time-based to width-based. By design, the RA cannot however change the primary channel of a link. As a result, if the primary channels overlap (P overlap in Figure 12), changing the channel width of an individual link by the RA doesn't change the way the spectrum is shared; it always remains

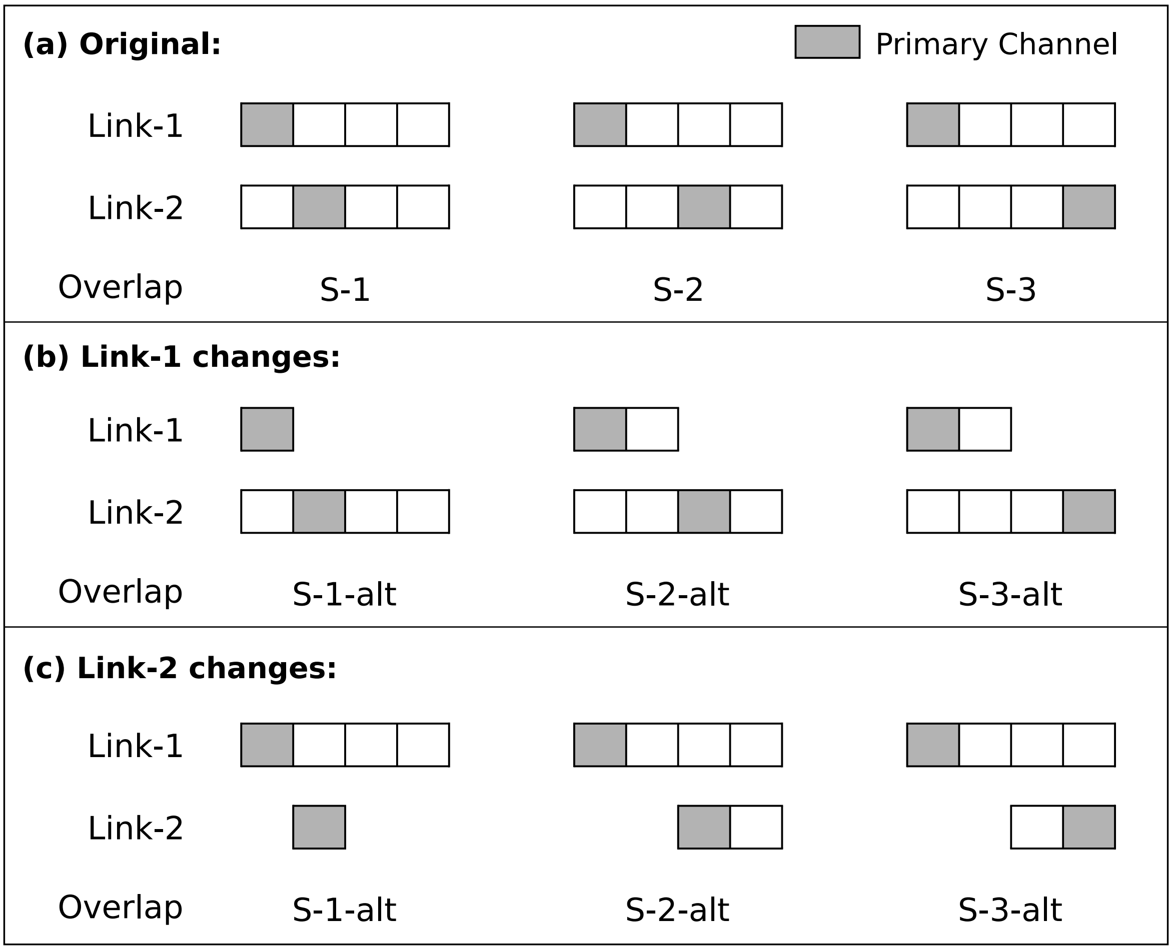


Figure 14: Original overlaps (S-1, S-2 and S-3) that yield time-based spectrum sharing *could* be changed by the RA of either link-1 or link-2 to alternative overlaps (S-1-alt, S-2-alt, S-3-alt) that yield width-based spectrum sharing.

timed-based. However, in case of other overlaps (S-1, S-2 and S-3), the RA's preemptive change of an individual link's channel width can result into alternate overlap scenarios that yield width-based spectrum sharing. Figure 14 shows how the original overlaps of S-1, S-2 and S-3 that resulted in time-based spectrum sharing *could* be changed by the RA of either link-1 or link-2 to alternative overlaps that result in width-based spectrum sharing[3].

In this section, through another set of experiments, we investigate how this alternate width-based spectrum sharing using a reduced channel width compares against the original time-based spectrum sharing using the entire 80 MHz width. The experimental setup and methodology is the same as described in §5.3. Since our chipset's default RA scheme won't change the channel width, we explicitly force the change of width and consider the two possible cases: (i) Link-1's RA reduces its channel width (ii) Link-2's RA reduces its channel width. We compare the performance of each of the two links in the original overlap settings (S-1, S-2 and S-3) versus the new overlap settings (S-1-alt, S-2-alt and S-3-alt) for the two cases. Figures 15 and 16 show

[3]Note that this is not *pure* width-based spectrum sharing as the two links still do some time-based sharing (although disproportionately) in the remaining overlapping part of the spectrum.

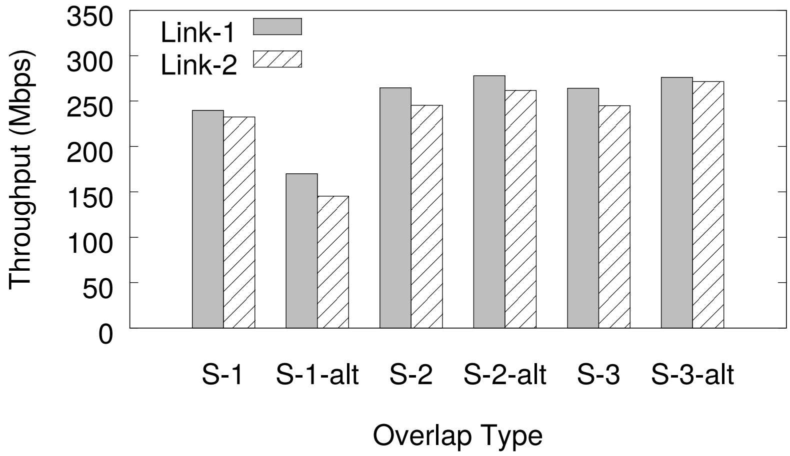


Figure 15: **Link-1 changes width:** Link-1 and Link-2 throughput in the original and alternative overlap settings.

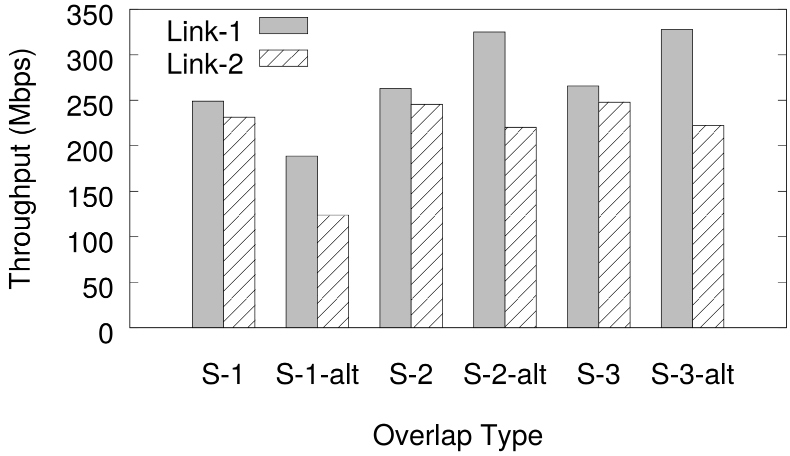


Figure 16: **Link-2 changes width:** Link-1 and Link-2 throughput in the original and alternative overlap settings.

the absolute throughput of the two links in the six different overlap settings when link-1 and link-2 change their widths respectively.

From Figures 15 and 16, we make the following observations: (i) The change from S-1 to S-1-alt by either link-1 or link-2 leads to their own throughput degradation and thus a good RA scheme would not do such a change. This throughput degradation is expected because time-based spectrum sharing with another 80 MHz sender with equivalent PHY rate results in roughly half of the no interference throughput (S-1 in Figure 14a). On the other hand, reducing to 20 MHz with width-based spectrum sharing (S-1-alt in Figure 14b/c) results in roughly quarter of the no interference throughput which is further reduced slightly as the narrow link does lose some share of the airtime to the wide link. (ii) When link-1 makes the change from S-2 to S-2-alt or S-3 to S-3-alt, it does yield small throughput gains for link-1. However, the same is not true for link-2 and it is seen to suffer throughput degradation instead. This suggests that reducing channel width to change from time-based sharing to width-based sharing doesn't always provide gains. It depends on the particular link quality (in our setup link-1 has better quality than link-2).

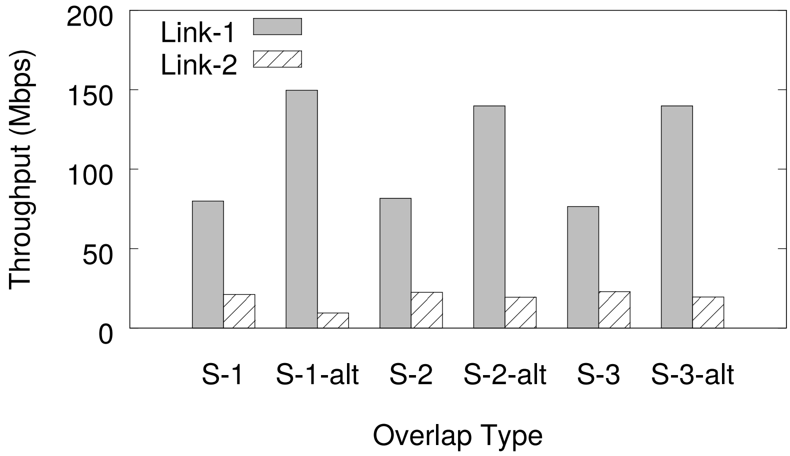


Figure 17: **Link-1 changes width (slow Link-2):** Link-1 and Link-2 throughput in the original and alternative overlap settings.

The above observations suggest that there exist at least some scenarios where the RA could achieve throughput gains by changing to width-based spectrum sharing via reducing the channel width. But it did not happen in case of our chipset's default RA scheme. We suspect that this is because RA schemes have traditionally never considered the channel access time in their design as they could not do anything about it. However, with wide and dynamic channel width, RA schemes can now reduce the channel width and thereby also reduce the channel access time, which can provide potential throughput gains. This result suggests the need for fundamental changes to the design of existing RA schemes by taking into consideration the channel access time and the dynamic channel width mechanism.

The potential gains of link-1 by re-designing the RA scheme seem small from Figure 15. However, one possible scenario where the gains could be maximum is when a 80 MHz link-1 shares the spectrum with a 80 MHz link-2 having *slow* PHY rate. In practice such a scenario is patently possible if link-2 has poor link quality. We emulated this scenario by fixing link-2's PHY rate to VHT MCS 0 and single MIMO stream. The results for this new scenario are shown in Figure 17. We see that from S-2 to S-2-alt or from S-3 to S-3-alt, link-1 can gain about 70-80% in throughput. In this case, link-1 also achieves a gain of about 85% in throughput when it changes from S-1 to S-1-alt. We do not claim that such high gains would be common place and it remains to be seen via a in-the-wild measurement study. However, the point here is that the potential throughput gains can be very high.

In summary, a link could achieve substantial throughput gains in certain overlap cases (S-1, S-2 and S-3) if existing RA schemes are re-designed to consider channel access time and the dynamic channel width mechanism. However, high gains may not always be possible and it depends on the link's quality and the PHY rate of the other link.

5.3.5 Other combinations of the primary channels

In all the experiments above, we fixed the primary channel of link-1 to be the leftmost channel (Figure 3a). It is also possible that the primary channel of link-1 could be the rightmost channel (Figure 3b) thereby yielding symmetrically mirrored combinations. As a sanity check, we performed experiments using those combinations and as expected they did not yield any different results.

One different possibility other than symmetrically mirrored combinations is that of link-1 having one of the two middle channels as the primary channel. We performed experiments with the middle-left channel of link-1 as the primary channel (Figure 3b). The results we obtained with this configuration of link-1 are similar to the results presented above. We thus skip them for brevity. Overall what this suggests is that in a symmetric sensing scenario where the senders of both the links can perfectly sense each other's transmissions, the relative positions of the primary channels do not make any difference as long as the reduction in channel width due to overlap remains the same.

5.3.6 Symmetric Sensing – Results Summary

We summarize the above observations in the following key take-aways:

- When a narrow link overlaps the secondary channels of a wide link (with dynamic channel width), the narrow link has an advantage for channel access in the shared part of the spectrum. However, the narrow link doesn't have an exclusive access to the shared spectrum i.e. it still loses some share to the wide link. If the narrow link has fast PHY rate (40 MHz link-2 above), it allows greater chance for the wide link to gain channel access to the shared spectrum, thereby losing more airtime share and thus suffering more throughput degradation. On the other hand, if the narrow link has slow PHY rate (20 MHz link-2 above), it suffers less throughput degradation as it loses less airtime share to the wide link.

- A single 80 MHz link in general yields less than double the throughput of a 40 MHz link (due to increased noise floor). Thus when a 40 MHz wide link overlaps with the secondary channels of a 80 MHz wide link, the resulting two links (which are *effectively* 40 MHz wide) together yield more throughput than a single 80 MHz link. In other words, the two links share the spectrum more efficiently.

- When two links can perfectly sense each other's transmissions (symmetric sensing), the relative positions of their primary channels does not affect the overall behavior as long as they result in the same reduction of width (e.g. S-2 and S-3 overlaps in Figure 10).

- The dynamic channel width mechanism works to yield width-based spectrum sharing only when the overlapping links are of reduced widths and they overlap with non-primary channels. In other words, the dynamic channel width mechanism works only when heterogeneous channel widths overlap with non-primary channels.

- When the channel widths are not heterogeneous, i.e. when a 80 MHz wide link finds itself doing time-based spectrum sharing with another 80 MHz link, it is possible (not always) for the RA of either links to reduce the channel width and achieve gain in throughput by doing width-based spectrum sharing. However, the current RA schemes do not seem to do so as traditionally they have never considered the channel access time. It is thus a future research opportunity to re-design RA schemes considering the channel access time and the dynamic channel width mechanism.

6 Conclusion and Future Work

In this work, we conducted a systematic measurement study using commodity hardware to understand the functioning of the dynamic channel width mechanism of 802.11ac. In particular, we studied the symmetric sensing case where the spectrum sharing nodes could perfectly sense each other's transmissions. We studied exhaustive combinations of channel width and primary channel position and uncovered novel findings which to the best of our knowledge were not reported in the literature before.

This measurement study is still incomplete without the asymmetric sensing case which is currently in progress. We believe that the asymmetric sensing scenario would yield even more interesting insights. A natural extension of this measurement study is to build upon these insights and design better channel selection schemes that would lead to efficient spectrum utilization. Another possible dimension of future work is to re-design the existing link-layer rate adaptation schemes based on our observation that they could achieve significant throughput gains by considering the channel access time and the dynamic channel width mechanism.

Although 802.11ac is only evolutionary in nature, it still has interesting aspects other than the much acclaimed MU-MIMO. Through this study and the planned future work, we hope that we are able to bring the research community's attention to these other aspects of 802.11ac.

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