Performance Enhancement and Evaluation of IEEE 802.11ah Multi-Access Point Network using Restricted Access Window Mechanism

Orod Raeesi[†], Juho Pirskanen[⋆], Ali Hazmi[†], Jukka Talvitie[†], Mikko Valkama[†]
[†]Tampere University of Technology, Korkeakoulunkatu 1, FI-33720, Tampere, Finland
[⋆]Broadcom Corporated, Tampere, Finland
E-mail: {orod.raeesi, ali.hazmi, jukka.talvitie, mikko.e.valkama}@tut.fi, juho.pirskanen@broadcom.com

***Abstract*—Internet of Things (IoT) and Machine-to-Machine (M2M) applications are typically characterized by moderate investment costs to the M2M devices and infrastructure, in addition to the high reliability and energy efficiency requirements. The new Sub-1 GHz WiFi standard, namely the IEEE 802.11ah, is being introduced to address these requirements deploying its recently specified MAC and PHY features and mechanisms. In this paper, we present an extensive analysis of IEEE 802.11ah network performance by means of realistic system level simulations. In particular, we focus on realistic performance evaluation and enhancement study of the IEEE 802.11ah network when multi-access points (multi-APs) with relatively high number of associated stations (STAs) are considered. The performance evaluation of the multi-AP IEEE 802.11ah network considers one of the main proposed MAC enhancement schemes for collision reduction, namely, the Restricted Access Window (RAW) mechanism. The analysis results confirm the importance of this novel mechanism to improve substantially the overall system performance from both network throughput and energy efficiency perspectives. Overall, the technical findings reported in this article strengthen the prospects of IEEE 802.11ah as one of the key enabling technologies for wide-scale low-cost and energy-efficient M2M deployments and IoT applications in the future.**

I. Introduction

The Internet of Things concept is rapidly evolving. It is expected to transform noticeably our daily life. Many technologies, applications and illustrations of the IoT ideas are now already deployed or being under investigation, leading smoothly to the second stage of the IoT evolution. For instance, the future expansion of IoT and M2M communication for sensor networking is predicted to be enormous [1] [2]. At first glance, different business areas have different use cases and different requirements but when considered further, there exist several common nominators for IoT and M2M industries. These nominators are at least: moderate investment cost of the M2M devices and infrastructure, reliability and long operating times of battery powered end devices, security and simple system integration to the Internet and existing infrastructures.

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Currently, there exists several radio technologies, which are based on IEEE 802.15 [3] radio standards such as ZigBee [4] and 6lowPan [5] or based on Bluetooth specifications [6]. In addition, different M2M applications rely on IEEE 802.11 WLAN/WiFi standard family or utilize cellular networks, most notably GSM, 3G or even LTE. However, those applications must operate with standard implementation as currently no WLAN or cellular technology variant exists that is specifically and explicitly designed for M2M or sensor network purposes.

Due to increasing interest of IoT, M2M and sensor applications, also the WLAN industry has taken first steps to address this business segment by defining new IEEE 802.11ah amendment [7] [8] to IEEE 802.11 baseline standard focusing mainly on these applications. In this paper, we first discuss IEEE 802.11ah technology by briefly describing motivations and main features recently introduced in IEEE 802.11 PHY and MAC specifications. Additionally we present extensive system level studies on IEEE 802.11ah network performance based on realistic system level simulations. Our main contributions, in this paper, are the performance evaluation and enhancement study of the IEEE 802.11ah network when multi-access points (multi-APs) with relatively high number of associated stations (STAs) are considered. The access points are assumed to be unsynchronized and no coordination between them is used. This represents a typical and very challenging scenario for IEEE 802.11ah deployment as high interference between the APs is expected and noticeable degradation of the throughput is likely to occur. The analysis and evaluation of the system performance take into account one of the most important proposed schemes in the IEEE 802.11ah MAC specification for throughput enhancement, namely, Restricted Access Window Mechanism (RAW). To further enhance the system performance the use of RAW with simple link adaptation scheme is also evaluated in this article.

The remainder of this paper is organized as follows. Section 2 presents a brief overview and fundamentals of the IEEE 802.11ah technology. After presenting the IEEE 802.11ah use cases and requirements, the main MAC and PHY features are briefly described. We focus mainly on the RAW mechanism and its main parameters. In Section 3, we discuss the theoretical maximum throughput of IEEE 802.11ah with single AP for reference. In Section 4 we present extensive system

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level studies on IEEE 802.11ah performance when multi-AP scenario is considered. Finally, Section 5 concludes the paper.

II. IEEE 802.11AH OVERVIEW AND FUNDAMENTALS

In this section, we first discuss shortly different use cases and requirements that were identified at the beginning of the IEEE 802.11ah standardization work. Secondly, we describe some of the main MAC and PHY features that have been developed for IEEE 802.11ah [9][10].

A. Use Cases

At the beginning of the standardization process in IEEE 802.11ah task group, several use cases were presented for this new amendment by different industry parties. These use cases can be categorized in three major groups. These groups include sensors and meters, back-haul link for sensor/meter data and extended range Wi-Fi applications [11]. In the first group, users and manufacturers want to extend the battery life of end devices as long as possible to minimize operating expenses of the sensor network. Different scenarios were identified within these groups, like smart grid - meter to pole, environmental/agricultural monitoring, industrial process sensors, health-care/fitness and home or building automation and control applications. In the second group, i.e., Back-haul networks for sensor/meter Data, the IEEE 802.11ah technology is designed to co-exist at same frequencies with other standards like IEEE 802.15.4 and IEEE 802.15.4g and provide transmission technology for a back-haul link. The aim is that IEEE 802.11ah performs without degradation of throughput and reliability when co-existing with other technologies. Finally, the third group, namely Extended Range Wi-Fi, was introduced to promote traditional Wi-Fi and extending Wi-Fi coverage. Main motivation for this is the operators increased interest to offload cellular data to Wi-Fi networks.

B. Requirements

IEEE 802.11ah defines an OFDM physical layer operating in the license-exempt bands below 1 GHz. It should have enhancements to the IEEE 802.11 Medium Access Control (MAC) to support this PHY, and provides mechanisms that enable coexistence with other systems at the bands including IEEE 802.15.4 and IEEE P802.15.4g[12].

IEEE 802.11ah should support mode of operation in which at least 100 kbps PHY data rate is provided with coverage of 1 km [13]. Another requirement for IEEE 802.11ah is that it should support beyond two thousand stations for outdoor applications. It should also provide an enhanced power saving mechanism to support battery-powered operation with long replacement cycle [14].

C. IEEE 802.11ah MAC Features

The IEEE 802.11ah introduces new MAC features and enhancements to address the IoT and M2M requirements. These enhancements can be classified in four different categories. First, some enhancements on the power saving capabilities. Second, new features to allow the support of large number of stations. Third, the development of new access mechanism and the definition of various frame formats and finally some interference mitigation mechanisms. In the following we give a short overview of these MAC features.

1) Power saving features: The IEEE 802.11ah standard supports two different power saving strategies referred to as Non-TIM STA and TIM STA [15].

In the case of Non-TIM STA, the IEEE 802.11ah device does not receive Traffic Indication Map (TIM) information element (IE) from the beacons frames that are regularly broadcasted by the AP. The TIM IE is used by AP to indicate whether it has buffered downlink data for a STA. Rather, the Non-TIM STA sends PS-Poll frame to the AP to request AP to deliver any buffered DL data for it. The motivation for this power saving scheme is that in certain applications the sleeping time can be very extensive and the accuracy of the sensor's internal clock might be so low that synchronization to the beacon target transmission time is lost during sleep time. Instead of extensively waiting TIM IE from the beacon, the non-TIM STA sends PS-poll frame and remains waiting response from the AP.

The TIM STAs, however, are receiving periodically TIM IEs from the beacon frame to detect whether AP has any buffered data for it. When STA detects that AP has buffered data for it, the STA sends PS-poll frame to request downlink data delivery.

In order to efficiently benefit from the above power saving techniques, IEEE 802.11ah introduces also some improvements on the PS-Poll mechanisms. In addition it extends the maximum idle period for a given STA.

2) Support of large number of stations: In the IEEE 802.11 specifications, the TIM is basically defined as bitmap that uniquely maps to the Association Identifier (AID) of the STAs. A bit is set when the corresponding STA has buffered data at the AP, and the corresponding STA then transmits the power-saving poll (PS-Poll) frame to the AP to poll the buffered data. As the maximum size of an IE is 256 bytes, a maximum of approximately two thousands AIDs can be supported. However, as described in the IEEE 802.11ah use case document, even up to 6000 STAs need to be supported in some scenarios. Moreover, using a bitmap to support 6000 STAs may increase the beacon size significantly. Hence, efficient addressing/encoding methods are needed.

In order to support higher number of STAs, the concept of hierarchical TIM bitmap and TIM segmentation has been adopted in the IEEE802.11ah specifications framework. The hierarchy of TIM comprises 4 pages, each containing 32 blocks. Each block is further divided into 8 sub-blocks of 8 bits each. A STA is identified by its page index, block index within the page, sub-block index within the block, and its bit position within the sub-block, and the address of the STA is encoded in its AID [9].

3) Enhanced channel access mechanisms: The requirement to support high number of STAs, introduced the need to control the channel access and avoid collisions in more efficient manner. The selected method was to introduce restricted access window (RAW) on top of normal enhanced distributed channel access with transmit opportunity (EDCA TXOP) [7]. The basic principle of the RAW is very simple as it aims to reduce number of STAs performing random access simultaneously.

In RAW mechanism, AP allocates a medium access period in the beacon interval, called RAW, which is divided into one or more time slots. The AP may assign to a group of STAs a time slot inside the RAW at which the STAs are permitted to contend for medium access. A STA that receives RAW information in a beacon transmitted by the AP determines whether it is allowed to use RAW interval, as well as the start time and the duration of the RAW. If a STA has uplink data and is allowed to access the wireless medium within the RAW, it will contend for medium access at the start of the assigned time slot. A STA in its assigned time slot can start contending as soon as it gets any uplink data from upper layers. STAs stop attempting to access the medium as soon as their assigned time slot is finished. It should be noted that there may be some STAs which are not allowed to use the RAW.

Based on the information about the RAW duration, T_{RAW}, and the time slot duration, T_{slot}, each STA calculates the number of time slots, N_{RAW}. The time slots in the RAW are indexed from 0 to (N_{RAW} - 1). A STA determines the index of the time slot, i_{slot}, in which it is allowed to start accessing the medium based on the following mapping function

$$i_{\mathrm{slot}} = (x + N_{\mathrm{offset}}) \bmod N_{\mathrm{RAW}}. \tag{1}$$

The parameter x in (1) refers to the index of the STA. The variable N_{offset} represents the offset value in the mapping function, which improves the fairness among the STAs in the RAW. A RAW example in which part of the beacon interval is assigned to RAW can be seen in Figure 1.

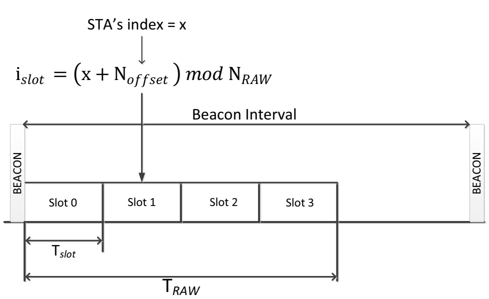

Fig. 1. Slot assignment procedure in RAW mechanism

In order to further improve the system performance when high numbers of devices are transmitting small data packets, as in typical M2M and IoT deployments, the IEEE 802.11ah aims to reduce the overhead in the MAC headers. Hence, short MAC header has been defined. The size of MAC header for typical 802.11 data frame is 28 bytes, which is reduced to 18 bytes in IEEE 802.11ah. In addition, IEEE 802.11ah introduces several null data packet (NDP) frames, also known as short frames, such as short ACK, short block ACK, short CTS, and short PS-Poll. Moreover, as overhead may also arise from the communication protocol, the IEEE 802.11ah introduces new frame exchange protocol referred as speed frame exchange (SFE) which reduces protocol overhead. Compared to normal DCF, SFE uses the data frame as the ACK to previous data frame. Simply, the SFE enables an AP and non-AP STA to exchange a sequence of uplink and downlink frames during a reserved time.

4) Interference mitigation mechanism using sectorization: The sectorization is simply the partition of the coverage area of a basic service set (BSS) into sectors, each containing a subset of stations. This partitioning is achieved through a set of antennas or a set of synthesized antenna beams to cover different sectors of the BSS. The aim is mainly to reduce the interference between BSSs, usually referred in the literature as overlapping BSS (OBSS) problem. Two types of sectorization schemes have been introduced in the IEEE 802.11ah specifications: group sectorization and TXOP-based sectorization.

In the group sectorization case, a beacon interval-based operation allows STAs to transmit in different sectors following a time division multiplexing scheme. The AP assigns group sectorization capable STAs belonging to a sector into group(s) identified by the group ID(s).

In TXOP-based sectorization, the AP starts a TXOP with omni-beam transmission that will reach both STAs supporting TXOP-based sectorization and STAs not supporting TXOP-based sectorization in order to set up the network allocation vector (NAV) protection. Then, the AP switches to the sectorized beam transmission. With the sectorized beam transmission and reception, the hidden node problems are mitigated in TXOP-based sectorization BSS operation.

D. IEEE 802.11ah PHY Features

The IEEE 802.11ah can be seen as a down-clocked version of the IEEE 802.11ac [16] which in turn is an evolution of the IEEE 802.11n [17]. The IEEE 802.11ah defines its modes by using 10-times down-clocking of the IEEE 802.11ac channel bandwidths. Consequently, 2MHz, 4MHz, 8MHz and 16 MHz channels are defined. In order to be able to achieve longer transmission ranges the IEEE 802.11ah introduces also a new mode using the 1 MHz channel bandwidth.

The IEEE 802.11ah will use the sub 1 GHz ISM band. The availability within this band varies from one country to another. For instance the IEEE 802.11ah channelization is defined as 863-868 MHz in Europe, 916.5-927.5 MHz in Japan, 755-787 MHz in China, 917.5-923.5 MHz in South Korea, 866-869 MHz, 920- 925 MHz in Singapore and 902-928 MHz (U.S). More detailed information for these countries channelization is available in [7].

The IEEE 802.11ah adopts the Orthogonal Frequency Division Multiplexing (OFDM) and Multi Input Multi Output (MIMO) techniques. Downlink Multi-User MIMO (DL MU-MIMO), which is firstly introduced in the 802.11ac, is also employed by the IEEE 802.11ah system. In IEEE 802.11ah, 1 MHz and 2 MHz channels have been adopted as common channel bandwidths such that IEEE 802.11ah stations have to always support them. Other modes are optional. In the 2 MHz channel, 64 point Fast Fourier Transform (FFT) is used

TABLE I
IEEE 802.11AH MCSs AND DATA RATES FOR 2 MHz CHANNEL AND ONE SPATIAL STREAM

Mode	Mod.	CR	Bits per OFDM symb.	Theo. rate (Mbps)
MCS0	BPSK	1/2	52	0.7
MCS1	QPSK	1/2	104	1.3
MCS2	QPSK	3/4	104	2.0
MCS3	16QAM	1/2	208	2.6
MCS4	16QAM	3/4	208	3.9
MCS5	64QAM	2/3	312	5.2
MCS6	64QAM	3/4	312	5.9
MCS7	64QAM	5/6	312	6.5
MCS8	256QAM	3/4	416	7.8

to generate an OFDM symbol, and among the 64 subcarriers, the number of subcarriers used to transmit data is 52. Table I shows the MCSs and the corresponding data rates using 2 MHz channel with a single spatial stream.

III. IEEE 802.11AH PERFORMANCE LIMITS WITH SINGLE ACCESS POINT

In order to evaluate the capabilities of IEEE 802.11ah technology prior to its deployment, its theoretical performance limit has to be assessed. In the next sections we will evaluate the theoretical maximum throughput of the IEEE 802.11ah system using some assumptions regarding the channel and the traffic model.

A. *Maximum Throughput of IEEE 802.11ah*

The theoretical maximum throughput (TMT) that can be achieved in an IEEE 802.11 network depends on the DATA packet size and the characteristics specified in each amendment [18]. In this section, the IEEE 802.11ah TMT is determined. Here, we assume a scenario where a single AP and a single STA having always a packet available for transmission is considered. For this study, we assume no errors in transmission of the frames (ideal channel) and no losses due to collisions. Also, beacons and propagation delay are neglected.

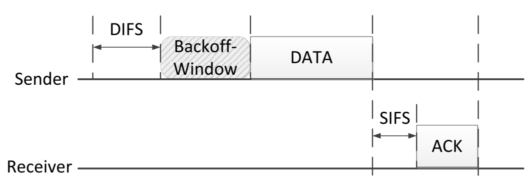

Fig. 2. One complete transmission cycle in basic access scheme

Based on the previous assumptions, to calculate TMT in bits per second, the size of the DATA packet in bits should be divided by the time it takes for having a complete transmission cycle. Based on Figure 2, TMT for basic access schemes can be written as

$$TMT^{\text{basic}} = \frac{8 \times L_{\text{payload}}}{\text{DIFS} + T_{\text{BO}} + \text{DATA} + \text{ACK} + \text{SIFS}} \tag{2}$$

DATA and ACK specified in (2) are the duration of those packets and T_{BO} is the average time taken for backoffs before initiating the transmission cycle.

Since it is assumed that there are no errors in the transmission of a given packet, the contention window (CW) will not increase exponentially. Therefore, T_{BO} is constant and can be calculated as follows

$$T_{\text{BO}} = \frac{\text{CWmin}}{2} \times \text{SlotTime}. \tag{3}$$

In addition to PHY header, ACK which is a control frame should be also sent with the basic data rate. Therefore, duration of the control frames can be calculated as

$$T_{\text{control}} = \text{ceil}\left(\frac{8 \times L_{\text{control}}}{L_{\text{sym}}^{\text{basic\_datarate}}}\right) \times T_{\text{sym}} + \text{PHY} \tag{4}$$

Use of ceiling in the equation is due to using OFDM as the transmission technique which requires integer number of symbols to be transmitted for each packet.

The duration of DATA packets is expressed in (5) in which R shows the data rate used to send the DATA packet and $L_{\text{sym}}^{\text{basic\_datarate}}$ represents the number of data bits in one OFDM symbol (N_{DBPS}) when basic data rate is used.

$$T_{\text{data}} = \text{ceil}\left(\frac{8 \times (L_{\text{payload}} + \text{MAC})}{\frac{R}{\text{basic\_datarate}} \times L_{\text{sym}}^{\text{basic\_datarate}}}\right) \times T_{\text{sym}} + \text{PHY} \tag{5}$$

Now, putting the above elements together allows us to evaluate the maximum throughputs. Figure 3 shows the TMT, calculated for three different MCSs of IEEE 802.11ah, with lines representing the analytical formulas and symbols showing the empirical simulation results. For completeness, TMT when RTS/CTS are used, is also shown in Figure 3. Since the analytical model is generally proved to be precise [18], perfect matching of analytical and simulation results proves the accuracy of the simulator. As it was expected, since there is neither collisions nor errors in the transmissions, basic access scheme has better performance in all the MCSs, compared to RTS/CTS scheme, due to not being forced to send excessive packets in each transmission cycle.

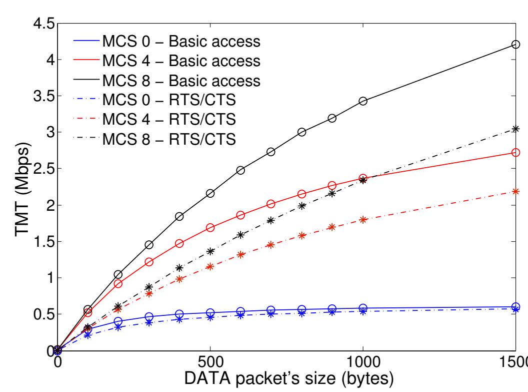

Fig. 3. Theoretical maximum throughputs of IEEE 802.11ah

IV. IEEE 802.11AH PERFORMANCE EVALUATION WITH MULTIPLE ACCESS POINTS

The above analysis is highly simplistic and theoretical. In this section, we present extensive and more practical system level studies on IEEE 802.11ah performance based on system level simulations. The simulation environment used in these studies is the Omnet++ tool which is an open-source platform widely used for network simulations [19]. The main focus is on the multi-AP scenario, with high number of STA'a, as it is expected to be the typical IEEE 802.11ah deployment scenario. The access points are assumed to be unsynchronized and no coordination strategies are used. When it comes to STAs, sensor application is the main use case that will be considered. Uplink traffic where 10 data packets of size 256 bytes are sent uniformly within the beacon interval of 100 ms from each STA to the nearest AP.

First we will start with a basic multi-AP scenario, where only 2 APs are considered. In this case the overlapping basic service set problem is investigated. Second, we extend the network to higher number of APs, and simulate the system performance when RAW mechanism is used jointly with simple link adaptation scheme.

A. Overlapping Basic Service Sets (OBSS) problem

The OBSS problem refers to the case in which two or more BSSs, that are unsynchronized and operating at the same channel, are close enough to hear each other. In these cases, transmissions by some STAs in one BSS will affect the STAs in the other one, and eventually degrade the overall performance [20].

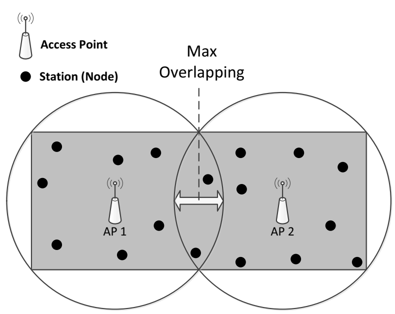

Fig. 4. OBSS problem setting

In this section, the effects of OBSS problem on IEEE 802.11ah are evaluated using one of the scenarios introduced in [21], in which there are two BSSs and two APs as illustrated in Figure 4.

To study the OBSS effect, the cases in which there are OBSS problems with different max overlapping areas (shown in Figure 4) are compared to the two isolated BSSs case, all using MCS 0 with low traffic (one packet is generated per second). The STAs are randomly positioned in a shadowed rectangular area shown in Figure 4. To simulate the isolated scenario, for reference, one BSS is simulated with STAs randomly positioned in a square within that and two BSSs

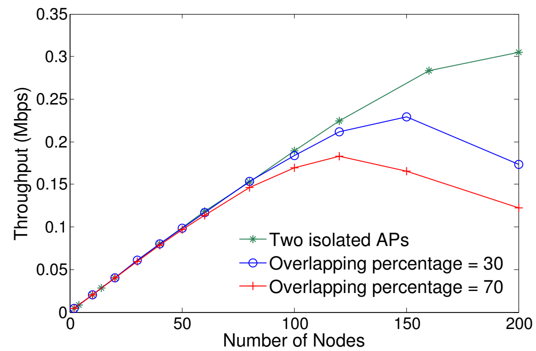

Fig. 5. Throughputs in OBSS scenarios

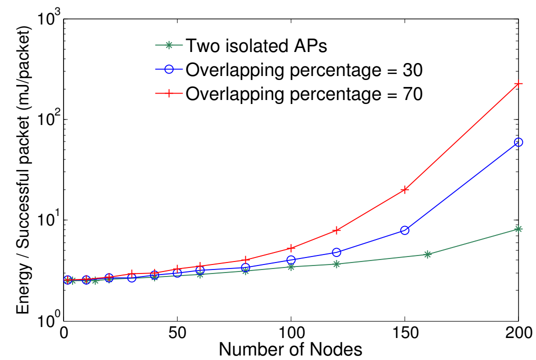

Fig. 6. Energy efficiency in OBSS scenarios

case is approximated by multiplying the number of STAs and throughput of one BSS by 2. Results regarding throughput and energy efficiency can be seen in Figures 5 and 6 respectively. "Overlapping percentage" parameter in the results shows the amount of overlapping area, with "0" being the case that two BSSs are tangent to each other and "100" the case in which two BSSs are exactly on top of one another.

As it can be seen in Figure 5 and Figure 6, the performance is substantially degraded in all the metrics depending on the "Overlapping percentage". There are lots of mechanisms to cope with OBSS problems such as sectorization [7], power control [22], etc. Below, we evaluate the realistic multi-AP IEEE 802.11ah network including the raw and link adaptation mechanisms.

B. Typical multi-AP scenario

In this section we extend the 2-APs case to 9-APs, where the APs are placed uniformly in a playground of 500 meters square. Figure 8 illustrates this evaluation scenario. The main system settings used in the simulations are shown in Table I and Table II. Outdoor channel scenario is considered. The channel parameters and path loss models can be found in [23]. The IEEE 802.11ah MAC basic timing parameters and their definitions are given in Table II.

To evaluate the performance from energy consumption (in mJ/packet) point of view, each state of the transceiver

TABLE II
IEEE 802.11AH MAC-LAYER PARAMETERS (2 MHZ MODE)

Parameter	Description	Value
T_{sym}	Symbol duration	40 μs
MAC	MAC header	14x8 bits
PHY	PHY header	6xT_{sym}
ACK	Acknowledgment	0x8 bits (only PHY header)
RTS	Request to send	20x8 bits
CTS	Clear to send	0x8 bits (only PHY header)
SlotTime	The slot time	52μs
SIFS	Short interframe space	160 μs
DIFS	DCF interframe space	SIFS + 2SlotTime
CWmin	Min. backoff window size	15
CWmax	Max. backoff window size	1023
m_{long}	Long retry limit	4
m_{short}	Short retry limit	7

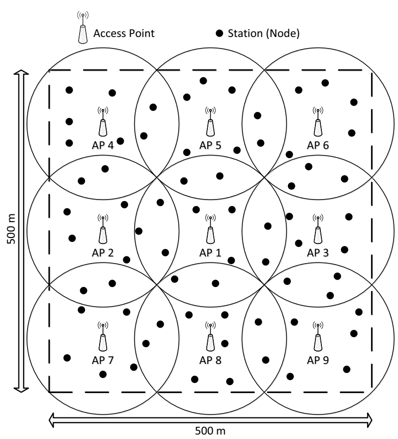

Fig. 7. Typical multi-AP network: 9 APs are considered. The APs are placed uniformly in a playground of 500x500 m^2

TABLE III
STA ENERGY CONSUMPTION VALUES IN DIFFERENT MODES

Mode	Energy consumption (mW)
Transmission	255
Receive and channel sensing	135
Sleep	1.5

should have a particular power consumption assumed. Table III summarizes the energy consumption in different STA modes. Transmission mode is only used for sending RTS and DATA, receiving mode refers to receiving beacon, CTS and ACK, sleep mode refers to the times when STA does not have anything to send and all the other timings are considered to be idle. These power consumption values represent realistic values of latest transceivers. For a sake of comparison, we also simulate the case where only one AP is used to serve the same amount of STAs in the same playground.

1) RAW and link adaptation parameters optimization: As discussed earlier, the value of parameter N_{RAW} needs to be tuned depending on the configuration settings. The optimum value of N_{RAW} can then be used in the throughput and energy efficiency assessment of the studied multi-AP scenario. Such optimization study was conducted in [24] in a single AP case. In [24] we concluded that N_{RAW} equal to 10 is the best option for similar sets of parameters. To tune the RAW parameters for the 9-AP case, extensive simulations have been additionally conducted. The simulations showed that N_{RAW} equal to 10 is still valid in the 9-APs case, and provide best throughput for wide range of STA population. Regarding the link adaptation scheme that will be jointly used with RAW, a simple Auto Rate Fallback (ARF) as described in [25] [26] will be considered.

2) Multi-AP performance results: Finally the overall performance results of the multi-AP network scenario using the IEEE 802.11ah technology are shown in this section. Both 9-AP and 1-AP cases are illustrated. The throughput performances for 1-AP and 9-AP cases are shown respectively in Figure 8 and Figure 9. As can be easily noticed the Multi-AP configuration provides better throughput for all the modes when compared to the 1-AP case. It can be also seen that the RAW scheme highly improves the system performance with respect to basic scheme (DCF). A further improvement can be achieved when link adaptation is also used. The energy efficiency performance follows the same trend. As shown in Figure 10 and Figure 11, Multi-AP settings assure lower energy consumption of the network compared to 1-AP deployment. Again, further energy efficiency improvement can be achieved when RAW and link adaptation mechanisms are used. Hence these findings clearly demonstrate the importance of RAW mechanism in practical IEEE 802.11ah deployments.

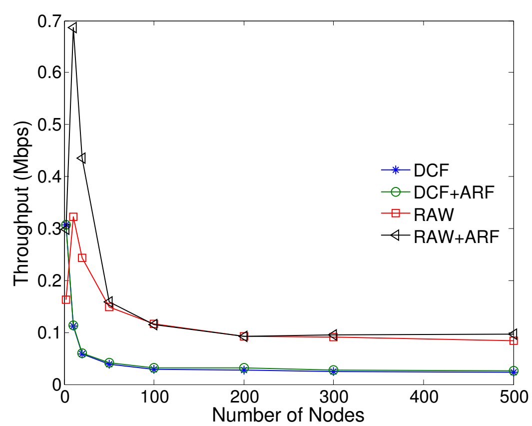

Fig. 8. Throughputs for one AP case

V. CONCLUSIONS

In this paper we first presented an overview of the recent MAC and PHY features included in the IEEE 802.11ah specifications. In addition, we conducted extensive system level studies of IEEE 802.11ah performance based on system level simulations. Specifically, we focused on the performance evaluation and enhancement schemes of IEEE 802.11ah networks in the practical challenging cases of multi-access points (multi-APs) deployments with high number of associated stations (STAs). In order to enhance the multi-AP system performance with high number of stations, we formulated and analyzed

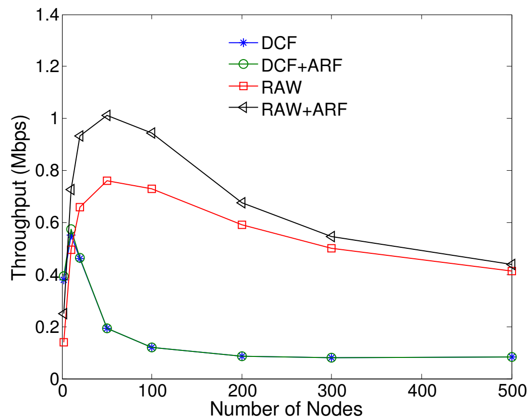

Fig. 9. Throughputs for nine APs case

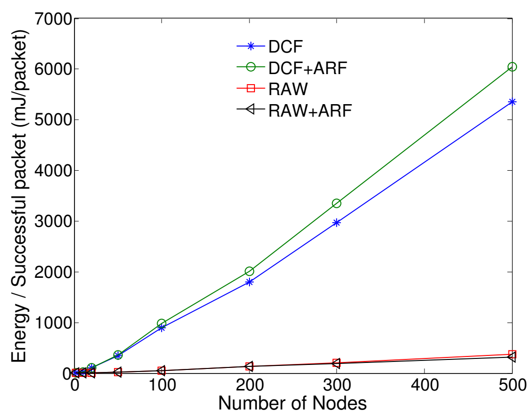

Fig. 10. Energy efficiency for one AP case

the use of Restricted Access Window (RAW) Mechanism, enabled by the IEEE 802.11ah specifications, together with a simple link adaptation scheme. The reported extensive simulation results clearly demonstrate the importance of these mechanisms to substantially improve the system throughput as well as the system and device-level energy efficiency in the emerging M2M and IoT applications. Our future work includes incorporating also the sectorization features in multi-AP OBSS deployment scenarios, to further enhance the energy-efficiency of the overall network with high numbers of stations

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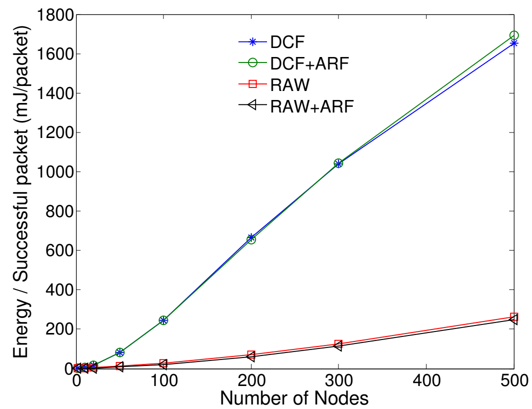

Fig. 11. Energy efficiency for nine APs case

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