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An Optimization of Network Performance in IEEE 802.11ax Dense Networks

Marek Natkaniec, and Mateusz Kras

***Abstract*—The paper focuses on the optimization of IEEE 802.11ax dense networks. The results were obtained with the use of the NS-3 simulator. Various network topologies were analyzed and compared. The advantage of using MSDU and MPDU aggregations in a dense network environment was shown. The process of improving the network performance for changes in the transmitter power value, CCA Threshold, and antenna gain was presented. The positive influence of BSS coloring mechanism on overal network efficiency was revealed. The influence of receiver sensitivity on network performance was determined.**

***Keywords*—dense networks; IEEE 802.11ax; network optimization; BSS coloring**

I. Introduction

THE IEEE 802.11 standards family focuses on the PHY (Physical) layer and MAC (Medium Access Control) layer specifications for WLANs (Wireless Local Area Networks) [1]. More than 20 years have passed since the publication of the first IEEE 802.11 standard. During this time, the standardization committee developed many extensions to improve the overall functioning of the network.

The IEEE 802.11ax standard, also known as the sixth generation Wi-Fi network, is a response to the growing user's expectations regarding high transmission rates, low latency services, the growing number of devices and wireless dense networks in such environments as stadiums, shopping malls and residential buildings [2]. This new extension offers a throughput of up to 9.6 Gbps, which gives about 37% increase compared to the IEEE 802.11ac standard, reduction of transmission delay and jitter as well as greater reliability of the wireless network. Again, great emphasis was placed on more efficient use of the available frequency bands and reducing the negative impact of interference. Compared to the IEEE 802.11ac extension, the physical layer has been modified by adding, among many others, the OFDMA (Orthogonal Frequency Division Multiple Access) technique and 1024-QAM modulation. The MAC layer has also been updated by introducing second NAV (Network Allocation Vector) and trigger frame supporting UL MU-MIMO mode operation. Moreover, new mechanisms related to energy management and supporting dense environments have been introduced [3].

The work consists of six chapters. Chapter 2 provides an overview of the literature. Chapter 3 discusses the concept of dense networks. The spatial reuse solutions introduced in IEEE 802.11ax are explained in Chapter 4. Chapter 5 contains the simulation results obtained for three different scenarios. The last chapter summarizes this work.

II. Background

In recent years, there have been many papers devoted to the performance analysis of the IEEE 802.11ax extension. Due to limitations in the implementation of new standard mechanisms in network devices, a significant part of the publication work was based on simulations or analytical models.

In the article [4], the authors presented the simulation analysis of IEEE 802.11ax with the use of the NS-3 simulator. All possible MCS (Modulation Coding Scheme) values were analysed for saturation conditions and compared with IEEE 802.11n and IEEE 802.11ac standard extensions. For each MCS value, the throughput was 32% higher compared to IEEE 802.11n (2.4 GHz band), and 25-27% higher compared to 802.11ac (5 GHz band). The authors concludes that using 1024-QAM modulation the IEEE 802.11ax network can double the throughput in the 2.4 GHz band and obtain nearly 50% higher throughput in the 5 GHz band. Similar research was conducted in [5]. The results show a 37% increase in throughput compared to the IEEE 802.11ac standard assuming 20 MHz channel width and a guard interval of 800 ns. Additionally, the author presented the results obtained from the simulations in relation to the calculated theoretical maximum throughput defined as throughput efficiency. This indicator fluctuates around 80%. The similar results presented in both mentioned papers allow the conclusion that reliable results were obtained and the expected profit from the newly introduced modulation is in the range of 25-35%. In both studies, the performance analysis was carried out for single networks with only one access point and one station. The comparison of the IEEE 802.11ax standard with its predecessor was also presented in [6]. The simulation analysis was carried out for three environments: low-density (2 and 4 clients), medium-density (8, 16 and 32 clients) and very dense (64, 128, 256 and 512 clients). The network operated in the 5 GHz band with the widest available channel - 160 MHz and a guard interval

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M. Natkaniec is with Faculty of Computer Science, Electronics and Telecommunications, Institute of Telecommunications, AGH University of Science and Technology, Poland (e-mails: natkanie@agh.edu.pl, matikrass@wp.pl).

Mateusz Kras is with AGH University of Science and Technology, Poland (e-mail: matikrass@wp.pl).

of 800ns. In each analysed scenario, the IEEE 802.11ax extension was found to be more efficient. The average increase in throughput was about 9%. When analyzing the results presented in the article, it should be noted that the simulations lasted only 2 seconds. Such a short simulation time and lack of warm-up time may be a source of errors in the presented results. In the case of dense networks, the above-mentioned gain is possible to achieve only if the neighboring networks are properly separated - it is related to the minimization of interference.

The performance results for all available channel widths are also presented in [4]. The results show a double gain of efficiency measured as throughput for the 40 MHz channel compared to the basic 20 MHz channel. The 80 MHz channels turned out to be about 4 times more efficient. The widest available channel - 160 MHz, for low MCS values, showed an 8.5-fold increase in throughput and about a 6-fold increase with 1024-QAM modulation. By carrying out simulations for the lowest-order modulation, the maximum network coverage was determined. The network performance deterioration was observed at a distance greater than 50 m and the 80 MHz channel. In the 40 MHz and 20 MHz channels, significant packet losses were noticed at distances of 70 and 90 meters, respectively. These results were obtained using a 3200ns guard interval. The analysis of network range versus the channel width is shown in [5]. The author examined the achieved throughput for two distances. It has been shown that the maximum throughput using the 160 MHz channel and MCS 9 is achievable within a radius of only 3-4 meters. Surprisingly, the older 802.11ac extension achieves greater throughput than 802.11ax at certain distances. This is possible with shorter guard period of 400ns which is not compatible with the 802.11ax standard. The analysis of the literature shows that the maximum network efficiency can be achieved only in the close proximity of the station to the access point.

The impact of the guard interval length on the achieved network throughput has also been investigated. The work [4] presents the results of simulations for all types of modulation and three lengths of the guard interval: 800 ns, 1600 ns and 3200 ns. The use of shorter guard interval allowed for an increase of throughput. The gain from using the guard interval of 1600 ns was about 11%, while for 800 ns the gain was 18%. However, the increase in throughput is not constant and depends, among other parameters, on the modulation used and the channel width. The smallest gain was achieved for the 160 MHz channel and MCS 11. The obtained results are similar for devices operating in the 2.4 GHz and 5 GHz bands.

Mechanisms increasing the spatial reuse of the radio channel were analyzed in [7] and [8]. A dedicated simulator for testing the performance of dense networks was designed. The researchers carried out BSS coloring analysis for many scenarios, taking into account different network densities. Three open areas with dimensions of 25x25, 50x50 and 100x100 meters were examined, in which 10 access points and 10 stations were placed. In the centrally located AP, BSS coloring was used to compare the achieved throughput with the other parts of the network. In the most dense environment, a 450 percent increase in throughput was achieved by using network coloring mechanism. Significantly lower latency and channel occupancy were also achieved. In the second cited article, the impact of changing the CCA Threshold (Clear Channel Assessment Threshold) parameter on the throughput obtained in the network was examined. The analysis was carried out only for two networks with maximum of 15 working devices. Changing the value from -82 dBm to -50 dBm increased throughput by approximately 79% with 15 devices in the network, while for 2 devices in the network, the increase was 44%. By increasing the CCA Threshold, average latency and jitter decreased by about 60-70%. The work analyzed the results achieved both in the downlink and in the uplink transmissions, achieving similar results. Unfortunately, in both studies, all the simulations lasted for less than 20 seconds, which from our own experience makes the results somewhat unreliable. The analysis of the literature shows that the mechanisms that have been implemented in the IEEE 802.11ax standard significantly improve network performance. However, scenarios with a very large number of networks and nodes located in buildings still remain to be explored.

An extensive simulations of OFDMA (Orthogonal Frequency-Division Multiplexing) technique were performed using the Matlab software. The obtained throughput results were compared with the OFDM (Orthogonal Frequency-Division Multiplexing) [9]. For a configuration with one access point working as the sender, the throughput doubled with 9 stations connected to the network. In the second scenario, where both access points and stations worked as transmitters, a more than 5-fold increase in throughput was obtained. The more devices working in the network, the greater the profit from the use of OFDMA. In [10], the authors presented the results of performance analysis for OFDMA using their own extension to the NS-3 simulator. The use of OFDMA significantly increased the efficiency of dense networks with several or even several dozen of active devices. Irrespective of the number of devices operating in the network, the highest throughput was obtained when the number of RU (Resource Units) allocated to random access was equal to 0. The delivery rate of BSR (Buffer Status Report) frames on the number of stations and the number of allocated resource units was also presented. The maximum value of BSR delivery rate was observed for the highest number of allocated RUs. The number of allocated RUs also affects network latency. If the number of RUs allocated is too low, the station may be blocked because it will not be able to send a BSR frame. The paper shows trade-off between the obtained throughput and the ability of the network to support new devices.

The authors in [11] tested the impact of MPDU (MAC Protocol Data Unit) aggregation and frame size on the throughput obtained in a network consisting of one access point and several dozen of stations. The greater the number of aggregated frames, the greater the throughput obtained in the network. Increasing the number of aggregated frames from 10 to 60 allowed for a 7-fold increase in throughput for a 20 MHz channel. Reducing the size of frames from 2000 bytes to 500 bytes resulted in a 10-fold decrease in throughput for the basic channel, while for a 160 MHz channel the throughput decreased by 300 percent. Sending very small frames highly limits the achieved values of throughput. The efficiency of the dynamic sensitivity control algorithm for access points was presented in [12] and [13]. The analysis was carried out in a very dense environment: 100 apartments, each with an access point and five connected devices. The authors modified the existing libraries of the NS-3 simulator. The use of the DSC (Dynamic Sensitivity Control) algorithm resulted in an increase in the FER (Frame Error Rate) by about 28% and the hidden stations existence by 15%. Despite the increase in these negative metrics, overall network performance increased by 7%.

To the best of our knowledge, the results presented in this work are the first that take into account the influence of all four crucial PHY parameters like CCA Threshold, transmitter power, antenna gain, and receiver sensitivity as well as aggregation at the MAC layer on the efficiency of IEEE 802.11ax dense networks in office and residential area scenarios. Moreover, it presents the gain which can be obtained with the use of BSS coloring mechanism.

III. DENSE NETWORKS

The development of technology, the increase in mobility and the popularity of the IoT (Internet of Things) has resulted in a significant increase in the number of devices connected to the Internet. In addition to the increase in the number of devices, the number of wireless networks is also constantly increasing. It is predicted that in 2022, Wi-Fi networks will handle more than half of all Internet traffic [14].

To handle the increasing number of users, networks consisting of a large number of access points are designed. A dense network can be defined as any environment with a high concentration of users connected wirelessly and using network services. The concept of dense networks in WLANs can be represented as a large number of access points with a small range to offer the largest possible capacity. High density can be observed in city centers, shopping malls, stadiums and office and residential buildings. Areas densely built up with multi-storey residential buildings turn out to be particularly problematic. Currently, almost every apartment has a Wi-Fi access point. These devices usually work with the manufacturer's default settings, because the vast majority of users do not have sufficient knowledge and awareness about the configuration of individual 802.11ax standard parameters.

Due to the large number of devices coexisting in a given area, several negative effects can be observed that have a significant impact on network performance. It is worth to mention such phenomena as the hidden and/or exposed station scenarios as well as deadlock effect or the signal amplification effect due to interference. Unfortunately, the initial reservation of the radio channel with RTS (Request To Send)/CTS (Clear To Send) frames, usually used in the case of hidden station scenario, does not always solve the described problems [15]. In dense networks, the improved configuration of devices is of particular importance for the achieved throughput from the point of view of the entire analysed area. One misconfigured network node can disrupt transmissions in all neighboring areas, because all the devices usually compete for the same radio channel. When planning dense networks, it is extremely important to find the right balance between the values of such parameters as transmitter power, antenna gain, CCA Threshold and the use of directional antennas.

In the next chapter, an attempt was made to optimize the selected settings of network devices. It will be shown that proper configuration of access points reduce the level of interference and frame collisions.

IV. SPATIAL REUSE IN IEEE 802.11AX

The limited number of orthogonal channels, especially in dense environments, severely limits assumed network performance. For this reason, IEEE engineers introduced several solutions to increase the spatial reuse of the radio channel. It allows to increase the number of parallel transmissions and therefore improve spectral efficiency of the network. In order to improve the operation of the network in dense environments, a mechanism called BSS coloring has been proposed. In the preamble of the physical layer there is a 6-bit field containing the color identifier. Based on this additional identifier, the access point can assess whether simultaneous use of the channel is possible and verify whether the received frame comes from its own network. If the received frame comes from another overlapping network (BSS) it is considered as interference and it may drop it. If a collision in color is detected, the access point may initiate a network color change procedure. If the color ID value is equal to zero, the BSS coloring mechanism is disabled. BSS coloring allows for dynamic adjustment of CCA parameters or Tx power levels. The network coloring mechanism, in addition to increasing the spectral efficiency, is also aimed at reducing energy consumption, which is possible thanks to the quick identification of the origin of the frames [2].

Increasing the spatial utilization of the network is also achieved by dynamically adjusting carrier detection sensitivity called DSC (Dynamic Sensitivity Control). Setting an appropriate DSC Threshold is a compromise between a sufficiently small threshold to detect transmission in our own network and a sufficiently high threshold to prevent transmission blocking by the operation of other neighboring networks. A change in transmit power was combined with a change in the OBSS Preamble Detection (OBSS/PD) threshold. The rule is that the higher the sensitivity threshold, the lower the transmit power. Stations can change these parameters dynamically. When tuning the mechanism, it is also important to take into account the capture effect for preventing losses from frame collisions [16].

Another improvement to reduce inter-BSS interference and therefore the frame collision probability is the extension introduced to NAV mechanism. The aim of the NAV vector is to prevent station access to the channel for a specified time period. In the previous solution with a single NAV vector, there was a risk that the station, having received a special CF-End control frame from a foreign network, would reset the vector and would want to start transmitting, causing a collision. The situation is very common in dense environments where many OBSSs (Overlapping Basic Service Sets) are present and where hidden and exposed terminal problems exist. In the 802.11ax standard, resetting NAV vectors is performed separately for our own network and all OBSS.

V. PERFORMANCE EVALUATION

To analyse the performance of IEEE 802.11ax network, the NS-3 simulator in version 3.31 was used [17]. NS-3 is a discrete event simulator, which means that all state changes occur in discrete moments of time, and the events last infinitely short. The NS-3 software was chosen because of the extensive implementation of the IEEE 802.11ax standard, detailed documentation and huge possibilities of configuration including definition of very complicated research scenarios. The most important simulation parameters common to all scenarios are summarized in Table I. In all figures, the error of each simulation point for the 95% confidence interval did not exceed ± 2%.

TABLE I
SIMULATION PARAMETERS.

Parameter	**Value**
Frequency band	5 [GHz]
Channel width	20 [MHz]
Rx Noise Figure	7 [dBm]
Guard Interval	800 [ns]
Propagation model	HybridBuildingsPropagationLossModel
MCS	5 (64-QAM 2/3) and 11 (1024-QAM 5/6)
RTS/CTS	Disabled
Fragmentation	Disabled
Transport protocol	UDP
Traffic type	CBR
Queue size	500 [frames]
Frame size	1500 [Bytes]
Aggregation	MPDU and MSDU
QoS	Disabled
Mobility	Disabled

A. *Scenario 1 - Office environment*

In this scenario, network performance was analysed in an office environment. The network topology is shown in Fig. 1 and consists of 4 rooms. An access point was located in the center of each room at a height of 3 m. Each AP device was connected to 25 stations arranged in a grid of 5 devices in each row. The stations generate CBR type traffic and send frames to the AP.

It was assumed that the CCA Threshold = -92 dBm, the devices are equipped with one antenna, and the variable parameters are as follows: Tx gain = 0-20 dBi, Rx gain = 0-20 dBi, Rx sensitivity = -112 - -42 dBm and Tx power = 2-20 dBm. The offered load was set at 300 Mbps. By changing the values of the antenna's gain and the sensitivity of the receiver for the Tx power equal to 16 dBm, 98 simulation points were collected, from which the surfaces for throughput, average delay, its variability and packet losses were plotted. The obtained throughput, mean frame delay and jitter as a function of receiver sensitivity and antenna gain are presented in Fig. 2 - Fig. 4 respectively.

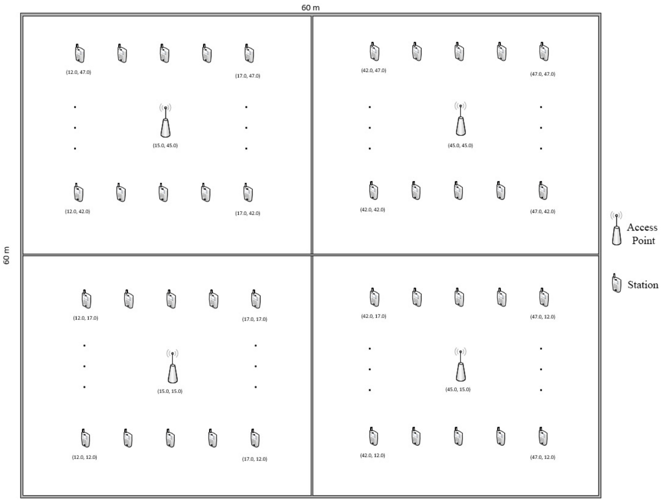

Fig. 1. The dense network topology in office environment.

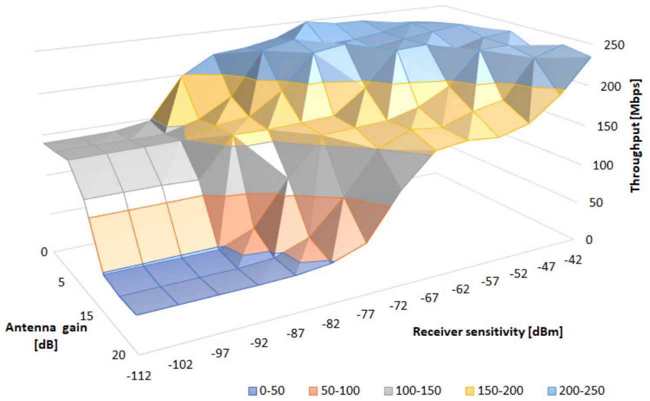

Fig. 2. Throughput vs antenna gain and receiver sensitivity for scenario 1.

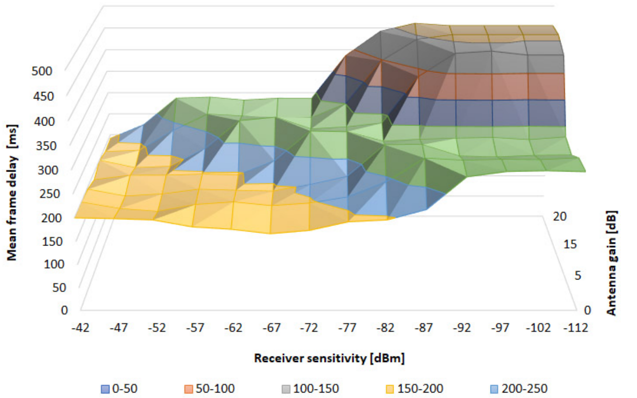

Fig. 3. Frame delay vs antenna gain and receiver sensitivity for scenario 1.

The proposed method is aimed at optimizing the operation of the network in the analysed environment. Observing the figures, it was found that too high antenna gain and very high sensitivity of the receiver cause the transmission to be

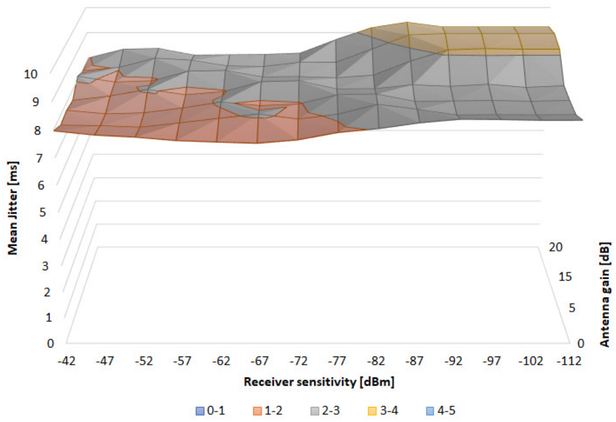

Fig. 4. Jitter vs antenna gain and receiver sensitivity for scenario 1.

detected even by distant stations. This situation leads to a drastic increase in the number of collisions and a long periods in accessing the radio channel. The difference between the lowest and highest value of the obtained throughput was even 560%. The optimal operation of the network was observed for zero antenna gain and receiver sensitivity equal to -67 dBm.

After finding the optimal values of the examined parameters, another simulations were carried out for the increasing the offered load. Three configurations of wireless network were adopted: the worst - with antenna gain 20 dB and receiver sensitivity -112 dBm, default values in the NS-3 simulator - with 0 dB antenna gain and receiver sensitivity -101 dBm, and optimal - with 0 dB antenna gain and receiver sensitivity -67 dBm (Fig. 5). Due to space limitations, only the results of the obtained throughput values are presented in the article. The difference between the optimal and the worst configuration is as much as 6 times higher throughput, a 63% decrease in average latency and a 32% decrease in average jitter. The conducted analysis shows that too high values of antenna gain and receiver sensitivity are not recommended for dense networks.

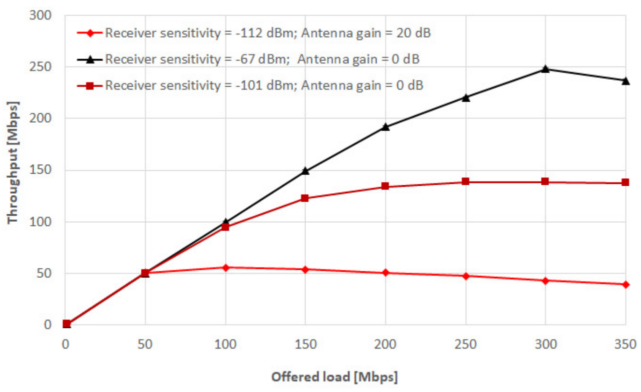

Fig. 5. Throughput vs offered load for selected values of parameters for scenario 1.

For the optimal value of the antenna gain, a similar optimization was carried out for the Tx power and receiver sensitivity (Fig. 6). The delay and jitter figures are presented in Fig. 7 and Fig. 8 respectively.

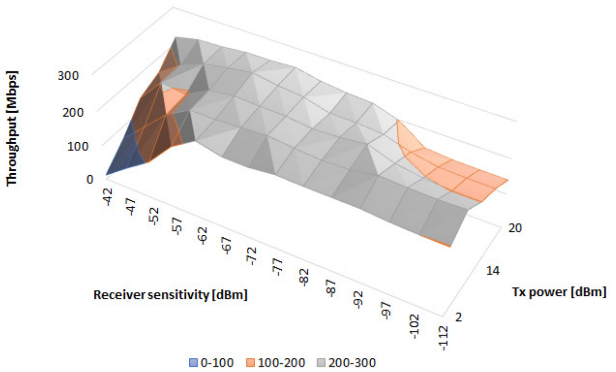

Fig. 6. Throughput vs Tx power and receiver sensitivity for scenario 1.

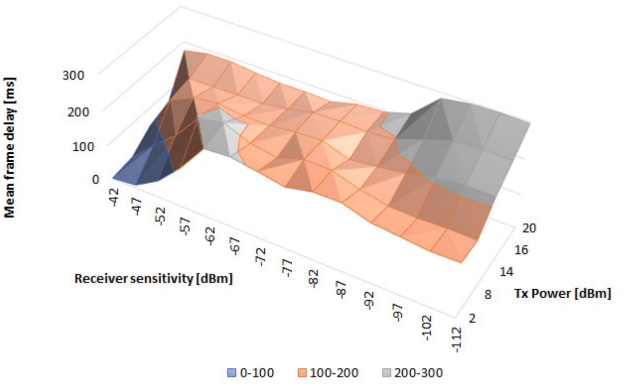

Fig. 7. Mean delay vs Tx power and receiver sensitivity for scenario 1.

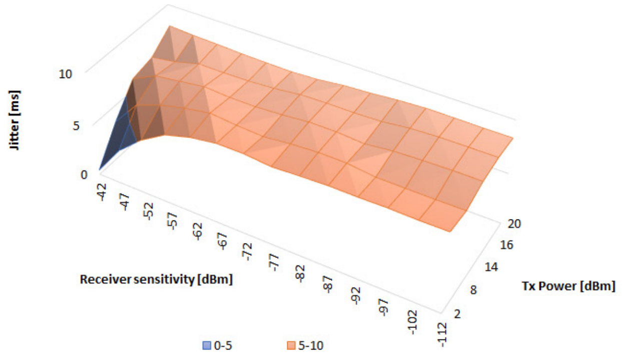

Fig. 8. Jitter vs Tx power and receiver sensitivity for scenario 1.

The maximum throughput was observed for the Tx power of 16 dBm and the cross-section of the surface was made in relation to this plane (Fig. 9).

The analysis shows that the network works most effectively for a receiver sensitivity of -62 dBm and a Tx power of

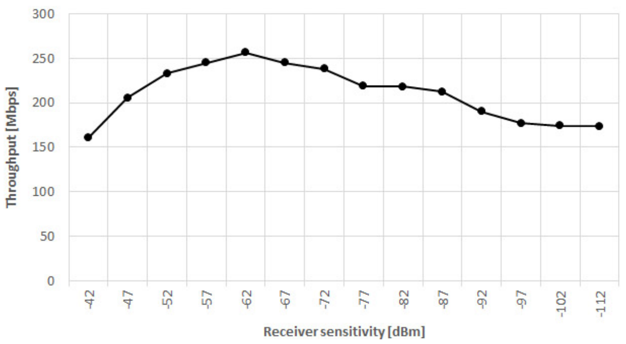

Fig. 9. Throughput vs receiver sensitivity for scenario 1.

16 dBm. The simulations carried out show that with other assumed parameters, stations are usually able to receive signals from networks located in neighboring rooms, which results in mutual blocking of transmission possibilities (according to the operation of the CSMA/CA algorithm) and a decrease in network efficiency.

The conducted research shows that too high values of antenna gain and receiver sensitivity are not recommended for dense networks. It should also be remembered that when planning the purchase of WLAN devices, one of the basic criteria is to ensure high sensitivity of the receiver, both in the AP and in client stations. This guarantees error-free transmission even at large distances between devices, but unfortunately it may bring low performance for a dense networks. Since after purchasing the devices, the user has no influence on the sensitivity of the receiver, in order to optimize the network operation, the possibility of changing other parameters defined in the IEEE 802.11ax standard should be considered. CCA Threshold seems to be a parameter that can affect the obtained results, and thus can have a large impact on performance.

B. Scenario 2 - Dense residential area

In the second scenario, we presented dense residential area. In each apartment, one access point was set at a height of 3 m and one station located 1 m above the floor. The station is located 5.1m from the AP (see Fig. 10). All simulations assumed only the uplink transmission (to observe the negative impact of collisions in dense environment).

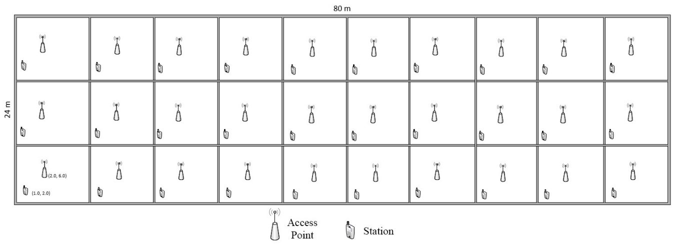

Fig. 10. The dense network topology in residential area.

The scenario examined the impact of the use of frame aggregation on the total achieved performance. Aggregation A-MSDU 8kB, A-MPDU 65kB and a combination of both aggregations of 4kB A-MSDU and 32kB A-MPDU and A-MSDU 11kB and A-MPDU 1024kB were analysed (Fig. 11 - Fig. 13).

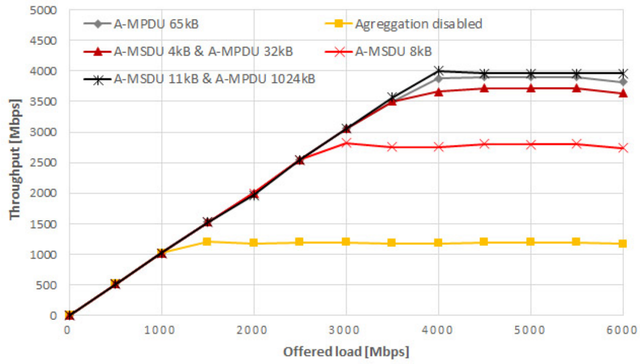

Fig. 11. Throughput vs offered load for scenario 2.

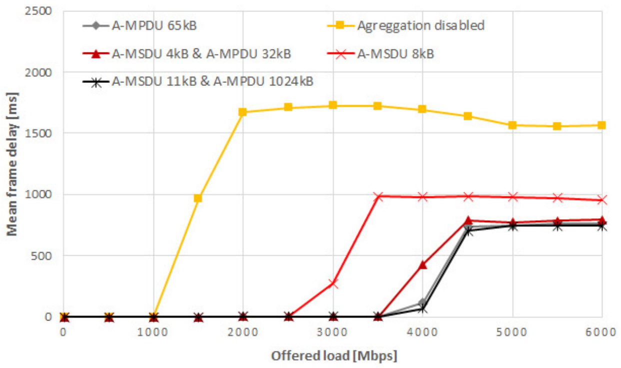

Fig. 12. Frame delay vs offered load for scenario 2.

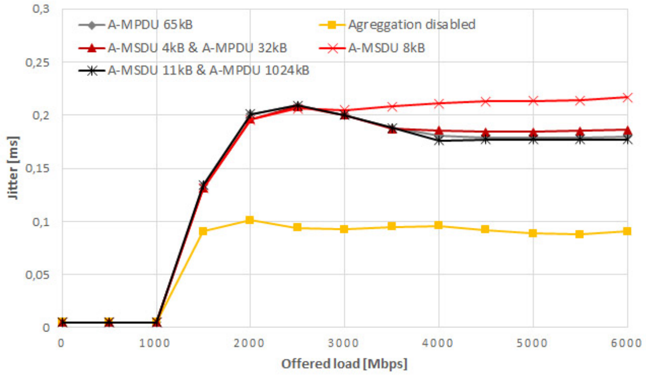

Fig. 13. Jitter vs offered load for scenario 2.

Using the largest aggregation size, a more than 3-fold increase in throughput was obtained and a 43-percent decrease in frame delay at the expense of a 2-fold increase in jitter. Aggregating frames allows to reduce overhead and, as shown, significantly increase the achieved throughput. It is possible using aggregation to send many frames in one access to the radio channel, thus improving the overall performance of the network.

C. Scenario 3 - Super dense residential area

In the third scenario, we focused on super dense residential area, where two client devices operated within each network, and the total number of apartments (and AP) was 40 (Fig. 14). In each apartment, at a height of approx. 3 m, there is a centrally located access point.

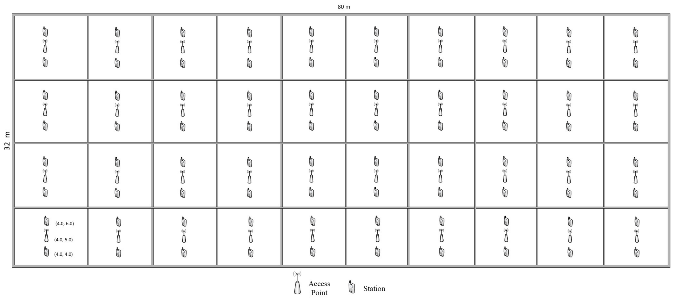

Fig. 14. The dense network topology in residential area.

In the conducted research, the total offered load was 5.2 Gbps (saturation conditions). It was also assumed that Rx sensitivity = -68 dBm, Tx power = 0.5-20 [dBm] and CCA Threshold = -52 - -92 dBm. For the change of the CCA Threshold value and the Tx power, the results for 30 simulation points were collected and a surface was plotted, which illustrates the throughput, mean delay and jitter metrics (Fig. 15 - Fig. 17).

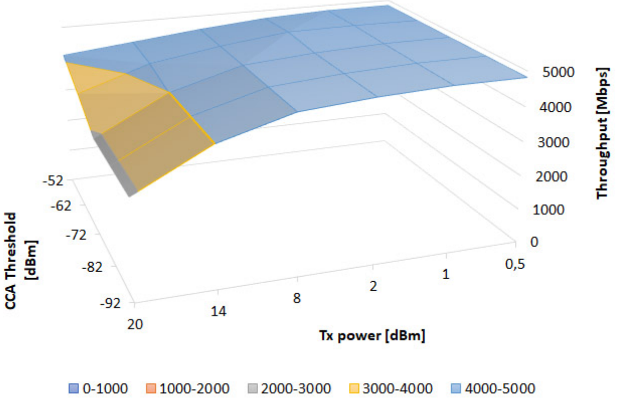

Fig. 15. Throughput vs CCA Threshold and Tx Power for scenario 3.

Again, the difference between the lowest and highest value of the obtained throughput was 67%. Therefore, for the determined optimal parameters (highest throughput) - Tx power 1 dBm and CCA Threshold -62 dBm, the worst - Tx power 20 dBm and CCA Threshold -92 dBm, as well as default values in the NS-3 simulator - Tx power 16 dBm and CCA Threshold -62 dBm, the throughput as a function of offered traffic was presented (Fig. 18).

Again, due to space limitations, only the results of the obtained throughput values are presented in the article. Comparing the optimal configuration with the worst one resulted in a 60% increase in throughput, a 22% decrease in delay and a 57% decrease in jitter. The obtained results confirm the validity of optimizing parameters for specific topology and operating conditions. The analysis of the assumed metrics shows that a too low CCA Threshold (higher negative value of CCA Threshold) combined with high Tx power leads to performance degradation. The network devices detect transmissions from distant stations and treat the channel as busy, which in consequence causes queue overflows and frame dropping.

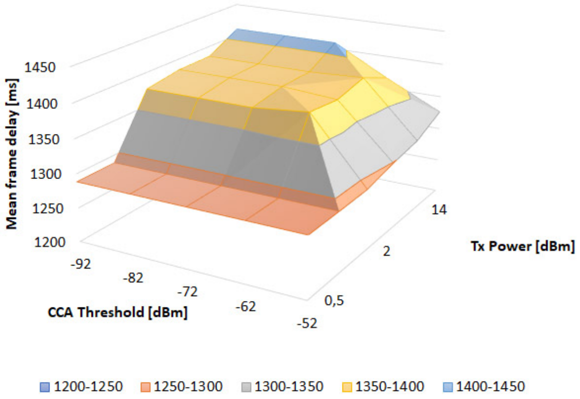

Fig. 16. Frame delay vs CCA Threshold and Tx Power for scenario 3.

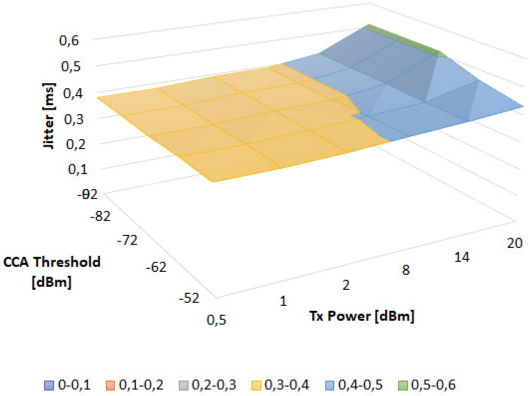

Fig. 17. Jitter vs CCA Threshold and Tx Power for scenario 3.

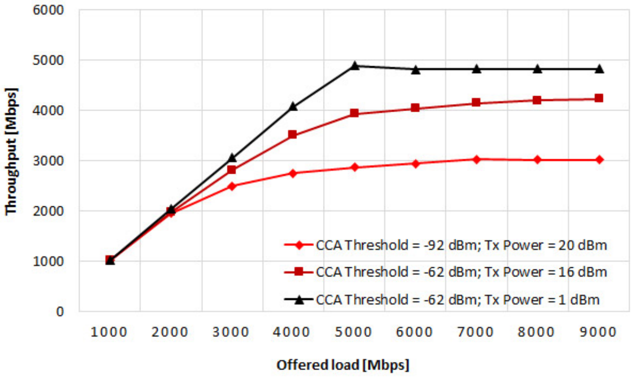

Fig. 18. Throughput vs offered load for selected values of parameters for scenario 3.

For the third scenario, the operation of the BSS coloring mechanism, which was designed to improve the efficiency of dense networks based on the IEEE 802.11ax standard, was also analyzed. Fig. 19 compares the throughput obtained with BSS coloring mechanism enabled and disabled for different values of the OBSS/PD parameter.

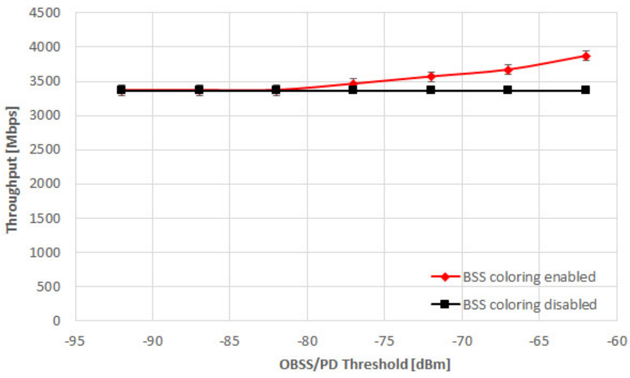

Fig. 19. Throughput vs OBSS/PD Threshold for coloring mechanism enabled and disabled for scenario 3.

The largest throughput increase, approx. 15%, was obtained for the OBSS/PD threshold equal to -62 dBm. If the value of this parameter is too low (higher negative value of OBSS/PD), the coloring mechanism does not bring any profit, because too low OBSS/PD level makes the AP able to recognize and receive too many transmissions. It should be also remembered that setting too high values of OBSS/PD may cause hidden terminal problem and as a consequence performance anomalies. The lower profit from BSS coloring than presented in other research papers may be due to the fact that the walls in the considered buildings provide partial separation of individual networks.

VI. CONCLUSION

The aim of the work was to analyse the dense networks based on the IEEE 802.11ax standard. The conducted research allowed to optimize their parameters to maximize the overall network efficiency. Three different dense network topologies were analysed. The presented results allow to conclude that in dense networks, frame collisions significantly limit the network efficiency. One of the analyzed scenarios showed that the use of aggregation effectively reduces the protocols overhead and improves the achieved network efficiency. It was proved that parameters such as CCA Threshold, transmitter power, antenna gain and receiver sensitivity are extremely important for the efficient operation of dense networks (observed differences were up to the 560%). Setting the transmit power for too high values and the CCA Threshold parameter for too low values leads to the deterioration of the network performance (in the last scenario by 40%). These parameters, as shown in the paper, can be used to optimize the operation of dense WLAN networks. The paper also reveals that the usage of the BSS coloring mechanism can bring a 15% increase in throughput for dense networks.

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