Evaluation of IEEE 802.11 coexistence in WLAN deployments

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***Abstract* –** Wi-Fi has become a successful technology since the publication of its first WLAN standard due to continuous advances and updates while remaining always backwards compatible. Backwards compatibility among subsequent standards is an important feature in order to take advantage of previous equipment when publishing a new amendment. At present, IEEE 802.11b support is still mandatory to obtain the Wi-Fi certification. However, there are several harmful effects of allowing old legacy IEEE 802.11b transmissions in modern WLAN deployments. Lower throughput per device is obtained at slow rates, but also the effect known as performance anomaly, which nearly leads to starvation of fast stations, has to be taken into account. Finally, backwards compatibility mechanisms pose an important penalty in throughput performance for newer specifications. This paper presents a thorough analysis of the current state of IEEE 802.11, comparing coverage range and throughput performance among subsequent amendments, and focusing on the drawbacks and benefits of including protection mechanisms.

***Keywords* –** WLAN · IEEE 802.11 · Coexistence · Backwards compatibility

1. Introduction

Since the publication of the first WLAN IEEE 802.11 standard specification in 1997, different new amendments have come out. The original IEEE 802.11 allowed wireless communications of 1 and 2Mbps in the 2.4GHz frequency band employing FHSS (Frequency Hopping Spread Spectrum), DSSS (Direct Sequence Spread Spectrum) and infrared (IR) technology at the physical layer (PHY). Later, in 1999 IEEE 802.11b was published including higher transmission rates of 5.5 and 11Mbps at 2.4GHz with CCK (Complementary Code Keying) PHY. Also in 1999, IEEE 802.11a came out providing high rate communication up to 54Mbps at 5GHz and with OFDM (Orthogonal Frequency-Division Multiplexing) PHY modulation. However, this specification was not backwards compatible with previously published specifications. Thus, in 2003, IEEE 802.11g standard appeared to offer IEEE 802.11a's high rates in the 2.4GHz using the same OFDM PHY modulations. In 2009, IEEE 802.11n specification was released, which included enhancements for allowing high throughput (HT) capabilities (higher bit rates up to 600Mbps) and operation at both bands, 2.4GHz and 5GHz. IEEE 802.11n uses a modified OFDM PHY, two different channel bandwidths (20 and 40MHz), frame aggregation mechanisms and improved FEC (Forward Error Correction). Nevertheless, the most important feature is that it enables spatial multiplexing with up to 4 spatial streams using MIMO (Multi-Input Multi-Output) techniques, thus leading to HT performance. The standard document IEEE 802.11-2012 [1] published in 2012 includes a review of all these previous amendments. Moreover, other IEEE 802.11 specifications (cf. Table 1) came out in the last years that provide additional features to the IEEE 802.11 Medium Access Control (MAC) protocol. Also, the IEEE 802.11ac amendment presents enhancements for very high throughput (VHT) operation only in the 5GHz band through channel bandwidth extension (20, 40, 80 and 160MHz), high density modulation, improved FEC, frame aggregation, higher number of spatial streams (up to 8) and downlink MU-MIMO (multiuser MIMO) to transmit different streams to several client stations simultaneously. IEEE 802.11ac represents the latest advance in Wi-Fi technology and the successor of IEEE 802.11n. The higher data rates offered by IEEE 802.11ac allow video delivery of higher quality in mobile terminals and also are suitable for high-density environments with high number of clients per access point (AP). Future IEEE 802.11ax standard (expected in 2019) aims at increasing 4 times throughput performance, and thus, at improving efficiency in dense environments.

Wi-Fi has become a successful technology since the publication of its first WLAN standard due to the continuous advances and updates while remaining always backwards compatible. On the other hand, IEEE 802.11n/ac have become very popular since their certification by the Wi-Fi Alliance. Thus, previous amendments have lost influence in WLAN penetration in front of IEEE 802.11n/ac: the latter have increased their presence with respect to IEEE 802.11g, whereas IEEE 802.11b and IEEE 802.11a penetration remains very residual [2]–[3]. Backwards compatibility among subsequent standards is an important feature in order to take advantage of previous equipment when publishing a new amendment. However, there are several harmful effects of allowing old legacy IEEE 802.11b transmissions in modern Wi-Fi deployments. First, we have to take into account the lower user throughput obtained at slow rates. Second, the effect known as the performance anomaly has to be considered, which arises in networks with stations operating at different physical bit rates, and can lead to fast stations being nearly starved whereas slow clients practically do not perceive any rate decrease [4]. This effect has been later reduced with the introduction of frame aggregation mechanisms, Block Acknowledgement frames and the usage of Transmission Opportunity (TXOP) control in IEEE 802.11n/ac amendments. And third, there is the need for backwards compatibility mechanisms to allow coexistence between new and previously defined amendments; these mechanisms pose an important penalty in throughput performance for newer specifications. At present, IEEE 802.11b support is still mandatory to obtain the Wi-Fi certification. In this regard, some chipset manufacturers are pushing to remove such requirement due to the unnecessary complexity of implementing the old modulation and coding scheme set. However, the pressure of an important sector of that industry to deprecate IEEE 802.11b, a question being considered by the Wi-Fi Alliance and the IEEE P802.11 WG, is facing the opposition of those who defend that IEEE 802.11b is still useful today in M2M (Machine-to-Machine) and IoT (Internet of Things) applications due to the lower costs of a simpler technology. With this regard, IEEE P802.11 WG is working on forthcoming IEEE 802.11ah amendment in order to enable the IoT application use case.

Different studies in the literature have evaluated the influence of backwards compatibility mechanisms in IEEE 802.11g performance in presence of legacy IEEE 802.11b devices [5]; in this way, reference [6] points out the IEEE 802.11g degradation, as compared to IEEE 802.11a, which does not include such mechanisms. Reference [7] presents IEEE 802.11n performance penalty taking into account different operating modes and transmission rates; however, this study has been carried out with an IEEE 802.11n pre-standard version (Draft 4.0, 2008) and the higher transmission rates have not been considered. Moreover, reference [8] studies interoperability between IEEE 802.11n and IEEE 802.11a/g in terms of synchronization issues due to the utilization of a compatible preamble, but performance degradation is not included in the evaluation. With regard to IEEE 802.11ac amendment, comparison with IEEE 802.11n has been exposed in [9], but it only presents the influence of frame aggregation mechanisms in throughput performance. On the other hand, reference [10] provides measurement results in a typical office building. Other published papers concentrate in the introduction of larger channel width and MU-MIMO [11], the comparison of MU-MIMO and single-user MIMO (SU-MIMO) [12], the impact of channel width and MU-MIMO in efficiency and interference characterization [13], and the analysis of the inefficiency and unfairness when channels of variable bandwidth coexist [14]. Thus, a thorough analysis of the current state of IEEE 802.11 specification, focusing on the drawbacks and benefits of including protection mechanisms to allow backwards compatibility among subsequent amendments, has not been yet published in the literature. To the best of our knowledge, this is the first paper providing such study. Section 2 shows a comparison of IEEE 802.11 standards’ capabilities in terms of coverage and throughput issues. Next, Section 3 evaluates the effects of guaranteeing coexistence of IEEE 802.11

specifications. Finally, Section 4 concludes the paper and presents some final recommendations for the deployment of future Wi-Fi networks.

Amendment	Description
IEEE 802.11 (1997)	1 and 2Mbps at 2.4GHz with FHSS, DSSS and IR PHY
IEEE 802.11b (1999)	1, 2, 5.5 and 11Mbps at 2.4GHz with CCK PHY
IEEE 802.11a (1999)	6, 9, 12, 18, 24, 36, 48 and 54Mbps at 5GHz and with OFDM PHY
IEEE 802.11g (2003)	6, 9, 12, 18, 24, 36, 48 and 54Mbps at 2.4GHz and with OFDM PHY
IEEE 802.11h (2003)	Spectrum and transmit power management extensions, Dynamic Frequency Selection (DFS) and Power Control (PC) mechanisms, to solve interference problems at 5GHz
IEEE 802.11i (2004)	Security enhancements: Temporal Key Integrity Protocol (TKIP) and Counter Mode (CTR) with Cipher-Block Chaining Message Authentication Code (CBC-MAC) Protocol (CCMP) encryption methods and Robust Security Network Association (RSNA) protocol (authentication through 802.1x and Extensible Authentication Protocol (EAP))
IEEE 802.11e (2005)	MAC enhancements for the prioritization of traffic classes through the modification of MAC parameters
IEEE 802.11r (2008)	Definition of authentication and association messages in order to complete fast and secure handoffs between Basic Service Sets
IEEE 802.11k (2008)	Radio Resource Measurements (RRM) of WLANs to facilitate its management and maintenance
IEEE 802.11n (2009)	HT capabilities with MIMO (bit rates up to 600Mbps) at 2.4GHz and 5GHz
IEEE 802.11w (2009)	Definition of protected management frames to increase their security through data confidentiality
IEEE 802.11z (2010)	Automatic set-up of a direct link between client devices while also remaining associated with the access point
IEEE 802.11p (2010)	Intra-vehicle, vehicle to vehicle and vehicle to infrastructure communications
IEEE 802.11v (2011)	Network management of client devices through the exchange of network information
IEEE 802.11u (2011)	Interworking with external networks thus enabling information transfer from/to external networks (e.g. 4G networks)
IEEE 802.11s (2011)	Mesh networking: mechanisms to form self-configuring multi-hop networks for broadcast, multicast and unicast data delivery
IEEE 802.11ae (2012)	Mechanisms for prioritization of management frames
IEEE 802.11ad (2012)	PHY and MAC modifications for VHT at 60GHz
IEEE 802.11aa (2012)	MAC enhancements for robust audio and video streaming while maintaining coexistence with other types of traffic
IEEE 802.11af (2013)	Utilization of IEEE 802.11 technology within licensed television spectrum, taking advantage of unused white spaces
IEEE 802.11ac (2013)	VHT operation (bit rates up to 7Gbps) at 5GHz

Table 1. Description of IEEE 802.11 amendments.

2. Comparison of IEEE 802.11 WLAN standards

2.1 Coverage

The coverage of an IEEE 802.11 AP is the area surrounding it within which communication with that AP is possible. Among the most important factors determining the dimensions of this area, first, we have the characteristics of the environment affecting the propagation of waves, the frequency and transmitted power, which usually depend on local regulations, but also the PHY used. The following two figures provide a comparison on the expected cell radius for different technologies in different environments[1]. Figure 1 represents received power vs. distance for four channel propagation models at 2.4GHz: TGn (A,B,C) and TGn (D) represent office and open-office environments (A, B and C without line of sight, D adds line of sight) according to the specifications of the TGn [15], TGah (pico) consists of outdoor pico-

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[1] In all cases, we assume 20dBm of transmitted power and isotropic antennas.

cell scenarios (antenna of the AP at rooftop level), and TGah (D2D) represents outdoor device to device environments [16]. Figure 2 shows the maximum cell radius for different PHY configurations in each of the four chosen scenarios. Both the most reliable (i.e. slowest) and the fastest modulations are represented for each IEEE 802.11 generation (11a/b/g/n/ac), assuming 20MHz channels and one spatial stream for MIMO capable PHYs. Faster modulations and coding schemes have more complex constellations and use less redundancy and, thus, will require a stronger received signal than slow modulations. Therefore, higher modulations are available for shorter distances. The receiver sensitivity used to compute the cell radius shown in Figure 2 is taken from the datasheets of different products available in the market (cf. [17] for a client device, [18] for an AP). Regarding the frequency used, note that transmissions in higher frequencies (i.e. IEEE 802.11a/ac in 5GHz) undergo higher propagation losses. With coverage in mind, there are other phenomena that should also be considered when designing an IEEE 802.11 WLAN:

- **Obstacles**: each wall and floor reduces received power between 10 and 20dB, depending on the building material [19].
- **Regulations**: maximum allowed transmitted power is determined by local regulations and may change from one country to another and from one frequency band to another. For example, IEEE 802.11a/n/ac WLANs are allowed to transmit 23dBm in the UNII 1 and 2, and up to 30dBm in UNII 3 if certain conditions are met. This increased power is intended to compensate for the increased propagation losses of higher frequencies.
- **Modulation and Coding Scheme (MCS)**: high order modulations require higher SNIR (Signal to Noise and Interference Ratio) but, paradoxically, they should be used with lower transmitted power to avoid amplifier distortion due to high peak to average ratios [20]. For example, it is recommended that the maximum transmitted power for IEEE 802.11n's MCS 7 is 4-5dB lower than for MCS 0. This power reduction is translated into 10 to 40m smaller cell radius (depending on the channel model).
- **Channel bonding**: IEEE 802.11n/ac can bond two or more 20MHz channels to increase the PHY rate. However, since the maximum transmitted power is the same as with 20MHz, the power density of the signal is decreased along with SNIR when the bandwidth is increased. The general rule of thumb is that SNIR is reduced 3dB every time the bandwidth is doubled. This reduction in SNIR is translated into 5 to 30m smaller radius for 40MHz (depending on the channel model used), or 15 to 60m in the case of 80MHz.

- **Spatial diversity**: MIMO technology present in IEEE 802.11n/ac allows spatial multiplexing to increase rate, but also enables the implementation of spatial diversity techniques, which improve reliability and increase range. Multiple Ratio Combining or Transmitter beamforming, for example, may improve received signal by 2 to 4dB (i.e. 10-35m of increased range).

2.2 User Throughput

Despite the different frequency bands and PHY rates of the subsequent amendments, the MAC operation has been continually based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism and works as follows. Before initiating a transmission, a station senses the channel to determine whether it is busy. If the medium is sensed idle during a period of time called the Distributed Inter-frame Space (*DIFS*), the station is allowed to transmit. If the medium is sensed busy, the transmission is delayed until the channel is idle again. In this case, a slotted binary exponential backoff interval is uniformly chosen in [0, *CW*-1], where *CW* is the contention window. The backoff timer is decreased as long as the channel is sensed idle, paused when a transmission is in progress, and resumed when the channel is sensed idle again for more than the *DIFS*. When the backoff timer expires, the station attempts transmission. After each data frame is successfully received, the receiver transmits an acknowledgment (*ACK*) frame after a Short Inter-frame Space (*SIFS*) period. The value of *CW* is set to its minimum value, CW_{min}, in the first transmission attempt and after each successful transmission; increases in integer powers of 2 at each retransmission, up to a pre-determined value CW_{max}. MAC protocol has evolved in the latest amendments (IEEE 802.11n/ac) with the introduction of frame aggregation mechanisms, the employment of Block Acknowledgement frames and the usage of TXOP control.

We analyze user throughput for the different amendments. For comparison purposes, our first evaluation scenario consists in a single radio link composed of two stations (a transmitter and a receiver) that exchange data frames under ideal transmission conditions. Hereafter, the influence of an increasing number of stations is shown.

The various amendments present differences in the physical layer convergence procedure (PLCP) preamble and header duration, as can be observed from Table 2. IEEE 802.11b includes a long and a short preamble. On the other hand, IEEE 802.11n presents different transmission modes (Non-HT, HT Mixed and HT Greenfield) and thus three preamble types (cf. Figure 3):

- Non-HT preamble: it employs PLCP preamble/header used by legacy IEEE 802.11b, IEEE 802.11g or IEEE 802.11a. Support is mandatory.

– HT Mixed Format preamble: it consists of an HT preamble preceded by an IEEE 802.11a/g non-HT preamble. Support is mandatory.

– HT Greenfield Format preamble (purely HT preamble). Support is optional.

IEEE 802.11ac also offers non-VHT transmission modes (Non-HT, HT Mixed, HT Greenfield) and VHT mode. Preamble types of the non-VHT modes correspond to those shown for IEEE 802.11n (cf. Figure 3). VHT preamble is exposed in Figure 4 and its support is mandatory.

The throughput computation, *S*, in Mbps follows next expression:

$$S = \frac{L_{data} \times 8}{T_{message}} \tag{1}$$

$$T_{message} = DIFS + T_{Backoff} + T_{data} + \delta + SIFS + \delta + T_{ACK} \tag{2}$$

L_{data} consists in the payload size of data frames in Bytes. *DIFS* and *SIFS* are given in Table 2, δ consists in the propagation delay, which can be neglected at typical WLAN distances, T_{ACK} corresponds to the duration of an *ACK* frame and T_{data} represents the transmission time of a data frame, which depends mainly on the size of the payload and the PHY rate. Under ideal transmission conditions we consider $T_{Backoff}$ is, on average, $CW_{min}/2$ times the slot time. Times are expressed in µs.

T_{data} and T_{ACK} computation depends on the IEEE 802.11 amendment used in the transmission.

Thus, for IEEE 802.11b T_{data} follows next expression:

$$T_{data} = T_{preamble/header} + \frac{(L_{header} + L_{data}) \times 8}{r} \tag{3}$$

Standard, rate	PLCP Preamble/Header	DIFS	SIFS	CW_{min}	CW_{max}	Slot Time
IEEE 802.11b, 1Mbps	192µs	50µs	10µs	31	1023	20µs
IEEE 802.11b, 2, 5.5, 11Mbps	96µs	50µs	10µs	31	1023	20µs
IEEE 802.11a	20µs	34µs	16µs	15	1023	9µs
IEEE 802.11g	20µs	28µs	10µs	15	1023	9µs
IEEE 802.11n HT Mixed, 5GHz	Non-HT preamble/header + 16µs + variable*	34µs	16µs	15	1023	9µs
IEEE 802.11n HT Greenfield, 5GHz	24µs + variable*	34µs	16µs	15	1023	9µs
IEEE 802.11n HT Mixed, 2.4GHz	Non-HT preamble/header + 16µs + variable*	28µs	10µs	15	1023	9µs
IEEE 802.11n HT Greenfield, 2.4GHz	24µs + variable*	28µs	10µs	15	1023	9µs
IEEE 802.11ac VHT	36µs + variable*	34µs	16µs	15	1023	9µs

* Variable value that depends on the number of spatial streams (cf. Table 3)

Table 2. Values for PHY and MAC parameters per amendment.

where r corresponds to the PHY rate (in Mbps), $T_{preamble/header}$ is given in Table 2 and L_{header} is 36Bytes long (including MAC and LLC headers).

For IEEE 802.11a T_{data} is as follows:

$$T_{data} = T_{preamble/header} + 4\left\lceil \frac{\left(22 + \left(L_{header} + L_{data}\right) \times 8\right)}{4r} \right\rceil \tag{4}$$

For IEEE 802.11g T_{data} is:

$$T_{data} = T_{preamble/header} + 4\left\lceil \frac{\left(22 + \left(L_{header} + L_{data}\right) \times 8\right)}{4r} \right\rceil + T_{SignalExtension} \tag{5}$$

where $T_{SignalExtension}$ is 6µs.

With regard to IEEE 802.11n, T_{data} and T_{ACK} computation depends on the transmission mode (Non-HT, HT Mixed or HT Greenfield). In case of employing the Non-HT mode, T_{data} follows Eq. (3), (4) or (5), depending on the PLCP preamble/header used. Concerning HT Mixed mode, T_{data} is:

$$T_{data} = T_{preamble/header} + T_{preamble\_streams} + 4\left\lceil \frac{\left(T_{sym} \times N_{symbols}\right)}{4} \right\rceil + T_{SignalExtension} \tag{6}$$

with

$$T_{preamble\_streams} = 4 \times \left(N_{LTF} - 1\right) \tag{7}$$

$$N_{symbols} = \left\lceil \frac{\left(16 + 6 \times N_{ES} + \left(L_{header} + L_{data}\right) \times 8\right)}{N_{DBPS}} \right\rceil \tag{8}$$

where $T_{SignalExtension}$ is 6µs for 2.4GHz band and 0µs for 5GHz, and T_{sym} corresponds to the symbol duration (3.6µs for short guard interval, GI, and 4µs for long GI). N_{ES} and N_{DBPS} depend on the MCS chosen and are fixed in the standard specification. N_{LTF} corresponds to the number of long training symbols, which depends on the number of spatial streams, N_{SS} (cf. Table 3).

Number of spatial streams, N_{SS}	**IEEE 802.11n N_{LTF}**	**IEEE 802.11ac N_{VHTLTF}**
1	1	1
2	2	2
3	4	4
4	4	4
5	-	6
6	-	6
7	-	8
8	-	8

Table 3. Number of long training symbols for IEEE 802.11n and IEEE 802.11ac without STBC.

Moreover, IEEE 802.11n was the first amendment allowing frame aggregation. Two levels of aggregation are defined: MSDU aggregation (A-MSDU), which wraps multiple frames into a single MAC level frame, all sharing a unique IEEE 802.11 MAC header; and MPDU aggregation (A-MPDU), which wraps multiple IEEE 802.11 MAC frames into a single physical level frame. Only support of A-MPDU is mandatory for both transmission and reception. A Block Acknowledgement (*BA*) is transmitted by the receiver after a *SIFS*, instead of an *ACK* frame.

With A-MPDU aggregation, $N_{symbols}$ is computed as follows:

$$N_{symbols} = \left\lceil \frac{\left(16 + 6 \times N_{ES} + \left(L_{header} + L_{data}\right) \times K \times 8 + L_{deli} \times \left(K - 1\right) \times 8\right)}{N_{DBPS}} \right\rceil \tag{9}$$

where K is the number of aggregated frames of equal size and L_{deli} is the size of the delimiter between aggregated frames (4Bytes).

With respect to HT Greenfield, T_{data} is:

$$T_{data} = T_{preamble/header} + T_{preamble\_streams} + T_{sym} \times N_{symbols} + T_{SignalExtension} \tag{10}$$

where $T_{SignalExtension}$ is again 6µs for 2.4GHz band and 0µs for 5GHz, T_{sym} corresponds to the symbol interval and $T_{preamble\_streams}$ and $N_{symbols}$ follow Eq. (7) and (8)/(9), respectively.

With regard to IEEE 802.11ac, T_{data} and T_{ACK} computation also depends on the transmission mode chosen (Non-HT, HT Mixed, HT Greenfield or VHT). In case of employing Non-HT, HT Mixed or HT Greenfield, T_{data} follows Eq. (4), (6) or (10), respectively, for 5GHz. In case of VHT format, T_{data} is:

$$T_{data} = T_{preamble/header} + T_{preamble\_streams} + 4\left\lceil \frac{\left(T_{sym} \times N_{symbols}\right)}{4} \right\rceil \tag{11}$$

with

$$T_{preamble\_streams} = 4 \times N_{VHTLTF} \tag{12}$$

where $N_{symbols}$ follows Eq. (8)/(9) and N_{VHTLTF} corresponds to the number of VHT long training symbols (cf. Table 3).

T_{ACK} computation follows T_{data} equations but using them with 14Bytes in substitution for L_{header} and L_{data}. In case frame aggregation is used, the *BA* frame of 32Bytes is considered instead of the regular *ACK* frame. IEEE 802.11n and IEEE 802.11ac allow frame aggregation of up to 64 individual frames, building an A-MPDU of maximum 64KB for IEEE 802.11n and of 1MB for IEEE 802.11ac, and observing a fixed maximum frame duration. The employment of HT Greenfield mode includes larger maximum frame duration of 10ms, whereas other transmission modes fix it to 5.484ms.

In the following, we consider different connections using physical bit rates and payload sizes (from short frames of 100Bytes to larger ones of 1500Bytes of data). For PHY other than IEEE 802.11n and IEEE 802.11ac, *ACK* frames are transmitted at the highest mandatory rate of the employed PHY that is less than or equal to the rate of the previously received data frame. In relation to IEEE 802.11n and IEEE 802.11ac, mandatory HT and VHT PHY MCS are employed, respectively; the highest indexed MCS with a number of spatial streams, a modulation and a coding rate value per stream less than or equal to that of the received data frame is used for corresponding *ACK/BA* transmission. Mandatory rates and MCS for the different PHY are shown in Table 4; detailed information about mandatory MCS in IEEE 802.11n and IEEE 802.11ac PHY is presented in Table 5. For example, after a successful reception of a data frame modulated using IEEE 802.11n's MCS 12 and 40MHz bandwidth (two spatial streams, 16-QAM and coding rate 3/4 yielding 162Mbps), a station will respond with an *ACK/BA* frame using MCS ≤ 4 and 20MHz (MCS 4 uses one stream, 16-QAM and coding rate of 3/4, yielding 39Mbps).

Tables 6 - 8 represent throughput performance for IEEE 802.11a/g, IEEE 802.11n and IEEE 802.11ac, respectively, in a single radio link scenario composed of a transmitter and a receiver. These values are used henceforth as the benchmark to assess the penalty incurred by different compatibility mechanisms. Obviously, transmissions gain in efficiency with the rise in the payload size, regardless of the PHY used. With regard to IEEE 802.11n, HT Greenfield and HT Mixed modes have been considered. VHT preamble has been chosen for IEEE 802.11ac.

Standard	Mandatory
IEEE 802.11b	1, 2, 5.5 and 11Mbps
IEEE 802.11a	6, 12 and 24Mbps
IEEE 802.11g	6, 12 and 24Mbps
IEEE 802.11n	MCS 0, 1, 2, 3, 4, 5, 6 and 7 (Bandwidth channel 20MHz, and 1 spatial stream)
IEEE 802.11ac	MCS 0, 1, 2, 3, 4, 5, 6 and 7 (Bandwidth channel 20, 40 and 80MHz, and 1 spatial stream)

Table 4. Mandatory rates and MCS per amendment.

MCS	Modulation	Cod. Rate	Data Rate (Mbps)					
			20MHz		40MHz		80MHz	
			800ns GI	400ns GI	800ns GI	400ns GI	800ns GI	400ns GI
0	BPSK	1/2	6.5	7.2	13.5	15.0	29.3	32.5
1	QPSK	1/2	13.0	14.4	27.0	30.0	58.5	65.0
2	QPSK	3/4	19.5	21.7	40.5	45.0	87.8	97.5
3	16-QAM	1/2	26.0	28.9	54.0	60.0	117.0	130.0
4	16-QAM	3/4	39.0	43.3	81.0	90.0	175.5	195.0
5	64-QAM	2/3	52.0	57.8	108.0	120.0	234.0	260.0
6	64-QAM	3/4	58.5	65.0	121.5	135.0	263.3	292.5
7	64-QAM	5/6	65.0	72.2	135.0	150.0	292.5	325.0

Table 5. Mandatory MCS in IEEE 802.11n and IEEE 802.11ac PHY.

HT Greenfield mode shows better performance in comparison with results observed for HT Mixed mode. Note that HT Greenfield mode consists in a pure HT mode, i.e. it does not allow backwards compatibility (cf. Section 3.1.2) and presents a shorter PLCP preamble/header size (cf. Figure 3 and Table 2). Differences are obviously reduced with the increase in the time spent on the transmission of a frame, i.e. with the growth in payload size, the employment of frame aggregation or the use of slower MCS. In relation to IEEE 802.11ac, note that some configurations are penalized in front of IEEE 802.11n for the same nominal bit rate. This fact is due to the larger PLCP preamble/header size of the former for the same number of spatial streams (cf. Eq. (7) vs Eq. (12)) – VHT preamble natively allows backwards compatibility (cf. Section 3.1.3). Frame aggregation of IEEE 802.11n/ac shows a notable rise in performance. However, with regard to IEEE 802.11ac, efficiency remains still worse for high transmission rates and increased number of streams – the highest MCS at 160MHz (8 streams and 6933.3Mbps of nominal bit rate) achieves a penalty of 67.96% employing A-MPDUs built of 1500 Bytes frames. This efficiency will be improved with the use of MU-MIMO, which allows the simultaneous transmission of multiple frames addressed to different receivers. This feature is, however, optional. IEEE 802.11n introduced the optional Channel State Information (CSI) mechanism that was later also included in IEEE 802.11ac. It provides a description of the current channel conditions from the receiver and can be used to compute the most suitable transmission rate. CSI complete measurement and transmission is, however, time and bandwidth expensive, and, therefore, its applicability is limited [21]. Thus, in this study we have not considered CSI.

IEEE 802.11a/g	**Frame Size (Bytes)**			
	100		**1500**	
	Throughput	**% Loss efficiency**	**Throughput**	**% Loss efficiency**
6 Mbps	2.164	**63.93**	5.372	**10.46**
9 Mbps	2.687	**70.14**	7.784	**13.51**
12 Mbps	3.011	**74.91**	10.019	**16.51**
18 Mbps	3.483	**80.65**	14.123	**21.54**
24 Mbps	3.744	**84.40**	17.603	**26.65**
36 Mbps	4.047	**88.76**	23.543	**34.60**
48 Mbps	4.217	**91.21**	28.189	**41.27**
54 Mbps	4.217	**92.19**	30.480	**43.56**

Table 6. Throughput (Mbps) comparison for IEEE 802.11a/g in a single radio link scenario.

On the other hand, the influence of an increasing number of stations is evaluated with the help of the model published by G. Bianchi in [22]. Obviously, an increase in the loss of efficiency can be observed with the rise in the number of contending stations in the scenario, e.g. for IEEE 802.11ac's highest MCS at 160MHz employing A-MPDUs built of 1500 Bytes frames, the penalty increases from 67.89% (single radio link) to 71% and 74% for 20 and 50 stations, respectively. The penalty due to the rise in the number of contending stations is accentuated for larger payload sizes and slower MCS.

IEEE 802.11n		Frame Size (Bytes)							
		100		A-MPDU 100		1500		A-MPDU 1500	
		Thr.	% Loss Effic.	Thr.	% Loss Effic.	Thr.	% Loss Effic.	Thr.	% Loss Effic.
HT Mixed	**20MHz, 1SS 7.2Mbps**	2.164	**69.95**	4.946	**31.31**	6.244	**13.27**	6.729	**6.54**
	20MHz, 1SS 72.2Mbps	3.744	**94.82**	42.892	**40.59**	32.459	**55.04**	67.763	**6.15**
	20MHz, 2SS 144.4Mbps	3.815	**97.36**	72.966	**49.47**	42.002	**70.91**	132.992	**7.90**
	20MHz, 3SS 216.7Mbps	3.744	**98.27**	94.517	**56.38**	45.164	**79.16**	193.719	**10.60**
	20MHz, 4SS 288.9Mbps	3.744	**98.70**	110.895	**61.61**	48.058	**83.37**	251.284	**13.02**
	40MHz, 1SS 150Mps	3.889	**97.41**	75.550	**49.63**	43.212	**71.192**	137.942	**8.04**
	40MHz, 4SS 600Mbps	3.815	**99.36**	153.43	**74.43**	52.242	**91.29**	469.405	**21.77**
Green-field	**20MHz, 1SS 7.2Mbps**	2.338	**67.52**	5.042	**29.97**	6.337	**11.99**	6.870	**4.584**
	20MHz, 1SS 72.2Mbps	4.271	**94.08**	43.892	**39.21**	35.077	**51.42**	68.660	**4.903**
	20MHz, 2SS 144.4Mbps	4.345	**96.99**	75.998	**47.37**	46.207	**68.00**	133.953	**7.23**
	20MHz, 3SS 216.7Mbps	4.244	**98.04**	99.206	**54.22**	50.230	**76.82**	195.705	**9.69**
	20MHz, 4SS 288.9Mbps	4.244	**98.53**	118.163	**59.10**	53.452	**81.50**	254.841	**11.79**
	40MHz, 1SS 150Mps	4.442	**97.04**	78.564	**47.63**	47.600	**68.27**	139.023	**7.32**
	40MHz, 4SS 600Mbps	4.327	**99.27**	166.612	**72.23**	59.142	**90.14**	480.503	**19.92**

Table 7. Throughput (Mbps) comparison for IEEE 802.11n in a single radio link scenario.

IEEE 802.11ac	Frame Size (Bytes)							
	100		A-MPDU 100		1500		A-MPDU 1500	
	Thr.	% Loss Effic.	Thr.	% Loss Effic.	Thr.	% Loss Effic.	Thr.	% Loss Effic.
20MHz, 1SS 7.2Mbps	2.118	**70.58**	4.939	**31.41**	6.219	**13.63**	6.719	**6.68**
20MHz, 1SS 72.2Mbps	3.608	**95.00**	42.606	**40.99**	31.771	**55.60**	67.665	**6.28**
20MHz, 8SS 693.3Mbps	3.423	**99.51**	149.839	**78.39**	48.058	**93.07**	559.074	**19.36**
40MHz, 1SS 150Mbps	3.744	**97.50**	75.106	**49.93**	42.002	**72.00**	140.616	**6.26**
40MHz, 8SS 1600Mbps	3.423	**99.79**	184.372	**88.48**	49.648	**96.90**	1058.289	**33.857**
80MHz, 1SS 325Mbps	3.889	**98.80**	120.272	**62.99**	49.648	**84.72**	292.049	**10.14**
80MHz, 8SS 3466,7Mbps	3.423	**99.90**	201.813	**94.18**	51.348	**98.52**	1663.418	**52.02**
160MHz, 8SS 6933.3Mbps	3.423	**99.95**	211.833	**96.95**	51.348	**99.26**	2221.58	**67.96**

Table 8. Throughput (Mbps) comparison for IEEE 802.11ac in a single radio link scenario.

3. Coexistence of IEEE 802.11 WLAN standards

In this section we show the effect of employing backwards compatibility mechanisms.

Penalties are observed just only for the sake of activating the compatibility mode, no matter if there are any associated stations of older amendments.

3.1 Backwards Compatibility mechanisms

Due to its CSMA-based MAC, IEEE 802.11 stations need to implement a mechanism to detect whether the medium is busy. This mechanism is called Clear Channel Assessment (CCA). In case of DSSS PHY and slow rates (1 and 2Mbps), CCA is implemented according to, at least, one of the following three methods:

- CCA Mode 1: CCA is activated if the energy of the medium is above an energy threshold.
- CCA Mode 2: CCA is activated if a DSSS signal is detected. The signal may be above or below the previous energy threshold.
- CCA Mode 3: CCA is activated if energy is above the energy threshold and a DSSS signal is detected.

The problem that arises when having slow DSSS PHY stations mixed with other devices operating at a different PHY is that the former cannot use CCA Mode 2; the effectiveness of a DSSS station's CCA is significantly reduced not being able to detect OFDM signals and relying solely on CCA Mode 1: IEEE 802.11 energy threshold is usually -80dBm, whereas, employing CCA Mode 2, frames could be detected at a lower energy (the receiver sensitivity is around -96dBm at 1Mbps). In consequence, many IEEE 802.11g/n frames under the energy threshold will go unnoticed for IEEE 802.11b stations and will incur in unexpected collisions, thus leading to a loss of performance. In order to minimize this problem, subsequent IEEE 802.11 specifications have included protection mechanisms to ease coexistence and backwards compatibility between successive standards. However, those compatibility mechanisms are a hindrance to the performance of newest technologies. The next revision of the standard (expected in 2017) will include a new mandatory Mode 6, which will report a busy channel upon detection of any energy above -62dBm. This will prevent collisions with nearby OFDM devices even though Mode 1 is not observed.

3.1.1 IEEE 802.11g

IEEE 802.11g amendment presents three mechanisms to provide backwards compatibility: the support by the IEEE 802.11g of the long PLCP preamble and header defined in IEEE 802.11b amendment (cf. Table 2), the use of Request To Send (RTS) / Clear To Send (CTS) and the use of CTS-to-self, being the former the most commonly used. In this case, IEEE 802.11g's preamble, header and signal extension with a total duration of 26µs is substituted by an IEEE 802.11b PLCP preamble and header with a global duration of 192µs (seven-fold increase!). It provides interoperability with IEEE 802.11b stations because these devices can receive the first part of the frame and be aware that the medium is busy due to an IEEE 802.11 transmission. This mechanism is activated in the Basic Service Set (BSS) for the single reason: to be backwards compatible with IEEE 802.11b. The second one, RTS/CTS, consists in a mechanism originally employed for addressing the hidden node problem. In this case, the transmitter first requests access to the medium by sending an RTS message. Intended receiver responds with a CTS message and afterwards the transmitter is allowed to send frames. Other nodes in the network will refrain from accessing the medium when receiving the above mentioned CTS message. Since RTS/CTS exchange uses the minimum bit rate of 1Mbps, the mechanism will avoid simultaneous IEEE 802.11b and IEEE 802.11g transmissions. However, it also includes an important amount of protocol overhead. Employing the third option, CTS-to-self, the IEEE 802.11g sender transmits a gratuitous CTS frame with identical source and destination address. Other IEEE 802.11b and IEEE 802.11g stations will avoid transmission attempts for the interval included in the *Duration field* of the CTS frame. Obviously, this mechanism also leads to protocol overhead. However, note that the single transmission of a CTS frame does not provide any protection in front of a possible collision of that CTS frame. In that case, the sender would not become aware of the collision and the data frame will follow notwithstanding, which will not be detected by IEEE 802.11b stations. Another important issue in mixed IEEE 802.11b and IEEE 802.11g networks is the choice of backoff parameters. IEEE 802.11b and IEEE 802.11g specifications manage different backoff parameters (minimum number of slots and slot time duration). IEEE 802.11b presents a minimum number of slots (CW_{min}) of 31 with 20µs of duration, whereas IEEE 802.11g employs 15 slots with 9µs. When operating in mixed mode, IEEE 802.11g adopts IEEE 802.11b parameters, thus spending a higher amount of time in collision avoidance. Moreover, the inter-frame space times employed also depend on slot size; thus, when operating in mixed mode, a *DIFS* value of 50µs is used in front of 28µs (cf. Table 2).

Table 9 shows throughput penalty suffered by IEEE 802.11g stations when using backwards compatibility mechanisms. From the table we can observe that these methods cause an important reduction of throughput regardless of the configuration employed. Obviously, this penalty grows with the reduction in payload size and the increase in bit rate. RTS/CTS mechanism presents the worst performance, whereas CTS-to-self provides the lowest penalty, in a single radio link composed of a transmitter and a receiver. However, note that RTS/CTS solves the hidden node problem and also minimizes the time spent in collision resolution in front of other solutions. Figure 5 presents performance for an increasing number of contending stations. The penalty is reduced with the rise in the number of stations. Moreover, RTS/CTS also gains in efficiency with respect to other backwards compatibility mechanisms when the time involved in the transmission of a frame is larger (larger payload size and slower MCS). With this regard, note that for 6Mbps of bit rate, 1500Bytes of payload, and a number of stations higher or equal than 20, RTS/CTS even overcomes original IEEE 802.11g performance[2]. Current IEEE 802.11g implementations employ IEEE 802.11b long PLCP preamble and header to preserve backwards compatibility (option (1) in Table 11).

IEEE 802.11g	Payload size (Bytes)	Thr.	Thr. long preamble and header 802.11b (1)	Thr. RTS/ CTS (2)	Thr. CTS-to-self (3)	% Penalty (1)	% Penalty (2)	% Penalty (3)
6Mbps	**100**	2.164	0.828	0.611	0.845	**61.74**	**71.79**	**61.01**
6Mbps	**1500**	5.372	4.240	3.780	4.267	**21.08**	**29.63**	**20.57**
9Mbps	**100**	2.687	0.895	0.646	0.913	**66.71**	**75.96**	**66.03**
9Mbps	**1500**	7.784	5.612	4.834	5.660	**27.90**	**37.89**	**27.29**
12Mbps	**100**	3.011	0.928	0.663	0.948	**69.18**	**77.98**	**68.53**
12Mbps	**1500**	10.019	6.688	5.612	6.756	**33.25**	**43.99**	**32.57**
18Mbps	**100**	3.483	0.968	0.684	0.990	**72.20**	**80.37**	**71.58**
18Mbps	**1500**	14.123	8.298	6.702	8.402	**41.25**	**52.54**	**40.51**
24Mbps	**100**	3.744	0.987	0.693	1.010	**73.62**	**81.49**	**73.03**
24Mbps	**1500**	17.603	9.388	7.396	9.522	**46.67**	**57.98**	**45.91**
36Mbps	**100**	4.047	1.007	0.703	1.031	**75.11**	**82.63**	**74.53**
36Mbps	**1500**	23.543	10.848	8.274	11.026	**53.92**	**64.86**	**53.17**
48Mbps	**100**	4.217	1.018	0.708	1.041	**75.87**	**83.22**	**75.31**
48Mbps	**1500**	28.189	11.739	8.782	11.949	**58.35**	**68.85**	**57.61**
54Mbps	**100**	4.217	1.018	0.708	1.041	**75.87**	**83.22**	**75.31**
54Mbps	**1500**	30.480	12.119	8.993	12.342	**60.24**	**70.50**	**59.50**

Table 9. Throughput (Mbps) comparison for IEEE 802.11g and backwards compatibility mechanisms in a single radio link scenario.

3.1.2 IEEE 802.11n

IEEE 802.11n amendment also allows high throughput capabilities preserving backwards compatibility with previously defined PHYs (IEEE 802.11, IEEE 802.11b, IEEE 802.11g at 2.4GHz, and IEEE 802.11a at 5GHz). In this way, IEEE 802.11n specification also includes protection mechanisms, and HT IEEE 802.11n transmissions are protected if there are other client stations that are non-HT and thus are not able to decode HT transmissions correctly. Depending on the values contained in HT Operation element (*HT*

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[2] Negative values for penalty in the figure mean an improvement with respect to original IEEE 802.11g performance.

Protection and *Non Greenfield HT STAs Present* fields) of *Beacon* and *Probe Response* frames, several protection frame exchanges are allowed:

- To transmit an initial frame with non-HT or HT Mixed format preamble that requires a response frame (using non-HT preamble). The remaining TXOP following previous exchange contains HT Greenfield format frames.
- RTS/CTS.
- CTS-to-self.
- L-SIG TXOP Protection. This mechanism consists in setting an *L-SIG Duration* value so that it covers a full HT exchange. All frames transmitted inside a protected TXOP employing L-SIG TXOP protection include HT Mixed format preamble with an *L-SIG Duration* that extends to the endpoint indicated by the MAC *Duration/ID* field.

Moreover, as exposed in Section 2.2, IEEE 802.11n presents three preamble types; the HT Mixed Format is mandatory and should be used whenever there are non-HT users.

Tables 10 and 11 show a comparison of RTS/CTS and CTS-to-self protection mechanisms, and the usage of HT Mixed format preamble or L-SIG TXOP[3], for different IEEE 802.11n configurations (channel bandwidth of 20MHz and 40MHz, different number of spatial streams and payload sizes), in a single radio link scenario composed of a transmitter and a receiver. From Table 10 we can observe the penalty suffered by IEEE 802.11n due to coexistence issues with IEEE 802.11g PHY at 2.4GHz and with IEEE 802.11a PHY at 5GHz[4]. Table 11 presents penalty with regard to backwards compatibility mechanisms with IEEE 802.11b PHY at 2.4GHz[5]. Results reveal important decrease in performance when coexistence methods with IEEE 802.11b PHY are allowed, in comparison to values obtained when compatibility with IEEE 802.11a/g PHY is enabled. HT Mixed format preamble is not used with IEEE 802.11b non-HT preamble, thus, in presence of IEEE 802.11b stations, protection mechanisms rely on the usage of RTS/CTS or CTS-to-self methods. Moreover, when operating in compatibility mode, IEEE 802.11n adopts IEEE 802.11b PHY parameters (larger contention window values, slot time and inter-frame space times, cf. Table 2). All mechanisms provide important protocol overhead, even for large payload sizes (non A-MPDU). Moreover, the shorter the payload size and the higher the PHY data rate employed, the larger is the penalty. Finally, note that the employment of frame aggregation leads to important

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[3] L-SIG TXOP is used instead of HT Mixed mode when frame aggregation is being employed.

[4] RTS and CTS frames are transmitted at 6Mbps, i.e. IEEE 802.11g and IEEE 802.11a minimum basic rate.

[5] RTS and CTS frames are transmitted at IEEE 802.11b minimum basic rate of 1Mbps.

performance efficiency and thus to an important decrease in throughput penalty. When the number of contending stations increases (Figures 6 and 7), RTS/CTS mechanism presents better performance (less penalty) than other solutions for larger payload sizes and slower MCS, even when IEEE 802.11b PHY parameters are adopted for backwards compatibility reasons. Again, this benefit[6] becomes more evident with the employment of frame aggregation mechanism (Figure 7), so it is recommendable to use it whenever possible.

IEEE 802.11n	Payload size (Bytes)	Thr. +	Thr. HT Mixed / L-SIG TXOP [2] (1)	Thr. RTS/CTS (2)	Thr. CTS-to-self (3)	% Penalty (1)	% Penalty (2)	% Penalty (3)
20MHz, 1SS 7.2Mbps	**100**	2.338	2.164	1.730	2.009	7.47	26.00	14.09
	A-MPDU 100	5.042	4.946	4.976	5.011	1.92	1.31	0.62
	1500	6.337	6.244	5.959	6.154	1.46	5.97	2.88
	A-MPDU 1500	6.870	6.729	6.777	6.826	2.05	1.36	0.64
20MHz, 1SS 72.2Mbps	**100**	4.271	3.744	2.602	3.014	12.35	39.09	29.45
	A-MPDU 100	43.892	42.892	39.792	41.878	2.28	9.34	4.59
	1500	35.077	32.459	25.957	30.136	7.47	26.00	14.09
	A-MPDU 1500	68.660	67.763	67.554	68.139	1.31	1.61	0.76
20MHz, 2SS 144.4Mbps	**100**	4.345	3.815	2.629	3.331	12.21	39.50	23.36
	A-MPDU 100	75.998	72.966	64.492	70.156	3.99	15.14	7.69
	1500	46.207	42.002	31.587	37.999	9.10	31.64	17.76
	A-MPDU 1500	133.953	132.992	129.807	131.986	0.72	3.10	1.47
20MHz, 3SS 216.7Mbps	**100**	4.244	3.744	2.592	3.271	11.79	38.94	22.94
	A-MPDU 100	99.206	94.517	80.465	89.479	4.73	18.89	9.80
	1500	50.230	45.164	33.417	40.678	10.09	33.47	19.02
	A-MPDU 1500	195.705	193.719	186.978	191.533	1.01	4.46	2.13
20MHz, 4SS 288.9Mbps	**100**	4.244	3.744	2.592	3.271	11.79	38.94	22.94
	A-MPDU 100	118.163	110.895	92.502	104.618	6.15	21.72	11.46
	1500	53.452	48.058	34.813	42.766	10.09	34.87	19.99
	A-MPDU 1500	254.841	251.284	240.240	247.812	1.40	5.73	2.76
40MHz, 1SS 150Mps	**100**	4.442	3.889	2.664	3.387	12.45	40.03	23.75
	A-MPDU 100	78.564	75.550	66.330	72.337	3.84	15.57	7.93
	1500	47.600	43.212	32.232	38.936	9.21	32.29	18.20
	A-MPDU 1500	139.023	137.942	134.561	136.904	0.78	3.21	1.52
40MHz, 4SS 600Mbps	**100**	4.327	3.815	2.622	3.320	11.83	39.40	23.28
	A-MPDU 100	166.612	153.43	119.766	140.892	7.91	28.12	15.44
	1500	59.142	52.242	37.140	46.332	11.67	37.20	21.66
	A-MPDU 1500	480.503	469.405	431.101	456.109	2.31	10.28	5.08

+ HT Greenfield preamble and header is used

Table 10. Throughput (Mbps) comparison for IEEE 802.11n and backwards compatibility mechanisms with IEEE 802.11g PHY for 2.4GHz and IEEE 802.11a for 5GHz in a single radio link scenario.

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[6] Again, the negative values for penalty in the figures reveal the improvement with respect to original IEEE 802.11n.

IEEE 802.11n	Payload size (Bytes)	Thr. +	Thr. RTS/CTS (1)	Thr. CTS-to-self (2)	% Penalty (1)	% Penalty (2)
20MHz, 1SS 7.2Mbps	**100**	2.338	0.624	0.869	**73.33**	**62.84**
	A-MPDU 100	5.042	4.567	4.739	**9.42**	**6.01**
	1500	6.337	4.234	4.854	**33.19**	**23.40**
	A-MPDU 1500	6.870	6.202	6.443	**9.72**	**6.21**
20MHz, 1SS 72.2Mbps	**100**	4.271	0.709	1.045	**83.40**	**75.55**
	A-MPDU 100	43.892	24.298	29.339	**44.64**	**33.16**
	1500	35.077	9.355	12.784	**73.33**	**63.56**
	A-MPDU 1500	68.660	60.861	63.644	**11.36**	**7.31**
20MHz, 2SS 144.4Mbps	**100**	4.345	0.711	1.049	**83.63**	**75.86**
	A-MPDU 100	75.998	31.715	40.885	**58.27**	**46.20**
	1500	46.207	9.997	14.315	**78.36**	**69.02**
	A-MPDU 1500	133.953	107.16	116.100	**20.00**	**13.33**
20MHz, 3SS 216.7Mbps	**100**	4.244	0.708	1.043	**83.31**	**75.43**
	A-MPDU 100	99.206	35.146	46.771	**64.57**	**52.85**
	1500	50.230	10.173	14.679	**79.75**	**70.78**
	A-MPDU 1500	195.705	143.345	159.802	**26.75**	**18.35**
20MHz, 4SS 288.9Mbps	**100**	4.244	0.708	1.043	**83.31**	**75.43**
	A-MPDU 100	118.163	37.263	50.598	**68.46**	**57.18**
	1500	53.452	10.299	14.942	**80.73**	**72.05**
	A-MPDU 1500	254.841	172.697	197.160	**32.23**	**22.63**
40MHz, 1SS 150Mps	**100**	4.442	0.714	1.054	**83.93**	**79.26**
	A-MPDU 100	78.564	32.153	41.616	**59.07**	**47.03**
	1500	47.600	10.060	14.446	**78.86**	**69.65**
	A-MPDU 1500	139.023	110.381	119.889	**20.60**	**13.76**
40MHz, 4SS 600Mbps	**100**	4.327	0.711	1.048	**83.57**	**75.78**
	A-MPDU 100	166.612	41.026	57.794	**75.38**	**65.31**
	1500	59.142	10.493	15.355	**82.26**	**74.04**
	A-MPDU 1500	480.503	253.317	309.677	**47.28**	**35.55**

+ HT Greenfield preamble and header is used

Table 11. Throughput (Mbps) comparison for IEEE 802.11n and backwards compatibility mechanisms with IEEE 802.11b PHY in a single radio link scenario.

In fact, this is the default behaviour of many commercial products, as we observed in a small experiment: an AP configured to operate in mixed mode serves three laptops. One of them uses an old IEEE 802.11b NIC, another an IEEE 802.11b/g, and the third has an IEEE 802.11n-compatible card. A TCP flow is then created in the AP towards the IEEE 802.11n station. Figure 10 shows the evolution of the TCP, averaged over 3-second windows. During the whole experiment, the AP uses A-MPDU aggregation and RTS/CTS protection. We disassociate the 11b and 11g stations at 20 and 40s. Even though the effect of compatibility is minimized by the use of aggregation (1 to 16Mbps without aggregation, as shown in Figure 8), Figure 10 still shows a noticeable improvement as legacy 11b/g stations are removed.

3.1.3 IEEE 802.11ac

IEEE 802.11ac amendment allows very high throughput capabilities also preserving backwards compatibility with IEEE 802.11a and IEEE 802.11n (at 5GHz). As shown in Section 2.2, IEEE 802.11ac provides different transmissions modes, but only one of them is specific of VHT (the other ones were defined for IEEE 802.11n). In addition, VHT format is mandatory and allows direct compatibility with previous specifications at 5GHz band. Thus, in this case, the use of other mechanisms such as RTS/CTS and CTS-to-self are not necessary for coexistence and, in consequence, no penalty is applied.

3.2 Coexistence in real life and good practices

A survey we conducted recently in Barcelona[7] led us to conclude that the aforementioned protection mechanisms for backwards compatibility are painfully recurrent. According to our survey, 65% of HT BSSs operate either in Mode 1 (non-member protection mode) or Mode 3 (non-HT mixed mode). Moreover, although only 0.08% of the APs detected support IEEE 802.11b exclusively, near 95% keep backwards compatibility by supporting IEEE 802.11b rates. During our monitoring, only 1% of the APs had been in contact with a legacy IEEE 802.11b station (*Non_ERP_STA_present* flag set in *Beacon* frames); however, the presence of an IEEE 802.11b station produces a harmful chain reaction in dense environments since neighboring BSSs also activate their protection mechanisms. In consequence, that 1% of APs serving IEEE 802.11b stations caused that almost 10% of the APs require protection against IEEE 802.11b.

As shown in the previous section, fast stations supporting latest IEEE 802.11 amendments incur in severe penalties just by running those protection mechanisms in response to the presence of a legacy device. If the fast stations have to actually share the channel with those legacy stations, the penalty due to the performance anomaly is further exacerbated. To avoid the resulting performance degradation, administrators of enterprise-level deployments use to ban oldest stations by configuring the basic rate set appropriately. For example, if an AP requests mandatory support of, at least, IEEE 802 11g rates (in our survey, only 3% of the APs), old IEEE 802.11b stations will be banned from that BSS; if that BSS is expected to give service to IEEE 802.11b stations, the slowest rates (i.e. 1 and 2Mbps) could be excluded from the supported rate set. Alternatively, the use of IEEE 802.11e's TXOP or IEEE 802.11n's aggregation, reduce the harmful effect of slow stations. As an example, Figures 8 and 9[8] show: a) the throughput obtained by an HT-capable station using the highest MCS with (64-QAM 5/6) with 4, 2 and 1 spatial streams (288.8, 144.4 and 72.2Mbps, respectively) and sharing the channel with a legacy station at 1Mbps and an IEEE 802.11g station at 54Mbps; and b) the throughput obtained by a VHT station using the highest MCS (256-QAM 3/4) with 8, 2 and 1 spatial streams (693.3, 173.3 and 86.7Mbps,

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[7] ~12,000 APs were detected in different measurement campaigns in urban, commercial and residential areas in both the 2.4 and 5GHz bands throughout the city of Barcelona and surrounding areas at different hours. A laptop equipped with an IEEE 802.11n USB dual-band (Alfa Network UBDo-a) card and an external omnidirectional antenna (Air Live WAE-5AG) were employed in order to capture management frames (Beacon, Probe Request and Response). A later analysis of the captured frames led to the results exposed.

[8] Results in Figures 8 and 9 have been obtained following the methodology described in [23].

respectively) sharing the channel with an IEEE 802.11a station at 6 and 54Mbps. In all cases, the bandwidth is 20MHz, and the legacy station is in saturation transmitting 1500Bytes frames. Without aggregation, HT and VHT features go unnoticed since the resulting throughput ranges from less than 1Mbps to near 20Mbps, depending on the rate of the legacy station.

4. Conclusions

This paper presents a thorough analysis of the current state of IEEE 802.11 specification, comparing subsequent amendments in terms of coverage range and throughput performance, and focusing on the drawbacks and benefits of including protection mechanisms to allow backwards compatibility. The shorter ranges for faster modulations and the larger ranges for slowest MCS are shown, taking into consideration receiver sensitivity values reported by near a dozen datasheets from different vendors and manufacturers. IEEE 802.11n HT Greenfield mode presents better performance in comparison with IEEE 802.11 Mixed mode, whereas, in IEEE 802.11ac VHT mode, some configurations are penalized in front of IEEE 802.11n for the same nominal bit rate. Under ideal transmission conditions, these differences are only due to the variations in the length of PLCP preamble/header among transmission modes. Obviously, frame aggregation of IEEE 802.11n/ac shows a notable rise in performance. However, with regard to IEEE 802.11ac, important penalties are still observed for high transmission rates and increased number of streams. On the other hand, the employment of mechanisms that allow backwards compatibility with IEEE 802.11b leads to important penalties in throughput performance for newer specifications, regardless of the protection mechanism employed. For the case of IEEE 802.11n, the usage of frame aggregation is the way to reduce high penalties, so it is recommendable to use it whenever possible. The employment of RTS/CTS as protection mechanism offers important benefits for an increasing number of involved contending stations, even overcoming original IEEE 802.11g/n performance, when the time involved in the transmission of a frame is larger. The survey that we conducted in Barcelona shows that, although the presence of IEEE 802.11b is minimal, it produces a harmful chain reaction in dense environments, forcing a considerable number of APs to activate their protection mechanisms. IEEE 802.11ac operates on the 5GHz band, thus avoiding backwards compatibility issues with IEEE 802.11b. Mandatory VHT mode allows direct compatibility with previous specifications at 5GHz band and hence, no penalty is incurred. Forthcoming IEEE 802.11ax specification is also expected to be backward compatible with IEEE 802.11 legacy devices, and TGax is contemplating the design of new types of preambles with this regard. We plan to study the mechanisms when available at the TGax as part of our future work.

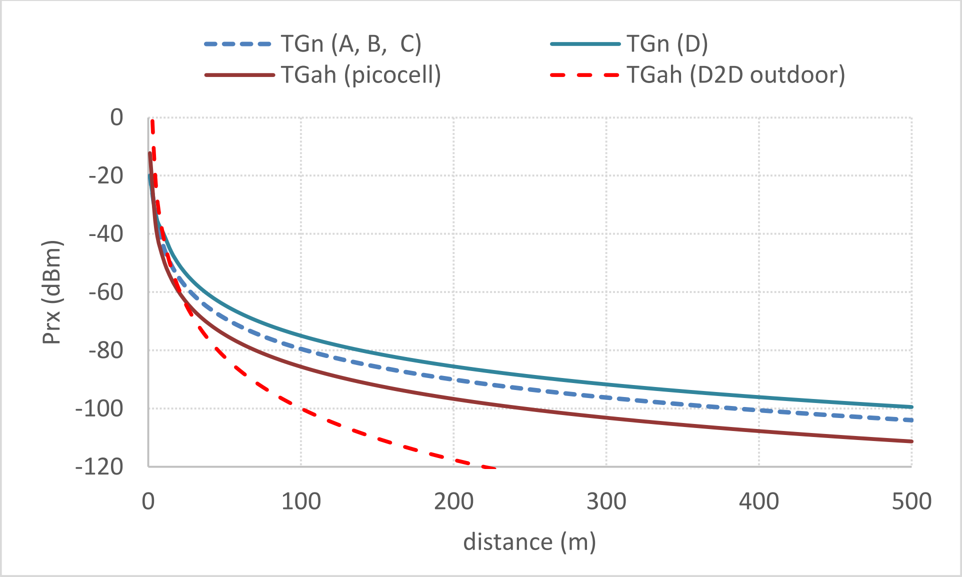

Figure 1. Decay of the received power (dBm) with distance (m) in different propagation environments.

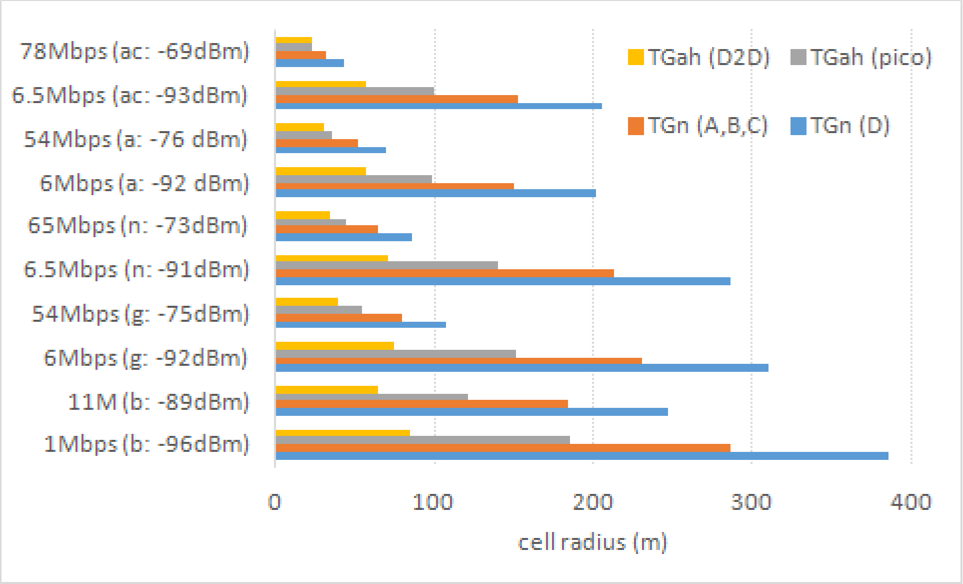

Figure 2. Expected maximum and minimum cell radius (m) for different technologies in different propagation environments.

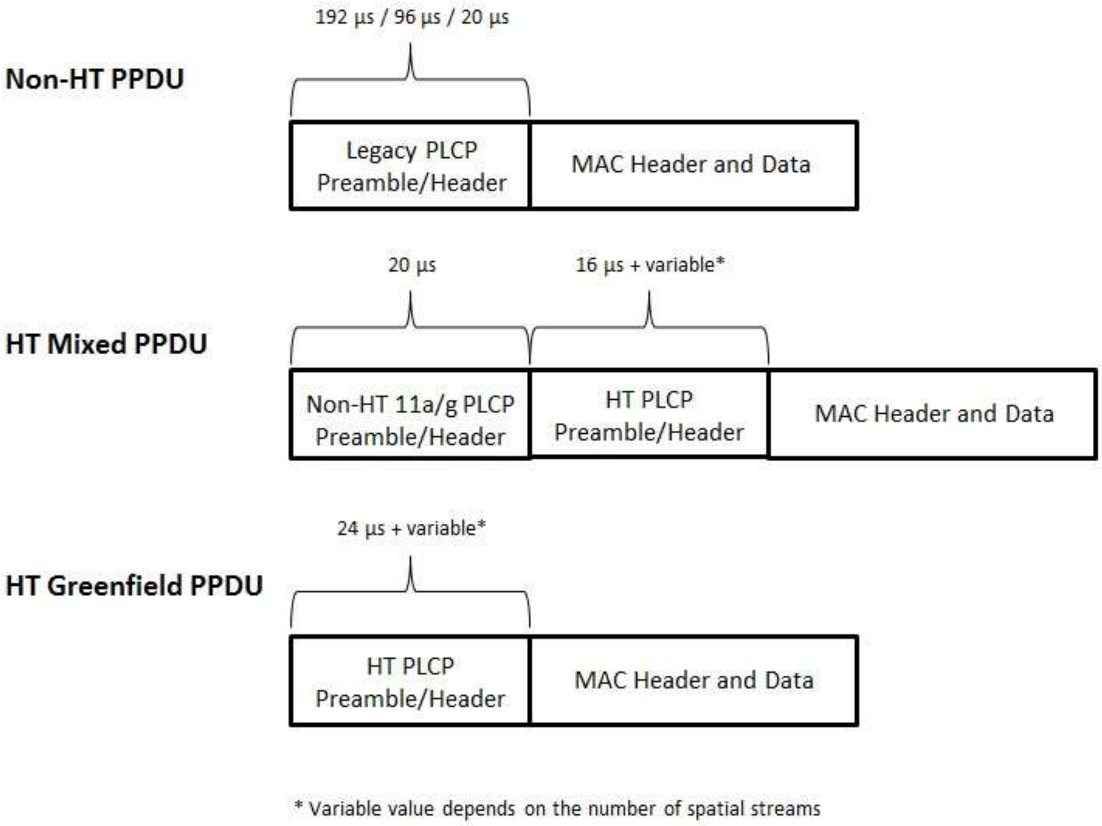

Figure 3. IEEE 802.11n PPDU formats.

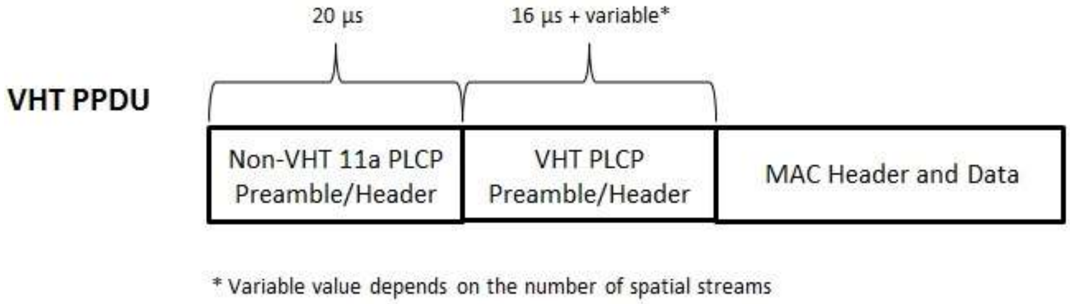

Figure 4. IEEE 802.11ac VHT PPDU format.

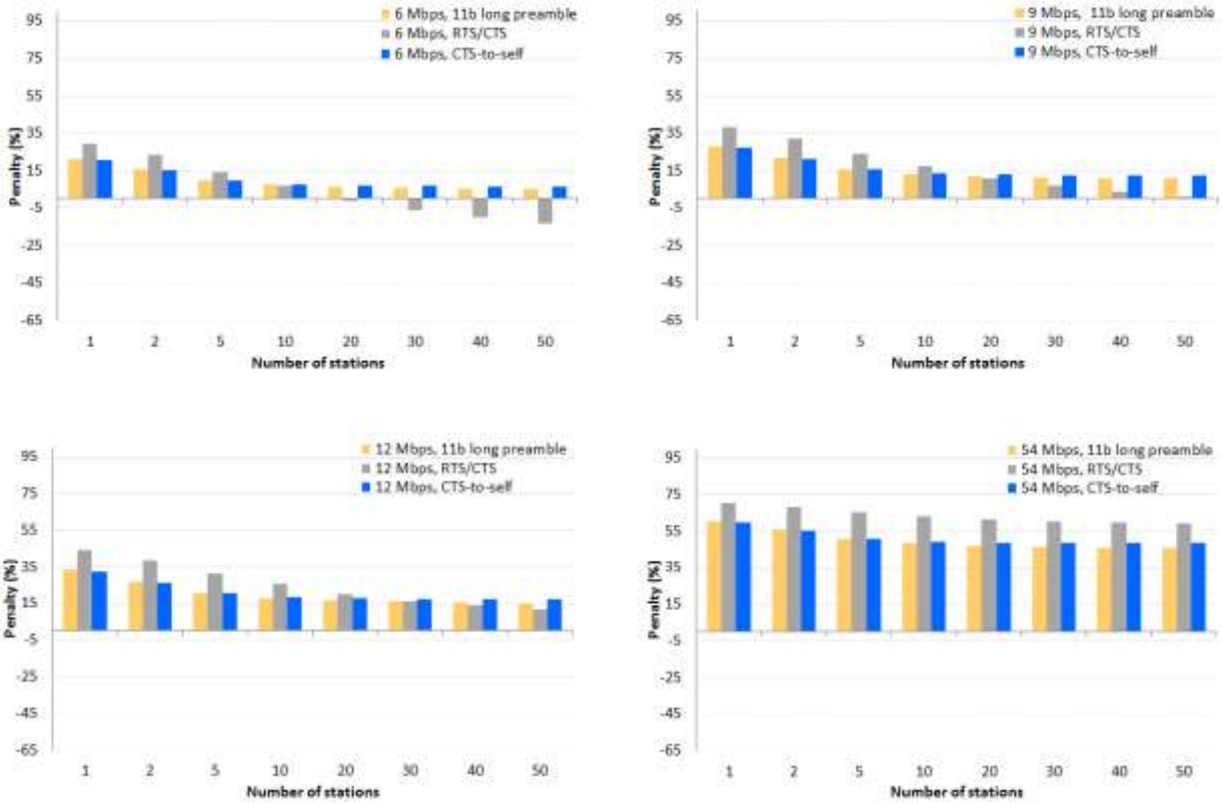

Figure 5. Penalty (%) for IEEE 802.11g backwards compatibility mechanisms, payload size of 1500Bytes and an increasing number of stations.

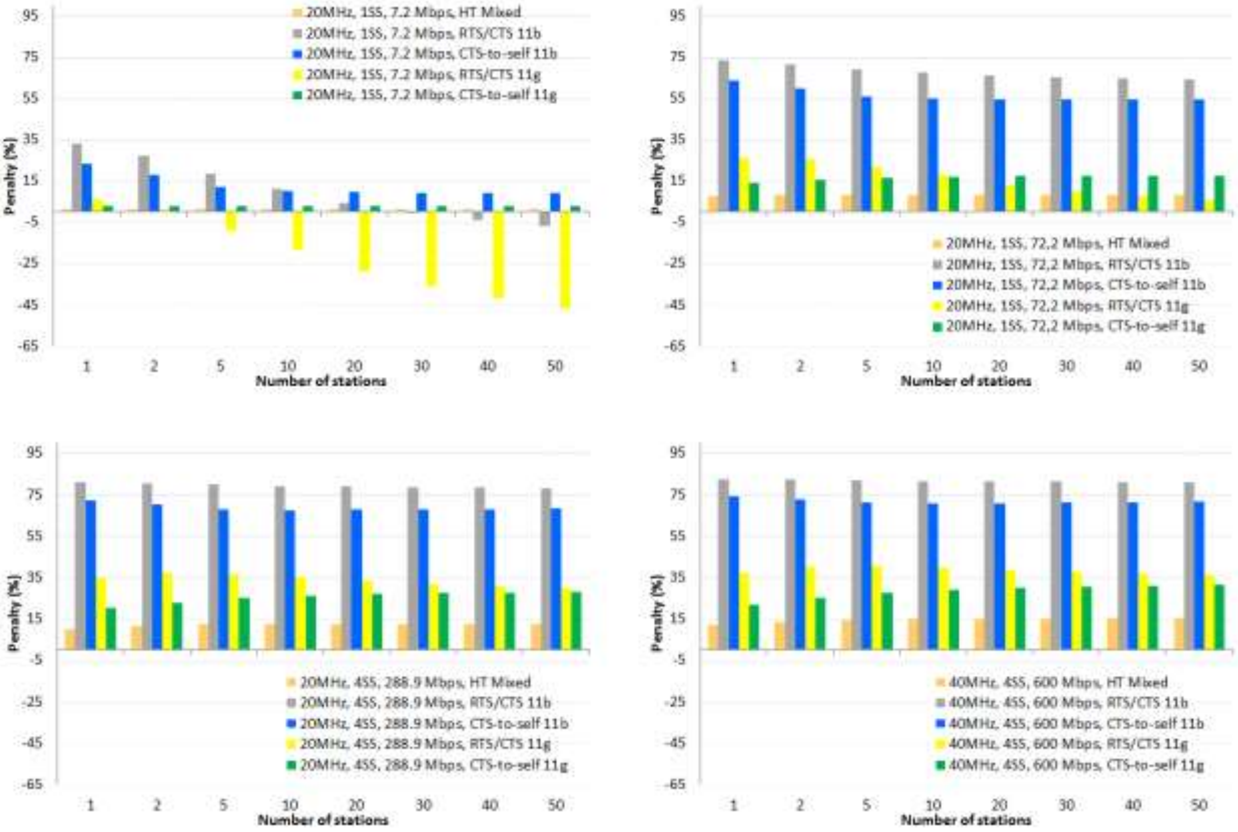

Figure 6. Penalty of efficiency (%) for IEEE 802.11n backwards compatibility mechanisms, payload size of 1500Bytes and an increasing number of stations.

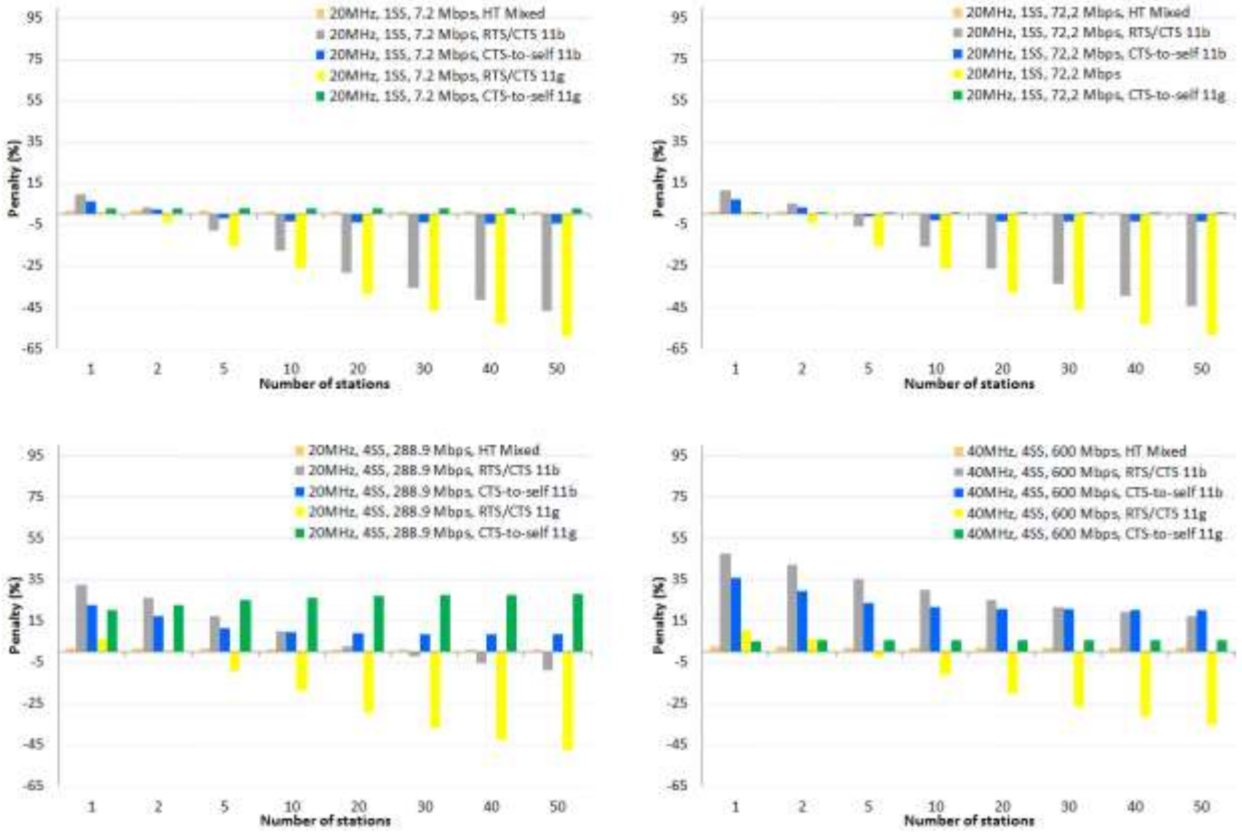

Figure 7. Penalty (%) for IEEE 802.11n backwards compatibility mechanisms, employing A-MPDUs built of 1500 Bytes frames and an increasing number of stations.

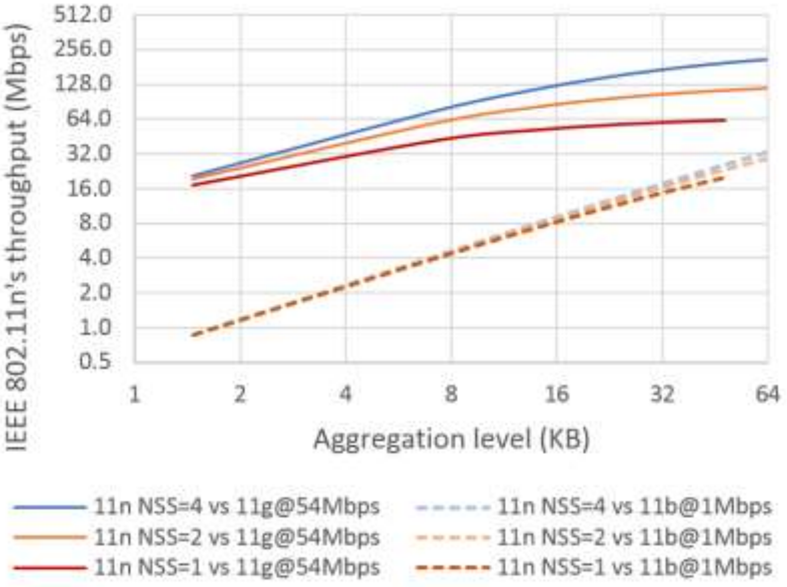

Figure 8. Throughput of an IEEE 802.11n station in competition with one legacy device.

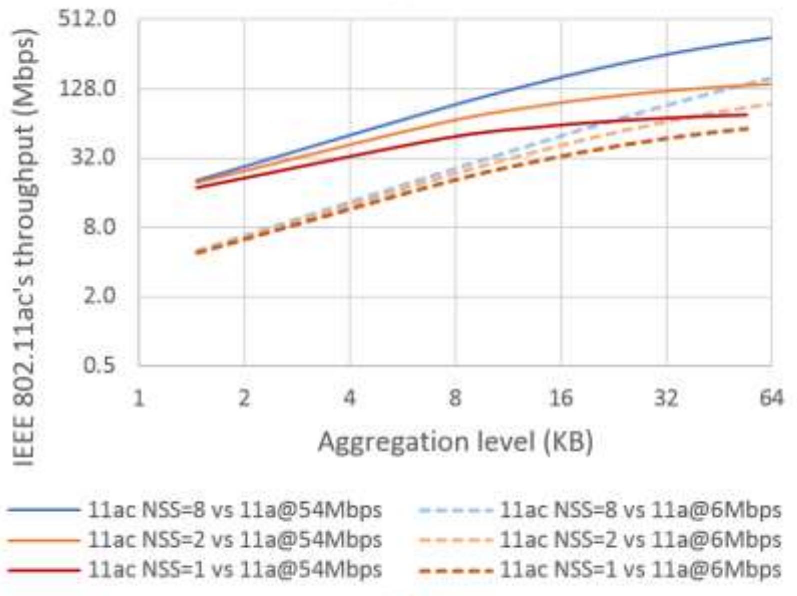

Figure 9. Throughput of an IEEE 802.11ac station in competition with one legacy device.

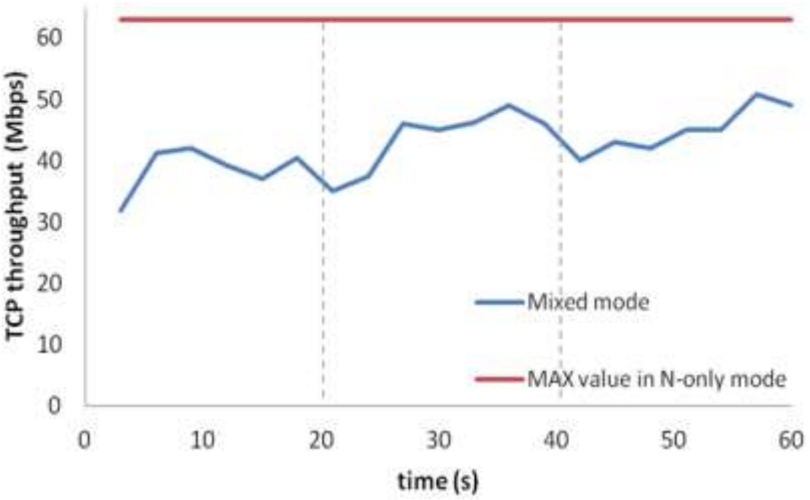

Figure 10. Throughput evolution vs. time for an AP configured to operate in mixed mode that serves three devices: an IEEE 802.11b, an IEEE 802.11b/g and an IEEE 802.11n-compatible device.

5. References

[1] IEEE, “IEEE Std 802.11–2012. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Revision of IEEE Std 802.11-2007”, March 2012

[2] Aruba Networks, “802.11ac In-Depth”, 2012.

http://www.arubanetworks.com/pdf/technology/whitepapers/WP_80211acInDepth.pdf

[3] Analyst finds 802.11ac Wi-Fi access point penetration nearly doubling every quarter

http://www.cablinginstall.com/articles/2014/09/infonetics-ac-ap-doubling.html

[4] M. Heusse, F. Rousseau, G. Berger-Sabbatel, A. Duda, “Performance anomaly of 802.11b”, in Proc. of IEEE INFOCOM 2003, March 2003.

[5] M. Vucinic, B. Tourancheau, A. Duda, “Simulation of a backward compatible IEEE 802.11g network: Access delay and throughput performance degradation”, in Proc. of IEEE MECO 2012, June 2012.

[6] P. Mahasukhon, M. Hempel, C. Song, H- Sharif, “Comparison of throughput performance for the IEEE 802.11a and 802.11g Networks”, in Proc. of IEEE AINA 2007, May 2007.

[7] T. Selvam, S. Srikanth, “Performance study of IEEE 802.11n WLANs”, in Proc. of IEEE COMSNETS 2009, January 2009.

[8] R.P. Fabris Hoefel, A. Michielin Camara, “Interoperability between IEEE 802.11n and IEEE 802.11a/g devices: Analytical and simulation results”, in Proc. of IEEE CCECE 2011, May 2011

[9] E. H. Ong, J. Kneckt, O. Alanen, Z. Chang, T. Huovinen, T. Nihtila, “IEEE 802.11ac: Enhancements for very high throughput WLANs”, in Proc. of IEEE PIMRC 2011, September 2011.

[10] M.-D. Dianu, J. Riihijarvi, M. Petrova, “Measurement-based study of the performance of IEEE 802.11ac in an indoor environment”, in Proc. of IEEE ICC 2014, June 2014.

[11] O. Bejarano, E.W. Knightly, P. Minyoung, “IEEE 802.11ac: from channelization to multi-user MIMO”, IEEE Communications Magazine, Vol. 51, No. 10, pp.84-90, October 2013.

[12] A.P. Theeksha, S. Srikanth, “Performance analysis and mode selection of IEEE SU-MIMO and MU-MIMO in 802.11ac”, in Proc. of ICRTIT 2013, July 2013.

[13] Y. Zeng, P.H. Pathak, P. Mohapatra, “A first look at 802.11ac in action: Energy efficiency and interference characterization”, in Proc. of IEEE IFIP Networking Conference 2014, June 2014.

[14] S. Han, X. Zhang, K. Shin, “Fair and Efficient Coexistence of Heterogeneous Channel Widths in Next-Generation Wireless LANs”, IEEE Transactions on Mobile Computing, January 2016.

[15] IEEE P802.11, “TGn Channel Models”, doc.: IEEE 802.11-03/940r4, 2004.

[16] IEEE P802.11, “TGah Channel Models”, doc.: IEEE 802.11-11/0968r4, 2015

[17] AirMagnet 802.11a/b/g/n Wireless PC Card (C1060) Datasheet, 2010 http://airmagnet.flukenetworks.com/assets/AirMagnet_802.11abgn_WirelessPCcard_TechSpec.pdf

[18] Cisco Aironet 1830 Series Access Points, 2016 http://www.cisco.com/c/en/us/products/collateral/wireless/aironet-1830-series-access-points/datasheet-c78-735582.pdf

[19] D. Plets, W. Joseph, K. Vanhecke, E. Tanghe, and L. Martens, “Simple indoor path loss prediction algorithm and validation in living lab setting”, Wireless Personal Communications, Vol. 68, No 3, pp. 535-552, February 2013.

[20] A. Amini, D. Lu, C. Edelman, “Effects of high peak-to-average ratio on 5GHz WLAN power amplifier”, in Proc of DesignCon 2002.

[21] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, K. Almeroth, “A practical framework for 802.11 MIMO rate adaptation”, Elsevier Computer Networks, Vol. 83, No. C, pp. 332-348, June 2015.

[22] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function”, IEEE Journal on Selected Areas in Communications, Vol. 18, No. 3, pp. 535-547, March 2000.

[23] E. Garcia-Villegas, D. Viamonte, R. Vidal, J. Paradells, “Achievable bandwidth estimation for stations in multi-rate IEEE 802.11 WLAN cells”, in Proc. of IEEE WoWMoM 2007, June 2007.