Abstract

M2M communications are projected to be one of the fastest growing technology segments of the IT sector in the next years. Sensor and actuator networks connect communication machines and devices so that they automatically transmit information, serving the growing demand for environmental data acquisition. IEEE 802.11ah Task Group addresses the creation of a new standard for giving response to the particular requirements of this type of networks: large number of power-constrained stations, long transmission range, small and infrequent data messages, low data-rates and non-critical delay. This article explores the key features of this new standard under development, especially those related to the reduction of energy consumption in the MAC Layer. In this direction, a performance assessment of IEEE 802.11ah in four typical M2M scenarios has been performed.

Keywords: IEEE 802.11ah, M2M, WLANs, WSNs, Power Saving Mechanisms

1 Introduction

Several studies forecast an annual growth rate over 20% in the number of M2M connections globally [1], even exceeding the world’s population in 2017 with 10 billion mobile-connected devices and seeing a $1.2 trillion revenue opportunity by 2020 [2].

The different technologies currently used for performing M2M applications can be organized into two groups: Mobile Cellular Networks (MCNs) and Wireless Sensor Networks (WSNs). With respect to MCNs, and apart from GSM/GPRS/EDGE, the 3rd Generation Partnership Project (3GPP) is working on specifications to standardize the deployment of M2M applications in UMTS and LTE networks. As for WSNs, different systems (Zigbee, 802.15.4, 6LoWPAN, Bluetooth or even proprietary radio solutions) have been considered for transmitting data in such M2M scenarios. However, none of them has become a prevailing technology due to the diversity of applications and scenarios.

Being aware of the lack of a M2M wireless standard and taking into consideration the current success, wide knowledge and implantation of Wi-Fi, the IEEE Task Group 802.11ah (TGah) was created in 2010
with the goal of specifying a Sub-1GHz global Wireless Local Area Network (WLAN) standard for future M2M communications with large number of devices, long range and long operating duration.

Similarly to the IEEE 802.11 High Efficiency WLAN Study Group (HEW SG) \[3\] -focused on the enhancement of the efficiency and performance of Wi-Fi deployments-, IEEE 802.11ah also aims to adapt the current Wi-Fi standard to specific requirements by slightly modifying its current PHY and MAC layers.

This article introduces the IEEE 802.11ah \[4, 5\] amendment, which will allow WLANs to manage hundreds or even thousands of low capability M2M devices with sporadic traffic. As IEEE 802.11 has become the dominant standard for WLANs and one of the most deployed technologies, the release of the new IEEE 802.11ah amendment will facilitate the deployment of energy-efficient wireless networks.

Apart from describing the main features of the IEEE 802.11ah amendment, its feasibility in terms of packet delivery and energy efficiency has been evaluated for different application areas: agriculture, smart metering, industrial automation and animal monitoring.

The remainder of this article is organized as follows: In Section \[2\] IEEE 802.11ah general scenarios and requirements are introduced. Section \[3\] describes the main features of the amendment in terms of PHY and MAC layer. In Section \[4\] we present the different scenarios used in our evaluation as well as the results obtained for different figures of merit. Finally, in Section \[5\] our conclusions are presented and the open challenges are summarised.

## 2 Scenarios and Requirements

M2M communications refer to any technology that enables devices to exchange information and to perform actions without the manual assistance of humans. It is expected that M2M communications will be one of the major technological drivers in the next decade, mainly in the following areas: Metering and control of utilities (electricity, gas, heat and water), eHealth, Intelligent Transport Systems (ITS), Surveillance, Home Automation and Industrial Automation and Control.

### 2.1 Scenarios

IEEE 802.11ah Task Group (TGah) has defined several application areas that would motivate the use of this new Sub-1GHz standard \[5\]:

1. Sensor Networks
Current Wi-Fi networks are not capable of properly supporting sensor networks due to three main reasons:

• **The absence of power saving mechanisms:** The particular energy constraints of sensor networks are not taken into account in the IEEE 802.11 standard, that does not include energy saving mechanisms especially designed for this kind of devices.

• **The use of unsuitable bands:** Due to their short wireless coverage and high obstruction losses, current Wi-Fi bands require the use of intermediate nodes, which adds complexity to the network, stating thereby the lack of an IEEE 802.11 standardized implementation in a more suitable band for low rate and long range networks.

• **The existence of low cost alternatives:** The scarce use of Wi-Fi for data communication between low-capable and battery-powered nodes has lead to the upsurge of low power alternatives, such as IEEE 802.15.4, 6LoWPAN, Zigbee or Sub-1GHz proprietary protocols, all of them categorized as WSNs.

2. Backhaul networks for sensors

Not only as final infrastructure but also as backhaul, IEEE 802.11ah networks could take advantage of their large coverage and act as an intermediate step in communications between final devices (IEEE 802.15.4 nodes, for instance) and data collectors.

2.2 Requirements

For supporting M2M communications, IEEE 802.11ah has been designed to fulfil the following requirements [4]:

• Up to 8,191 devices associated to an AP through a hierarchical ID structure

• Adoption of Power Saving strategies

• Minimum network data rate of 100 kbps

• Operating carrier frequencies around 900 MHz (license-exempt)

• Access Point coverage up to 1 km in outdoor areas

• One-hop network topology
• Short and infrequent data transmissions (data packets ~ 100 bytes)
• Cost-effective solution for network device manufacturers
• High reliability by considering Sub-1GHz band, which is less congested and guarantees a long range

3 Main Technological Features

In order to satisfy the previously described requirements, IEEE 802.11ah proposes new PHY and MAC layers. These new layers include several modifications with respect to consolidated IEEE standards -specially at the MAC level- for supporting the particular constraints of M2M communications.

IEEE 802.11ah PHY Layer can be considered as a Sub-1GHz version of IEEE 802.11ac one. Similarly, IEEE 802.11ah MAC Layer gathers most of IEEE 802.11 main characteristics, adding some novel power management mechanisms.

3.1 PHY layer

IEEE 802.11ah operates over different Sub-1GHz ISM bands depending on the country regulations: 863-868 MHz in Europe, 902-928 MHz in US and 916.5-927.5 MHz in Japan. China, South Korea and Singapore also have specific channelizations [5]. 1 MHz and 2 MHz have been adopted as common channel bandwidths, although in some countries 4, 8 and 16 MHz are also supported.

PHY transmission is an OFDM based waveform consisting of 32 or 64 tones/sub-carriers (including tones allocated as pilot, guard and DC -Direct Current-), which are spaced by 31.25 kHz. The supported modulations include BPSK, QPSK and from 16 to 256-QAM. Technologies like single user beamforming, Multi Input Multi Output (MIMO) and Downlink Multi-User MIMO (DL MU-MIMO)- which was firstly introduced in the IEEE 802.11ac - are also used by the 802.11ah system.

3.2 MAC Layer

The design of the MAC Layer aims to maximize the number of STAs conforming the network while assuring their minimum energy consumption. There are 3 different kinds of STAs according to the IEEE 802.11ah draft [6], each with its procedures and time periods to access to the channel (see Figure 1):

1. TIM Stations
This is the only kind of STA that needs to listen to AP beacons to send or receive data. Their data transmissions have to be performed within a Restricted Access Window (RAW) period with three differentiated segments (Multicast, Downlink and Uplink). STAs with a high traffic load should use this procedure to access the channel, because it combines periodic data transmission segments with energy efficiency mechanisms. These novel features are described in detail in the rest of Subsection 3.2.

2. Non-TIM Stations

Non-TIM STAs do not have to listen to any beacons to transmit data. During the association process, they directly negotiate with the AP a transmission time within a Periodic Restricted Window (PRAW). Next transmission times can be either periodically defined or renegotiated according to the STAs requirements. Although Non-TIM STAs can periodically transmit data, it is advisable to use TIM STAs for high data applications in order to achieve a better management of channel resources.

3. Unscheduled Stations

These STAs do not need to listen to beacons either. Even inside a RAW or PRAW period, they can send a poll frame to the AP asking for accessing the channel. The response frame shall indicate an interval (outside the RAW and PRAW restricted windows), during which unscheduled STAs can access the channel. This procedure is meant for STAs which want to join the network or with sporadic traffic.

3.2.1 Support of Large Number of Associated TIM STAs

One of the biggest issues that complicates the adoption of IEEE 802.11 for transmitting data in M2M scenarios is the low number of STAs that can be simultaneously associated to a single AP. For this reason, TGah has defined a novel hierarchical method for grouping STAs, which besides supporting a larger number

![Figure 1: Distribution of channel access restricted windows among signalling beacons](image-url)
of them, it allows to categorize them according to the type of application they are executing, their power level or even their desired QoS (Figure 2(c)). These are its two main characteristics:

1. The design of a new Association IDentifier (AID) that classifies STAs into pages, blocks (also called TIM groups in this article), sub-blocks and STAs’ indexes in sub-blocks.

2. The division of the partial virtual bitmap belonging to the Traffic Indication Map (TIM) Information Element (IE) into smaller bitmaps, one for each TIM Group.

During the association stage, the AP allocates to each STA an AID, whose structure is detailed in Figure 2(b). This AID is unique for each STA and consists of 13 bits which include the different hierarchical levels, so that the maximum number of supported STAs is increased from 207 in IEEE 802.11 to 8191 (= $2^{13} - 1$) in IEEE 802.11ah.

3.2.2 Power Saving Mechanisms for TIM STAs

To face the energy consumption of sensor devices, IEEE 802.11ah includes a Power-Saving Mode (PSM) aimed to exploit low-power states of the network interface, by deactivating the RF module during non-traffic periods.

**TIM and Page Segmentation**  In order to reduce the time a STA is competing for the channel as well as to increase its total sleeping time, IEEE 802.11ah uses a scheme called *TIM and page segmentation*. Thus, the hierarchical distribution of STAs in groups is not only used for organizational purposes, but also for performing a scheduled signalling and allocation system of available channel resources to the different TIM Groups.

Unlike IEEE 802.11, only a limited number of IEEE 802.11ah STAs, those that belong to a certain TIM Group, are able to compete for accessing to the channel in a determined time period. This fact leads to a significant reduction of energy consumption in STAs, since they only have to compete with other STAs of their same TIM Group, listen to their corresponding TIM beacons and can be in sleep mode otherwise.

The signalling system is an extension of the IEEE 802.11 existing one, as besides using TIM beacons for STA-level signalling, it also uses DTIM beacons for TIM Group-level signalling. The purpose of these two kinds of beacons is described below:

1. DTIM (Delivery Traffic Indication Map) Beacons: They inform about which TIM Groups have pending data (unicast or multicast) in the AP. All information about RAW properties (RAW segments duration,
(a) Hierarchical Association of stations

(b) AID Frame Structure

(c) AID Stations Map

(d) Effect of DTIM and TIM mapping over STAs. TIM7 group is signalled in DTIM map, so all STAs in that group listen to TIM7 beacon. Only STAs #1538 and #1539 are signalled in TIM7 beacon and, therefore, have a contention time for accessing the channel.

Figure 2: Example of IEEE 802.11ah hierarchical signalling
2. TIM (Traffic Indication Map) Beacons: Each TIM beacon informs a TIM Group about which specific STAs have pending data in the AP. Between two consecutive DTIMs, there are as many TIM beacons as TIM Groups.

By using this system, any STA can enter into a power saving state if it does not have any packet to transmit and at least one of these two conditions is met: 1) it observes in the DTIM beacon that there is no downlink traffic addressed to its TIM Group or 2) it observes in the DTIM beacon that there is downlink traffic addressed to its TIM Group but itself does not explicitly appear in the TIM beacon.

**Advanced Signalling Modes**  Within the *TIM and page segmentation* scheme, when the number of network pages is greater than one, IEEE 802.11ah offers two possible advanced signalling modes:

1. **Non-TIM Offset**: The signalling information of a determined TIM Group is transmitted in the same beacon as many times as existing pages in the network. This is the default mode in IEEE 802.11ah.

2. **TIM Offset**: This mode includes a 5-bit field contained in the DTIM beacon that allows TIM Groups from different pages to be separately scheduled over their own TIM beacons.

While the TIM Offset mode shows a lower energy consumption compared to the Non-TIM one, its behaviour with respect to the maximum number of supported STAs, Packet Delivery Ratio (PDR) and Network Efficiency is slightly worse [7].

### 3.2.3 Channel Access for TIM STAs

Basically, the IEEE 802.11ah channel access for TIM STAs combines an AP-centralized time period allocation system with the Distribution Coordination Function (DCF) medium access technique within those periods.

Regardless of the advanced signalling mode, time between 2 consecutive TIMs contains a RAW formed by one Downlink (DL) segment, one Uplink (UL) segment as well as one Multicast (MC) segment placed immediately after each DTIM beacon, as can be observed in Figure [1].

The data transmission procedures for the downlink and uplink cases are detailed below:

- **Downlink**: When an AP needs to send a packet to a STA, the DTIM beacon has to include the TIM Group to which belongs that STA in its bitmap. Similarly, the corresponding TIM beacon also includes that STA in its bitmap. Each signalled STA has to listen its TIM beacon to know when to contend.
This contention will be done using the Distributed Coordination Function (DCF). When the backoff of a STA expires, it sends a PS-Poll frame in order to get its corresponding data.

- **Uplink**: When a STA wants to send an uplink message to the AP, it must first listen its corresponding TIM Group for knowing when to contend for the channel. In this case, the contention is also done through a DCF scheme. Both Basic Access (BA) and RTS/CTS mechanisms can be used.

**Sub-Slotting Mechanisms** To ensure the maximum channel occupancy and energy savings, TGah also proposes the division of the DL/UL RAW segments in several time slots, so that each slot only contains a few STAs with data to receive/send. It could be even considered a TDMA approach if only one STA per slot is assigned.

Thanks to the sub-slotting, STAs belonging to the same TIM group could be also distributed over different sub-slots. Therefore, they would even save more energy by competing for the channel against fewer other STAs and extending their sleeping time [8].

### 3.3 Long Sleeping Periods

All STAs regulated by the *TIM and Page Segmentation* scheme are forced to listen to every DTIM beacon, even when they are most likely to not have data to send or receive for a long time.

This is the reason why IEEE 802.11ah also offers TIM, Non-TIM and Unscheduled STAs the possibility to set very long doze times (up to years), by extending several of their IEEE 802.11 parameters during the initial handshake between them and the AP.

However, the corresponding clock drift produced by such long doze times has to be considered, as the higher the time a STA has been asleep, the further in advance it should wake up to avoid possible synchronization problems with the network.

### 3.4 Support for Small Data Transmission

In order to reduce the overhead when the data packet size is small, three new enhancements have been proposed. Firstly, while IEEE 802.11 contains a 28-byte MAC header, IEEE 802.11ah proposes a short 18-byte version by using AIDs instead of MAC addresses [9].

Secondly, TGah has defined several null data packet (NDP) frames, which only consist of PHY header. These frames can be used to create short ACKs, short Block ACKs, short CTSs and short PS-Polls. And
finally, a Speed Frame Exchange [6] mechanism has been developed, so that if a STA has data to transmit, it can notify a successful reception by transmitting its data frame instead of an ACK.

4 Performance Assessment

All our IEEE 802.11ah simulations are based on a fully connected network, where packets are delivered from the source to the destination in just one hop. We also assume ideal channel conditions, without communication errors, delays or capture effects.

Besides, each STA is only capable of receiving and transmitting one data packet per DTIM interval. These intervals have been split into TIM intervals, whose DL/UL RAW segments are only occupied by TIM STAs. RTS/CTS mechanism has been implemented in uplink communications. The proportion between $\psi \in \{\text{DL}, \text{UL}\}$ RAW segments size is equal to the DL/UL traffic fraction ($\beta_\psi$), and we assume that the multicast RAW segment is able to accommodate only one data packet.

The simulations have been performed in a custom environment developed in MATLAB. The considered parameters are presented in Table 1.

| $T_{\text{TIM}}$  | 200 ms | $T_{\text{SIFS}}$ | 160 ms | $L_{\text{beacon}}$ | 25 bytes |
|-------------------|--------|-------------------|--------|--------------------|----------|
| $N_{\text{TIM}}$  | 8      | $T_{\text{DIFS}}$ | 264 $\mu$s | $L_{\text{DATA}}$ | 100 bytes |
| $N_{\text{DTIM}}$ | 1000   | $T_{\text{slot}}$ | 52 $\mu$s | $L_{\text{PS-POLL}}$ | 14 bytes |
| $L_{\text{TIM}}$  | 62 bytes | $C_{\text{W}_{\text{min}}}$ | 16 | $L_{\text{ACK}}$ | 14 bytes |
| $L_{\text{DTIM}}$ | 102 bytes | $C_{\text{W}_{\text{max}}}$ | 1024 | $L_{\text{RTS}}$ | 20 bytes |
| Bit Rate          | 150 kbps / 900 kbps / 1.8 Mbps | $R_{\text{max}}$ | 7 | $L_{\text{CTS}}$ | 14 bytes |

Table 1: List of Simulation Parameters

Four figures of merit are analysed for each scenario:

- Packet Delivery Ratio ($PDR_\psi$)
  This figure of merit computes the percentage of packets that successfully reached the destination versus the number of packets generated.

- Packet Delivery Delay ($PDD_\psi$)
  This figure measures, in number of DTIMs, the time that a packet takes to be successfully transmitted since it is generated.

- Channel Occupancy ($\eta_\psi$)
It is the ratio between the number of packets successfully delivered and those that the network could theoretically be able to deliver.

- **Energy Consumption and Battery Duration**

The last figure of merit analysed is the mean time consumed in four different states per node and the estimation of the battery duration. The consumption of energy is a key factor for the battery-powered networks, as it affects their lifetime.

The energy consumed can be divided in four states that depend on the state of the node:

- **Receiving**: STAs in PSM mode which have not entered into a Long Sleeping Period must listen to all the DTIM beacons. If a STA is signalled in a DTIM beacon with downlink data or it has data to transmit, it will also listen to its corresponding TIM beacon. A STA receiving a data packet, a CTS or an ACK is also in receiving state. Overhearing of packets addressed to other STAs is also affecting the time a STA is in receiving mode.

- **Idle**: It is referred to Backoff periods and interframe spaces such as SIFS and DIFS.

- **Transmitting**: When STAs transmit frames both in the downlink (PS-Poll, ACK) and the uplink (RTS, DATA) communications.

- **Sleeping**: When STAs switch off their radio module.

### 4.1 Scenarios

As we commented in Section 2, there exist many fields of applications for a wireless network, such as: smart agriculture, home automation, smart cities, etc. We have considered four different applications applied in the literature whose main parameters are summarised in Figure 3.

As shown, the same DL inter-arrival time (i.e., the time between two consecutive packets) is assumed in all the scenarios. The control messages are sent every 4 minutes, as in [10]. Moreover, we assume different data rates depending on the scenario. The larger the scenario area, the lower the assumed data rate.

#### 4.1.1 Scenario 1: Agriculture

A WSN applied to agriculture is presented in [11]. The main idea is to control the environmental humidity of agricultural fields in order to adapt the irrigation system. Depending on the humidity measurements, the irrigation system is accordingly activated over time. The sensors transmit a message every 120 seconds. As
we consider that a node only is able to transmit, at least, one packet every DTIM period and knowing that a DTIM period is 1.6 seconds, the inter-arrival time of 120 seconds results in a traffic pattern of 1.2%. The huge area to cover implies a high number of STAs distributed over it.

4.1.2 Scenario 2: Smart Metering

In [12], authors focus on the management of the electric consumption in a house. Different sensors placed inside a house report the measurement of the electric consumption of the different electrical appliances. The placed sensors transmit their measurements every 50 seconds. In this scenario, the number of STAs will depend on the number of home devices that will be managed by the AP, in order to obtain a report of the electric consumption, though these devices will not be higher than few tens.

4.1.3 Scenario 3: Industrial Automation

In this scenario, the described application in [13] is a temperature control of refrigerating chambers. The basic idea is to monitor the temperature of these chambers in order to ensure the best conservation conditions of fruit and vegetables. For that reason, different sensors placed inside the chambers report their measurements every 180 seconds. In order to ensure the coverage and not to break the cool chain inside an industrial
warehouse, it is necessary to distribute hundreds of STAs over the area.

4.1.4 Scenario 4: Animal Monitoring

Over the last years, the natural environment conservation has become crucial. The control of the animals that habit in these protected natural areas is manually done and could provoke stress to both animals and plants. For that reason, in [14], the use of a WSN to collect some useful data is proposed. Measurements are sent every 60 seconds. Although the area to cover is large, the scenario can be divided in sectors depending on the different flora and fauna that has to be controlled.

4.2 Channel Occupancy

The results of $\eta_{psi}$ for all the scenarios simulated are reflected in Table 2. As observed, in all the scenarios, the available resources are not fully used. The scenario that shows the highest usage of the resources is the one applied in the agriculture field, since it (is the one that) has the lowest data rate and the greatest number of nodes. In the rest of the scenarios the $\eta_{psi}$ is below 3%. The results reflect that for these kind of applications, the 11ah amendment is able to manage a huge number of STAs with a single AP.

| Scenario                  | Downlink | Uplink |
|---------------------------|----------|--------|
| Agriculture               | 31.6     | 37.6   |
| Smart Metering            | 0.82     | 0.2    |
| Industrial Automation     | 0.98     | 0.88   |
| Animal Monitoring         | 2.95     | 0.85   |

Table 2: Channel Occupancy results (in %).

4.3 Packet Delivery Ratio and Packet Delivery Delay

In all analysed scenarios, the results achieved in terms of PDR for both traffic directions, uplink and downlink, are 100%. As expected, due to the low values of $\eta_{psi}$, the network is able to transmit all generated traffic. Moreover, the PDD$_{psi}$ achieved is zero. Hence, all packets are transmitted at the DTIM interval in which they were generated.

4.4 Energy consumption and Battery Estimation

The time consumed in each state and the energy consumed per bit are shown in Figure 4. It is worth noting that a node, in mean, remains 99% of its time in the sleeping state in all scenarios. Hence, the
(a) Scenario 1: Agriculture
Energy consumed per bit = 117 µJ/bit

(b) Scenario 2: Smart Metering
Energy consumed per bit = 12 µJ/bit

(c) Scenario 3: Industrial Automation
Energy consumed per bit = 12.7 µJ/bit

(d) Scenario 4: Animal Monitoring
Energy consumed per bit = 11.7 µJ/bit

(e) Battery Lifetime

Figure 4: Time consumed in each state, energy consumed per bit and Battery Lifetime
energy consumption is assumed to be very low. The highest value is obtained, as expected, in the agriculture scenario due to the considered data rate and the presence of a large number of STAs.

Moreover, different types of batteries have been used to estimate STAs battery lifetime. Results are shown in Figure 4(e). The maximum battery duration is achieved at the Industrial Automation scenario. Results show that a duration of 18 years is theoretically achieved. The lowest duration, which corresponds to the Agricultural scenario, is approximately 3 years.

5 Conclusions

The current limitations that do not allow Wi-Fi to play an important role in M2M communications can be solved with the adoption of the new IEEE 802.11ah standard. Its new energy saving mechanisms ensure an efficient use of the limited energy resources available in the sensor nodes and its operation at Sub-1GHz band achieves larger coverage areas than in IEEE 802.11. The number of simultaneously operating STAs has also been increased up to 8191 and, in addition, all of them can be managed by a single AP by using a new hierarchical organization.

In this article, the feasibility of the new IEEE 802.11ah amendment has been evaluated. Due to the infrequent data exchange in M2M applications, a large number of STAs could share a single IEEE 802.11ah AP, as long as their activity periods were properly distributed over time. Besides assuring the performance of communications, energy efficiency becomes a key factor in such applications based on battery-powered nodes. In average, in the considered scenarios, results show that STAs remain in sleeping mode more than 99% of the time; showing the high energy efficiency of IEEE 802.11ah.

In the future, and due to the heterogeneous requirements of M2M applications, the design of QoS traffic differentiation mechanisms in TIM STA based networks will be necessary for merging different applications managed by a single AP. In addition, there is still pending work regarding the performance of Non-TIM and Unscheduled STAs as well as their integration with TIM STAs in a single WLAN.

Acknowledgements

This work was partially supported by the Spanish government through the projects TEC2012-32354 and IPT-2012-1028-120000 and by the Catalan Government (SGR2009#00617).
References

[1] Matt Hatton. Machina research: The global M2M market in 2013. http://www.telecomengine.com/sites/default/files/temp/CEBIT_M2M_WhitePaper_2012_01_11.pdf, January 2013.

[2] M2M Magazine. Connected Devices Market at $1.2 Trillion by 2020, October 2012.

[3] Laurent Cariou and et al. High-efficiency WLAN. https://mentor.ieee.org/802.11/dcn/13/11-13-0331-05-0wng-hi

[4] Stefan Aust and Tetsuya Ito. Sub 1GHz Wireless LAN Propagation Path Loss Models for Urban Smart Grid Applications. In Computing, Networking and Communications (ICNC), International Conference on, 2012.

[5] Stefan Aust, R Venkatesha Prasad, and Ignas GMM Niemegeers. IEEE 802.11ah: Advantages in Standards and Further Challenges for Sub-1GHz Wi-Fi. In Communications (ICC), IEEE International Conference on, 2012.

[6] IEEE. Proposed TGah Draft Amendment. https://mentor.ieee.org/802.11/dcn/13/11-13-0500-01-00ah-proposed

[7] T. Adame, A. Bel, B. Bellalta, J. Barcelo, J. Gonzalez, and M. Oliver. Capacity analysis of IEEE 802.11ah WLANs for M2M communications. In Multiple Access Communications, volume 8310 of Lecture Notes in Computer Science, pages 139–155. Springer International Publishing, 2013.

[8] Albert Bel, Toni Adame, Boris Bellalta, Jaume Barcelo, Javier Gonzalez, and Miquel Oliver. CAS-based channel access protocol for IEEE 802.11ah WLANs. European Wireless (EW) Conference, May 2014, submitted and under review.

[9] Yuan Zhou, Haiguang Wang, Shoukang Zheng, and Z.Z. Lei. Advances in IEEE 802.11ah standardization for machine-type communications in sub-1ghz WLAN. In Communications Workshops (ICC), 2013 IEEE International Conference on, pages 1269–1273, 2013.

[10] Thomer M. Gil and et al. Scoop: a hybrid, adaptive storage policy for sensor networks. MIT CSAIL Technical Report, January 2006.

[11] Million Mafuta, Marco Zennaro, Antoine Bagula, Graham Ault, Harry Gombachika, and Timothy Chadza. Successful deployment of a wireless sensor network for precision agriculture in malawi. Net-worked Embedded Systems for Enterprise Applications, IEEE International Conference on, 0:1–7, 2012.
[12] D. Niyato, Lu Xiao, and Ping Wang. Machine-to-machine communications for home energy management system in smart grid. *Communications Magazine, IEEE*, 49(4):53–59, 2011.

[13] Pilar Barreiro Elorza, Eva Cristina Correa Hernando, Francisco Javier Arranz Saiz, Belen Diezma Iglesias, Luis Ruiz Garcia, Morris Villarroel, Jose Ignacio Robla Villalba, and Javier Garca-Hierro. *Smart Sensing Applications in the Agriculture and Food Industry*, pages 1–33. Nova Science Publishers, Nueva York, EEUU, June 2011.

[14] Alan Mainwaring, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. Wireless sensor networks for habitat monitoring. In *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, WSNA ’02, pages 88–97, New York, NY, USA, 2002. ACM.

[15] CC2420 datasheet. [http://www.ti.com/lit/ds/symlink/cc2420.pdf](http://www.ti.com/lit/ds/symlink/cc2420.pdf)