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A Performance Analysis of IEEE 802.11ax Networks

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***Abstract*—The paper is focused on the forthcoming IEEE 802.11ax standard and its influence on Wi-Fi networks performance. The most important features dedicated to improve transmission effectiveness are presented. Furthermore, the simulation results of a new transmission modes are described. The comparison with the legacy IEEE 802.11n/ac standards shows that even partial implementation of a new standard should bring significant throughput improvements.**

***Keywords*—802.11ax, dense networks, performance analysis**

I. INTRODUCTION

THE IEEE 802.11ax [1] is another extension of the IEEE 802.11 standard aimed at significantly increasing the throughput achieved in local wireless computer networks, especially in the environment of the dense networks. The significance of the introduced changes is emphasized by the designation of the IEEE 802.11ax network according to the new nomenclature as Wi-Fi generation 6 (where IEEE 802.11ac is generation 5, IEEE 802.11n - generation 4, etc.). Greater efficiency is achieved thanks to the introduction of new modulations and coding techniques, and the use of Orthogonal Frequency Division Multiple Access (OFDMA), as well as Uplink Multi User (UL-MU) allowing simultaneous transmission of multiple stations to one access point (AP). In addition, mechanisms to control the transmission power level and sensitivity of Clear Channel Assessment (CCA), as well as the so-called network coloring are introduced to allow greater spatial density of simultaneous transmissions on the same frequency channels. It should be noted that the standardization process has not yet been completed and the final shape of some of the postulated changes is not yet known.

This paper presents the results of simulations in which the performance of newly introduced modulations was compared to those known from the IEEE 802.11n/ac network. Similar studies were undertaken in work [2] of another author, and this article focuses on separate scenarios. In addition, the presented research is based on the newer version of the IEEE 802.11ax draft as well as the newer version of the ns-3 simulator. In paper [3], the authors focused on the results from the use of multiuser transmission. In article [4], in addition to a thorough discussion of the new standard, there are analyzes of the impact of bandwidth allocation in multiuser mode on the overall throughput and potential profits resulting from the receiver's Dynamic Sensitivity Control (DSC). There are also many research papers that investigate some other aspects of IEEE 802.11ax networks, e.g. QoS or performance evaluation [5], [6], [7], [8], [9], [10].

The paper is organized as follows. Chapter 2 of this paper describes the physical layer improvements introduced by the IEEE 802.11ax extension, while Chapter 3 discusses the most important improvements associated with the MAC layer. Chapter 4 contains a description of the simulations carried out and discusses the results obtained. Chapter 5 summarizes this work.

II. PHYSICAL LAYER IN IEEE 802.11AX STANDARD

In order to increase spectral efficiency and support simultaneous up/down (uplink/downlink, UL/DL) transmission in the IEEE 802.11ax extension, the use of new modulations is foreseen and transmission parameters changed in Orthogonal Frequency Division Multiplexing (OFDM) technology. The new physical layer has been designated High Efficiency (HE).

A. Modulation and coding

The IEEE 802.11ax standard uses 6 types of modulation. The novelty introduced by the standard is the extension of the list of modulations known from the IEEE 802.11ac standard by 1024 Quadrature Amplitude Modulation QAM) modulation. Of course, the use of such high order modulation is only possible in the case of very good channel quality, which is limited to transmission only over short distances. For this modulation the standard provides correction codes with efficiency 3/4 or 5/6. The appearance of new modulation therefore results in expanding the list of available modulation and coding schemes (MCS) from 9 to 11.

It should be noted that the 4-fold reduction of the interval between subcarriers modulated by OFDM technique introduced in the IEEE 802.11ax standard is associated with a 4-fold increase in the duration of transmitted symbols (from 3.2 µs to 12.8 µs). The standard provides three possible Guard Intervals (GI) protection periods for transmitted symbols: 0.8 µs, 1.6 µs and 3.2 µs, which results in the same or lower transmission overhead as in the case of the IEEE 802.11ac network. This overhead is 20% for GI = 3.2 µs, 11% for GI = 1.6 µs and 6% for GI = 0.8 µs, while for IEEE 802.11ac it was 20% for GI = 0.8 µs and 11% for GI = 0.4 µs. On the other hand, a longer protection period minimizes the impact of inter-symbol interference that may be the result of multipath signal transmission.

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B. *Subcarriers, available channels and rates*

Beginning with the IEEE 802.11a standard (1999) [12], Wi-Fi networks use OFDM transmission. In existing extensions of the standard, the spacing between subcarriers should be 312.5 kHz, which results in the use of 64 subcarriers for a 20 MHz channel. The new standard is still based on OFDM technique, however, the subcarrier intervals are shortened to 78.125 kHz, resulting in a number of subcarriers of 256, of which 234 can be used for data transmission, and the remaining ones serve as pilot or protective signals - they are not used for any transmission however they are helpful in limitation of inter-channel interferences (Fig. 1). The effect of such transmission organization is a significant improvement in the spectral efficiency of the new standard.

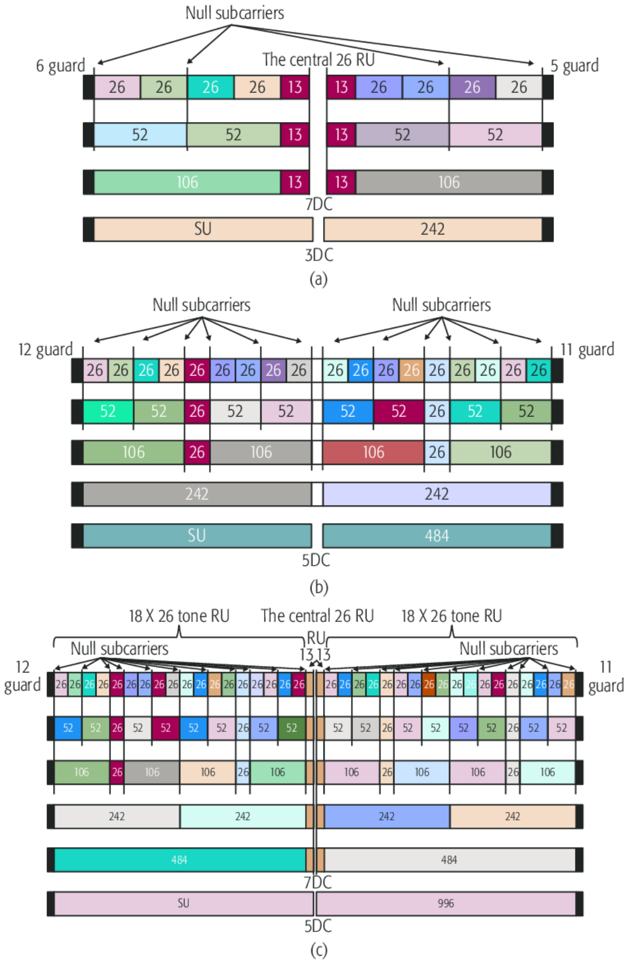

Fig.1. Scheme of subcarriers in the IEEE 802.11ax standard: a) Resource Unit (RU) locations in a 20 MHz HE PPDU; b) RU locations in a 40 MHz HE PPDU; c) RU locations in a 80 MHz HE PPDU [6]

Similarly to the IEEE 802.11ac standard, the possible channel widths are: 20 MHz, 40 MHz, 80 MHz or 160 MHz (also possible as two separate 80 MHz channel bonding mode). The issue of transmission of many data streams using the Multiple Input Multiple Output (MIMO) technique remains also not changed - a maximum of 8 (4 to one station) can be used. The use of a channel with maximum width using highest MCS (11), lowest GI (0.8 µs) and 8 parallel MIMO streams gives the theoretical maximum transmission data rate of the new standard of 9.6 Gbps. Comparing with the maximal theoretical transmission data rate of WiFi of previous generation (IEEE 802.11ac) which is 6,9 Gbps, this is almost 40% improvement.

There is also a new possibility of allocation of Resource Unit (RU) within the channel resources, i.e. a set of subcarriers for a selected transmission. In this way, simultaneous, collision-free transmission of several stations within a selected channel becomes possible. The allocation of RU is managed by AP. Not all RU sizes are acceptable - Fig. 1 shows a scheme for dividing the 20 MHz channel into RU. In addition, Table 1 provides information on how many RUs of a given type can be isolated on wider radio channels.

TABLE I
MAXIMUM NUMBER OF RUS FOR EACH CHANNEL WIDTH

RU type	*20 MHz*	*40 MHz*	*80 MHz*	*160 MHz / 80 MHz + 80 MHz*
26-tone	9	18	37	74
52-tone	4	8	16	32
106-tone	2	4	8	16
242-tone	1	2	4	8
484-tone	N/A	1	2	4
996-tone	N/A	N/A	1	2
2x996-tone	N/A	N/A	N/A	1

C. *Frame formats*

The new standard defines 4 types of PHY Protocol Data Unit (PPDU) physical layer frames: Single User (SU) PPDU for transmission between two stations, Extended Range (ER) SU PPDU for transmission between two stations over long distances, Multi User (MU) PPDU for downstream transmission to many users using MU-MIMO or MU-OFDMA, and Trigger Based (TB) PPDU for upstream transmission of many users. While SU PPDU frames are equivalent of data frames from earlier extensions of the standard, ER PPDU frames are intended only for transmission using the slowest modes (MCS) without MIMO technology, with the preamble extended to maximize the reliability of the transmission. The use of MU PPDU and TB PPDU frames will be discussed in the next chapter.

As in earlier IEEE 802.11n/ac standards, to maintain backward compatibility with IEEE 802.11a/g standards networks, the frame begins with a preamble divided into two parts, the first of which has a format compatible with these legacy standards. This allows older devices to correctly detect the new frames of IEEE 802.11ax equipment and reserve the time needed to not disturb such transmissions. The rest of the preamble contains the control information necessary for the new standard. In addition to information related to the transmission mode (MCS, channel width, number of spatial streams), it also contains information typical of the MAC layer (BSS network identifier - Basic Service Set, so-called network color, transmission direction or remaining TXOP time). Such a procedure is aimed at increasing the reliability of network operation, even at the expense of extended transmission time caused by the fact that preamble is transmitted using low but reliable MCS. For MU PPDU transmissions, the preamble provides information on the subcarrier allocation for individual transmissions. At the end of the preamble, there are also training sequences necessary for MIMO transmission.

III. MAC LAYER IN IEEE 802.11AX STANDARD

Improvements introduced by the IEEE 802.11ax standard allow simultaneous transmission of multiple stations to an access point (UL-MU) and introduce a new mode of downlink simultaneous transmission to many devices based on OFDMA. In addition, network coloring and dual virtual carrier tracking (NAV) mechanisms allow in some cases to solve the problem of exposed stations and thus increase the spatial use of the radio channel. Finally, improvements have been made to reduce energy consumption to extend the life of battery-powered devices.

A. *Multi-user transmission*

The possibility of simultaneous data transmission by AP to many clients was introduced in the IEEE 802.11ac extension. It was based on the MIMO technique (the so-called Multi User MIMO, MU-MIMO) – thanks to beamforming and division of spatial streams, recipients could receive in the same time different signals. In practice, this technique has found limited use, because it requires adequate spatial separation of receivers, which in the case of dense networks may be difficult condition to meet. Therefore, the IEEE 80211ax standard proposes another method of such transmission scheme, based on OFDMA multiple access. The AP may decide on the allocation of available OFDM subcarriers for individual recipients. In this case, the MU PPDU frame will be transmitted and the stations will be notified of RU assignment by the preamble. Further, frames for stations are transmitted simultaneously in dedicated RUs, starting from the preamble for each recipient. This allows for customization of the transmission mode for each receiver.

The standard also introduces the possibility of simultaneous transmission of multiple users to the AP (Fig. 2). It is triggered by the access point using the trigger frame (TF).

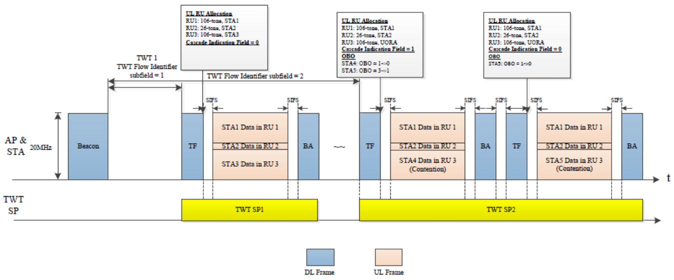

Fig.2. UL MU-MIMO example transmissions [11]

It contains, similarly to MU PPDU frame, a description of the subcarrier allocation for individual stations. Designated receivers transmit in their assigned bands. It is also possible to allocate part of the band for free access as part of the Uplink OFDMA Random Access (UORA) function. In order to minimize the risk of collision, stations that use such RU will have to precede the transmission by waiting for a random number of slots, checking that no one has started transmission in the mentioned RU. The procedure resembles the classic backoff mechanism. The resource allocation is made by AP based on the demand previously reported by the stations. Confirmation of the received data by the AP is done using a special block confirmation frame (BA). In addition, the TF frame can be transmitted as part of the MU PPDU frame, which allows, for example, for simultaneous confirmation of received data by multiple stations.

B. *Other improvements*

The technique called network coloring involves the introduction of additional randomly generated network identifiers in the preamble of the physical layer, which gives the receiver a possibility to quickly recognize where a given transmission comes from without need of reception and decoding of the entire frame. If the transmission is associated with another network operating in the same area, i.e. Overlapping BSS (OBSS), the receiver may e.g. stop further receiving in order to save energy (called microsleep mode).

Increased spatial efficiency of the IEEE 802.11ax network is mainly seen in the use of dynamic transmission power control and the sensitivity of the carrier detection mechanism Clear Channel Assistance (CCA). Optimal power usage for transmission allows for reduction of the radio channel blocking range and limits the interference introduced to other networks operating nearby. What is more, it reduces energy consumption. The DSC function through dynamic selection of the CCA threshold will in turn allow to ignore some transmissions and treat them as noise, thus solving in some cases the problem of exposed stations. However, the details of these mechanisms have not yet been definitively established.

Another improvement is the introduction of the dual virtual carrier tracking (NAV) mechanism. Current version of this mechanism after detecting the transmission, prevent the station from channel access for a fixed period of time based on information from the header of the received frame, so that the detected transmission procedure could proceed undisturbed. IEEE 802.11ax devices will have a double NAV mechanism - one dedicated to BSS in which the device works and the other one responsible for all OBSS networks. This gives a possibility to ignore control frames from other networks to prevent the pending NAV counter reset. This may happen in legacy stations.

IV. SIMULATION ANALYSIS OF IEEE 802.11AX

This chapter presents selected results of performance tests of the new standard obtained using the ns-3.30 simulator (in development version) [13], in which the IEEE 802.11ax standard is partially implemented. As the simulation tool used does not currently allow to examine all features related to IEEE 802.11ax standard, the presented research focuses on checking the performance of new MCS modes in various research scenarios. Therefore, the presented studies do not include multiuser transmissions.

The first three scenarios involved data transmission between the AP and the station located 1 m away and focus on the impact of MCS, channel width and GI parameters on transmission efficiency. The fourth scenario examines the transmission range, while the fifth one analyzes the impact of the number of stations on network performance. The last scenario compares the network performance in typical small network scenario. The most important simulation parameters common to all scenarios are summarized in Table 2. The throughput is defined as the rate of successful message delivery over a wireless channel measured at the network layer.

TABLE II
THE VALUES OF PARAMETERS ASSUMED IN SIMULATIONS

Parameter	*Value*
Transport layer protocol	UDP
Traffic type	CBR
Offered load	1 Gbps (saturation)
Packet size	1472 B
EDCA class	BE
RTS/CTS	Disabled
Fragmentation	Disabled
Mobility	-
Rx Noise Figure	7 [dB]
Tx Power	5 [dBm]
CCA Threshold	-82 [dBm]
Energy Detection Threshold	-88 [dBm]
Propagation model	LogNormal

A. *Analysis of throughput versus the MCS selected*

This scenario compares the throughput achieved by single station using IEEE 802.11ax network in the 2.4 GHz and 5 GHz frequency band with the IEEE 802.11ac network operating in the 5 GHz band and IEEE 802.11n operating in the 2.4 GHz band. The channel width was 20 MHz for 2.4GHz band and 40 MHz for 5GHz frequency band. The throughput of all available MCSs were compared using GI = 800 ns (Fig. 3). Under these assumptions, the IEEE 802.11ax network turns out to be more efficient than IEEE 802.11n/ac for each selected MCS, which indicates that a 4-fold increase in the number of modulated OFDM subcarriers improves performance even despite a 4-fold increase in symbol duration. This is the result of reduced proportional GI overhead. In the 2.4 GHz band, the throughput was higher by approx. 32% compared to the IEEE 802.11n network for each MCS, while in the 5 GHz band the improvement was 25–27%. Thanks to the use of a higher order modulation (1024-QAM for MCS = 10 and 11) than in existing networks, IEEE 802.11ax in optimal conditions allows to provide more than twice the throughput in the 2.4 GHz band and about 50% higher throughput in 5 GHz band. It should be noted, however, that when the IEEE 802.11ac network uses a lower value of GI = 400 ns, the achieved throughput may be slightly higher than those in the IEEE 802.11ax network [2].

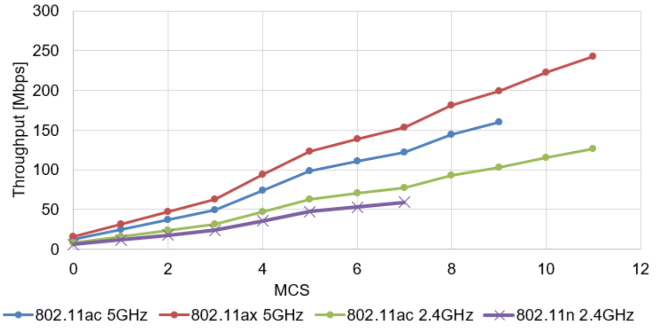

Fig. 3. Throughput of IEEE 802.11 network versus the MCS selected

B. *Analysis of channel width and Guard Interval*

Similar to the IEEE 802.11n network in the 2.4 GHz band, the IEEE 802.11ax standard can operate using a 40 MHz channel width instead of the standard 20 MHz channel. In the 5 GHz frequency band, the permissible widths are the same as those provided for IEEE 802.11ac networks, i.e. 20 MHz, 40 MHz, 80 MHz and 160 MHz (also as two separable 80 MHz channels bonded together). The extension of the IEEE 802.11ax channel results in an increase in transmission throughput - similarly to previous standards. The simulations (Fig. 4) show that the network throughput using a 40 MHz channel width is about 2 times higher than the basic channel width. The 80 MHz channel provides more than a 4-fold increase in performance for the lowest MCS and about 3.6 times higher bandwidth for the highest MCS, while the 160 MHz channel gives a 8.5-fold increase in bandwidth for the lowest MCS and 6-fold when highest order modulation is being used. Similar observations can be made by analyzing the bandwidths for other GI values (Fig. 5 and Fig. 6).

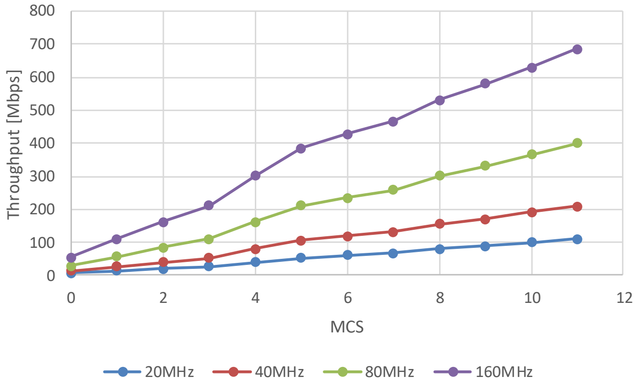

Fig.4. Throughput of IEEE 802.11ax network versus the MCS selected for different channel widths and GI=3200 ns

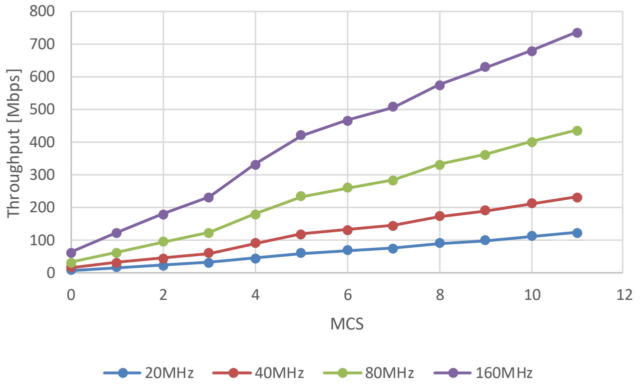

Fig.5. Throughput of IEEE 802.11ax network versus the MCS selected for different channel widths and GI=1600 ns

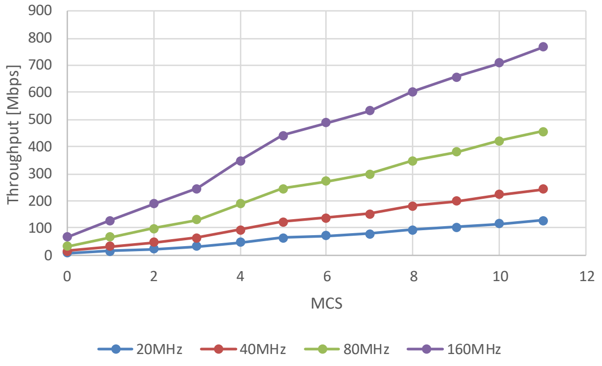

Fig.6. Throughput of IEEE 802.11ax network versus the MCS selected for different channel widths and GI=800 ns

Fig. 7 presents the throughput obtained for different MCSs used for transmission in 20 MHz channel. Usually, the use of the shorter GI guard period improves network throughput by approximately 11% for GI = 1600 ns and about 18% for GI = 800 ns. However, this gain is not constant as some portion of transmission overhead (e.g. preamble and inter-frame periods) remains unaffected by GI reduction. Thus the obtained throughput gain is slightly reduced by increasing of MCS or channel width. The lowest gains can be observed with MCS = 11 being used on 160 MHz-wide channel. The throughput is increased by approximately 8% for GI = 1600 ns and about 12% for GI = 800 ns. This trend can be observed in Fig. 8 and Fig. 9 which show throughput gains obtained during simulation. As the results observed for both – 20 MHz and 40 MHz channels operating in 2.4 GHz band – are almost identical to 5 GHz band case (Fig. 7 - 9), they are not presented separately.

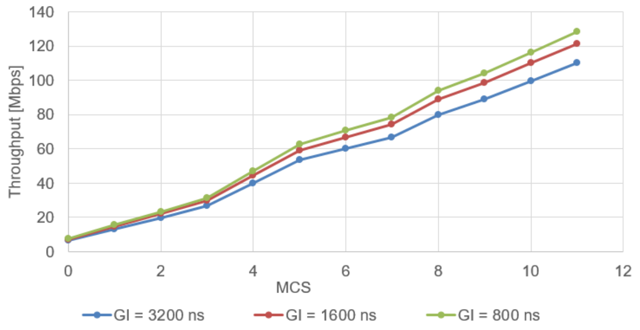

Fig.7. Throughput of IEEE 802.11ax network versus the MCS selected for different GIs and 20 MHz channel

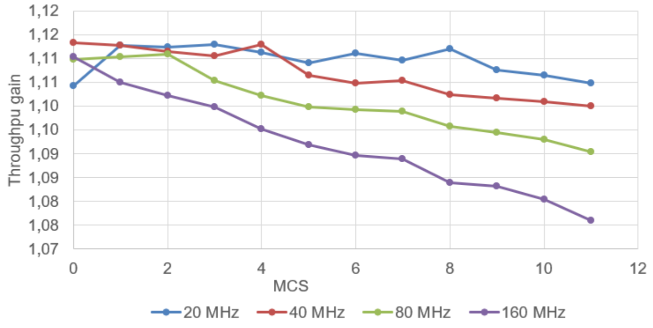

Fig.8. Throughput gain of GI = 1600 ns (comparing with GI = 3200 ns) according to MCS and channel width being used.

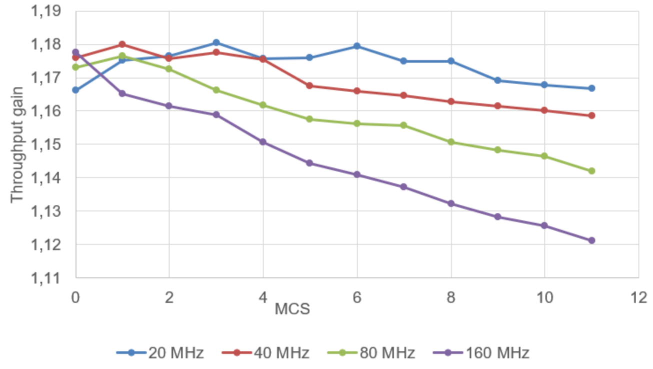

Fig.9. Throughput gain of GI = 800 ns (comparing with GI = 3200 ns) according to MCS and channel width being used.

C. *Analysis of transmission range*

The transmission range was examined by increasing the distance between the AP and the station using the lowest MCS and the largest GI value for three channel widths: 20 MHz, 40 MHz and 80 MHz. The results are presented in Fig. 10. Losses resulting from the deterioration of the signal quality occur above 50 m in the case of networks operating in the 80 MHz channel, above 70 m when the 40 MHz channel is being used and above 90 m for the basic width channel operation. This means that with a 4-fold channel extension, the effective network coverage has decreased almost 2-fold. It should be noted that the simulations took into account only the decrease in signal strength with distance, hence it was impossible to observe the impact of other negative phenomena occurring in the channel such as multi-path fades. Thanks to introduction of new special ER PPDU IEEE 802.11ax frames, the transmission reliability should be strengthen in the event of such phenomena.

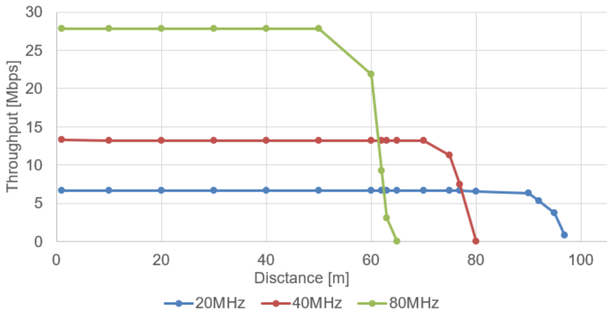

Fig.10. Throughput of IEEE 802.11ax network versus the distance for different channel widths

D. *Analysis of number of stations on network efficiency*

In this research scenario, the impact of the number of transmitting stations in the network on its overall efficiency in the IEEE 802.11ax and IEEE 802.11ac networks was analyzed. Due to the lack of implementation of the MU transmission mode, only SU PPDU frames were used. In addition, due to the computational cost of the study, it was limited to a 20 MHz channel and the number of 40 stations was not exceeded. The results are presented in Fig. 11. They clearly show that the use of new modulations significantly improves network performance, however collisions occurring with the increase in the number of transmitting devices continue to degrade the overall transmission throughput. The use of MU PPDU and TB PPDU transmission should significantly improve the network efficiency.

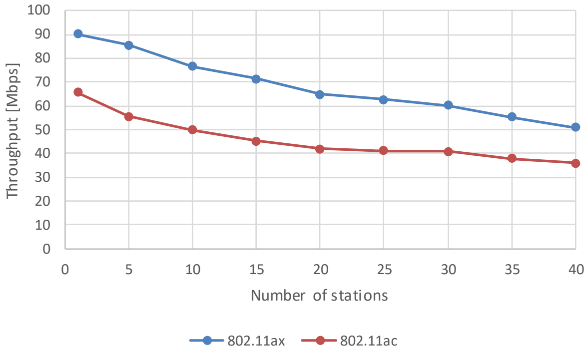

Fig.11. Throughput of IEEE 802.11ax and IEEE 802.11ac networks versus number of stations for 20 MHz channel width, maximum MCS and GI=800 ns

E. Efficiency in small flat network scenario

In the last studied scenario, the small network consisting of 5 single-antenna devices located in small flat (5x5x3 m) divided into two rooms is considered. 4 devices transmit uplink traffic using the highest possible MCS to one central node. The 40 MHz bandwidth is considered for 2.4 GHz band devices while for 5 GHz band ones the 80 MHz channels are used. The total throughput reached according to cumulative offered load and network type is presented in Fig. 12. The results confirm observations, that upgrade of 2.4 GHz band IEEE 802.11n network to IEEE 802.11ax standard is highly beneficial. In studied scenario it improves per station throughput from 25,75 Mb/s to about 44,7 Mb/s, which means that throughput was increased of 73,5% when 40 MHz bandwidth is in use. However, IEEE 802.11ax network operating on 2.4 GHz is still outperformed by IEEE 802.11ac devices operating on 5 GHz band with 80 MHz-wide channel transmission. The per station throughput reached in this case is 70 Mb/s for IEEE 802.11ac while IEEE 802.11ax gives 80 Mb/s, which is only about 14% higher result. If we consider cumulative throughput of two-band network in such scenario, then the total performance changes from 383 Mb/s for IEEE 802.11n/ac network to 498,7 Mb/s for IEEE 802.11ax case – this means 30% of total throughput gain. However, as the MU uplink transmission was not studied, the real performance improvement of such deployment obtained by full IEEE 802.11ax implementation should be much higher.

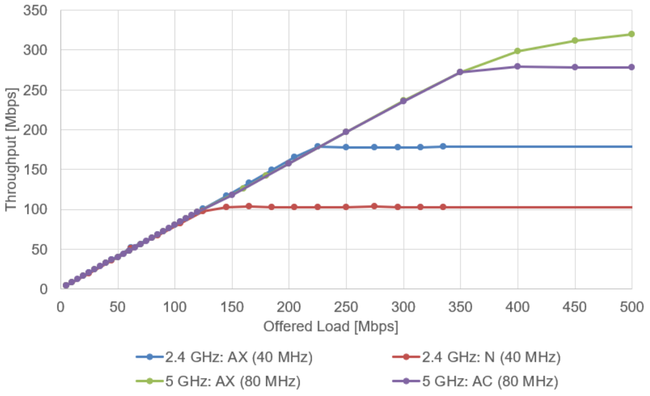

Fig.12. Throughput of small network (5 stations, 4 transmissions) deployed in small flat according to offered load and type of IEEE 802.11 standard being used.

V. CONCLUSION

The introduction of the IEEE 802.11ax standard will be a very important step in the development of wireless local area networks. Numerous improvements are introduced to meet the requirements of users, i.e. support a significant number of stations deployed in a small area, provide a higher throughput than before, and extending the battery operation time thanks to energy efficiency. This article attempts to discuss the functions of the IEEE 802.11ax standard and presents several simulation scenarios. The obtained results clearly show that even a partial implementation of the standard, i.e. the introduction of only new modulations and improvements of OFDM technique should result in a significant increase in performance. Even double improvement of the transmission throughput of the 2.4 GHz band networks compared to the IEEE 802.11n standard can be expected. On the other hand, in the 5 GHz band case the performance improvement is not so pronounced (up to about 25%). However, it should be remembered that the full implementation of the standard should increase up to 4 times the total network efficiency.

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