Evaluation of the Co-Existence of RAW and TWT Stations in IEEE 802.11ah using NS-3

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ABSTRACT

Minimizing the energy consumption is one of the main challenges in Internet of Things (IoT) networks. Recently, the IEEE 802.11ah standard has been released as a new low-power Wi-Fi solution for IoT. It has several features, such as Restricted Access Window (RAW) and Target Wake Time (TWT), that promise to improve energy consumption. In this paper, we present an extension of the IEEE 802.11ah module in ns-3 with support for the TWT feature. We study how the energy consumption is affected by the co-existence of RAW and TWT stations (STAs). The results show that the presence of RAW STAs can have an extreme negative effect on the energy efficiency of TWT STAs. Proper scheduling of channel access for both RAW and TWT STAs can mitigate this effect without negatively affecting throughput of RAW STAs.

KEYWORDS

IEEE 802.11ah, Restricted Access Window (RAW), Target Wake Time (TWT), ns-3, Internet of Things (IoT), Energy Consumption

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1 INTRODUCTION

Predictions state that in the near future, the Internet of Things (IoT) will consist of billions of devices connected across the Internet. At the moment, various low-power wireless network technologies have been proposed to connect these IoT devices. However, the IEEE 802.11ah standard, compared to competing technologies, offers a good trade-off between range, throughput and energy efficiency, allowing the connection of up to 8192 devices with one access point (AP). In order to improve the energy consumption of power-limited stations (STAs) in dense networks, different mechanisms are offered on the MAC layer, such as Restricted Access Window (RAW) and Target Wake Time (TWT). Although the standard is promising, the hardware is not on the market yet. However, researchers have been investigating it already for a few years. Early research was based on analytical modeling of the saturated network state, which does not accurately capture realistic IoT network behavior and is arduous to adapt to non-saturated network conditions.

To evaluate IEEE 802.11ah more realistically, we implemented the standard in the ns-3 network simulator [11, 14]. This simulator module supports many of the features introduced by the IEEE 802.11ah standard, such as sub-1GHz channel models, fast association, RAW, Traffic Indication Map (TIM) segmentation. Particularly, RAW aims to reduce collisions in dense IoT networks, where hundreds of STAs are connected to one AP, by dividing them into groups and only allowing one group to access the channel in specific intervals, or during shared slots that all the STAs can access.

In this paper, we present our implementation of TWT, as an extension to our previously published IEEE 802.11ah module for ns-3. TWT helps to reduce the energy consumption by letting STAs sleep and only waking up to transmit their packets, skipping multiple beacons without being disassociated from the network. Using our implementation, we evaluate the effects of co-existing TWT and RAW STAs. To our knowledge, existing research has focused solely on RAW or TWT, not showing the mutual influence of these mechanisms on each other. To address this, we present the evaluation of the co-existence of RAW and TWT in a network, where we assume RAW STAs have higher traffic, while TWT STAs have sporadic traffic. We show how the number of RAW STAs influences the energy efficiency of TWT STAs, and propose a more optimal channel access schedule to mitigate this negative influence.

The rest of the paper is organized as follows. Section 2 compares our work to current state of the art research. Section 3 provides an overview of RAW and TWT and their implementation in the ns-3 simulator. In Section 4, we provide the results of the simulations, where we evaluate RAW and TWT in terms of energy efficiency. Finally, conclusions and future work are discussed in Section 5.

2 RELATED WORK

The IEEE 802.11ah standard made its first appearance in October 2013 and was officially released in June 2017. Since then, researchers have been investigating the advantages and challenges in the design of PHY and MAC layer schemes [3, 6, 8].

However, since the hardware is not on the market yet, the evaluation has been done mostly using analytical models [5, 9]. Most relevant to the research presented in this article is the work focusing on RAW and TWT. Several studies have been done on the calculation of the energy consumption of RAW and TIM, given specific network and traffic conditions [7, 9, 13, 15, 16].

To our knowledge, only the research done by Beltramelli *et al.* [5] evaluated the TWT feature, using an analytical model and comparing it to RAW. However, they do not consider the impact

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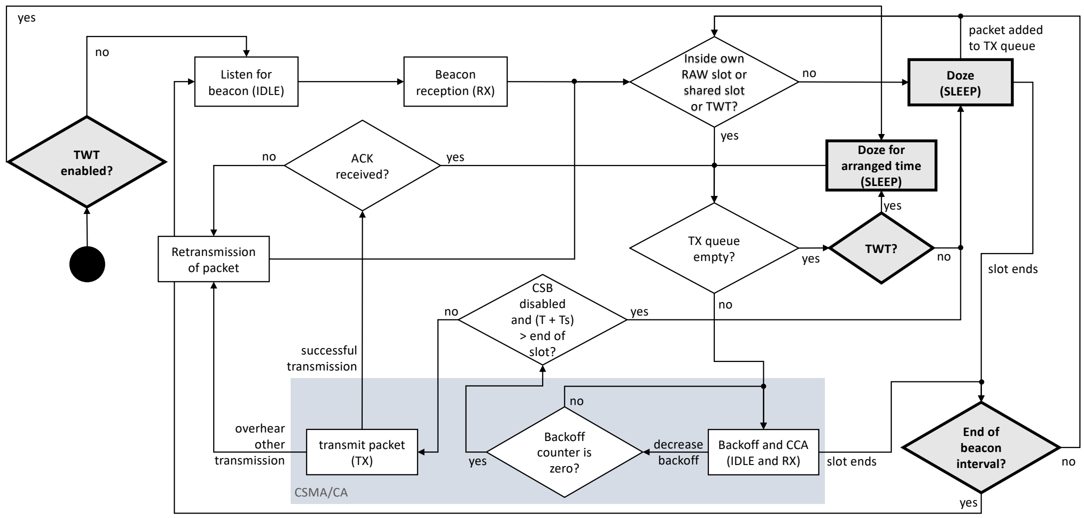

Figure 1: Radio state diagram for the developed energy model of IEEE 802.11ah with RAW and TWT

of sleeping time on the results, or the simultaneous usage of both RAW and TWT in the same network.

In this paper, we study the co-existence of RAW and TWT using our simulator, where we assume RAW STAs have higher traffic, while TWT STAs have sporadic traffic. We show how the number of RAW STAs influences the energy efficiency of TWT STAs.

3 RAW AND TWT NS-3 IMPLEMENTATION

RAW and TWT are two main features of the IEEE 802.11ah standard that allow better management of the energy consumption of resource-constrained STAs. The RAW mechanism was already part of the previously published version of our IEEE 802.11ah ns-3 module [14]. Recently, we extended it with support for TWT, which is available as open source in the latest release[1].

3.1 Restricted Access Window (RAW)

Numerous studies have shown that traditional channel access methods such as Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) and Time-Division Multiple Access (TDMA) are not suitable for dense IoT networks, due to lack of scalability and increase of delays [12]. For this reason, a more flexible paradigm called RAW has been introduced in IEEE 802.11ah. It combines the advantages of CSMA/CA and TDMA.

In this mechanism, STAs are split into groups, and only one group can access the channel during a specific interval using CSMA/CA. Groups can be further split into fixed-duration slots in order to reduce the number of contending STAs even more. During a RAW slot, only the STAs belonging to that slot are allowed to access the channel. To manage the grouping information, the AP broadcasts beacon frames that contain the RAW Parameter Set (RPS) at the fixed-length beacon interval. The RPS contains the configuration parameters, such as the number of groups, each group start time, duration, number of slots per group and assigned STA list. The STAs belonging to a RAW group have sequential association IDs (AIDs) and are assigned to RAW slots in a round-robin fashion.

As the standard does not suggest any algorithm to manage these parameters, there is a lot of flexibility in order to manage the grouping configuration. This has many advantages, such as an increase in energy efficiency and scalability and reduction of contention and collisions. Another advantage is introduced by the fact that the configuration can be adjusted from beacon to beacon, with the possibility to adapt the configuration to the network dynamics.

An in-depth description of RAW and the dynamic grouping configuration interface implementation in ns-3, can be found in our previous work [11, 14].

3.2 Target Wake Time (TWT)

TWT is a mechanism that allows STAs to agree with the AP to remain into the doze (i.e., deep sleep) state for extended periods of time, skipping the reception of multiple beacons without being disassociated from the network. The STAs and the AP exchange information that includes the time length during which the STA will be in the doze state, and when it should wake up to send and receive data. The negotiation of these parameters allows the AP to optimally schedule the wake-up periods of different STAs, in order to avoid simultaneous wake-ups. This minimizes channel contention and reduces the required amount of time a STA needs to be awake [1].

In our simulator implementation, TWT STAs agree with the AP an amount of time in which they can sleep, skipping the reception of any beacons that occur during this interval. When these STAs wake up, they send their buffered packets, before going back to sleep for the agreed amount of time. Figure 1 shows the implemented STA state diagram that is used to determine the radio state and calculate energy consumption for both TWT and RAW STAs. In addition, we implemented an alternative more optimal channel access scheme, where the AP reserves a RAW slot for TWT STAs,

[1] https://github.com/imec-idlab/IEEE-802.11ah-ns-3

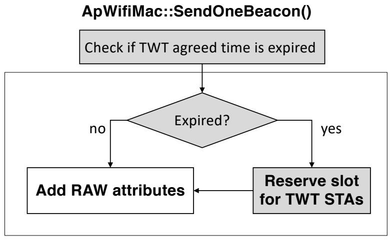

Figure 2: Modification in the *ApWifiMac* class (dark background) to reserve a seperate RAW slot for TWT STAs

when their wake-up timer expires. This avoids contention among TWT and RAW STAs. Its implementation is illustrated in Figure 2.

4 RESULTS AND DISCUSSION

In this section, we present the results of the energy efficiency of TWT in a network consisting of both STAs using TWT and RAW. We use our simulation framework [14] extended with the TWT feature. As no off-the-shelf IEEE 802.11ah hardware is available, we use the energy consumption values of the AT86RF215 Atmel radio [2] in the results, because it uses similar PHY modulations and it also covers sub-1-GHz frequencies.

4.1 Simulation Setup

In our simulator, RAW STAs are assigned to a specific RAW slot, which occupies part of the beacon interval's airtime. Any airtime not assigned to a specific RAW slot is considered a shared slot and can be accessed using CSMA/CA by any STA. TWT STAs are implemented to sleep for extended periods of time, corresponding to their data transmission interval. By default, they are scheduled to wake up during a non-RAW shared slot, and will compete with each other and RAW STAs that try to use this shared airtime. Since the AP knows when TWT STAs will be awake, it can alternatively reserve an empty RAW slot, where only TWT STAs will wake-up and access the channel (cf., Figure 2). We compare these two approaches and refer to them as "Mixed" (i.e., TWT STAs access the channel during the shared slot together with RAW STAs) and "Separated" (i.e., TWT STAs are given an empty RAW slot during which RAW STAs are not allowed to access the channel). Subsequently, we evaluate the energy efficiency of TWT STAs sending sporadic traffic, for different numbers of RAW STAs with higher traffic. We have used the configuration in Table 1. With these simulations we want to see how TWT STAs are influenced by the number of RAW STAs in a network. In the following graphs, we provide the energy efficiency in terms of bits per Joule, representing the total number of payload bits that can be transmitted with 1 Joule of energy. A higher value represents better energy efficiency [10].

4.2 Single TWT STA

In this scenario, we evaluate the behaviour of a single TWT STA in a network with 10 to 500 RAW STAs. Figure 3 shows the comparison of the energy efficiency in kilobits per Joule of the TWT STA on the y-axis, being influenced by the number of RAW STAs in a 802.11ah network.

Table 1: Default PHY and MAC layer parameters used in our experiments

Parameter	Value
Transmission power	0 dBm
Transmission gain	0 dB
Reception gain	3 dB
Noise Figure	3 dB
Voltage	3.3 V
Propagation loss model	Outdoor, macro [4]
Error Rate Model	YansErrorRate
Wi-Fi mode	MCS1, 1 MHz
Station distribution	uniformly random
Capture Effect	enabled
CWmin	15
CWmax	1023
Payload size	16 bytes
Cross Slot Boundary (CSB)	enabled
MAC header type	legacy header
Queue size	10 packets
Beacon Interval	1.024 s
Avg Packet Arrival Interval (TWT STAs)	10s
Avg Packet Arrival Interval (RAW STAs)	1s
Number of RAW groups	10
Number of slots per group	1
Power consumption	**Value**
Receiving (P_{rx})	92 mW
Idle (P_{idle})	20 mW
Transmission (P_{tx})	204 mW
Sleeping (P_{sleep})	99 nW

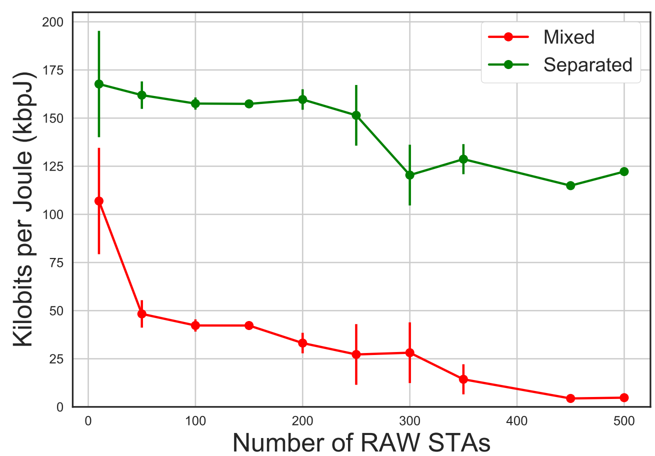

Figure 3: Energy efficiency of one TWT STA, influenced by the number of RAW STAs in a network, comparing the mixed and separated strategies

Our results show how reserving airtime for the TWT STAs only (i.e., separated) can lead, without affecting the throughput of RAW STAs (not depicted), to a significant increase in energy efficiency of TWT STAs. For 10 RAW STAs, this improvement is about 60%, while for 500 STAs energy efficiency is up to 1000 times better in the separated compared to the mixed case. This is due to the fact the shared slot causes contention for the TWT STA, forcing it to stay awake longer while trying to access the channel and increasing its energy consumption. Moreover, the separated approach scales better, leading to a decrease in energy efficiency of only 26% when

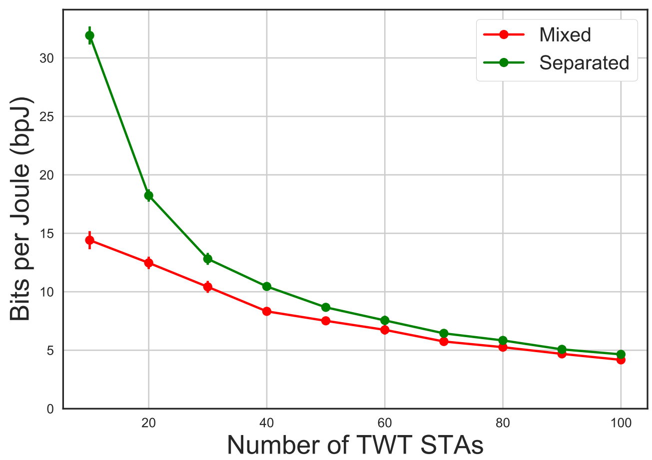

Figure 4: Energy efficiency of an increasing number of TWT STAs, in a network with 250 RAW STAs, comparing the mixed and separated strategies

increasing the number of RAW STAs from 10 to 500. On the other hand, the mixed approach results in an 800-fold decrease. The decrease in efficiency of the separated approach is due to the use of the cross slot boundary (CSB) feature. Even if RAW STAs cannot start accessing the channel during the slot reserved for the TWT STA, their ongoing transmissions can cross into this slot, causing limited contention as the number of RAW STAs increase.

4.3 Multiple TWT STAs

In this scenario, we compare the behaviour of a different amounts of TWT STA in the network, co-existing with a fixed number of 250 RAW STAs. Figure 4 shows the comparison of the energy efficiency in kilobits per Joule, for an increasing number of TWT STAs on the y-axis. In this case our results show how the the improvements of the separated compared to the mixed approach reduce as the number of TWT STAs in the network increases. The improvement of the separated approach is over 120% for a single TWT STA, while it drops to only 11% when over 100 TWT STAs are connected to the network. This is due to the fact that as more TWT STAs use the network, their chances of waking up during the same beacon interval, and contending for channel access during their reserved slot increase. Note that in our experiments a relatively high TWT packet arrival interval of 10s was used. For lower traffic arrival rates, a higher number of TWT STAs would be able to co-exist.

5 CONCLUSION

In this paper, we present our implementation of TWT, as an extension to our previously published IEEE 802.11ah module for ns-3. Moreover, we have evaluated the effects of co-existing TWT and RAW STAs on energy efficiency and proposed an alternative more optimal channel access strategy. We have shown how the energy efficiency of TWT STAs can be significantly improved in face of co-existence with RAW STAs by reserved airtime during which RAW STAs cannot access the channel. In our experiments, the energy efficiency improved up to 1000 times when using this strategy, compared to shared channel access, if the network contains 500 RAW STAs. This strategy did not have a noticeable effect on RAW throughput. However, as the number of TWT STAs increases, also the contention among them increases, reducing the improvement. That is why a more dynamic slot assignment approach is needed to increase performance for co-existing RAW and TWT STAs.

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