Evaluation of the IEEE 802.11ah Restricted Access Window Mechanism for dense IoT networks

Le Tian, Jeroen Famaey and Steven Latré
Department of Mathematics and Computer Science, University of Antwerp – iMinds
Email: firstname.lastname@uantwerpen.be

***Abstract*—IEEE 802.11ah is a new Wi-Fi draft for sub-1Ghz communications, aiming to address the major challenges of the Internet of Things (IoT): connectivity among a large number of power-constrained stations deployed over a wide area. The new Restricted Access Window (RAW) mechanism promises to increase throughput and energy efficiency by dividing stations into different RAW groups. Only the stations in the same group can access the channel simultaneously, which reduces collision probability in dense scenarios. However, the draft does not specify any RAW grouping algorithms, while the grouping strategy is expected to severely impact RAW performance. To study the impact of parameters such as traffic load, number of stations and RAW group duration on optimal number of RAW groups, we implemented a sub-1Ghz PHY model and the 802.11ah MAC protocol in ns-3 to evaluate its transmission range, throughput, latency and energy efficiency in dense IoT network scenarios. The simulation shows that, with appropriate grouping, the RAW mechanism substantially improves throughput, latency and energy efficiency. Furthermore, the results suggest that the optimal grouping strategy depends on many parameters, and intelligent RAW group adaptation is necessary to maximize performance under dynamic conditions. This paper provides a major leap towards such a strategy.**

***Index Terms*—IEEE 802.11ah, ns-3, restricted access window, RAW.**

I. Introduction

The Internet of Things (IoT) introduces a novel dimension to the world of information and communication technology where connectivity is available anytime, anywhere for anything. To make this into reality, a large number of battery-powered smart things, such as sensors and actuators, need to be connected to the Internet in an energy efficient manner. Current low-power IoT communication technologies can be categorized in two groups: wireless personal area network (WPAN) and low-power wide area network (LPWAN) technologies. WPAN technologies (e.g., ZigBee, Bluetooth Low Energy) provide medium throughput (i.e., up to a few hundred kilobit per second) at short range (i.e., tens of meters), while LPWAN technologies (e.g., SigFox, LoRA) focus on long-range communications (i.e., up to several kilometers) with very low throughput (i.e., up to at most a few kilobit per second). Due to the short range of the former and low throughput of the latter, both types of technologies are only applicable in a limited set of IoT scenarios. As such, a gap still exists for a low-power IoT communication technology that offers sufficient throughput over longer ranges.

978-1-5090-2185-7/16/$31.00 2016 IEEE

The newly released IEEE 802.11ah Wi-Fi standard, marketed as Wi-Fi HaLow, fills this gap. It is a wireless PHY and MAC layer protocol that operates in the unlicensed sub-1Ghz frequency bands (e.g., 863–868Mhz in Europe and 902–928Mhz in North-America). As other Wi-Fi standards, it supports several modes, which offer a trade-off between range, throughput and energy efficiency. This allows it to support ranges from 100 m up to and over 1 km and data rates between 150 kbps and 8 Mbps. Therefore, it has the potential of achieving much higher ranges than existing WPAN and much higher throughput than both WPAN and LPWAN technologies. On the MAC layer, IEEE 802.11ah introduces mechanisms such as hierarchical organization, short MAC header, restricted access window (RAW), traffic indication map (TIM) segmentation and target wake time (TWT), which all aim to increase efficiency in face of a large amount of densely deployed, energy constrained stations.

The RAW feature divides stations into groups, limiting simultaneous channel access to one group and therefore reducing the collision probability in dense networks. However, the standard does not specify the grouping strategy, which is responsible for deciding how to split stations into groups. Concretely, the access point (AP) should implement a grouping strategy that determines the number of groups, time duration of each group, and how to divide stations among them. Furthermore, the AP is free to dynamically adapt these parameters. We hypothesize that the optimal group count, duration and station division depends on a wide range of scenario variables, such as number of stations, network load and traffic patterns.

The goal of this paper is to determine the optimal RAW parameters (i.e., group count, group duration, and station division) as a function of the network conditions. We consider optimal performance not only in terms of throughput, but also latency and energy-efficiency. The scenario under consideration is an IoT monitoring platform, where a large number of sensor stations upload data readings at various intervals. We consider this study the first step towards the development of intelligent grouping strategies that dynamically adapt RAW parameters based on the current network conditions. To achieve this goal, we have made several novel contributions. First, we have implemented a sub-1Ghz PHY model, the IEEE 802.11ah MAC protocol and its RAW feature in the ns-3 event-based network simulator, in order to accurately evaluate RAW performance. The simulation software is also available as open source[1] for other researchers to experiment with. Second, we have conducted an in-depth analysis of the RAW mechanism in order to determine its optimal parameters under a variety of scenarios in terms of throughput, latency and energy-efficiency.

The remainder of this paper is structured as follows. Section II introduces related research on IEEE 802.11ah. Section III provides an overview of the most prominent IEEE 802.11ah features, both on the PHY and MAC layer. Details on our ns-3 implementation model are provided in Section IV. In Section V, we provide the simulation results and evaluate the performance of RAW. Finally, conclusions and future work are discussed in Section VI.

II. Related work

Even though the IEEE 802.11ah standard has not been officially released, researchers have been investigating it already for a few years, both in terms of PHY and MAC layer aspects. Several works provide a deep overview of the key mechanisms of the protocol [1], [2], [3], [4], [5], including advantages and challenges in the design of physical layer and MAC schemes. In addition, Adame et al. [3] conduct a performance assessment of IEEE 802.11ah in four common machine-to-machine (M2M) scenarios, i.e. agriculture monitoring, smart metering, industrial automation, and animal monitoring.

Several recent works study physical layer aspects of 802.11ah and sub-1Ghz communications [6], [7], [8], [9], [10], [11]. Link budget, achievable data rate and optimal packet size of 802.11ah is studied by Hazmi et al. [6]. Li and Wang [11] present indoor coverage performance and time delay comparison between IEEE 802.11g and 802.11ah for wireless sensor nodes in M2M communications. Aust and Prasad [9] proposed a software defined radio (SDR) platform for 802.11ah experimentation, operating at the 900MHz ISM-band, and used it to perform an over-the-air protocol performance assessment. Casas and Papaparaskeva [10] introduce an architecture for a programmable IEEE 802.11ah Wi-Fi modem based on Cadence-Tensilica DSP. Moreover, Aust, Prasad and Niemegeers [8] built a real-time MIMO-OFDM testing platform for evaluating narrow-band sub-1GHz transmission characteristics.

More relevant to our research are works that study the MAC layer of 802.11ah, mainly focusing on performance of the RAW mechanism [12], [13], [14], [15], [16], [17], [18]. Ogawa et al. [13] propose a grouping method that exploits the random arbitration interface space number scheme and evaluate the average number of contending stations, throughput performance and energy-efficiency in saturation mode. Zheng et al. [14] study the impact of the grouping strategy on network performance and propose an analytical model to track the throughput under saturated traffic. Raeesi et al. [15], [16] provide an analytical model and simulation results to evaluate IEEE 802.11ah under saturated conditions in terms of throughput, packet latency and energy efficiency. Similarly, Qutab et al. [12] propose new holding schemes for the non-cross slot boundary case in the RAW mechanism, in which stations prevent their transmission from crossing the boundary of their allocated RAW slot, to improve saturated throughput and energy efficiency. Park [17] studies transmission latency and energy efficiency performance when RAW is applied to solve the hidden nodes problem for a large outdoor network. Finally, Park et al. [18] propose an algorithm to determine the optimal size of RAW slots, considering the relationship between the estimated number of devices and the size of RAW in saturation mode. However, their approach only considers number of upload stations as a relevant input variable to determine the RAW parameters, while we argue that other aspects, such as traffic load and pattern, are equally important. Moreover, they do not consider division of stations (i.e., each station randomly selects a RAW group).

In comparison to the research outlined above, the work presented in this paper is novel in several ways. First, our performance analysis is based on network simulation results, rather than analytical modeling, which results in higher fidelity in terms of MAC protocol behavior. Previously, only Raeesi et al. [15] performed actual packet-based network simulations. However, they considered only the saturated network state and did not evaluate the separate influence of different parameters on RAW performance. Second, we consider different network loads and not just the saturated state, which significantly influences the optimal RAW parameter values. Third, to our knowledge, we are the first to consider a broad range of RAW parameters (i.e., group count, duration and station division among groups), network parameters (i.e., number of stations, network load, traffic patterns) and evaluation metrics (i.e., throughput, latency and energy-efficiency) and to consider their respective influence on each other.

III. Overview of the 802.11ah protocol

IEEE 802.11ah operates at sub-1GHz, supporting long distance transmission, 8192 nodes connected to a single AP and high energy efficiency. These features make it an attractive standard for long-range IoT applications, such as sensor-based monitoring, smart meters and home automation. Throughout this section we highlight aspects of the standard that are important for our subsequent evaluation. For a more detailed overview of the standard, the reader is referred to existing literature [5].

A. PHY layer

The IEEE 802.11ah PHY layer inherits characteristics from 802.11ac and adapts them to sub-1Ghz frequencies. Its channel bandwidths range from 1 to 16 MHz, with only 1 and 2 MHz support mandatory. Operating at low frequency and narrow bandwidth allows 802.11ah to transmit at greater distances (up to 1 km) and with considerably less power consumption than traditional Wi-Fi technologies, which use frequencies in the 2.4 and 5 GHz bands.

In order to leverage the trade-off between range, throughput and energy efficiency, IEEE 802.11ah utilizes different

[1] https://www.uantwerpen.be/en/rg/mosaic/projects/ieee-802-11ah/

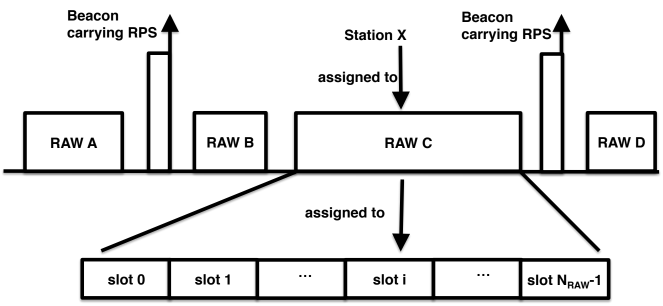


Fig. 1. Schematic representation of the restricted access window mechanism or RAW

TABLE I
802.11AH MCSS FOR 1, 2 MHZ, NSS=1, GI=8 μs

MCS Index	Modulation	Coding rate	Data rate (Kbps) 1 Mhz	2 Mhz
0	BPSK	1/2	300	650
1	QPSK	1/2	600	1300
2	QPSK	3/4	900	1950
3	16-QAM	1/2	1200	2600
4	16-QAM	3/4	1800	3900
5	64-QAM	2/3	2400	5200
6	64-QAM	3/4	2700	5850
7	64-QAM	5/6	3000	6500
8	256-QAM	3/4	3600	7800
9	256-QAM	5/6	4000	Not valid
10	BPSK	1/2 with 2x repetition	150	Not valid

sets of modulation and coding schemes (MCSs), number of spatial streams (NSS) and duration of the guard interval (GI). Supported coding schemes include binary conventional coding (BCC), which is mandatory, as well as the optional low density parity check (LDPC). Table I lists data rates and their MCSs when GI and NSS are 8 us and 1, respectively for 1 and 2 MHz bandwidth.

B. MAC layer

The MAC layer of IEEE 802.11ah, besides inheriting characteristics from IEEE 802.11ac, adds several novel functionalities, such as hierarchical organization, short MAC header, TIM segmentation, TWT and RAW, which all help it to address the requirements of dense IoT networks. To simplify operations and improve scalability with a huge number of associated stations, the range of Association Id (AID) values for stations is extended to 8192. The hierarchical organization mechanism organizes stations by AIDs according to a four-level structure, including pages, blocks, sub-blocks and stations. Stations are divided into N_P pages of N_B blocks each, each block includes N_{Sbu-B} sub-blocks of N_S stations each, these number are variable and can be configured by users. To reduce MAC header overhead, the 802.11ah standard defines a new backward incompatible format of shortened headers for data, management and the new control frames, both the legacy and new MAC headers can be used in 802.11ah.

In other 802.11 standards, beacons trigger power saving (PS) station contention for the channel, which is the bottleneck of the whole power management framework since stations have to wake up to listen to every beacon. IEEE 802.11ah introduces the TIM segmentation mechanism to split information transmitted in TIM into several segments and to transmit TIM segments separately. The AP uses the delivery traffic indication map (DTIM) beacon to broadcast to stations in which TIM segments it has pending data, between two consecutive DTIM beacons, there are many TIM beacons carrying TIM segment information. Stations belonging to these TIM segments only need wake up to listen to their corresponding TIM beacon, thus they can maintain a long power-saving state. Power consumption can be further reduced by TWT for stations transmitting data only occasionally. TWT stations can negotiate a time slot with the AP when they should wake up to exchange frames. Therefore they can stay in a power-saving state for very long periods of time between their TWT slots.

The restricted access window or RAW mechanism, which is the main focus of this paper, aims to reduce collisions and improve throughput when hundreds or even thousands of stations are simultaneously contending for channel access [19]. It restricts the number of stations that can simultaneously access the channel, by splitting them into groups and only allowing stations that belong to a certain group to access the channel at certain times. Figure 1 schematically depicts how RAW works. The airtime is split into intervals, each of which is assigned to one RAW group. Each interval is preceded by a beacon that carries a RAW parameter set (RPS) information element that specifies the stations that belong to the group, as well as the interval start time and duration. Moreover, each RAW interval can consist of multiple slots, over which the stations of the group are split evenly. As such, the RPS also contains the number of slots in each RAW interval and their duration. Outside of RAW intervals, the channel can be accessed by any station.

Different from previous IEEE 802.11 technologies, each station uses two back-off states for Enhanced Distributed Channel Access (EDCA) to manage transmission inside and outside its assigned RAW slot respectively. The first back-off function state is used outside RAW and the second is used inside RAW slots. For the first back-off state, the station suspends its back-off at the start of each RAW and restores it to resume back-off at the end of the RAW. For the second back-off state, stations start back-off with initial back-off state at the beginning of their own RAW slot and discard the back-off state at the end of their RAW slot.

IV. 802.11AH IMPLEMENTATION IN NS-3

NS-3 is a discrete-event network simulator, publicly available for research and development. It contains a collection of NetDevice objects, much like an actual computer contains separate interface cards for Ethernet, Wi-Fi, or Bluetooth. Currently, ns-3 comes with support for several IEEE 802.11 standards, including 802.11a, 802.11b, 802.11g, 802.11n and since recently 802.11ac. Their implementation is modular and consists of 4 main components:

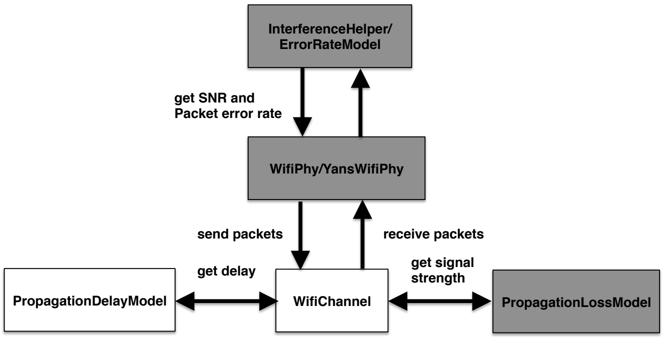


Fig. 2. NS-3 PHY models and interactions

- WifiChannel: An analytical approximation of the physical medium over which data is transmitted (i.e., the air in case of Wi-Fi), consisting of propagation loss and delay models.
- WifiPhy: The PHY part of the protocol, takes care of sending and receiving frames and determining loss due to interference.
- MacLow: Implements RTS/CTS/DATA/ACK transactions, the distributed coordination function (DCF) and enhanced distributed coordination function (EDCA), packet queues, fragmentation, retransmission and rate control.
- MacHigh: Implements management functions such as beacon generation, probing, association and authentication.

The former two comprise the PHY layer and the latter two the MAC layer. We implemented IEEE 802.11ah by adapting the 802.11ac version of the models. The remainder of this section provides a high level overview of our implementation. For more details the reader is referred to our previous work [20].

A. PHY layer

Figure 2 shows the components of the ns-3 PHY model. Our work in implementing 802.11ah focused on the components marked in the figure: InterferenceHelper/ErrorRateModel, WifiPhy/YansWifiPhy and PropagationLossModel.

1) WifiPhy/YansWifiPhy: We defined the modulation and coding schemes MCS0 to MCS9 for channel bandwidths 1, 2, 4, 8 and 16 Mhz (cf. Table I), while MCS10 is currently not supported by our implementation. Moreover, IEEE 802.11ah uses different packet formats than previous standards. As such, those formats were implemented, as well as the way of calculating the sending/receiving duration of preamble, header and payload.

2) InterferenceHelper/ErrorRateModel: Since 802.11ah defines a new packet format, the way of calculating SNR and error rate for 802.ah, which is based on the physical packet header and payload, is added in InterferenceHelper model. Our implementation supports both the YansErrorRateModel and NistErrorRateModel.

3) PropagationLossModel: This model determines the signal strength at the receiver based on the distance between sender and receiver. We implemented the indoor and outdoor propagation loss models for 802.11ah developed by Hazmi et al. [6]. The proposed indoor propagation loss model is the same as that of 802.11n, and the outdoor models include one for macro deployments and one for pico or hotzone deployments.

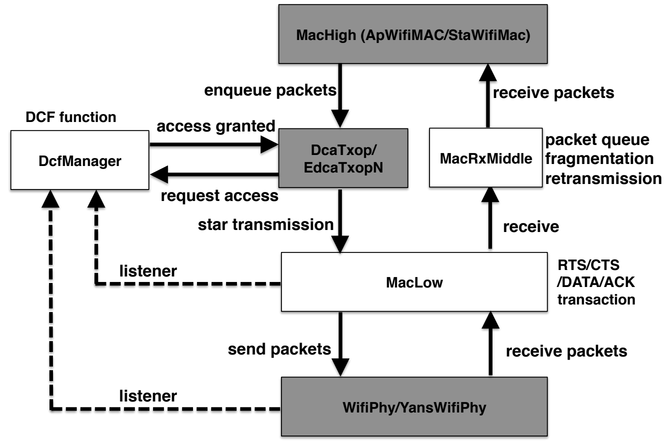


Fig. 3. NS-3 MAC models and interactions

B. MAC layer

Of the new features of IEEE 802.11ah listed in Section III, our simulator currently supports RAW. Figure 3 depicts the components of the Wi-Fi MAC layer in NS-3. Our implementation focuses mainly on the MacHigh and DcaTxop/EdcaTxopN components.

1) MacHigh: The new RPS element was added to the beaconing scheme in ApWifiMac, to carry RAW group information from the access point (AP) to the stations. We implemented a RAW information recognition module that reads RAW information carried by the beacon and uses it to control station behavior, i.e., making sure stations are not accessing the channel during RAW slots they do not belong to. Finally, since RAW assignment is based on the AID, which was previously not implemented in ns-3, we added an AID assignment scheme, which allows the AP to assign an AID to stations during the association exchange.

2) DcaTxopN/EdcaTxopN: The double back-off mechanism, which is new in IEEE 802.11ah, was implemented in the DcaTxop and EdcaTxopN models, supporting both QoS and non-QoS data transmissions. Based on the behaviors set in the MacHigh component, stations start to contend for the channel in the appropriate period with the proper back-off state.

V. Results and Evaluation

In this section we outline our results obtained using the ns-3 implementation of IEEE 802.11ah. The experimental setup is described, and the influence of several network-related parameters on RAW performance is evaluated.

A. Experimental setup

We consider an IoT sensor-based monitoring scenario, where a large number of battery-powered sensors send measurements to a back-end server (through the AP) at specific

TABLE II
DEFAULT PHYSICAL LAYER PARAMETERS USED IN OUR EXPERIMENTS

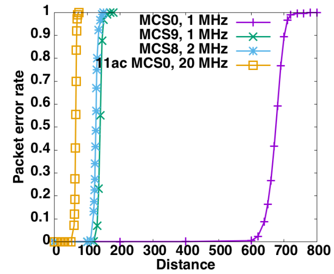
Parameter	Value
Frequency (Mhz)	900
Transmission power (dBm)	0
Transmission gain (dB)	0
Reception gain (dB)	3
Noise Figure (dB)	3
Coding method	BCC
Propagation loss model	Outdoor, macro [6]
Error Rate Model	NistErrorRate, YansErrorRate

TABLE III
DEFAULT MAC LAYER PARAMETERS USED IN OUR EXPERIMENTS

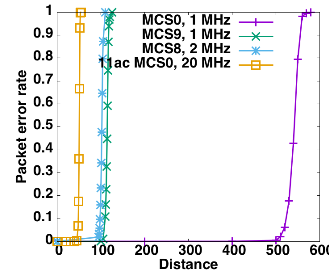
Parameter	Value
CWmin	15
CWmax	1023
AIFSN	3
Traffic access categories	AC_BE
Payload size (bytes)	256
MAC header type	legacy header
RTS/CTS	not enabled
Beacon Interval	Equal to RAW group duration
RAW group duration (s)	0.1
Number of slots per group	1
Cross slot boundary	enabled
Station distribution	randomly
Wi-Fi mode	MCS8, 2 Mhz
Rate control algorithm	constant

time intervals. The default PHY and MAC layer parameters are shown in Tables II and III respectively. Note that these are the default parameter values, and some of them take different values in specific experiments (e.g., the Wi-Fi MCS mode), which is explicitly mentioned. Given the low-power nature of battery powered sensors, transmission power is limited to 0 dBm. Like 802.11ac, 802.11ah uses binary conventional coding (BCC) and low density parity check coding (LDPC) as forward error correction (FEC) schemes to improve transmission range. The packet payload size is fixed to 256 bytes. Although we did perform experiments with larger payload sizes, they were omitted from the paper as results in terms of optimal RAW parameters did not show significant differences. The main difference is that a larger payload results in reduced header overhead and therefore increased throughput closer to the theoretical maximum. Given the IoT scenario under study, where sensors send data readings consisting of a few bytes to the AP, we consider a small payload size to be the most realistic.

RAW performance is evaluated in terms of three metrics: throughput, latency and average active time per station (i.e., energy efficiency). Throughput is calculated based on the successfully received packets by AP per seconds and latency is defined as the average time between a packet entering the transmit buffer of the station and arriving at the network layer of the AP. As ns-3 currently does not support 802.11 energy-efficiency mechanisms, such as TIM, we estimate energy-consumption as the sum of timeslot durations during which stations can (i.e., inside their RAW slot) and want to (i.e., send buffer is not empty) send data. As such, stations are assumed to sleep both outside their assigned RAW slots and inside their RAW slots when their send buffer is empty. Since both RAW groups and slots restrict the number of stations that can simultaneously contend for channel access, it was decided to configure each RAW group to consist of a single slot, for simplicity and improved interpretability of the results. For an evaluation of the effect of RAW slots rather than groups on performance, we refer the reader to our previous work [20]. During each simulation run, up to 512 sensors generate packets over a 600 s period. When this period ends, the simulation continues until all send buffers are empty and all remaining packets have been received. The transmit queues of stations are configured to be large enough so that no packets will be dropped during simulation due to buffer overflow. In order to avoid the hidden node problem from affecting the results, stations are randomly placed in a circle around the AP within a distance of at most half the maximum transmission range. The influence of hidden nodes on RAW was studied by Park [17]. No rate control algorithm (RCA) is used on the MAC layer. Moreover, by default the MCS8 data rate is used with a 2 Mhz bandwidth. All results are averaged over 10 iterations, with the variability of results over these iterations quantified using the relative standard error (RSE). Finally, the depicted throughput and latency results are averaged over the steady state period between 100 and 600 s simulation time.



(a) YansErrorRate Model



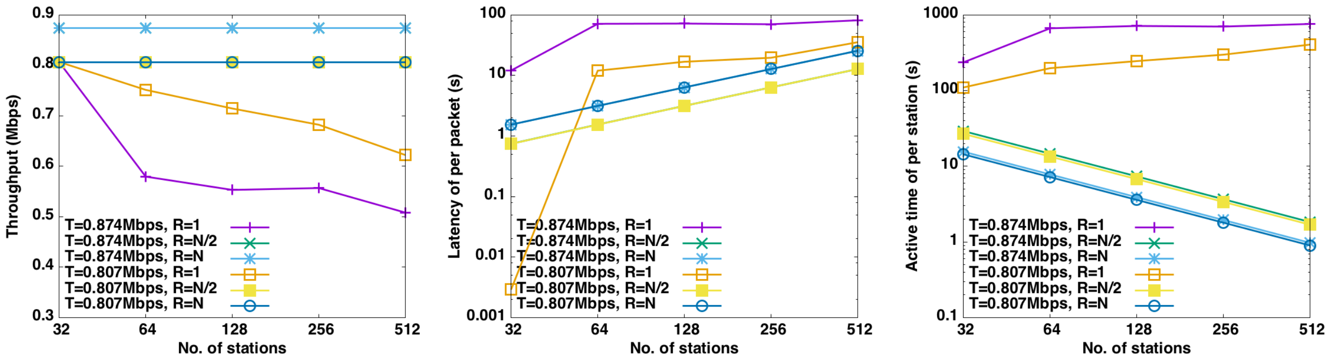
(b) NistErrorRate Mode

Fig. 4. Packet error rate as a function of uplink distance using the Yans and Nist error rate models, for various IEEE 802.11ah Wi-Fi modes and compared to IEEE 802.11ac

B. IEEE 802.11ah physical layer evaluation

This section evaluates physical layer packet error rate as a function of distance for different 802.11ah Wi-Fi MCS modes for outdoor macro deployments (cf. Table I), using the parameters defined in Table II. As a benchmark, we compare to 802.11ac in MCS0 mode, using the same physical parameters, which has a theoretical data rate of 6.5 Mbps for a 20 Mhz channel.

Figure 4a shows transmission range of the different Wi-Fi modes when YansErrorRateModel is used, IEEE 802.11ah can transmit over distances of up to 640 m with a packet error rate below 10% and up to 670 m with an error rate below 50% using MCS0 with 1 Mhz bandwidth, which achieves data rates up to 300 kbps. Results also clearly show that using modes that provide higher data rates significantly reduces the maxi-



(a) Throughput (b) Latency (c) Power consumption

Fig. 5. Influence of number of stations (N), number of RAW groups (R) and different traffic loads (T) on throughput, latency and power consumption

mum transmission distance. For example, MCS9 with 1 Mhz bandwidth and MCS8 with 2 Mhz bandwidth are capable of achieving a data rate up to 4 Mbps and 7.8 Mbps respectively, but they only allow error-free transmission up to 130 and 110 m respectively. For comparison, IEEE 802.11ac only has a range of up to 60 m with a data rate of 6.5 Mbps and an error rate of 10% (at an equal 0 dBm transmission power). As shown in Figure 4b, transmission range becomes shorter when NistErrorRateModel is applied, around 150, 20 and 10 m are lost for Wi-Fi modes MCS0 with 1 Mhz, MCS9 with 1 Mhz and MCS8 with 2 Mhz bandwidth respectively. Experimental results have shown that the Nist model is the more realistic of the two [21]. It should be noted that the 1 km range promised by 802.11ah could potentially be realized using the MCS10 mode together with LDPC coding, since it is capable of bridging higher distances. This mode's implementation is left for future work.

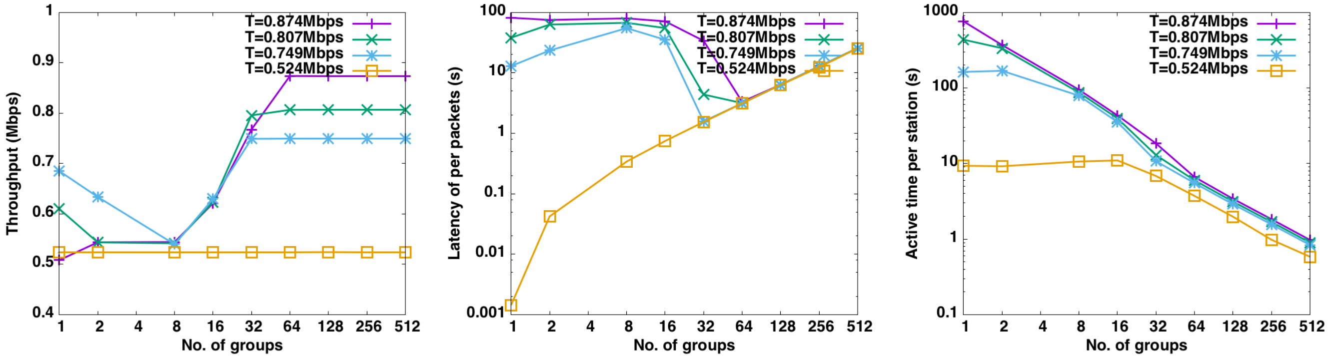
C. Homogeneous traffic patterns

The goal of this section is to assess the influence of the total number of stations connected to the AP and total traffic load on the optimal number of RAW groups. The stations have a homogeneous traffic pattern, each sending one packet every X seconds, with $X = N \times L/T$. Here, N, L and T equal the number of stations, the payload size (i.e., 256 bytes) and the total traffic load (i.e., 0.874, 0.807, 0.749 and 0.524 Mbps) respectively. Given the relatively small payload, the maximum throughput that can be achieved using the MCS8 with 2 Mhz bandwidth mode equals about 1 Mbps at the MAC layer. As such, 0.874 and 0.807 Mbps equal a relatively high network load, while the other two result in a medium and low load.

Figure 5 depicts performance in terms of the three evaluation metrics as a function of number of stations, for two traffic loads and 3 RAW group counts. The number of RAW groups R either equals 1 (i.e., no RAW), the number of stations divided by two, or the number of stations (i.e., no contention occurs). The graphs clearly show that a lack of RAW (i.e., $R = 1$) results in poor scalability in dense network deployments, in terms of throughput, latency and power consumption. For a high traffic load (i.e., $T = 0.874$), performance degrades already in a network of 64 stations, with a throughput drop of over 34%, an average latency increase of up to 71 seconds per packet, and increased rather than decreased power consumption.

In contrast, when using $N/2$ and N RAW groups, even for 512 stations, the throughput almost remains unchanged, the latency stays below 13 s and 26 s respectively, and power consumption decreases with more stations. The reason is straightforward, splitting stations into RAW groups reduces contention, and in turn collision probability and retransmissions. Such retransmissions clearly decrease throughput and increase latency. Moreover, the use of RAW allows stations to sleep outside their slots, which obviously results in decreased power consumption as the number of groups increases. Without RAW, increasing the number of stations requires them to contend longer before they are able to send their messages, thus reducing sleep periods. The RSE of throughput, latency and power consumption are below 2.5%, 16.78% and 8.6% respectively, with the exception of the following cases for $R = 1$: 32 and 64 stations with $T = 0.874$, and 64–512 stations with $T = 0.807$. For these two cases, the RSE of throughput varies from 11.9% to 21.1% which implies the network is in the unstable state which results in higher variability among experiments. The RSE of latency and power consumption range from 37.3% to 190.7% and from 30.8% to 111.86% respectively. This high variability is caused by the infinite transmit queue of stations. As the rate of packets is on the edge of what is attainable, a slight decrease in achievable throughput causes a growing transmit queue and therefore extremely long queuing times. It also increases collision probability, which in turn results in greater power consumption. As such, the use of infinite transmit queues cause small variations in throughput to result in huge variations in latency and energy consumption.

The reason $R = N$ results in similar throughput as $R = N/2$ but a higher latency can be explained as follows. Specifically, the MAC layer of the stations continuously receives new packets from the application layer and puts them in the



(a) Throughput (b) Latency (c) Power consumption

Fig. 6. Influence of number of RAW groups and different traffic loads on throughput, latency and power consumption for 512 stations

TABLE IV
OPTIMAL NUMBER OF RAW GROUPS IN TERMS OF THROUGHPUT, LATENCY AND POWER CONSUMPTION FOR DIFFERENT TRAFFIC LOADS (T) AND NUMBER OF STATIONS (N)

N	T = 0.874 Mbps			T = 0.807 Mbps			T = 0.749 Mbps			T = 0.524 Mbps		
	throughput	lateny	power	throughput	lateny	power	throughput	lateny	power	throughput	lateny	power
512	64–512	64	512	64–512	64	512	32	32	512	1–512	1	512
256	32–256	32	256	32–256	32	256	16	16	256	1–256	1	256
128	16–128	16	128	16–128	16	128	1, 8–128	1	128	1–128	1	128
64	8–64	8	64	1, 8–64	1	64	1–64	1	64	1–64	1	64
32	8–32	8	32	1–32	1	32	1–32	1	32	1–32	1	32

transmit queue. For example, if N stations are divided into R RAW groups whose duration is D seconds, then the stations in one RAW group as a whole get $M = D \times R \times N/(R \times X) = D \times N/X$ new packets in total between two consecutive assigned RAW slots (with X the sending interval of each station). Those packets are to be sent in one RAW slot of D seconds by N/R stations. Although the number of new packets does not change with R, the number of stations N/R contending for the channel simultaneously is reduced when the number of RAW groups R increases. Therefore, increasing the number of RAW groups results in higher throughput until a certain value. However, too many RAW groups lead to packets staying longer in the transmit queue, which increases latency.

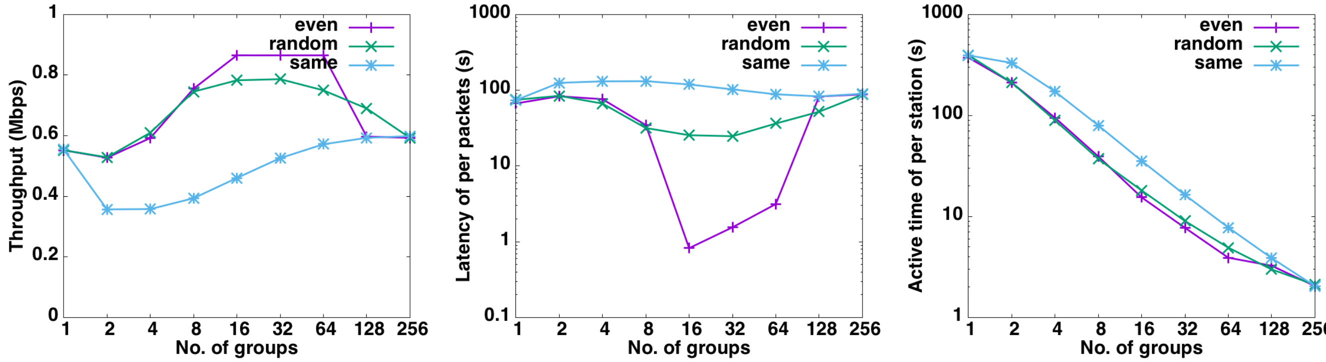
Figure 6 zooms in on RAW performance for 512 stations, plotting the evaluation metrics as a function of number of RAW groups, for four different traffic loads. The important conclusion here is that the optimal number of RAW groups depends on the evaluation metric and traffic load. Specifically, for a low load (i.e., $T = 0.524$), the best solution is actually not to use RAW (i.e., $R = 1$), while for $T = 0.749$, 0.807 and 0.874, it is best to use 32, 64 and 64 groups respectively when optimizing throughput and latency and to use 512 when minimizing power consumption.The RSE of throughput, latency and power consumption are below 1.2%, 5% and 2.6% in most cases, except for $R = 1$ and 2 and traffic loads $T = 0.807$ and 0.749, where the RSE of throughput, latency and power consumption goes up to 20.6%, 161.5% and 148.9% respectively.

Finally, Table IV gives an overview of the optimal number of RAW groups in terms of the three evaluation metrics and as a function of number of stations and traffic load. The table shows that the optimal number of RAW groups also depends on the total number of stations. For example, for 128 stations and a traffic load of 0.807 Mbps, the optimal number of RAW groups becomes $16--128$ for throughput, 16 for latency and 128 for power consumption.

D. Heterogeneous traffic patterns

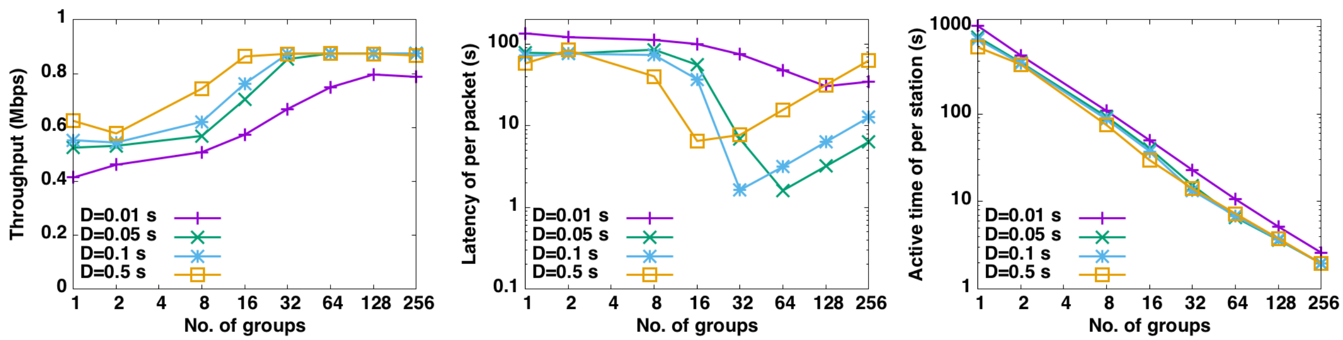
In this section, we study how heterogeneous traffic patterns influence the optimal number of RAW groups. Stations still send data every X seconds, but now X is not the same for all sensors, and is uniformly at random chosen from the set $\{0.25, 0.5, 2, 10\}$. We split stations among RAW groups in 3 ways: (i) each RAW group contains an equal number of stations with the same traffic intensity (i.e., even), (ii) stations are split across them randomly (i.e., random), or (iii) each group only contains stations of one type (i.e., same).

The results are depicted in Figure 7, which clearly reveals that how stations are split among groups significantly affects performance and optimal number of RAW groups. Evidently, splitting stations evenly among RAW groups results in the best performance. This is because when stations are grouped per traffic intensity, groups consisting of low intensity stations only may not have data to send during their RAW slots,



(a) Throughput (b) Latency (c) Power consumption

Fig. 7. Influence of number of RAW groups on throughput, latency and power consumption for different station distributions among groups and 256 stations



(a) Throughput (b) Latency (c) Power consumption

Fig. 8. Influence of number of RAW groups and RAW group duration on throughput, latency and power consumption for 256 stations and $T = 0.874$

resulting in wasted airtime that could have been used by high-intensity stations. The difference is significant, as evenly splitting stations results in a throughput up to 45% higher and a latency up to 90 times lower (i.e., more than 90 versus 1 second). These results prove the need for accurate traffic predictions of stations when developing a good RAW grouping strategy, so that traffic load can be spread as evenly as possible among groups. It should be noted that stations can not be split evenly among RAW groups when R=128, since there are only two traffic patterns per group. The RSE of throughput, latency and power consumption are below 3.0%, 18.0% and 18.7%.

E. Influence of RAW duration

In previous sections, we assumed a fixed RAW group duration of 0.1 s. Here, we study how performance is influenced by RAW duration, by evaluating four different RAW duration values (i.e., 0.01, 0.05, 0.1 and 0.5 s), and studying its synergy with number of RAW groups. The results, as a function of number of RAW groups, are depicted in Figure 8, for 256 stations and a total traffic load $T = 0.874$ Mbps.

The results show that a RAW duration values longer than a certain threshold are generally better for throughput, though a very short RAW duration of 0.01 s is unable to achieve the maximum throughput. However, in terms of latency a very high RAW duration (i.e., 0.5 s) performs worse, as stations need to wait longer until their RAW slot comes up. In terms of power consumption there are no significant differences. As such, the optimum RAW duration that is capable of both maximizing throughput and minimizing latency, can be found in the middle (i.e., given the used input parameters between 0.05 and 0.1 s). Moreover, it should be noted that the optimal number of RAW groups actually depends on the RAW duration. As such, selecting both RAW group count and duration simultaneously is a non-trivial optimization problem with mutual dependencies. The RSE of throughput, latency and power consumption is below 1.4%, 13.0% and 4.9% in most cases, except for $R = 1$ with 0.5 s RAW duration, where the RSE of throughput, latency and power consumption is 17.6%, 55.1% and 39.0%.

An important reason for the performance difference between different RAW duration values is that stations have to stop their back-off at the end of their assigned RAW slot and restart back-off at the beginning of their next slot. Switching between back-off states too often degrades RAW performance. Therefore, very short RAW duration values, which also increases number of beacons, should be avoided. Moreover, very longer RAW duration values reduce this kind of overhead, increasing throughput at the cost of higher latency, since stations have to wait longer until their slot comes up.

Finally, the RAW duration parameter provides another means to optimize in face of heterogeneous traffic patterns. Instead of attempting to divide traffic evenly among groups, the duration of groups with high traffic demands could be increased at the expense of those with lower demands.

VI. Conclusion and future work

In this paper, we describe our open source implementation of the IEEE 802.11ah PHY and MAC layer in the ns-3 event-based network simulator. The main goal is to evaluate the novel RAW mechanism in terms of throughput, latency and energy-efficiency. We assess the influence of number of stations, traffic load and traffic distribution on the optimal values of number of RAW groups and their duration. This thorough evaluation results in guidelines for the development of dynamic RAW grouping strategies in a variety of IoT network scenarios with varying conditions.

Simulation results reveal three key point on RAW. First, it acts as an effective solution to boost performance in dense IoT networks, showing a throughput increase of up to 70%, a latency reduction of up to 96% and a power consumption decrease of over 99% in the scenario under evaluation with 512 sensor stations. Second, the optimal number of RAW groups and their duration varies depending on the evaluation metrics and is influenced by the number of stations and the traffic load. Third, in order to maximize performance it is necessary to evenly balance traffic load across RAW groups or select a group duration relative to its traffic load.

Our conclusions support the hypothesis that the optimal RAW parameters (i.e., the number of groups, station distribution across groups and group duration) cannot be chosen statically. Consequently, our future work will focus on the design of intelligent strategies that automatically adapt RAW parameters in face of network dynamics.

In summary, RAW significantly improves throughput, latency and power consumption in highly dense power-constrained IoT networks. However, intelligent adaptive RAW grouping strategies are needed to maximize the potential gain of the mechanism.

Acknowledgment

The authors would like to thank Sébastien Deronne, for his valuable help in implementing IEEE 802.11ah in ns-3.

References

[1] Y. Zhou, H. Wang, S. Zheng, and Z. Z. Lei, "Advances in IEEE 802.11ah standardization for machine-type communications in sub-1GHz wlan," in *2013 IEEE International Conference on Communications Workshops (ICC)*. IEEE, 2013, pp. 1269–1273.

[2] W. Sun, M. Choi, and S. Choi, "IEEE 802.11ah: A long range 802.11 wlan at sub 1 ghz," *Journal of ICT Standardization*, vol. 2, no. 2, pp. 83–108, 2014.

[3] T. Adame, A. Bel, B. Bellalta, J. Barcelo, and M. Oliver, "IEEE 802.11ah: the WiFi approach for M2M communications," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 144–152, 2014.

[4] E. Khorov, A. Lyakhov, A. Krotov, and A. Guschin, "A survey on IEEE 802.11ah: An enabling networking technology for smart cities," *Computer Communications*, vol. 58, pp. 53–69, 2015.

[5] M. Park, "IEEE 802.11ah: sub-1-ghz license-exempt operation for the internet of things," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 145–151, 2015.

[6] A. Hazmi, J. Rinne, and M. Valkama, "Feasibility study of IEEE 802.11ah radio technology for IoT and M2M use cases," in *2012 IEEE Globecom Workshops*. IEEE, 2012, pp. 1687–1692.

[7] S. Aust and T. Ito, "Sub 1GHz wireless LAN propagation path loss models for urban smart grid applications," in *2012 International Conference on Computing, Networking and Communications (ICNC)*. IEEE, 2012, pp. 116–120.

[8] S. Aust, R. V. Prasad, and I. G. M. M. Niemegeers, "Performance study of MIMO-OFDM platform in narrow-band sub-1 GHz wireless LANs," in *11th International Symposium on Modeling & Optimization in Mobile, Ad Hoc & Wireless Networks (WiOpt)*. IEEE, 2013, pp. 89–94.

[9] S. Aust and R. V. Prasad, "Advances in wireless M2M and IoT: Rapid SDR-prototyping of IEEE 802.11ah," in *IEEE Local Computer Networks Conference*, 2014.

[10] R. A. Casas, V. Papaparaskeva, R. Kumar, P. Kaul, and S. Hijazi, "An IEEE 802.11ah programmable modem," in *IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2015.

[11] M. Li and D. Wang, "Indoor coverage performance comparison between IEEE 802.11g and IEEE 802.11 ah of wireless nodes in M2M network," in *Proceedings of the 1st International Conference on Internet of Vehicles*. Springer International Publishing, 2014, pp. 211–217.

[12] M. Qutab-ud din, A. Hazmi, B. Badihi, A. Larmo, J. Torsner, and M. Valkama, "Performance analysis of IoT-enabling IEEE 802.11ah technology and its RAW mechanism with non-cross slot boundary holding schemes," in *IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2015.

[13] K. Ogawa, M. Morikura, K. Yamamoto, and T. Sugihara, "IEEE 802.11ah based M2M networks employing virtual grouping and power saving methods," *IEICE Transactions on Communications*, vol. E96-B, no. 12, pp. 2976–2985, 2013.

[14] L. Zheng, L. Cai, J. Pan, and M. Ni, "Performance analysis of grouping strategy for dense IEEE 802.11 networks," in *2013 IEEE Global Communications Conference (Globecom)*, 2013, pp. 219–224.

[15] O. Raeesi, J. Pirskanen, A. Hazmi, T. Levanen, and M. Valkama, "Performance evaluation of IEEE 802.11ah and its restricted access window mechanism," in *IEEE International Conference on Communications Workshops (ICC)*, 2014, pp. 460–466.

[16] O. Raeesi, J. Pirskanen, A. Hazmi, J. Talvitie, and M. Valkama, "Performance enhancement and evaluation of IEEE 802.11ah multi-access point network using restricted access window mechanism," in *IEEE International Conference on Distributed Computing in Sensor Systems*, 2014, pp. 287–293.

[17] M. Park, "IEEE 802.11ah: Energy efficient MAC protocols for long range wireless LAN," in *2014 IEEE International Conference on Communications (ICC)*. IEEE, 2014, pp. 2388–2393.

[18] C. W. Park, D. Hwang, and T.-J. Lee, "Enhancement of IEEE 802.11ah MAC for M2M communications," *IEEE Communications Letters*, vol. 18, no. 7, pp. 1151–1154, 2014.

[19] K. Shin, I. Park, J. Hong, D. Har, and D.-h. Cho, "Per-node throughput enhancement in Wi-Fi densenets," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 118–125, 2015.

[20] L. Tian, S. Latré, and J. Famaey, "Implementation and validation of an IEEE 802.11ah module for ns-3," in *Workshop on ns-3 (WNS3)*, 2016.

[21] G. Pei and T. R. Henderson, "Validation of ofdm error rate model in ns-3," *Boeing Research Technology*, pp. 1–15, 2010.