Modelling of Energy Consumption in IEEE 802.11ah Networks for M2M Traffic

Luca Beltramelli and Patrik Österberg
Department of Information and Communication Systems
Mid Sweden University, Sundsvall SE-85170, Sweden
Email: luca.beltramelli@miun.se, patrik.osterberg@miun.se

***Abstract*—IEEE 802.11ah is a sub-1 GHz standard designed to meet the requirements of future machine-to-machine (M2M) communications. The standard should be able to support use cases for the M2M communications with thousands of stations capable of generating both periodic and aperiodic traffic for a single access point. In some cases, like environmental and agricultural monitoring, the nodes are typically powered by battery or through energy harvesting. For these applications it is important to use a communication technology that is energy efficient. IEEE 802.11ah tries to achieve this objective for networks with a large nodes number by introducing new energy saving mechanisms and a novel channel access mechanism. This work proposes a mathematical model to compute the energy consumption of an IEEE 802.11ah network.**

I. Introduction

Over the last few years the interest toward the Internet of Things (IoT), both from the academia and the business world, has been very high. A key enabling technology for the emerging IoT scenarios is Machine-to-Machine (M2M) communication [1]. This term intends to describe all those communication technologies that allow large number of devices to exchange information autonomously from human intervention. In general M2M applications are characterized by the high number of devices communicating to one another by means of sporadic and short transmissions. These devices will be geographically distributed and in general not connected to the power grid, relying instead on batteries or on energy harvesting. Therefore, one of the main design goals for the M2M communication technology of the future must be the low energy consumption. Some analysts foresee that the market for M2M technologies may quintuplicate in value in the next ten years [2]. Competing wireless technologies tailored for M2M communication include LoRaWAN, Weightless, LTE and 5G cellular system [3] [4].

The IEEE 802.11 standard group is trying to enter in the competition for M2M communication with a new amendment to their WLAN standard called IEEE 802.11ah [5]. The amendment is currently under development and its approval is expected by July 2016 [6] after which it will find commercial use under the name of Wi-Fi HaLow. IEEE 802.11ah is designed to operate in the 900 MHz ISM (Industrial, Scientific and Medical) band. The sub-1GHz band offers better channel characteristics, effectively increasing the maximum communication range to 1 km at the cost of reduced channel bandwidth. To decrease the energy consumption, new power-saving mechanisms have been introduced into the MAC layer, which may significantly increase the network lifetime.

The focus of this work is to study the communication originated from the stations and directed to the Access Point (AP) in a IEEE 802.11ah network. In fact, for most of the wide area monitoring scenarios in which the standard is expected to find application, the uplink communication is usually prevalent. In many cases the stations are low-power sensing devices that communicate to the AP periodic sensing information and aperiodic alarms. This work analyses the periodic traffic generated when the network is working in normal conditions. For this specific traffic, the paper introduces a mathematical model that describes the average energy efficiency of a station. The future extensions and developments to the model here presented could help in the design of IEEE 802.11ah networks; for instance by suggesting the optimal combination of the MAC layer parameters that can maximise the lifetime of the stations in the network.

This papers is organized as follow: Section II describes the IEEE 802.11ah standard, particularly the enhancements of the MAC layer. Section III contains the related work available in literature. Section IV describes the model used for the analysis. Finally section V close this work by presenting conclusions and future work.

II. IEEE 802.11ah

This section briefly covers some of the new features introduced by the IEEE 802.11ah specification, that are most relevant for this study. For a summary of all the PHY and MAC features of the IEEE 802.11ah we refer the reader to [7] or to the standard itself [5].

The most interesting use cases for which the IEEE 802.11ah is being developed are related to the concept of IoT. For this kind of applications it is essential to enable large number of devices, usually characterized by low data rate requirements, to transmit information both periodically and aperiodically. Moreover, some of the IoT applications like environmental and agricultural monitoring tend to indirectly put constraints on the energy consumption by requiring longer lifetime for the battery powered device.

To reduce the energy consumption of IEEE 802.11ah devices, new energy saving mechanisms have been introduced to the MAC layer of the standard. Some of the control and management frames have been redefined and shortened in length to reduce the overhead. The multiple access protocol has been modified and now it is an hybrid between the traditional CSMA/CA and the time division method for accessing the channel. An IEEE 802.11ah AP can support up to 8191 stations. The changes to the multiple access protocol were necessary in order to increase the throughput and alleviate the problem of the hidden terminal for the case of large number of stations. The problem of the hidden terminal for large network and the mitigation mechanisms adopted by IEEE802.11ah are the subject of M. Park's work [8].

To complement the IEEE 802.11e Enhanced Distributed Channel Access (EDCA), the standard introduces the concept of Restricted Access Window (RAW). A RAW is a time window during which only the stations specified by the AP in a beacon frame can attempt to access the medium. The standard defines the new RAW Parameter Set (RPS) element which, included in the beacon frames, informs the stations about the characteristics of the upcoming RAW. The use of multiple RAWs allow the AP to distribute the transmission attempt of the active stations over a longer period of time, reducing the collision probability.

The beacons divide the channel in RAWs, which in turn are subdivided in slots; maximum of 64 per RAW. Each slot is allocated to one or multiple stations belonging to the group assigned to the RAW. Inside each slot the contention of the medium is performed using the Distributed Coordination Function (DCF). Fig. 1 shows the division of a RAW in slots and the DCF used by the stations to contend for the channel.

In the case of uplink traffic, there is no way for the AP to know if a station has data to transmit and thus to assign slots without the risk of them going unused and wasting channel time. Although the RAW mechanism can be used both in uplink and downlink, the advantages of downlink RAW are more significant. In fact, through the use of a traffic indication map (TIM) it is possible for the AP to communicate to the stations if there is buffered information for them to retrieve. In addition, the AP can communicate the slot of the RAW during which a station may attempt to retrieve the buffered information. This allows IEEE 802.11ah to reduce channel congestion and increase energy efficiency for highly populated networks.

Because of the periodic nature and the management overhead, the use of RAW is more suited for non time critical periodic type of traffic, although with some adaptation to the standard it is possible to extend the RAW mechanism to operate in alarm situations [9].

III. Related Work

In literature, there are multiple studies conducted on the idea of Group Synchronized DCF (GS-DCF), which is also proposed in IEEE 802.11ah. Zheng et al. [10] compares the throughput of the GS-DCF protocol in the slot no-crossing and slot crossing cases. Their work illustrates the analytical expression of the throughput for the centralized uniform grouping and decentralized random grouping of stations. IEEE 802.11ah supports both, and the difference is that in the first one it is the AP that assigns the stations to the slots of a RAW, whereas in the second one the stations themselves randomly choose the slot to use.

In [11] a new energy conservation protocol is designed for IEEE 802.11ah, under the name of PS-OLi. The protocol, thought to be used for light and periodic traffic, configures wake up time and offset time of the stations to reduce the risk of collision among the stations that wake up after having been in doze state. Their analysis concentrates on the downlink communication from the AP to the stations whereas our work focuses on the uplink traffic more commonly found in monitoring applications.

In [12], the authors present an analytical expression to calculate the length of the RAW slots that can guarantee, with a arbitrary small uncertainty, that either one or all the stations active in the RAW will successfully transmit the data frame. In their design the AP can decide based on the knowledge of number of stations and transmission probability, the group size and slots length adequate. Although the authors make no considerations on the energy consumption, their mathematical description of the system based on Markov chains do not assume saturation condition. Adopting a similar approach for the study of the energy efficiency of IEEE 802.11ah may overcome the limits of current models based on the assumption of saturation condition.

Wang et al. [13] define an unconstraint optimization problem in order to find the number of stations and number of slots in a RAW that maximize the energy efficiency. However, their approach does not consider the eventuality of constraints in delay, throughput or MAC layer parameters in their optimization problem. In fact the solution of their optimization problem is infeasible because well out of the range of admitted value by the standard.

Zhao et al. [14] analyse, through the use of simulations, the collision probability and the energy consumption in a 802.11ah network. They directly compare the energy consumption of TIM and non-TIM stations for various number of RAWs.

IV. Model

The model used to describe the function of the RAW in this paper is similar to the one used by Wang et al. in [15]. In this work we are going to further develop their model by giving mathematical expressions to some of the energy components that they left unspecified. For sake of simplicity some assumptions are made:

1) the PHY channel is ideal, transmission delay and errors are neglected;
2) retransmission is only due to collisions.

In our model all devices enter a doze state at the end of their assigned RAW slot and the energy consumption in that state is considered negligible. It is then possible to express the average energy consumption E of the generic station S attempting to transmit in a slot of a RAW as:

$$E = E_{OH} + \sum_{i=0}^{N-1} E\left(i\right) P\left(i\right) \tag{1}$$

The energy consumption in (1) has two components:

1) E_{OH} is the energy required by the station to wake up and receive the beacon frame containing the RPS element with the parameters for the RAW. It can be considered as the overhead necessary for the RAW mechanism to function;
2) $E\left(i\right)$ is the energy consumed by the station S when the slot chosen for the transmission is shared with other i

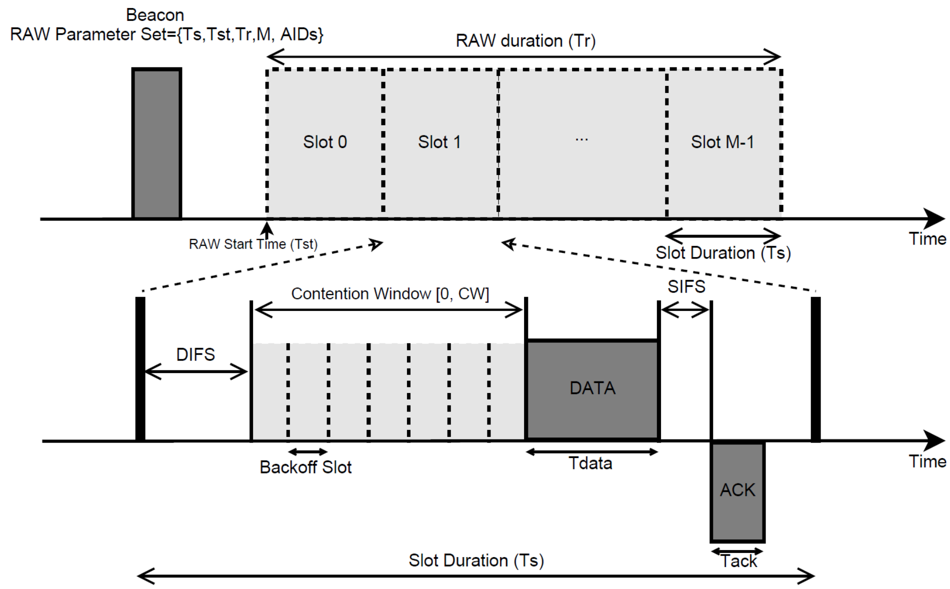

Fig. 1. RAW mechanism and DCF

stations. $P(i)$ is the probability of i stations choosing for their transmissions, the same slot chosen by station S.

We define M as the number of slots in a RAW and N as the number of stations assigned to that RAW with a packet to transmit. $P(i)$, the probability that i out of the total $N-1$ stations attempt to access the channel during the same slot chosen by station S has the following expression:

$$P(i) = \binom{N-1}{i}\left(\frac{1}{M}\right)^{i}\left(1-\frac{1}{M}\right)^{N-1-i} \quad (2)$$

for $i = 0, 1, \ldots, N-1$;

For simplicity we treat differently the case $i = 0$ from the case $i > 0$. Section IV-A analyses the case of S transmitting in a slot not selected by any other station. Section IV-B analyses the case of station S contending for accessing the channel with other stations.

A. Slot has only one station assigned

$P(0)$ is the probability that station S chooses for its transmission a slot that no other station has also chosen.

$$P(0) = \left(1-\frac{1}{M}\right)^{N-1} \quad (3)$$

Because the PHY channel is assume ideal, the station will succeed in the transmission at the first attempt. The energy consumption $E(0)$ in this case is:

$$E(0) = E_{SU} + E_{BO}(0) \quad (4)$$

where E_{SU} is the average energy consumption in the case of successful data transmission and $E_{BO}(0)$ is the average energy consumption of the Backoff mechanism. For basic DCF without Virtual Carrier Sensing (VCS), E_{SU} is equal to:

$$E_{SU} = P_{TX}T_{Data} + P_{RX}T_{ACK} + P_{ls}(DIFS + SIFS) \quad (5)$$

Where P_{TX}, P_{RX} and P_{ls} are respectively the power consumptions of the station in transmitting, receiving and listening state. T_{ACK} is the time required for transmitting the acknowledgement frame. T_{Data} is the time required for transmitting the data packet. $DIFS$ is the Distributed Interframe Space and $SIFS$ is the Short Interframe Space.

The value of $E_{BO}(0)$ depends on the length of the backoff procedure. Since there are no collisions, the average backoff timer ($\overline{T_{BO}}$) selected by the station is:

$$\overline{T_{BO}} = \frac{CW_0 - 1}{2}$$

Where CW_0 is the size of the minimum contention window. The average energy consumption for the backoff procedure can therefore be written as:

$$E_{BO}(0) = P_{ls}\overline{T_{BO}} \quad (6)$$

B. Slot has more than one station assigned

Consider a station S that attempts to transmit its packet in a RAW slot that was randomly chosen by at least one other of the $N-1$ stations assigned by the AP to the RAW. The probability of this event $P_{>0}$ is:

$$P_{>0} = 1 - P(0) = 1 - \left(1-\frac{1}{M}\right)^{N-1} \quad (7)$$

The expression for the energy consumption depends on the number of contending stations i:

$$E(i) = E_{SU}P_{SU}(i) + E_{BO}(i) + E_{CO}(i) \quad (8)$$

for $i = 1, \ldots, N-1$;

Compare to (4) there is a new term E_{CO} that describe the energy wasted by station S during a transmission that collided. Moreover the energy consumption of a successful transmission attempt is in this case multiplied by the probability P_{SU} of successfully transmitting the packet by the end of the slot.

P_{SU} is not present in (4) because the probability of collision in IV-A is null. The average energy wasted in failed transmissions attempts is:

$$E_{CO}(i) = \overline{N}_C(i) \times \left[P_{TX} T_{Data} + P_{ls}\left(T_{ACK} + DIFS + SIFS\right)\right] \tag{9}$$

Where $\overline{N}_C(i)$ is the average number of collisions that station S experience before a successful transmission.

To analyse this case, we assume as previously done by Park et al. in [16] that the network is working in saturation condition. From their work we use formula (14) to approximate the probability of transmission during a exponential backoff procedure with maximum backoff stage m:

$$\tau = \frac{2(1-2p)\cdot(1-p)}{(1-2p)\cdot(CW_0+1)+p\cdot CW_0\left(1-(2p)^m\right)} \tag{10}$$

Where p is the conditional collision probability. The value τ is equal to the reciprocal of the average contention window size.

It is possible at this point to introduce the energy efficiency η of the RAW mechanism for the uplink communication as:

$$\eta = \frac{L_{Payload}}{E} = \frac{L_{Payload}}{E_{OH} + \sum_{i=0}^{N-1} E(i)\, P(i)} \tag{11}$$

V. Conclusion

This paper has introduced a model for the calculus of the average energy consumption of a station transmitting uplink traffic in a IEEE 802.11ah network. This work constitutes a basic foundation for further analysis and studies, which can provide a guideline in the choice of the IEEE 802.11ah MAC layer parameters for supporting energy-constrained applications. The mathematical model presented here makes use of assumptions like ideal channel and saturation condition. Because these assumptions may not be compatible with the designed use case, the model requires further refining and improvements. Finally a validation phase needs to be conducted by means of a simulator.

VI. Future Work

Future research in this area may analyse the effects of the hidden terminal problem on the energy saving performance of IEEE 802.11ah. In fact whereas the adoption of different grouping strategies and the use of VCS can mitigate the problem of hidden terminal, they may also decrease the overall energy efficiency. In future work we also want to investigate the problem of choosing the parameter of the MAC protocol when the aim is to minimize the energy consumption of the RAW mechanism.

Acknowledgments

This research has been supported by grant 20140321 and 20140319 of the Swedish Knowledge Foundation.

References

[1] Y. K. Chen, "Challenges and opportunities of internet of things," in *Design Automation Conference (ASP-DAC), 2012 17th Asia and South Pacific*, Jan 2012, pp. 383–388.

[2] OneM2M, "The Interoperability Enabler For The Entire M2M Ecosystem," Tech. Rep., 2015.

[3] A. Biral, M. Centenaro, A. Zanella, L. Vangelista, and M. Zorzi, "The challenges of m2m massive access in wireless cellular networks," *Digital Communications and Networks*, vol. 1, no. 1, pp. 1–19, 2015.

[4] C. Goursaud and J.-M. Gorce, "Dedicated networks for iot: Phy/mac state of the art and challenges," *EAI endorsed transactions on Internet of Things*, 2015.

[5] "IEEE Draft Standard for Information Technology-Telecommunications and Information Exchange Between Systems-Local and Metropolitan Area Networks-Specific Requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 2: Sub 1 GHz License Exempt Operation," *IEEE P802.11ah/D6.0, February 2016 (Amendment to IEEE Std 802.11REVmc/D5.0)*, pp. 1–645, Jan 2016.

[6] Status of Project IEEE 802.11ah. IEEE P802.11- TASK GROUP AH. [Online]. Available: http://www.ieee802.org/11/Reports/tgah_update.htm

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

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

[9] G. Maduenno, C. Stefanovic, and P. Popovski, "Reliable and Efficient Access for Alarm-initiated and Regular M2M Traffic in IEEE 802.11 ah Systems," 2016.

[10] L. Zheng, M. Ni, L. Cai, J. Pan, C. Ghosh, and K. Doppler, "Performance analysis of group-synchronized DCF for dense IEEE 802.11 networks," *Wireless Communications, IEEE Transactions on*, vol. 13, no. 11, pp. 6180–6192, 2014.

[11] R. P. Liu, G. J. Sutton, and I. B. Collings, "Power save with offset listen interval for IEEE 802.11 ah smart grid communications," in *Communications (ICC), 2013 IEEE International Conference on*. IEEE, 2013, pp. 4488–4492.

[12] E. Khorov, A. Krotov, and A. Lyakhov, "Modelling machine type communication in IEEE 802.11 ah networks," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 1149–1154.

[13] Y. Wang, Y. Li, K. K. Chai, Y. Chen, and J. Schormans, "Energy-aware adaptive restricted access window for IEEE 802.11 ah based networks," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*. IEEE, 2015, pp. 1211–1215.

[14] Y. Zhao, O. N. Yilmaz, and A. Larmo, "Optimizing M2M Energy Efficiency in IEEE 802.11 ah," in *2015 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2015, pp. 1–6.

[15] X. Wang and D. P. Agrawal, "Analysis and optimization of energy efficiency in 802.11 distributed coordination function," in *Performance, Computing, and Communications, 2004 IEEE International Conference on*, 2004, pp. 707–712.

[16] 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, July 2014.