CAS-based Channel Access Protocol for IEEE 802.11ah WLANs

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Abstract—IEEE 802.11ah Task Group is currently working on the standardization of a new amendment with the focus placed on sensor and actuator networks. It will operate at sub-1GHz bands, ensuring transmission ranges up to 1 Km, minimum network data rate of 100 kbps and very low power operation. This new amendment will extend IEEE 802.11 potential to applications such as smart metering, plan automation, eHealth or surveillance.

In this paper, we propose novel channel access protocol for IEEE 802.11ah WLANs based on a smart use of the Channel Access Slots (CASs), in which the Restricted Access Windows (RAWs) can be divided. More concretely, our protocol optimizes the number of CASs, their length and their allocation to the stations (STAs). The presented scheme allows both the Access Point (AP) and the STAs to properly deliver data packets in densely populated scenarios, while maximizing the time they remain in sleep mode in order to keep the energy consumption low.

I. INTRODUCTION

In recent years, the appearance of the Smart Cities and Smart Grids concepts have motivated the growth of wireless networks based on sensor and actuator devices. This upward trend will continue over the next years, with over 10 billion mobile-connected devices in 2017 [1], so that the wireless industry could see a $1.2 trillion revenue opportunity by 2020 [2].

Wireless Sensor Networks (WSNs) and Cellular Networks [3] are currently used to send and receive data from sensors or power-constrained devices. WLANs could be also an alternative to those networks if several issues were solved, such as their high power consumption and their limitations with regard to the number of supported nodes.

In order to overcome those limitations, and to provide an effective solution for sensor and actuator networks, the TGah working group is developing the IEEE 802.11ah amendment [4]. Among other aspects, the new IEEE 802.11ah amendment will include new channel access techniques and enhanced power saving mechanisms, as well as other improvements in both PHY and MAC layers. It aims to support Wireless Sensor Networks and Backhaul Networks for Machine-to-Machine (M2M) Communications [5].

In this paper, we propose the CAS-based Channel Access protocol, a group-extension of the Scheduled PSM (Power Save Multi-Poll) IEEE 802.11n mechanism [6] that optimizes the channel occupancy and the energy savings by grouping STAs in different contention periods, the CASs, whose duration is obtained by solving a multobjective problem through Pareto frontiers [7].

The presented results show that, in an IEEE 802.11ah WLAN formed by hundreds of STAs, the CAS-based Channel Access protocol ensures a high reliability in terms of packet delivery, in addition to maximizing the time that STAs remain in sleep mode to save energy.

The remainder of this paper is organized as follows: Section II describes the main features of the amendment for the PHY and MAC layers. The CAS-based Channel Access protocol is presented in Section III, while results obtained in simulations, related to packet delivery ratio and energy consumption, are shown in Section IV. Finally, in Section V, we expose our conclusions and propose future work.

II. IEEE 802.11AH

For supporting the previously mentioned applications, IEEE 802.11ah is being designed with the following requirements [8]: up to 8191 associated devices to an AP, adoption of Power Saving strategies, minimum network data rate of 100 kbps, operating carrier frequencies around 900 MHz, coverage up to 1 km in outdoor areas, one-hop network topology and short and infrequent data transmissions (data packets ∼ 100 bytes).

The IEEE 802.11ah PHY layer uses OFDM and operates at the sub-1 GHz band as a 10 times down-clocked version of IEEE 802.11ac PHY layer, due to using narrower bandwidths. The channel widths adopted by IEEE 802.11ah are 2 MHz and 1 MHz [9].

The design of the MAC Layer includes new features to enhance the existing IEEE 802.11 ones. The major improvements that appear are those related to supporting a large number of STAs and power saving enhancements.

A. Supporting a large number of STAs

In IEEE 802.11, the MAC layer assigns an identifier called Association IDentifier (AID) to each STA. This identifier is a unique number used by the AP to communicate with STAs. The maximum number of associated STAs is 2007, due to the length of the partial virtual bitmap of Traffic Indication Map (TIM) Information Element (IE).

For increasing the number of associated STAs to a single AP, TGah has defined a novel 13-bit AID that classifies STAs into different hierarchical groups. During the association stage, the AP allocates an AID to each STA. This AID is unique for each STA and includes the different hierarchical levels. Therefore, it could be an effective way to categorize STAs.
according to their type of application, battery level or required Quality of Service (see Figure 1(a)). In [10], authors have developed a study about the maximum number of associated STAs in an IEEE 802.11ah network depending on the network data rate and the DL/UL traffic load.

B. Power Saving Mechanisms

IEEE 802.11ah extends the IEEE 802.11 PSM [11] by means of using a scheme called TIM and page segmentation, which makes an efficient use of the scarce energy resources available in the STAs.

Thus, TGah proposes a scheme based on hierarchical signalling. This hierarchy is reflected both in the classification of STAs in groups and in the signalling beacons. There are two classes of signalling beacons: the first ones are called DTIM (Delivery Traffic Indication Map) beacons and must be listened to by all STAs. They inform about which groups of STAs have pending data in the AP and also about multicast and broadcast messages.

The second ones are called simply TIM beacons and, between two DTIM beacons, there are as many as groups of STAs. Each TIM beacon informs a group of STAs about which specific ones have pending data in the AP. This data will be dropped after a certain time, determined by the size of the AP buffer and the STA association parameters. Figure 1(b) shows the behaviour of different STAs in a network according to their location within the AID map.

Setting long doze times (∼ months) to STAs can be achieved by extending several parameters of IEEE 802.11 during the network association process. However, in order to capture a particular beacon, a STA will need to wake up far in advance after one of these long sleeping periods to avoid possible clock drift [12].

C. Types of STAs

As defined in IEEE 802.11ah draft [4], there are three different kinds of STAs (TIM, Non-TIM and Unscheduled), each with its procedures and time periods to access the channel. Basically, the main difference between them is that TIM STAs are the only ones that have to listen to DTIM and TIM beacons. Non-TIM STAs can either negotiate their next channel access interval with the AP or determine periodic accesses. Finally, Unscheduled STAs can transmit anytime as long as the channel is free.

III. CAS-BASED CHANNEL ACCESS

Since the IEEE 802.11ah amendment is still under discussion, there are several aspects that have not been defined in detail yet, such as the channel access protocol.

In this paper, we propose the CAS-based Channel Access protocol. By means of this protocol, the RAWs (Restricted Access Windows) designated to the TIM STAs are divided into two different segments (Downlink and Uplink) which, in turn, are divided into CASs, i.e., independent contention periods. In each CAS, a selected group of STAs compete for transmitting data. Moreover, to ensure the maximum channel occupancy and energy savings, the size of these periods is optimally calculated.

A. Time Slotting

$N_{\text{CAS}_{\text{DL}}}$ and $N_{\text{CAS}_{\text{UL}}}$ are, respectively, the number of CASs contained in the Downlink (DL) and Uplink (UL) RAW segments. Each CAS has a length equal to a number of successful transmissions ($N$) plus the time of the minimum contention window ($CW_{\text{min}}$) and a guard time ($T_g$), equal to $\Delta_{\text{min}} + T_{\text{BFS}}$ in the UL case and $\Delta_{\text{min}} + T_{\text{BFS}}$ in the DL case. This guard time allows the network to detect up to one collision in each CAS without reducing the number of packets ($N$) able to be transmitted.

Figure 2 shows how allocation of CASs to STAs is performed depending on the kind of transmission:
the remaining time in their CAS is long enough to support access the medium, where STAs contend for it as long as contention in the UL CAS is also based on a random selection of the UL CASs and performance the first receive its corresponding TIM beacon. Afterwards, the corresponding data. Similarly, that STA will also be included in its corresponding Multicast distribution group along with the other TIM group STAs. Figure 3 shows how the time between 2 consecutive TIM beacons is split into one DL RAW segment, one UL RAW segment as well as a Multicast RAW segment placed immediately after each DTIM beacon. In our proposal, the proportion between DL/UL RAW segments size is equal to DL/UL traffic proportion.

The operation modes for the downlink and uplink cases are detailed below:

1) Downlink: In case an AP has stored packets for a STA, its CAS group will be added in the following DTIM map. Similarly, that STA will also be included in its corresponding TIM map. Once received this map, the STA will be capable of determining its DL CAS. Inside the DL CAS, STAs contend for the channel using the Distributed Coordination Function (DCF), by sending first a PS-Poll frame in order to get their corresponding data.

2) Uplink: A STA that needs to send data to an AP must first receive its corresponding TIM beacon. Afterwards, the STA will randomly select one of the UL CASs and perform its data transmission. Contention in the UL CAS is also based on the DCF.

C. Contention model

IEEE 802.11ah amendment uses DCF as mechanism to access the medium, where STAs contend for it as long as the remaining time in their CAS is long enough to support a complete transmission, independently of the suffered collisions. However, our proposal resets exponential backoff and retransmission counters in every CAS, so that collisions in previous CASs are not taken into account in the current contention period. In this manner, the only method for discarding a packet is to reach the maximum number of allowed collisions in a single CAS.

In order to ensure a fair access between all the STAs, a fair access between all the STAs, we assume a periodic reset of the backoff in combination with the random choice of the CAS performed by STAs. Thus, a STA that had attempted to transmit a packet in a congested UL CAS will use a new backoff (not affected by previous collisions) within the chosen UL CAS in the next DTIM interval.

D. CAS Parameter Setting

The aim of the CAS parameter setting is to maximize the number of packets that can be transmitted in every DL/UL RAW segment; i.e. to maximize the $N_{\text{CAS,s,ω}} \cdot N_{\text{ψ,ω}}$ product. It will depend on the kind of RAW segment $\psi \in \{\text{DL, UL}\}$ and the TIM period number $\omega \in \{\text{DTIM, TIM}\}$. Thus, the optimum size is obtained through a multiobjective game subject to $T_{\text{ψ,ω}}$ and formulated as follows:

Maximize: 

$$f(x,\omega) = [f_1(x,\omega), f_2(x,\omega), f_3(x,\omega), f_4(x,\omega)]$$

where $x = [N_{\text{CAS,s,ω}}, N_{\text{ψ,ω}}]$

$$f_1(x,\omega) = T_{\text{ψ,ω}} - N_{\text{CAS,s,ω}} \cdot (C_{\text{min}} \cdot t_{\text{slot}} + T_{\psi})$$

$$f_2(x,\omega) = T_{\text{ψ,ω}} - \left(\frac{T_{\text{ψ,ω}}}{N_{\text{CAS,s,ω}}}\right)$$

$$f_3(x,\omega) = N \cdot T_{\text{ψ,ω}} - T_{\text{ψ,ω}}$$

$$f_4(x,\omega) = \frac{T_{\text{ψ,ω}}}{N_{\text{ψ,ω}}} - N_{\text{CAS,s,ω}}$$

$L_{\text{slot}}$: Duration of an IEEE 802.11ah time slot

$T_{\text{ψ,ω}}$: Duration of a downlink/uplink segment

$T_{\text{ψ,ω}}$: Duration of a complete packet transmission

$$T_{\text{ψ,ω}} = L_{\text{ψ,ω}} \cdot \frac{r}{r} + T_{\text{SIFS}} + \frac{L_{\text{DATA}}}{r} +$$

$$+ T_{\text{ACK}} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{SIFS}}$$

$L$ : Frame Length

$r$ : Data rate

The first objective equation ($f_1(x,\omega)$) reflects the number of packets that can be transmitted by the STAs. The second
multiobjective problem, thanks to its genetic algorithm that maximizes the number of CASs and the number of packets that can be transmitted inside a CAS. Finally, the last objective tries to maximize the number of CASs with the maximum number of packets inside each CAS.

The MATLAB `gamultiobj` function is used to solve this multiobjective problem, thanks to its genetic algorithm that searches a local Pareto set of solutions \( (N_{\text{CAS,D}}, N_{\text{ψ,ω}}) \) under some restrictions. All these solutions are rounded to the nearest integer value. From this integer set of solutions, the combination with the highest value of \( N_{\text{CAS,D}} \cdot N_{\text{ψ,ω}} \) (see Fig. 4) is selected.

If different combinations achieve the same value of \( N_{\text{CAS,D}} \cdot N_{\text{ψ,ω}} \), the combination with the highest \( N_{\text{CAS,D}} \) value is selected. Thus, the higher the \( N_{\text{CAS,D}} \), the lower the probability of collision and the higher the time in sleep mode for the rest of STAs.

**IV. PERFORMANCE EVALUATION**

We simulate a fully connected IEEE 802.11ah network in MATLAB with different number of STAs and a duration expressed in number of DTIM periods \( (N_{\text{DTIM}}) \), where packets are delivered from the source to the destination in just one hop and there are no hidden terminals. We also assume ideal channel conditions, without communication errors, delays or capture effects.

Four different power states have been defined for IEEE 802.11ah STAs: receiving, idle, transmitting and sleeping. These STAs are only capable of receiving and transmitting one data packet per DTIM interval. These intervals have been split into a certain number of TIMs \( (N_{\text{TIM}}) \), whose DL/UL CASs can only be occupied by TIM STAs. We have not considered the presence of Non-TIM or Unscheduled STAs. Moreover, it is considered that the AP and all STAs have infinite buffers. The different parameters assumed in simulations are presented in Table I.

We have considered three different scenarios (Table II). At every DTIM period, a percentage of STAs is randomly selected. The AP generates one data message for each one of these STAs. Similarly, a percentage of randomly selected STAs generate a data message addressed to the AP. From that information, the proportion of DL/UL traffic in our network is determined.

**A. CAS Parameter Setting**

Time between two consecutive TIM beacons is divided into two RAW segments according to the proportion of DL/UL traffic. Next, the appropriate values of \( N_{\text{CAS,D}} \) and \( N_{\text{ψ,ω}} \) are calculated using the CAS Parameter Setting method of Section III.

Figure 4 shows the Pareto frontiers obtained from solving the multiobjective problems regarding to the parameters of Scenario B. For the DL case (Figure 4(a)), the best distribution uses 3 CASs \( (N_{\text{CAS,D}} = 3) \), allowing to transmit 3 packets each one \( (N_{\text{ψ,ω}} = 3) \). As for the UL case (Figure 4(b)), the \( N_{\text{CAS}} \cdot N \) product is maximized when \( N_{\text{CAS,D}} = 3 \) and \( N_{\text{ψ,ω}} = 5 \). In this scenario, there is no distinction between the CAS distribution of DTIM and TIM periods.

The results for all the scenarios are presented in Table III.

**B. Packet Delivery Ratio and Channel Occupancy**

In this subsection, behaviour of Packet Delivery Ratio (PDR) and Channel Occupancy \( (\eta) \) for \( \psi \in \{\text{DL,UL}\} \) RAW segments in the whole network is studied from the following equations:

\[
PDR_{\psi} = \frac{\text{Packets Delivered}_{\psi}}{\text{Packets Generated}_{\psi}}
\]
TABLE III
CAS PARAMETER SETTINGS FOR DIFFERENT SCENARIOS

<table>
<thead>
<tr>
<th></th>
<th>DL</th>
<th></th>
<th></th>
<th>UL</th>
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<td>N_{DL}</td>
<td>N_{CAS_{UL}}</td>
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<td>N_{CAS_{DL}}</td>
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<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
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<td>1</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

C. Energy Consumption

Figure 6 shows the average time a STA remains in each state. Results are shown for 600 STAs in Scenario A, 350 STAs in Scenario B and 250 STAs in Scenario C, respectively.

In all three cases, a STA remains on average more than 98% of the time in the sleeping mode, so that the energy consumed (i.e., the product between the time that each STA remains in every state and its corresponding power consumption) will be very low. Consequently, and due to the large fraction of time that nodes remain asleep, this protocol can be applied to a wireless network formed by battery-powered nodes.

Finally, the time in the receiving state is considerably higher compared to the transmitting state. The reason is the time consumed during listening to DTIM and TIM beacons, as well as overhearing packets addressed to other STAs within the same DL/UL CAS.

V. Conclusions

In this paper, the performance of our CAS-based Channel Access protocol for the new IEEE 802.11ah amendment has been evaluated. In the defined scenarios, simulation results have shown that our proposal achieves a good trade-off between energy consumption and PDR both in DL and UL RAW segments.

Our results show that, in the considered scenarios, STAs remain in the sleeping mode more than 98% of the time. As a consequence, energy consumed by nodes will be very low, what confirms the suitability of the presented protocol for battery-powered sensor and actuator networks.

Several areas for future work regarding the performance evaluation of the CAS-Based Channel Access mechanism have been detected, such as the design of a method to divide the RAW into DL/UL segments depending on real-time traffic or the comparison with other novel channel access mechanisms. Moreover, we also will take into account the presence of hidden terminals, non-TIM and Unscheduled STAs and the use of traffic differentiation mechanism, in addition to the existence of network association/disassociation and long sleeping mechanisms.
Fig. 5. Packet Delivery Ratio (PDR) and Channel Occupancy ($\eta$) for different traffic patterns

(a) DL=15% UL=15%

(b) DL=15% UL=30%

(c) DL=15% UL=45%

Fig. 6. Percentage of time spent in each state for different traffic patterns


