IEEE 802.11ac: Effect of Channel Bonding on Spectrum Utilization in Dense Environments

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***Abstract*-IEEE 802.11ac is a recent amendment that enhances the throughput of WLANs. It uses spatial diversity, new modulation and coding schemes (MCS), and channel bonding to increase the data rate. The channel bonding allows 802.11ac stations, also called Very High Throughput (VHT) stations, to operate on channels wider than the legacy 20 MHz channel in the 5 GHz band. Particularly, a VHT station may support up to 160 MHz transmissions. Increasing the channel width enhances the data rate but reduces the number of non-overlapping channels. For example, the 5 GHz spectrum in Europe offers either 19 non-overlapping 20 MHz channels or only two 160 MHz channels. In dense WLAN deployment environments, the use of channel bonding increases the number of networks and stations sharing the same medium, and may increase the collisions rate. In this paper we show that the spectrum utilization increases when it is divided into multiple narrow channels instead of fewer wide channels. This increase is very significant when the frame aggregation is disabled. We show that 8 × 20 MHz channels may offer 252 Mbps compared to only 51 Mbps in a 160 MHz channel.**

I. INTRODUCTION

Nowadays, IEEE 802.11 networks are widely deployed and offer an easy access to Internet and to many other services. They are supported by most communication devices such as computers, smartphones, cameras and HDTV. To support new applications with high throughput requirements and to satisfy an increasing number of users, the standard defines new amendments that offer high data rates such as 802.11n/ad/ac. Actually 802.11n is largely used and offers a data rate of up to 600 Mbps in the 2.4 GHz and 5 GHz bands. The 802.11ad is defined for the 60 GHz band. It is able to transmit at 6.8 Gbps and has a typical range of 10 meters only [2]. The 802.11ac [3] is increasingly supported by recent devices [4]. It is defined for the 5 GHz band and supports data rates up to 7 Gbps.

To reach this high data rate, 802.11ac uses spatial diversity (with up to 8 simultaneous spatial streams), new modulation and coding schemes (MCS), and channel bonding. Besides, this new amendment uses frame aggregation to enhance the MAC efficiency. It allows the aggregation of several MAC frames (i.e. MPDU) within an aggregated MPDU (A-MPDU). This A-MPDU is then delivered within a PHY frame (i.e. PPDU), as illustrated in Fig. 4, and should respect two constraints: 1) the A-MPDU length limit is 1048575 Bytes (about 1 MB), and 2) the maximum PPDU duration is 5484µs.

The frame aggregation feature reduces the transmission overhead and increases the effective throughput. It can be used by high throughput applications that need to deliver large amount of data (e.g. download a large file). In this case the MAC will have always many frames in the queue to send, and can aggregate them within A-MPDUs. However, many other applications, such as some real-time ones, cannot take a full advantage of frame aggregation. This is because they generate a small amount of data at regular intervals. This amount may fit within a single frame and does not necessary require an A-MPDU. So the MAC needs to access the channel periodically and sends individual frames frequently. Therefore, it is clear that scenarios with A-MPDU enabled and disabled are realistic in current networks.

Regarding the channel bonding, it allows a station to transmit over a wide network composed of 2 to 8 channels of 20 MHz. So 802.11ac devices, also called Very High Throughput (VHT) stations, may support up to 160 MHz transmissions. We note that frame aggregation, spatial diversity and channel bonding where initially defined by 802.11n with the support of up to 4 spatial streams and 40 MHz transmissions.

Channel bonding increases the transmission data rate but reduces the number of non-overlapping channels. Therefore, the European 5 GHz band contains either 19 non-overlapping 20 MHz channels or only two 160 MHz channels. In places with few networks, the spectrum is generally underused and may be organized into wide channels. But in areas with high WLAN deployment density, increasing the channel width increases the number of networks sharing the same medium, and increases, therefore, the collisions rate. Hence, it is more appropriate, in dense environments, to separate the available WLANs into narrow channels in order to reduce the collisions.

Another reason that motivates the use of narrow channels in dense areas is the effect of the overhead when the frame aggregation is not used. This overhead mainly includes Backoff time, PPDU overhead and acknowledgements. In fact, the Backoff parameters (i.e. SIFS and SlotTime) and the PPDU overhead have fixed durations regardless of the channel width. Besides, acknowledgements are always transmitted on a 20 MHz channel, so its duration does not depend on the channel width as well. Only the duration of the PPDU data

will be reduced when using channel bonding. Therefore, when A-MPDU is disabled, the overhead effect is more significant in wide channels [5], and it is more efficient to use multiple independent transmissions over narrow channels than one transmission on a wide channel.

In this paper we evaluate the spectrum utilization (i.e. the aggregated throughput of all nodes operating in the spectrum) as a function of the channel width. We consider a 160 MHz spectrum with non-overlapping channels, containing one of the following configurations: 1×160, 2×80, 4×40 or 8×20 MHz channels. We vary the number of contending nodes and we measure the throughput with and without frame aggregation. When the spectrum is totally occupied, we show that its utilization increases when reducing the channel width. This increase is more remarkable when disabling A-MPDU. Particularly we show that a spectrum without channel bonding (only 20 MHz channels) may provide 500% the achieved throughput when using the 160 MHz bonding.

To summarize, the contribution of this paper is to provide simulation results, using Network Simulator 3 (NS3) [17], which depict the spectrum utilization as a function of the channel width. This utilization is evaluated with and without A-MPDU, using two different MCS (a high and a low data rates) and in an increasingly dense environment.

The remainder of this paper is organized as follows. The next Section introduces related work studying channel bonding. Then we present 802.11ac in Section III. We dedicate Section IV to evaluate the effect of channel bonding on the spectrum utilization, and finally we conclude in Section V.

II. Related Works

The authors in [5] evaluate analytically the throughput of 802.11ac networks that use channel bonding, frame aggregation (A-MPDU and A-MSDU) and spatial diversity. But they neither provide results for the spectrum utilization nor do they validate their analytical model. In [6,7] the authors focus on the different parameters that may affect the performance of channel bonding in 802.11n networks, by comparing the throughput of 20 MHz and 40 MHz channels at various positions and conditions. They show that the efficiency of a wide channel may be affected significantly when the channel is shared by multiple networks and stations. Then they provide some recommendations for bonding decision. However, they only evaluate one particular channel at a time, and do not evaluate the entire spectrum usage. Besides, their study is limited to 802.11n and does not cover 802.11ac. In [8], the authors show that channel bonding in 802.11ac has a very low efficiency when the frame size is small. This is because the new amendment defines longer overhead than that of 802.11a. The transmission duration of this overhead does not depend on the channel width, and affects significantly the efficiency of wide channels. To resolve this problem, the authors propose a new scheme for parallel transmissions over primary and secondary channels. This scheme intends to maximize the usage of a given wide channel. It should be noted that this work does not compare the throughput of a wide channel with that of multiple narrow channels. In [9], the authors measure the network throughput in different deployment scenarios by considering non-overlapping and overlapping channels of random widths. Their results show that a spectrum composed of non-overlapping channels offers the highest throughput. However, this study still considers some particular scenarios with relatively few contending stations. Also, it does not provide a clear overview of the entire spectrum utilization in significant cases. The authors of [10] provide an experimental study, focusing on 802.11n/ac throughput and power consumption of smartphones in the absence of interference. This study measures the performance of channel bonding (up to 80 MHz) as experienced by four smartphones of different models. Another study [11] provides interesting empirical results, including an evaluation of channel bonding, but it only covers specific and limited scenarios. These two studies show that increasing the channel width enhances the channel throughput. However, they do not show the effect of wide channels on the throughput of the entire spectrum. In [12], the author considers a 802.11ac WLAN operating on 80 MHz channel when all its secondary channels are occupied by legacy 802.11a networks. This study shows that the static selection of 80 MHz for all transmissions (i.e. either transmit 80 MHz frames when the entire 80 MHz channel is idle, or defer when any 20 MHz channel is busy) provides very limited throughput when legacy networks are loaded even with a moderate traffic. Besides, it shows that dynamic width selection (i.e. selecting 80, 40 or 20 MHz that is idle for transmission when access is granted) outperforms static selection significantly and provides acceptable throughput in the same conditions. However, there is no evaluation of the aggregated spectrum throughput.

Many other works [13-16] study the performance of some new features of 802.11ac, including channel bonding. Nevertheless, their common limitation is the absence of a clear evaluation of the effect of channel bonding on the throughput of the entire spectrum. Besides, some of them focus on the throughput of one single wide channel and try to maximize it in particular environments with relatively limited network deployment density. Because a good planning of the radio spectrum is required to maximize the achieved throughput, we believe that it is necessary to measure the spectrum performance as a function of the number of available channels and their widths.

III. Presentation of 802.11ac Amendment

III-A. Channel bonding

802.11ac allows networks to operate on channels wider than the legacy 20 MHz width. A wide channel is obtained by aggregating 2, 4 or 8 different 20 MHz channels, which are classified into primary and secondary channels. Depending on the obtained width, we can find primary 20 MHz, secondary 20 MHz, primary 40 MHz, secondary 40 MHz, primary 80 MHz and secondary 80 MHz channels. The primary 40 MHz and 80 MHz channels contain the primary 20 MHz and 40 MHz channels, respectively. Fig. 1 shows this organization.

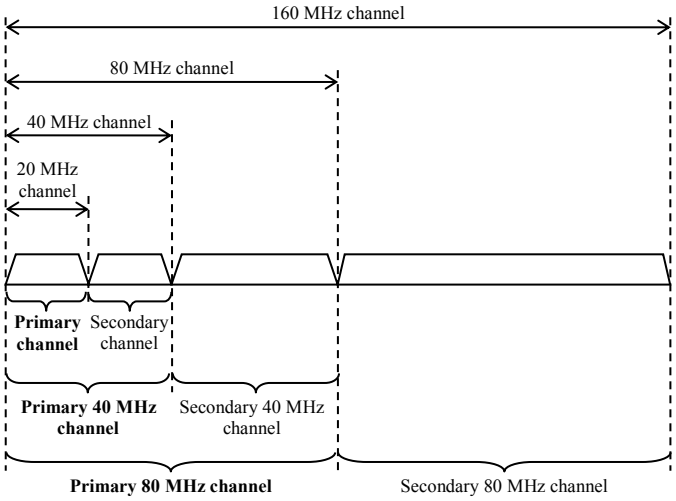

Figure 1. Primary and secondary channels in 802.11ac

We note that a wide channel should be able to operate on one of its primary channels. Thus, a station that operates on a 40 MHz channel contends for the access on its primary channel (i.e. primary 20 MHz channel). If this channel becomes busy the station defers its transmission. Otherwise it acquires it and may either 1) transmit a 40 MHz frame if the secondary channel was idle during the PIFS preceding the transmission start, or 2) transmit a 20 MHz frame if not. Fig. 2 depicts a scenario where a station contends for the medium access in a 40 MHz network. At the first acquisition of the primary channel (i.e. expiry of Backoff Time 1 - BT1), the secondary channel was busy during the previous PIFS. Consequently, the station starts a 20 MHz transmission. Then it contends again and gains the primary channel. As the secondary channel was idle during the PIFS interval preceding the expiry of BT2, the station starts a 40 MHz transmission this time.

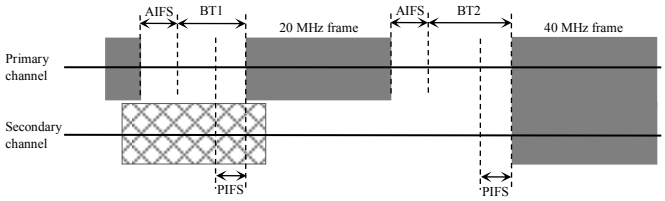

Figure 2. Channel access and transmission in 40 MHz WLAN

Generally speaking, a station should operate according to one of the following rules (section 9.19.2.8 of [3]), depending on the channel width:

- Transmits a 160 MHz frame if the secondary channel, the secondary 40 MHz channel, and the secondary 80 MHz channel were idle during the PIFS preceding the acquisition of the primary channel;
- Transmits a 80 MHz frame if the secondary channel, and the secondary 40 MHz channel were idle during the PIFS preceding the acquisition of the primary channel;
- Transmits a 40 MHz frame if the secondary channel was idle during the PIFS preceding the acquisition of the primary channel;
- Transmits a 20 MHz frame on the primary channel when it is acquired;
- Restarts the channel access attempt if the primary channel is busy.

According to the standard (section 10.39 of [3]), a 40, 80 or 160 MHz WLAN should use the same primary and secondary channels of other existing networks when possible. Besides, a 20 MHz WLAN should not operate on the secondary channel of an existing network. These requirements lead to conclude that the ideal configuration of wide channels is: same primary and secondary channels for all WLANs. This means that gaining the primary channel leads to gaining all the secondary channels. So in an ideal deployment scenario, networks will either send at the largest width or defer their transmissions. In this paper we only consider this ideal scenario (e.g. a 160 MHz network either sends 160 MHz frames or defers its transmissions and restarts the channel access attempt).

An obvious consequence of channel bonding is reducing the number of non-overlapping channels. In fact, 802.11ac is defined for the 5 GHz band. The different spectrum configurations as a function of the channel width in the European band are illustrated in Fig. 3. We obtained them based on table E-2 of [1,3]. We note that there are 9 more 20 MHz channels in the European 5 GHz band, having the following numbers: 149, 153, 157, 161, 165, 169, 173, 177 and 181. But we did not show them because they cannot be used for channel bonding. Fig. 3 shows that there are a total of 19 non-overlapping 20 MHz channels, but only 9×40, 4×80 or 2×160 MHz channels.

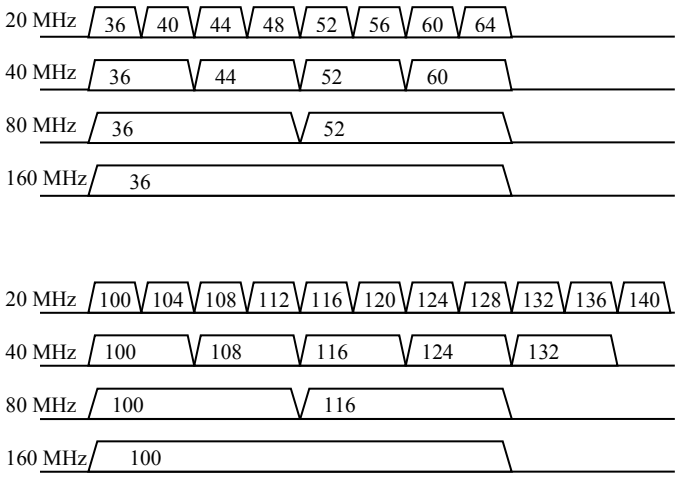

Figure 3. Channelization of the European 5 GHz bands

Increasing the channel width allows the stations to transmit more data and enhances the throughput of a particular WLAN. However, the number of available non-overlapping channels decreases. In dense WLAN deployment, many networks may need to share the same wide channel, leading to increase the

contention on the medium access, and hence increasing the collisions rate.

III-B. VHT Frame format and Aggregate MPDU (A-MPDU)

The OFDM PHY frame as defined by 802.11ac is called VHT PPDU and its format is illustrated in Fig. 4 for the case of 1 spatial stream. This frame has a minimum overhead of 40µs regardless of the channel width. The data part may contain a MPDU or an A-MPDU, and is transmitted over multiple OFDM symbols separated by Guard Intervals (GI). A symbol has a fixed duration of 3.2µs and contains a variable number of subcarriers that depends on the channel width. Thus the symbol capacity depends on the channel width. In addition to the legacy GI of 0.8µs, 802.11ac enables the use of a short GI of 0.4µs. Hence, short GI slightly improves the data rate as illustrated in Table 1.

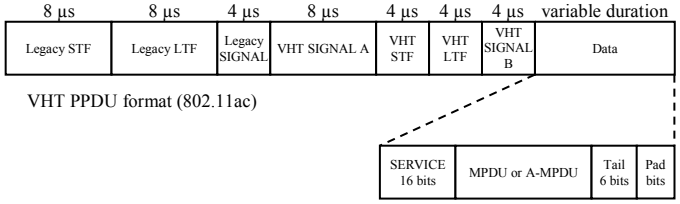

Figure 4. VHT PPDU format

The use of A-MPDU was initially defined by 802.11n with a maximum length of 65535 Bytes. But the VHT amendment increases this limit to 1048575 Bytes (about 1 MB). This new limit is subject to a maximum PPDU duration of 5484µs.

III-C. Modulation and Coding Schemes (MCS)

In addition to channel bonding and extending the A-MPDU maximum length, 802.11ac defines new MCS, indexed 8 and 9. Table 1 lists all MCS values and the corresponding data rates for different channel widths and GI. These rates are defined for 1 spatial stream, and it is straightforward to deduce the data rate for a given number of spatial stream (Nss), where Nss varies from 1 to 8, by multiplying the rates of Table 1 by the corresponding Nss. Thus, the highest rate of 802.11ac is 866.7 x 8 = 6933.3 Mbps (about 7 Gbps).

Table 1. Data rates (Mbps) – case of 1 spatial stream (Nss = 1)

MCS	**20 MHz** (52 data subcarriers)		**40 MHz** (108 data subcarriers)		**80 MHz** (234 data subcarriers)		**160 MHz** (468 data subcarriers)	
	GI 0.8µs	GI 0.4µs	GI 0.8µs	GI 0.4µs	GI 0.8µs	GI 0.4µs	GI 0.8µs	GI 0.4µs
0	6.5	7.2	13.5	15	29.3	32.5	58.5	65
1	13	14.4	27	30	58.5	65	117	130
2	19.5	21.7	40.5	45	87.8	97.5	175.5	195
3	26	28.9	54	60	117	130	234	260
4	39	43.3	81	90	175.5	195	351	390
5	52	57.8	108	120	234	260	468	520
6	58.5	65	121.5	135	263.3	292.5	526.5	585
7	65	72.2	135	150	292.5	325	585	650
8	78	86.7	162	180	351	390	702	780
9	-	-	180	200	390	433.3	780	866.7

IV. Evaluation Results

We use ns3 [17] to evaluate the effect of channel bonding on the spectrum utilization. We consider the simulation configuration of Table 2. All the measurements are based on UDP traffic belonging to the "Best Effort" category with Ethernet frame size of 1500 Bytes. Thus the MPDU length is 1538 Bytes. We set the different stations in the saturation condition (i.e. they always have data to send) to measure the highest achieved throughput.

Table 2. Simulation and transmission parameters

Parameters	Values
Simulator version	ns3.25 (March 2016)
Error rate model	Nist
Propagation loss model	Log distance
Network type	802.11ac
- Band and channels	5 GHz (UNII 1): channels 36 to 64
- Transmission Power	40mW (16.02dBm)
- GI	0.8µs
- SIFS	16µs
- SlotTime	9µs
- AIFS	43µs (SIFS + 3×SlotTime)
- CWmin	15
- CWmax	1023
- Maximum PPDU duration	5484 µs

We evaluate the spectrum utilization as a function of the channels width. We consider a spectrum of 160 MHz which is organized into one of the following configurations: 1) 8 channels of 20 MHz width, i.e. 8×20 MHz channels, 2) 4×40 MHz channels, 3) 2×80 MHz channels, and 4) 1×160 MHz channel. Each channel contains one Access Point (AP) to which the contending stations send their data.

We vary the number of contending nodes in the spectrum from 1 to 64 stations. The stations are equally distributed on the available channels. **Example 1**: if we have 4×40MHz channels and 6 stations, we set one station at each channel and we set a second station at the two first channels. **Example 2**: if we have 8×20MHz channels and 1 station, we set this station at the first channel and we leave empty the others. **Example 3**: if we have 40 stations, we distribute them like one of the following cases, 5 stations per 20 MHz channel, 10 stations per 40 MHz channel, 20 stations per 80 MHz channel or 40 stations at the unique 160 MHz channel.

We measure the throughput achieved by all the stations using a high (MCS = 7) and a low (MCS = 1) data rates. Moreover, we make our evaluation when A-MPDU is disabled and then enabled. We depict the obtained results in Fig. 5 and 6.

In Fig. 5, we evaluate the achieved throughput when the frame aggregation is disabled. This scenario is frequent and illustrates real-time applications which are intensively used, such as voice/video communication and network games. These applications transmit data periodically during long durations. The instantaneously generated data has a limited size and is typically delivered within one single frame (e.g. voice applications), so there is no need for aggregation. However the station needs to contend frequently for the channel to send its real-time flow.

Fig. 5 (a) and (b) illustrate the spectrum throughput using MCS=7 and MCS=1, respectively. When there is one station and 8×20MHz channels, only one 20 MHz channel is used. Therefore, we observe that a wide channel of 160 MHz outperforms a 20 MHz channel. But when the number of stations increases, all the 20 MHz channels become used, and their aggregated throughput exceeds that of the 160 MHz channel. For example, Fig. 5 (a) shows that in the presence of one single station, the spectrum throughput for 1×160 MHz configuration is 55 Mbps compared to only 31 Mbps when only one 20 MHz channel is used. But in the presence of 16 stations, a spectrum of 8×20 MHz channels achieves 252 Mbps compared to only 51 Mbps for a 160 MHz channel. Besides, we notice that the throughput of a 160 MHz channel decreases when the number of contending stations increases. This decrease is obviously caused by collisions. Similarly, Fig. 5 (b) shows that multiple 20 MHz channels outperform one single 160 MHz channel in dense environments. For example, in the presence of 16 stations a spectrum of 8×20 MHz channels achieves 80 Mbps compared to only 35 Mbps for a 160 MHz channel.

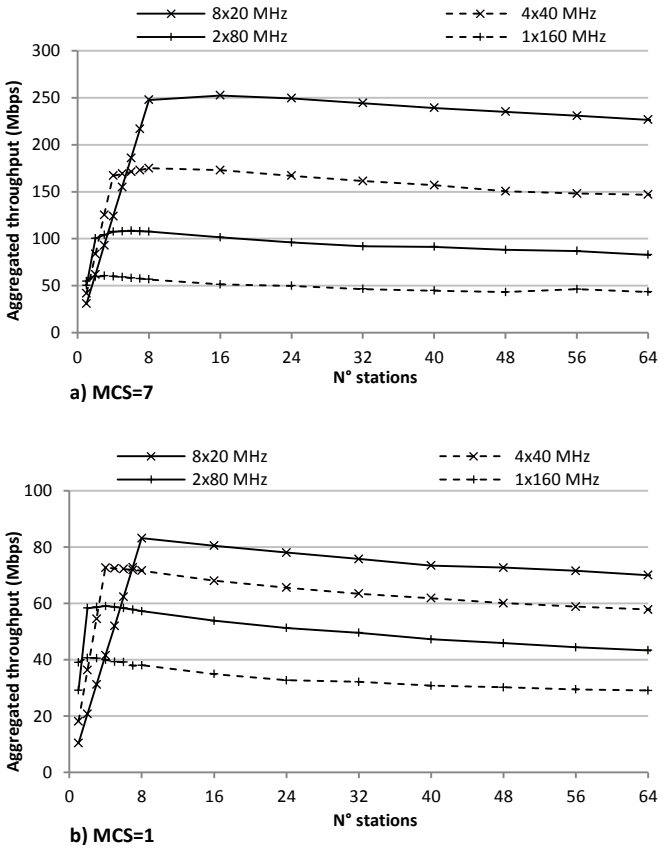

Figure 5. 160 MHz Spectrum throughput as a function of contending stations, without frame aggregation and using a) MCS=7 and b) MCS=1

In Fig. 6, we evaluate the achieved throughput when the frame aggregation is enabled. Thus each transmission contains an A-MPDU that has multiple frames and is acknowledged using a BACK. The number of frames per A-MPDU depends on the used MCS and is subject to the maximum PPDU duration. This scenario is also realistic and illustrates download applications which deliver data at the highest supported rate till the download end. According to Fig. 6(a), in the presence of 1 station, a spectrum of 8×20 MHz channels is partially used (i.e. only one 20 MHz channel is used) and offers 60 Mbps compared to 548 Mbps when using a spectrum of 1×160 MHz channel. But when the spectrum of 20 MHz channels is totally used (more than 7 stations), it outperforms a spectrum having one 160 MHz channel (e.g. 440 Mbps compared to 392 Mbps in the presence of 16 contending stations). This difference is lower than that of Fig. 5(a) when disabling the frame aggregation. This is because A-MPDU enhances the efficiency of wide channels significantly. We notice the same curve behavior of Fig. 6 (a) in Fig. 6 (b) as we still use frame aggregation. However, the throughput is reduces because we use a low data rate (MCS=1).

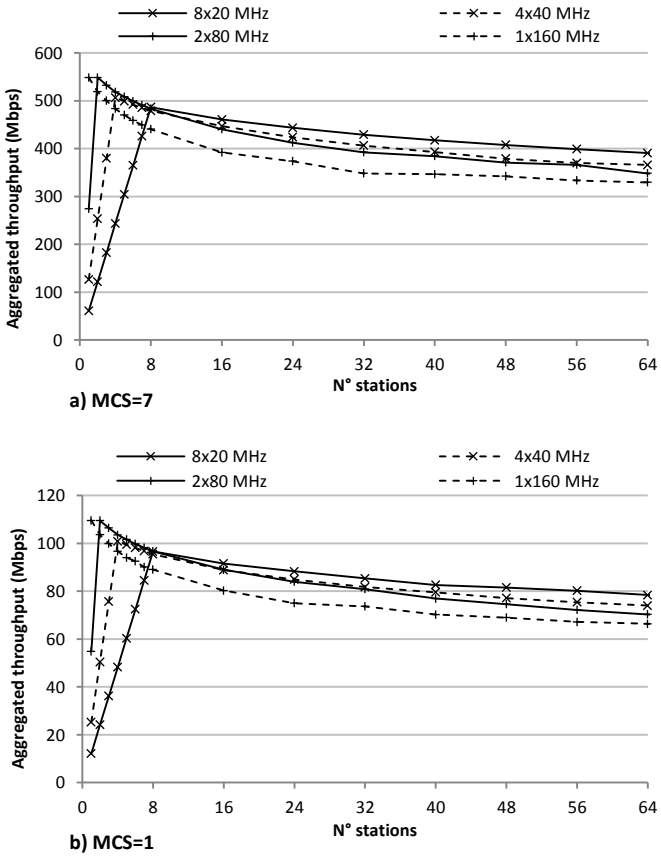

Figure 6. 160 MHz Spectrum throughput as a function of contending stations, with A-MPDU aggregation and using a) MCS=7 and b) MCS=1

V. CONCLUSION

In this paper we study the channel bonding which is used by 802.11ac to increase the transmission data rate. We highlight the fact that increasing the channel width limits the number of non-overlapping networks within a spectrum, and we focus on dense WLAN environments. We consider the case of a 160 MHz spectrum and we organize it into non-overlapping channels, then we measure the maximum throughput achieved by the entire spectrum. We show that increasing the channel

width decreases the spectrum throughput significantly when A-MPDU is disabled. This decrease is very important when using a high data rate. Particularly, 8×20 MHz channels may offer 252 Mbps compared to only 51 Mbps for a unique 160 MHz channel. We conclude that the usage of multiple narrow channels is always a good choice in dense environments and highly loaded networks.

Although we consider significant scenarios in this evaluation, we do not consider some frequent scenarios such as a highly loaded network in the presence of other networks with limited load. But this latter case may be approximated to a spectrum containing a unique WLAN that is highly loaded (1 contending node in the spectrum). For this scenario, our results show that 160 MHz channel always outperforms narrow channels significantly. This is because the sender takes advantage of the entire spectrum instead of a narrow channel. In real networks, it is possible that a station has a large amount of data to send while other networks are idle or have limited load. In this case, it is preferable to use a wide channel instead of a narrow one. Thus, an interesting future work is to define a selection algorithm that dynamically selects the channel width to maximize the spectrum throughput. This algorithm may be improved to become cooperative so it allows neighbor networks to decide together how to adjust their channel widths according to their loads.

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