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Performance comparison between Slotted IEEE 802.15.4 and IEEE 802.11ah in IoT based applications

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Abstract—**In this paper, we present a performance comparison between IEEE 802.15.4 which specifies the physical and media access control layers for low-rate wireless personal area networks (LR-WPANs) like ZigBee, and IEEE 802.11ah, a new global WLAN standard using sub-1 GHz frequency band, in terms of throughput and energy consumption. Both standards are targeting low power applications with relatively high number of nodes as in IoT and M2M applications. The simulations results demonstrate the better performance of IEEE 802.11ah throughput mainly in congested networks. However in particular cases, the IEEE 802.15.4 outperforms the IEEE 802.11ah from energy consumption point of view.**

Keywords - IEEE 802.15.4, IEEE 802.11ah, Slotted CSMA/CA, IoT, Throughput, Energy consumption, Fairness measure

I. Introduction

THE rapid development of new technologies specially in the wireless area has affected people's life style and brought new habits and recreations to their societies. It is expected that for each person, 1000 wireless devices will be available by year 2020 [1]. This will change the concept of connectivity from anywhere, any time for everyone to connectivity for anything by introducing internet of things [2]. The term of internet of things (IoT) was introduced for the first time by Kevin Ashton in 1999 [3] in which the vision of the future internet changes to a direction where the objects become an important part of the internet. The objects are uniquely identified and associated to the network with their known position and status. In addition, adding services and intelligence to this concept will expand the future internet which consequently affects the future life and the environment [4].

In other word, IoT consists of heterogeneous sets of devices using various communication strategies between them and different data servers. Therefore, it is expected that billions of objects will communicate to each other physically and virtually through the internet. When these numbers of devices, usually very high, are connected to the Internet to form the IoT network, the first challenge is to adjust the basic connectivity and networking layers between them. On the other hand, end point users must operate with battery for many years since replacing them is impossible due to high number devices. Currently, we witness an increasing momentum for wireless industry to explicitly take into account the key IoT requirements, such as lower complexity, reduced implementation and operation costs, broader coverage range and higher energy efficiency. The IEEE 802.15.4 standard is presently being used for wireless sensor networks and ZigBee applications characterized by similar requirements as in IoT and M2M applications. The ZigBee technology based on IEEE 802.15.4 standard is mainly targeting LR-WPAN applications[5][6]. It is also intended to be simpler and less expensive than other WPANs.

However, generally there is a lack of uniform support of the divers IoT requirement. Therefore, the need for a new wireless technology with simplified architecture, higher energy efficiency and uniform support of IoT based applications, motivated for a new amendment, namely the IEEE 802.11ah [7][8]. The IEEE 802.11ah is being developed to satisfy the IoT requirements, while maintaining acceptable user experience when coexisting with the legacy IEEE 802.11 releases. The IEEE 802.11ah is currently under standardization and it has not been released yet. One of the functional requirements of the IEEE 802.11ah is to enable coexistence with IEEE 802.15.4 and IEEE 802.15.4g [9]. In this paper we aim to present a performance comparison between IEEE 802.15.4 and IEEE 802.11ah standards by evaluating the energy consumption and the network throughput.

The remainder of this paper is organized as follows: The section II gives an overview of the IEEE 802.15.14 and IEEE 802.11ah standards. Then section III describes the simulation settings for both standards and in section IV the result of the simulations are shown. Finally conclusions are drawn in section V.

II. Overview

A. Overview of the IEEE 802.15.4

Regarding the ZigBee technology, which is based on the IEEE 802.15.4 standard and targeting low rate Wireless Personal Area Network (WPAN) applications, the MAC and PHY

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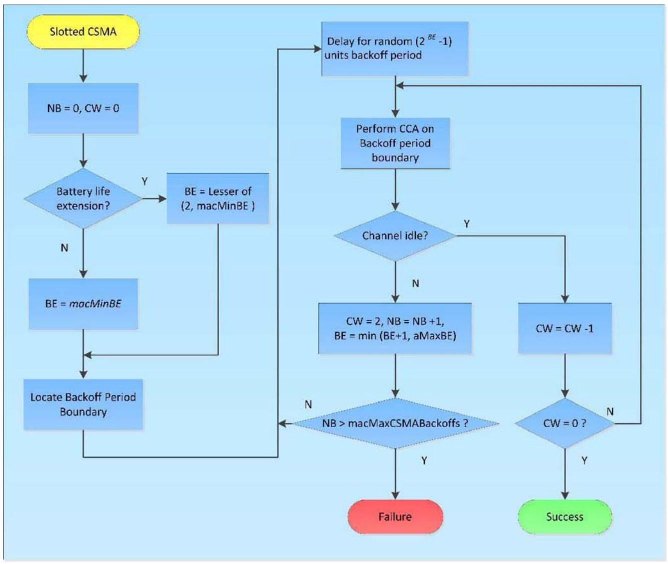


Fig. 1. Slotted SCMA/CA Algorithm in IEEE 802.15.4.

layers are described in [5] and [6]. The IEEE 802.15.4 standard defines two different channel access modalities: the Beacon-enabled modality which employs slotted CSMA/CA and the Beacon-less CSMA/CA which utilizes unslotted CSMA/CA. In this paper Slotted CSMA/CA is considered. In the Slotted CSMA/CA of IEEE 802.15.4 MAC, the coordinator referred to as PAN station broadcasts beacons to nodes in super-frame structure to synchronise them. The super-frame structure includes active and inactive sections. The active part further divided in two parts: Contention Access Period (CAP) and Contention Free Period (CFP). The CAP is an opportunity to access to the channel without contention which is assigned for the nodes with delay sensitive applications which are granted to them by AP, however, in CAP nodes contend to obtain access to medium. Considering slotted CSMA/CA, the process of sending a packet in MAC sub-layer is as follows: Four variables are initialized by the MAC, which are the contention window (*CW*=0), the number of backoffs (*NB*=0), the backoff exponent (*BE*=*macMinBE*), and number of retransmissions (*RT*=0). First of all, MAC chooses a random number for a backoff period in the range of $[0, 2^{BE}-1]$ units and delays the process until to decrement to zero. When the backoff is zero, the node performs the first clear channel assessment (CCA). If the two consecutive CCA are idle, the node sends the packets and waits for the acknowledgement (ACK) from the AP. Otherwise if one of the CCA is busy, *NB* and *BE* increment by one till their maximum values which are *macMaxCSMABackoffs* and *macMaxBE*, respectively and whole process commences again. If *NB* exceeds the *macMaxCSMABackoffs*, the packet is discarded in the consequence of the channel access failure. Furthermore, if the node does not receive the ACK, the *RT* increments by one till the maximum value (*macmaxFrameRetries*). In the case of exceeding *macMaxFrameRetries*, the packet is discarded and *RT* is initialized to zero. In the case of receiving ACK, the *CW* is initialized to zero and *BE* to *macMinBE* and MAC follows the CSMA/CA mechanism to re-access the channel. Figure 1 shows the flowchart of the CSMA/CA algorithm in IEEE 802.15.4.

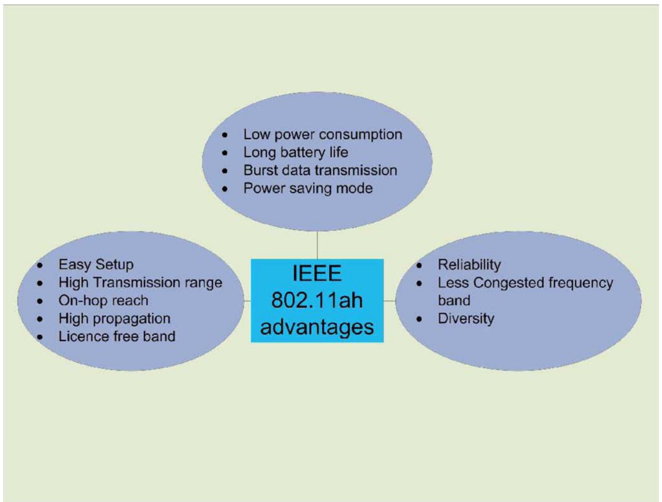


Fig. 2. Main advantages of a new sub 1 GHz IEEE 802.11ah [7].

B. Overview of the IEEE 802.11ah

The IEEE 802.11ah standard is one of the candidate standards for IoT and Machine to Machine (M2M) applications which is still in its preliminary stage of development. The IEEE 802.11ah task group is still developing the system design by collecting proposals which is expected to be available by year 2014. The target is to design a global Wireless LAN (WLAN) standard that operates in Sub-1 GHz frequency in ISM band and enables the WLAN devices to access to the network to send burst-data [7]. The exact operating bands consist of one or more from the following bands: 863-868.6 MHz (Europe), 950.8 MHz -957.6 MHz (Japan), 314-316 MHz, 430-432 MHz, 433.00-434.79 MHz (China), 917-923.5 MHz (Korea) and 902-928 MHz (USA).

By exploiting the sub-1-GHz spectrum, the coverage area of the IoT network will be increased which consequently improves the efficiency of many applications such as wireless sensor networks, and M2M. On the other hand, due to low path loss as a consequence of the lower frequency, energy consumption of the network can be reduced. In addition, by using simplified hardware-structure for the IoT device components, achieving low cost technology is also possible. All in all, these attributes make this band interesting in this regard. Figure 2 shows some advantages of IEEE 802.11ah.

The main functional requirements for IEEE 802.11ah, which is described in [10], are the following:

- The coverage range up to 1000 m.
- Data rate of 100 kbps and more.
- Compatible with the 802.11 WLAN legacies.

The target transmission range is very high compared to other technologies like ZigBee and Bluetough but in contrast, the objective data rate is relatively low compared to legacy IEEE 802.11 standards. The third requirement points out that the new standard should maintain the 802.11 WLAN users experience. This standard will be interoperable and compatible with the legacy standards like IEEE 802.11ac [11]. It means that the IEEE 802.11ah will be the adapted version of the

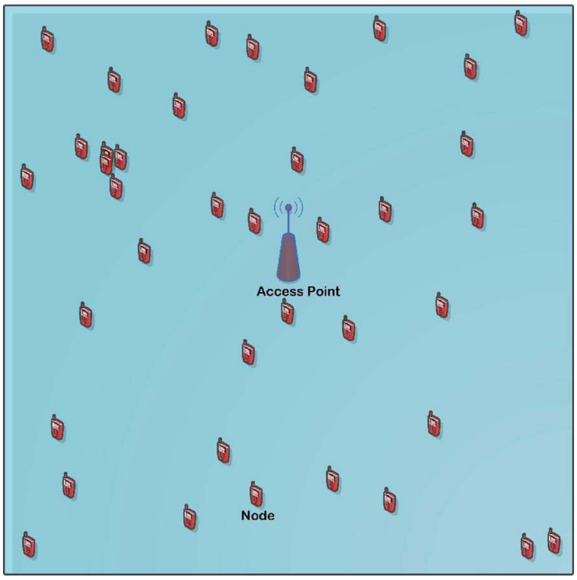


Fig. 3. Layout of randomly distributed nodes in the simulations. The AP is located in the middle of the playground. Other nodes are located in a uniformly distributed manner.

IEEE 802.11 legacy to meet the aforementioned requirements. However several required parameters of the IEEE 802.11ah are already available which makes it possible to simulate the performance of the standard.

The basic access to the medium in IEEE 802.11ah is using the Distributed Coordination Function (DCF) based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The DCF scheme can use two different mechanisms, one of them is the two-way handshaking technique known as basic access mechanism and the other one is utilizing a four-way handshaking technique known as RTS/CTS method. In the basic access mechanism, the immediate transmission of a packet, after a random interval called backoff Window, is responded with a positive acknowledgement (ACK) by the receiver. The sender will consequently be aware of successful transmission. In the RTS/CTS method each node having a packet to send, starts to reserve the channel by sending a RTSframe. Then, the receiver node acknowledges the RTS by sending a CTS frame. The normal transmission of the packet and acknowledgment take place after this process. This method increases the performance of the system by decreasing the collision duration when the nodes send large payload size. Since the collision might occur only on RTS frame which has a small size.

III. SIMULATION SETTINGS

The OMNeT++ simulator is chosen for this study which is a C++-based discrete event simulator and useful for simulating the communication networks, and other distributed and parallel systems. The OMNeT++ is an open-source simulator which is being used in academies, universities, and research-oriented institutes [12].

The main goal of this work is to discover the performance difference between the two standards. Hence, the throughput and energy consumption measures of the standards are studied and the performance of their PHY and MAC layers are

TABLE I. COMMON SETTINGS FOR BOTH STANDARDS.

Thermal noise	-111 dBm
Energy consumption in Transmission	255 mW
Energy consumption in receiving and channel sensing	135 mW
Energy consumption in idle	1 mW
Size of the payload	256 Bytes
Traffic	Uplink
Size of the playground	156 m * 156 m

TABLE II. SETTINGS FOR IEEE 802.15.4.

Bit rate	250 kbps
macMinBE	3
macMaxBE	5
macMaxCSMABackoffs	4
macMaxFrameRetries	3
Physical Header	5 Bytes
MAC Header	10 Bytes
ACK	11 Bytes
Backoff period	320 us
CCA	128 us
Receiver sensitivity	-85 dBm

compared to one another. The rest of this section describes the main settings and assumptions.

A. Simulation Environment

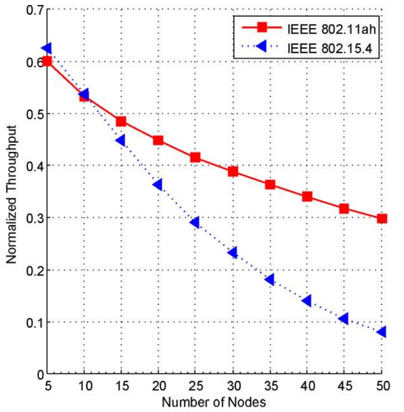
This paper simulates PHY and MAC layers performance of IEEE 802.15.4 and IEEE 802.11ah standards in sub-1GHz. In order to maximize the throughput in IEEE 802.15.4, we assume that beacon interval is very long and no inactive part has been utilized; also CFP period has been removed. One AP has been modelled and all the traffic is uplink meaning that each node transmits the packet to the AP and receives acknowledgment by the AP. Likewise, for the IEEE 802.11ah network, we assumed that we have one AP served by a variable number of sensors or stations (STA), i.e. the traffic is mainly uplink with a payload size of 256 bytes. The basic access mechanism is employed in this study due to using the small payload size.

Since the fairness of the comparison is an important factor, some assumptions and manipulations are taken into account in order to make the comparison as fair as possible. For instance, the size of payload is chosen 256 Bytes in both standards, even though the maximum payload in IEEE 802.15.4 is 127 Bytes.In addition, the same power consumption values are considered in both standards, and the simulations are performed in sub-1 GHz. Table I shows the common settings and Tables II and III present the settings for IEEE 802.11ah and IEEE 802.15.4, respectively.

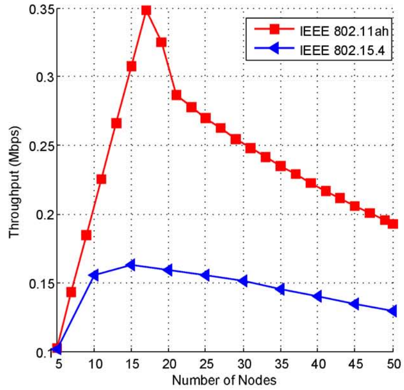
B. Simulation scenarios

In this paper, two main scenarios are taken into consideration: Ideal channel and non-ideal channel. Both scenarios are simulated with two different traffics: Saturated traffic and low traffic of inter arrival time of 100 ms. In ideal case, the degradation of the transmit power due to path loss is not considered, consequently, each node can hear other nodes, in other words, no hidden nodes problem does exist.

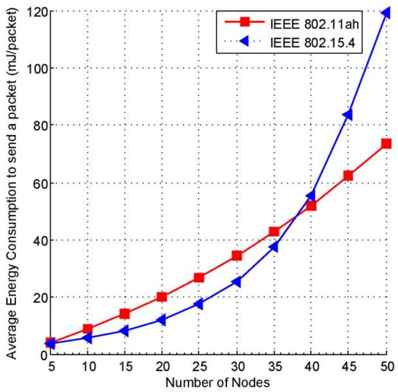
In non-ideal channel, transmitted power is degraded due to path loss. The applied model of path loss in this study is out-



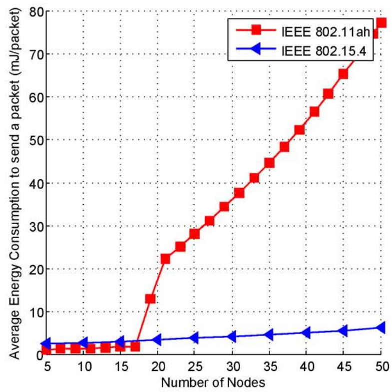
(a) Normalized throughput in ideal channel and saturated traffic.



(b) Throughput in low traffic ideal channel.



(c) Average energy consumption to send a packet in ideal and saturated traffic.



(d) Average energy consumption to send a packet in low traffic ideal channel.

Fig. 4. The throughput and energy consumption comparison between IEEE 802.11ah and IEEE 802.15.4 in ideal channel with two different traffics: Saturated an non-saturated traffic.

TABLE III. SETTINGS FOR IEEE 802.11AH.

Slot Time (ST)	52 us
DIFS	264 us
SIFS	160 us
Propagation Time	6 us
Physical Header	6 symbols (each symbol 40 us)
MAC Header	12 Bytes
ACK Frame size	Equals to PHY header
Bit rate	650 kbps
Short Retry Limit	7
Long Retry Limit	4
Minimum contention window	15
Maximum contention window	1023
Receiver sensitivity	-92 dBm

door scenario. Outdoor path loss model for macro deployment scenario is based on [13]. In non-ideal channel, path loss in dB is given by the following formula:

$$PL(d) = 8 + 37.6log_{10}(d) \qquad (1)$$

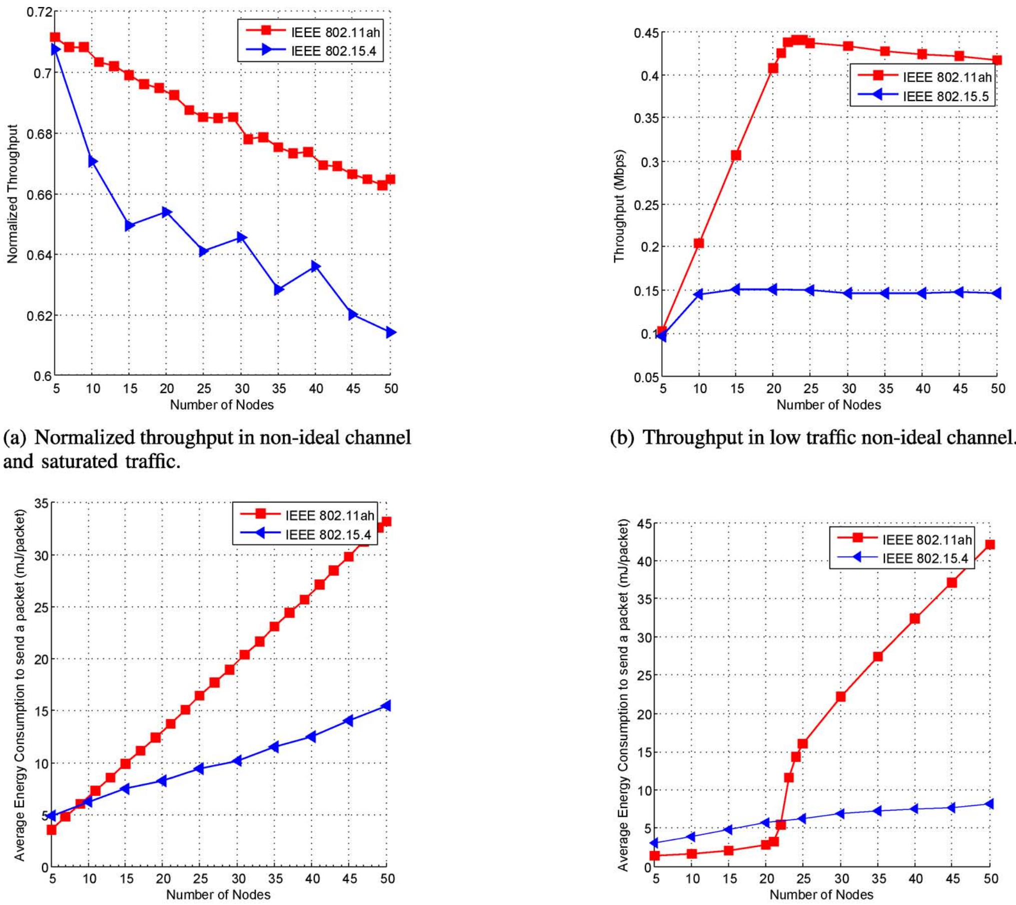
where d is the distance between transmitter and receiver in meter.

In order to maximize throughput some manipulations are considered. For example, the basic access mechanism is employed in IEEE 802.11ah rather than RTS/CTS mechanism. The basic access mechanism is more efficient when the payload size is relatively small. One AP is modelled and the uplink traffic is generated. To increase the simulation accuracy, each simulation scenario is randomly repeated 100 times and average of results is calculated by using the Monte Carlo method. Figure 3 shows one typical deployment of the nodes that are distributed uniformly in the playground.

In each scenario, two different traffics are simulated. The first one is saturated traffic which means each nodes always have a packet to send. The reason to consider this traffic is that, since this scenario is the harsh case in the sense of the traffic and the worst case in the sense of energy consumption, therefore, by analysing the saturated traffic, finding the asymptotic values for our metrics is possible which helps to obtain a good understanding of the problem. In the second traffic case, each node generates a packet with the inter arrival time of 100 ms with random starting time.

IV. SIMULATIONS RESULTS

As it mentioned earlier, our simulations are divided into ideal channel and non-ideal channel scenarios where each scenario is considering both saturated and non-saturated traffic cases. The throughput and energy consumption are the main metrics which are considered in this work. The result of both



(a) Normalized throughput in non-ideal channel and saturated traffic.

(b) Throughput in low traffic non-ideal channel.

(c) Average energy consumption to send a packet in non-ideal and saturated traffic.

(d) Average energy consumption to send a packet in low traffic non-ideal channel.

Fig. 5. The throughput and energy consumption comparison between IEEE 802.11ah and IEEE 802.15.4 in non-ideal channel with two different traffics: Saturated an non-saturated traffic.

metrics are in the Figure 4 and Figure 5 which are presenting ideal and non-ideal channel scenarios, respectively.

The throughput is defined as the fraction of time used by the network to successfully deliver one packet payload. The throughput provides the ratio of channel capacity used for the successful transmission and it is one of the useful network metrics. For a better understanding of the asymptotic capacity of the MAC layer, the saturated traffic is being used in simulations which is not the case in bursty traffics, however, to obtain the vision about normal scenarios in IoT and M2M applications, the low traffic is also simulated. It should be mentioned that normalized throughput is applied for saturated traffic which is obtained by dividing the normal throughput by the data rate. The normalized throughput is a better metric for analysing the saturated traffic. Figure 4(a) shows the throughput of two standards in saturated traffic. The throughput of both standards for the small number of nodes is roughly same, though it rapidly drops when the number of nodes is increasing. The steep of the drop for the IEEE 802.15.4 is more severe compared to the IEEE 802.11ah. The result for the low traffic is shown in the Figure 4(b). Throughput of both standards is increasing when the number of nodes is growing, then it again drops after the number of nodes reaches to 15 nodes for saturated case and 20 nodes for non-saturated case. As a result, in a very high number of nodes case, IEEE 802.11ah has better throughput compared to IEEE 802.15.4.

Throughputs in non-ideal channel are presented in the Figures 5(a) and 5(b). The IEEE 802.11ah in both saturated and non-saturated traffics have better performance in the case of non-ideal channel specially for high number of nodes. In other words, the throughput in congested networks has better performance for IEEE 802.11ah. The reason is that the MAC layer of the IEEE 802.11ah is more adapted for high number of nodes than the IEEE 802.15.4. In non-ideal channel the fairness of the transmission is reduced, since the closer nodes to the AP have higher probability to send their packet. In other word, AP receives the packets from closer nodes with higher SNR comparing to far nodes because the transmission power reduces due to path loss. Therefore, the closer nodes have higher probability to send their packets. In this case, network looses its fairness in obtaining access to the medium. The fairness measure can be calculated by Raj Jain's equation: [14]:

$$F(x_1, x_2, ..., x_n) = \frac{(\sum_{n=1}^{n} x_i)^2}{n. \sum_{n=1}^{n} x_i^2} \quad (2)$$

where n stands for the number of nodes and x_i is the throughput of the ith node. By using this equation, the value of fairness is ranging from $1/n$ to 1. The best case is 1 in which each node obtains the same allocation, in contrast $1/n$ is the worst case. In our study, for instance, in the case of 50 nodes in non-ideal channel and saturation traffic , the fairness measure gives 0.4 for both standards. It shows that both standards have about the same transmission fairness.

The energy has recently been a main design constraint in wireless technologies. The high number of nodes from one hand and smaller size of the future devices from other hand, pushes the new standards to be more energy efficient. We study the energy consumption of the whole network excluding AP to send a successful packet. Figures 4(c) presents the energy consumption in mJ to send a packet in ideal channel with saturated traffic. Energy consumption in IEEE 802.11ah is slightly greater than IEEE 80.15.4 for the number of nodes smaller than 40, But it is decreasing when the number of the nodes are increasing. However, As Figure 4(d) shows, the energy consumption in low traffic behaves differently. The IEEE 802.11ah has a slightly smaller energy consumption for number of nodes less than 17 but after that energy consumption is drastically increasing in comparison to the IEEE 802.15.4.

In non-ideal channel, the performance of the IEEE 802.15.4 for high number of nodes is better than IEEE 802.11ah in term of energy consumption. As shown in Figure 5(c), IEEE 802.15.4 consumes less energy to send a successful packet in saturated traffic. It means that this standard is more energy efficient compared to IEEE 802.11ah in this scenario with the above mentioned settings. Figure 5(d) also shows the energy consumption in low traffic which indicates better performance of the IEEE 802.15.4 for higher number of nodes. In this scenario, IEEE 802.11ah consumes less energy to send a successful packet.

V. CONCLUSION

In this paper, we evaluate both IEEE 802.15.4 and IEEE 802.11ah standards for their reactions to the network scalability in terms of throughput and energy consumption. For removing protocols dependency on the placements of nodes, many repetitions with randomly distributed nodes are performed. The throughput and energy consumption of both standards in ideal and non-ideal channel with two different traffics are calculated by using Monte Carlo method. The results of the throughput for the presented settings show that the IEEE 802.11ah outperforms the IEEE 802.15.4 in both idle and non-idle channel with two different traffics. In addition, It is shown that in the case of non-ideal channel, both standards have higher throughput compared to ideal channel but in sacrificing the transmission fairness. In the other words, the nodes which are closer to AP have higher probability to send their packets compared to farther nodes. In term of energy consumption, IEEE 802.15.4 consumes more average energy to send a successful packet compared with the rival standard in the case of small number of nodes in low traffic scenario. In contrast, energy consumption of the IEEE 802.11ah is relatively higher in congested networks. It is concluded that the performance of the IEEE 802.11ah is better in term of throughput but in the case of the energy consumption, the IEEE 802.15.4 still outperforms the IEEE 802.11ah specially in a dense network and non-saturated traffic.

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