Performance Analysis of MAC Energy-saving Strategies for WLANs

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ABSTRACT

The IEEE 802.11 protocol has become the *de facto* communication technology for WLANs (Wireless Local Area Networks). While considered reliable and efficient for applications requiring high datarate, IEEE 802.11 is often disregarded for energy-sensitive applications such as IoT (Internet of Things). In fact, the IEEE 802.11 standard and its amendments have introduced several energy-saving mechanisms over the years that are rarely used in practice.

In this paper, we consider seven possible energy-saving strategies for the MAC layer of IEEE 802.11. Using two case studies, we evaluate and compare these energy-saving strategies with regard to their network performance and energy saving. We conclude that most of the energy-saving strategies manage to support the levels of workloads considered in our case studies, and at the same time, they succeed to cut energy consumption by a factor ranging from two to eight. In particular, the "DL slot" strategy leads STAs to consume only half (or even less) of what they would without running any strategy, without trading off the attained levels of throughput. The "DL prompt + UL slot" strategy is the most efficient energy-wise, but this can come at the expense of a loss of throughput.

CCS CONCEPTS

• **Networks** → **Wireless local area networks**; **Network simulations**; *Link-layer protocols.*

KEYWORDS

Wi-Fi, 802.11, energy saving, IoT, performance evaluation

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1 INTRODUCTION

Wi-Fi is the *de facto* communication technology for WLANs (Wireless Local Area Networks). Thanks to the data rates offered in its last versions (*i.e.,* Wi-Fi 4, Wi-Fi 5, or Wi-Fi 6), this technology, based on the IEEE 802.11 standard, can support applications requiring high throughput, like, for instance, video streaming. Because Wi-Fi was originally not designed for energy-constrained devices, it was often disregarded as a serious candidate for energy-sensitive networks like IoT. Nevertheless, from the very first IEEE 802.11 standard and up to very recent amendments, multiple energy-saving mechanisms have been proposed for this technology (*e.g.,* PS-Poll, RAW, TWT). In our previous work [2], we overview the different MAC energy-saving mechanisms available in the IEEE 802.11 standard and its amendments, and compare them with regard to qualitative metrics.

As far as we know, relatively little has been done to quantitatively compare the different MAC energy-saving mechanisms proposed for IEEE 802.11-based networks. For example, [5–7, 9, 12] provide an analysis and a configuration of one or two MAC energy-saving mechanisms, but these works are incomplete as they do not take into account every MAC energy-saving mechanism. We believe that a comprehensive performance comparison of all the existing MAC energy-saving mechanisms for 802.11-based networks is still lacking. Indeed, a comparison study can help in identifying the best existing energy-saving mechanism for a targeted application or a given scenario, so that 802.11-based networks can make their share in reducing energy consumption.

To ease the performance analysis and the comparison of MAC energy-saving mechanisms, we represent them by "abstractions", which capture the main aspect of the strategy ruling each mechanism. By working at this level of abstraction, our study focuses on the key aspects impacting the radio medium sharing and the energy consumption of WLANs, leaving aside protocol details of the MAC energy-saving mechanisms.

As discussed in [4], there are mainly three approaches to evaluating the performance of a computer or communication system: performance measurement, analytic performance modeling, and simulation performance modeling. We selected the latest approach to conduct our study. On one hand, we dismissed the performance measurement approach, which appears unpractical since existing stations and access points do not implement all the possible IEEE 802.11 energy-saving mechanisms, let alone the ability to parametrize them. On the other hand, it seems to be a difficult matter to come up with accurate yet tractable analytical models to represent the behavior of WLANs that include heterogeneous devices in terms of traffic and energy-saving mechanisms.

To conduct our performance study, we designed and implemented a homemade simulator, named WE3S for WLAN Energy-Saving Strategies Simulator. This choice is motivated by several reasons. First, as far as we know, there is no simulator fully dedicated to IEEE 802.11 MAC energy-saving mechanisms. Besides, none of the existing network simulators includes the whole set of MAC energy-saving mechanisms, except for a few isolated modules. For example, ns-3 simulator implements PS-Poll[1] [11] and RAW[2] [10]. On the other hand, implementing our own simulator has several advantages. First, WE3S simulator focuses on the MAC layer and its energy-saving mechanisms, without including unrelated mechanisms such as ARP or authentication. Second, we ensure a fair comparison of the MAC energy-saving mechanisms by using an identical level of abstraction for their implementation. Finally, we use the simulator ns-3 to validate that our WE3S simulator is accurate in its medium sharing among stations.

We implemented multiple energy-saving strategies, corresponding to abstractions of the IEEE 802.11 MAC energy-saving mechanisms, in the WE3S simulator. We evaluate and compare these strategies in two different case studies, characterized by different number of stations, workload and the traffic direction. To summarize, the main contributions of this paper are as follows:

- we unify in a single framework the main MAC energy-saving strategies for WLANs;
- we design and implement a simulator, named WE3S, to evaluate the performance of each of these strategies in various scenarios and settings;
- we provide a fair quantitative comparison of these strategies with regard to their abilities at saving energy and satisfying throughput demands;
- we point out the potential great influence of the strategies' parameters on their overall performance;
- we provide insights on how, when, and which MAC energy-saving strategy to be used depending on the considered case study.

The rest of the paper is organized as follows. Section 2 describes the MAC energy-saving strategies we have identified. Section 3 presents the WE3S simulator and its validation. Section 4 presents our performance evaluation and comparison study. Section 5 provides a state-of-the-art on the MAC energy-saving mechanisms for WLANs. Section 6 concludes this paper.

2 STRATEGIES FOR ENERGY SAVING

In this section, we describe the main energy-saving strategies we have identified in the different IEEE 802.11 MAC energy-saving mechanisms. This description is complemented, for each energy-saving strategy, by a theoretical analysis estimating the doze time and the throughput of the STAs.

We consider a WLAN comprising one AP and a set of n_{STA} associated STAs. For the sake of conciseness, we use DL and UL to refer to downstream and upstream traffic, respectively. We use $r(i)$ to denote the datarate of STA i (*i.e.*, the rate at which the STA sends or receives data at the physical layer) with i in $\{1, \ldots, n_{\text{STA}}\}$. Each STA i has a buffer of size $l_{\text{buffer}}(i)$ to queue pending frames. Identically, the AP has a buffer of size l_{APbuffer}. We use $\lambda_{\text{DL}}(i)$ and $\lambda_{\text{UL}}(i)$ to denote the workload of STA i in downstream traffic (from the AP) and upstream traffic (towards the AP), respectively. Finally, frames of STA i are of length $l_{\text{frame}}(i)$. Each STA may apply (or not) an energy-saving strategy. Note that because of its central role, the AP does not run any energy-saving mechanism.

Depending on their selected energy-saving strategy, STAs will experience different performance. We use the following metrics to evaluate the performance of any given STA i (i in $\{1, \ldots, n_{\text{STA}}\}$):

- $X_{\text{DL}}(i)$ and $X_{\text{UL}}(i)$ refer to the attained throughput of STA i, at the MAC layer, in downstream and upstream, respectively.
- $t_{\text{doze}}(i)$ represents the doze time of STA i, which is the fraction of the time the STA was in a doze state and thus its radio turned off.
- $E(i)$ is the average energy consumption of STA i.

Table 2 summarizes the different notations used in the paper. In this paper, we consider seven possible strategies in addition to the default one referred to as the "No strategy", which will serve as ground data for comparison. These strategies can be divided into three classes, depending on the type of traffic they restrict. The first class restricts only the downstream traffic (Section 2.1), the second class only the upstream traffic (Section 2.2) and the last class restricts both (Section 2.3). We use Figure 1 to illustrate the rationale behind each strategy. Note that most of these strategies can be mapped to existing energy-saving mechanisms in the IEEE 802.11 standards. Table 1 reports the considered strategies and their corresponding IEEE 802.11 mechanisms (if any).

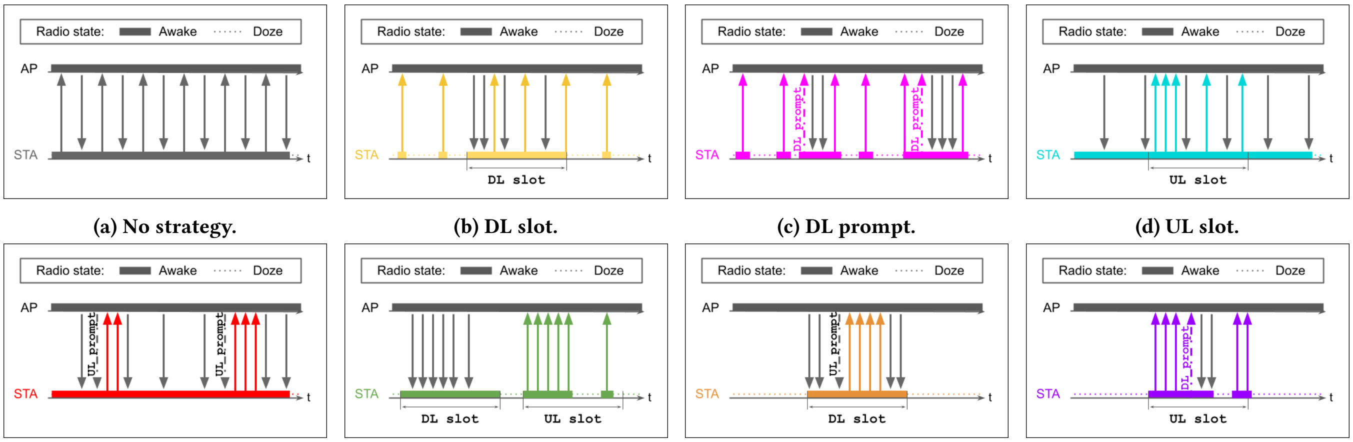
Strategy	Restricted traffic	Corresponding 802.11 mechanisms
No strategy	None	Default
DL slot	Downstream	S-APSD
DL prompt	Downstream	PS-Poll / U-APSD
UL slot	Upstream	TWT[2]
UL prompt	Upstream	None[1]
DL slot + UL slot	Both	TWT[3]
DL slot + UL prompt	Both	None[1]
DL prompt + UL slot	Both	PS-Poll + RAW

Table 1: Overview of the considered strategies and their corresponding IEEE 802.11 mechanisms (if any).
[1] **No mechanism uses such an energy-saving strategy in the IEEE 802.11 standard.**
[2] **For STAs in active mode (*i.e.*, its radio always turned on).**
[3] **For STAs in Power Save mode (*i.e.*, periodically switching its radio off to save energy).**

For each strategy, we consider one STA i that implements the strategy. We then provide analytical formulas to evaluate the upstream throughput and the doze time of STA i. To derive these formulas, we rely on the following assumptions:

(1) The delay each STA must wait to access the medium is zero. But STAs may need to wait until their energy-saving strategy enables them to transmit. This assumption holds only

[1]https://gitlab.com/shyam100v/ns-3-dev/-/tree/wifiPSM
[2]https://github.com/imec-idlab/IEEE-802.11ah-ns-3



(a) No strategy. (b) DL slot. (c) DL prompt. (d) UL slot.

(e) UL prompt. (f) DL slot + UL slot. (g) DL slot + UL prompt. (h) DL prompt + UL slot.

Figure 1: Possible strategies to save energy at the MAC layer of 802.11.

in WLANs with very low contention (*i.e.,* with a limited competition to access the medium).

(2) Frames are always successfully sent on their first attempt. This assumption applies to most WLANs, as STAs and APs dynamically adapt their transmission parameters to limit transmission errors.

(3) Frames arrive at each STA and the AP according to (independent) Poisson processes.

Note that we do not derive the analytical formulas for the downstream throughput that each STA attains since this requires making assumptions on the characteristics of the other STAs, like their energy-saving strategies and their workload.

2.1 Strategies restricting the downstream traffic

STAs may save energy by restricting the time periods on which they may receive their downstream traffic. Such strategies, which we refer to as restricting downstream traffic strategies, enable STAs to periodically switch to a doze state (*i.e.*, radio turned off). The rationale behind these strategies is that STAs know in advance when they are susceptible to receiving downstream frames from the AP. Then, STAs can safely switch to a doze state whenever they are out of a receiving period without risking missing any downstream frames. We now detail each of the two strategies that restrict the downstream traffic and we refer to them as the "DL slot" strategy and the "DL prompt" strategy, respectively.

2.1.1 DL slot. The "DL slot" strategy relies on periodic time periods independently allocated to each STA and called *DL slot*. From the standpoint of the AP, it must queue any downstream frames that arrive outside of the DL slots of their destination STA. The AP will attempt to send these pending frames upon the next DL slot. From the standpoint of STAs, they can safely switch to doze state whenever they are not in their DL slots. Note that STAs can send upstream frames at any time using the IEEE 802.11 CSMA/CA (Carrier Sense Mulitple Access/Collision Avoidance) approach.

The "DL slot" strategy involves three parameters that together define the sequence of slots: (i) t_{DLslot}, which timestamps the beginning of the first DL slot; (ii) T_{DLslot}, which refers to the time period between the beginnings of two consecutive DL slots; (iii) Δt_{DLslot}, which represents the duration of DL slots.

Under our assumption that access to the medium is immediate, the UL throughput of STA i is as follows:

$$X_{\text{UL}}(i) = min(\lambda_{\text{UL}}(i), r(i)) \tag{1}$$

Because STA i can doze provided that it is outside its DL slots and that it is not transmitting upstream frames, its doze time can be computed as:

$$t_{\text{doze}}(i) = \left(1 - \frac{\Delta t_{\text{DLslot}}(i)}{T_{\text{DLslot}}(i)}\right) \times \left(1 - \frac{min(\lambda_{\text{UL}}(i), r(i))}{r(i)}\right) \tag{2}$$

2.1.2 DL prompt. The "DL prompt" strategy relies on special frames – referred to as *DL prompt* – to let the STAs notify the AP when to send frames downstream. Thus, from the standpoint of the AP, every incoming frame destined to a STA using DL prompt must first be queued. Indeed, the AP can only send pending frames in return to the reception of DL prompt sent by the associated destination STA. From the standpoint of a STA, it can switch to a doze state at any time (unless it has just sent a DL prompt to poll the AP).

The "DL prompt" strategy involves only one parameter: T_{DLprompt} which denotes the period at which the STA sends its DL prompts to the AP.

Like with the "DL slot" strategy, we can use Eq. (1) to compute the UL throughput of STA i. As for the doze time, STA i wakes up only to send frames upstream or to retrieve frames downstream. Its doze time can be computed as follows:

$$t_{\text{doze}}(i) = 1 - \frac{min(\lambda_{\text{UL}}(i) + \lambda_{\text{DL}}(i)), r(i))}{r(i)} \tag{3}$$

2.2 Strategies restricting the upstream traffic

As an alternative to restricting downstream traffic, strategies may restrict the upstream traffic of STAs. In that case, their primary goal is to reduce the contention in the WLAN and not to save energy, which rather comes as a indirect benefit. Indeed, limiting contention will result in fewer collisions and hence fewer retransmissions.

2.2.1 UL slot. The "UL slot" strategy relies on periodical time periods called *UL slot*. Every STA can only transmit its upstream frames during its dedicated UL slots. If configured properly, this strategy can diminish the contention when multiple STAs use non-overlapping UL slots.

The "UL slot" strategy involves analogous parameters to the "DL slot" strategy: (i) t_{ULslot} which timestamps the beginning of the first UL slot; (ii) T_{ULslot} which refers to the time period between the beginnings of two consecutive UL slots; (iii) Δt_{ULslot} which represents the duration of UL slots.

Concerning the doze time of STA i, we have:

$$t_{\text{doze}}(i) = 0 \tag{4}$$

Despite our assumption that there is no delay in accessing the medium access, STA i may sustain losses that affect its UL throughput. This is known as the buffer overflow effect, owing to the limited size of the buffer of STA i. Indeed, any packets arriving outside of an UL slot must first be queued in the buffer of STA i before being eventually transmitted during the next UL slot. However, once the buffer of size $l_{\text{buffer}}(i)$ is full, any incoming packets will be dropped. This enables us to derive an upper bound on the UL throughput of STA i since the latter may send up to $\lambda_{\text{UL}}(i) \times \Delta t_{\text{ULslot}}(i)$ kbit during its UL slots and enqueue no more than $l_{\text{buffer}}(i) \times l_{\text{frame}}(i)$ bits outside its UL slots. Therefore, and given that the UL throughput cannot exceed the UL workload nor the physical datarate, we have:

$$X_{\text{UL}}(i) = \min\left(\lambda_{\text{UL}}(i), r(i), \frac{l_{\text{buffer}}(i) \times l_{\text{frame}}(i) + \lambda_{\text{UL}}(i) \times \Delta t_{\text{ULslot}}(i)}{T_{\text{ULslot}}(i)}\right) \tag{5}$$

2.2.2 UL prompt. Similarly to the "DL prompt" strategy, the "UL prompt" strategy relies on special frames – referred to as *UL prompt* – to let the AP notify the STAs when to send frames upstream. In practice, it is up to the AP to send UL prompts to STAs to enable them to transmit their upstream frames. Upon the reception of an UL prompt, if a STA has pending frames, it sends them immediately. Otherwise, it simply sends back an ACK. Note that if every STA of a WLAN implements a UL prompt strategy, then frame collisions cannot occur within the WLAN.

There is only one parameter to be configured with the "UL prompt" strategy: $T_{ULprompt}$ which denotes the period at which the AP sends its UL prompts to the STAs.

Like with the "UL slot" strategy, the "UL prompt" strategy does not allow STA i to doze: Eq. (4) can be used. The UL throughput will only depart from the UL workload if buffer overflow occurs at STA i. STA i needs to enqueue every arriving upstream frame until the reception of the next UL prompt. Therefore, we can derive an upper bound for the UL throughput of STA i since the latter cannot send more than $l_{\text{buffer}}(i) \times l_{\text{frame}}(i)$ bits (corresponding to the full exhaustion of its buffer) over a duration of $T_{\text{ULprompt}}(i)$. Given that upper bound and that the UL throughput is intrinsically lower than the UL workload and the physical datarate, we have:

$$X_{\text{UL}}(i) = \min\left(\lambda_{\text{UL}}(i), r(i), \frac{l_{\text{buffer}}(i) \times l_{\text{frame}}(i)}{T_{\text{ULprompt}}(i)}\right) \tag{6}$$

2.3 Strategies restricting both the downstream and the upstream traffic.

Lastly, strategies may restrict both downstream and upstream traffic. In theory, this should save energy by letting STAs switch to a doze state (as strategies restricting downstream traffic do) as well as reducing the level of contention in the WLAN (as strategies restricting upstream traffic do). Because there are two ways of restricting downstream traffic and two ways of restricting upstream traffic, there is a total of four combinations. However, we dismiss the strategy combining the "UL prompt" and "DL prompt" strategies, as they are incompatible by design. Note that the analytical formulas for these strategies can be derived from the ones given for the downstream and upstream strategies.

2.3.1 DL slot + UL slot. The "DL slot + UL slot" strategy relies on two separate sets of periodical time periods – namely, one set of DL slots and one set of UL slots. The AP cannot send downstream frames outside the DL slots dedicated to the destination STA. This enables the STA to safely switch to a doze state. STAs are not allowed to send upstream frames outside their dedicated UL slots.

2.3.2 DL slot + UL prompt. The "DL slot + UL prompt" strategy relies on periodical time periods and prompts. More precisely, STAs cannot send upstream frames unless the AP previously sent downstream a UL prompt. The AP can only send its downstream frames during the DL slots dedicated to the destination STA – including the UL prompts. Therefore, all the upstream and downstream traffic of a STA must be exchanged during the STA's DL slots.

2.3.3 DL prompt + UL slot. Similarly to the "DL slot + UL prompt" strategy, the "DL prompt + UL slot" strategy uses both periodical time periods and prompts. STAs cannot send upstream frames, including their DL prompts in order to fetch potential frames pending in the buffer of the AP, outside of their dedicated UL slots.

3 WE3S SIMULATOR

As discussed in Introduction, we have developed our own simulator, named WE3S, to evaluate the performance of the MAC energy-saving strategies and to compare them on a fair basis.

3.1 Description

WE3S is a discrete-event simulator, coded in Python 3.10, implementing the main mechanisms of the IEEE 802.11 MAC layer, namely the CSMA/CA with the Binary Exponential Backoff algorithm. Note that in WE3S when two nodes draw an equal backoff, the emitted frames will collide, and thus be retransmitted. WE3S enables frames to be aggregated for their transmission in a chunk of up to eight frames[3], with a single PHY header and MAC header. In return, the destination sends an ACK frame to acknowledge the reception of the frame or of the whole set of aggregated frames. The PHY layer is simplified: (i) STAs use fixed datarate to send or receive frames, (ii) instead of a propagation model for the radio channel, frames are simply prone to random errors upon their reception. WE3S does not implement layers above the MAC layer. Frames are generated at each node (AP or STA) following a Poisson process.

[3]This value can be configured in WE3S.

Symbol	Definition	Unit
	Scenario parameters	
n_{STA}	Number of STAs	-
$r(i)$	Physical datarate between the AP and STA i	Mbps
$\lambda_{\text{DL/UL}}(i)$	DL/UL workload of STA i	Mbps
$l_{\text{buffer}}(i)$	Buffer capacity of STA i	Number of frames
l_{APbuffer}	Buffer capacity of the AP	Number of frames
$l_{\text{frame}}(i)$	Size of the frames to/from STA i	bits
	Performance metrics	
$X_{\text{DL/UL}}(i)$	DL/UL throughput of STA i	Mbps
$t_{\text{doze}}(i)$	Doze time of STA i	%
$E(i)$	Average energy consumption of STA i	W
	Slot parameters	
$t_{\text{DL/ULslot}}(i)$	Time of the first DL/UL slot start of STA i	ms
$T_{\text{DL/ULslot}}(i)$	Period between two consecutive DL/UL slot starts of STA i	ms
$\Delta t_{\text{DL/ULslot}}(i)$	Duration of the DL/UL slots of STA i	ms
	Prompt parameter	
$T_{\text{DL/ULprompt}}(i)$	Period between two consecutive DL/UL prompts from/to STA i	ms

Table 2: Main notation used in this paper.

WE3S can handle a wide range of scenarios. While the WLAN must include a single AP, there is no limitation on the number of STAs. Each STA is defined by the following set of parameters: datarate, downstream and upstream workload, buffer capacity, and length of frames. Additionally, each STA may implement an energy-saving strategy whose parameters are described in Section 2.

Every simulation run generates a log of events, which can be exploited to compute the main performance metrics of each STA. Network performance metrics include the downstream and upstream throughput, as well as their associated rate of losses. WE3S also provides an estimate of the energy consumption of each STA. To do that, WE3S records the time each STA spends in each of the following states: transmission, reception, idle, and doze. Like the ns-3 energy consumption model, we use the numerical values of [3] to associate a level of energy to each of these states. We recall these values here: 1.28 W for the transmission state, 0.94 W for the reception state, 0.82 W for the idle state, and 0.1 W for the doze state. The WE3S source code is available at https://github.com/EstGue/WE3S/.

3.2 Validation of the medium sharing

To validate that the CSMA/CA approach as implemented in W3ES is accurately simulated, we compare WE3S to ns-3. We consider the following ns-3 scenario. Three STAs are located on a 1-meter radius circle around an AP. Each STA uses fixed transmission parameters (MCS HT15 with short Guard Interval on a 20 MHz channel) that lead to a datarate of 144.4 Mbps. The frame aggregation is enabled. The STAs have equal workloads, evenly divided between downstream and upstream traffic. These workloads are generated by UDP flows with packets of size 1440 bytes at a constant rate.

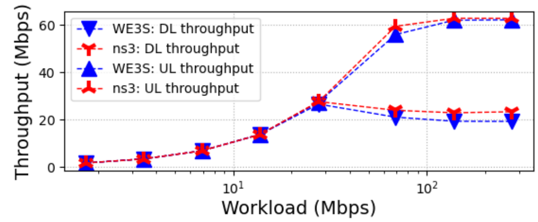


Figure 2: Accuracy of WE3S at reproducing the aggregated downstream and upstream throughput in a WLAN with 1 AP and 3 STAs.

We simulate the same scenario with WE3S by setting the number of STAs to three, the datarate to 144.4 Mbps, and by generating the same workloads to/from each STA.

Figure 2 shows the aggregated DL and UL throughput obtained with ns-3 (in red) and with WE3S (in blue) for various levels of workload. For workloads lower than 23.04 Mbps, ns-3 and WE3S show almost identical performance. For workloads higher than 46.08 Mbps, we can observe that the DL (resp. UL) throughput obtained with ns-3 is slightly higher than the DL (resp. UL) throughput attained with WE3S. The results of the two simulators differ by at most 3.5 Mbps for the DL throughput and 0.8 Mbps for the upstream throughput. Overall, Figure 2 shows the ability of WE3S at delivering fair estimates of throughput at different levels of workloads.

To conclude, it is worth noting that real-life WLANs typically operate at low or moderate levels of workloads. An occupancy rate of 30% of the medium is often already perceived as already quite loaded [1]. In Section 4, we will consider several case studies to evaluate the performance of various energy-saving strategies. These case studies, inspired by real-life scenarios, operate at low or moderate levels of workloads so that the returned values of WE3S for the throughput can be considered as accurate.

3.3 Validation of the energy-saving strategies

To validate the implementation of the energy-saving strategies in WE3S, we rely on the analytical formulas presented in Section 2. These latter give an insight on the bounds of the performance metrics when the time to access the medium approaches zero.

In WE3S, the time to access the medium is not null, but in a lightly-loaded network, this time can be limited. For the comparison, we consider the following scenario: $n_{\text{STA}} = 1$, $r = 100$ Mbps, $\lambda_{\text{DL}} = \lambda_{\text{UL}} = 5$ Mbps, $l_{\text{buffer}} = l_{\text{APbuffer}} = 20$ frames and $l_{\text{frame}} = 11,520$ bits. In addition, we deactivate the random errors on the frame reception to further reduce the number of retransmissions.

Concerning the energy-saving strategies, we use the following values for the different parameters: $t_{\text{DLslot}} = t_{\text{ULslot}} = 100$ ms, $\Delta t_{\text{DLslot}} = \Delta t_{\text{ULslot}} = 10$ ms and $T_{\text{DLprompt}} = T_{\text{ULprompt}} = 50$ ms.

Table 3 shows the results of the performance metrics obtained with the analytical formulas and with WE3S. The results are close for all the metrics. Concerning the doze time of the "DL slot" and the "DL prompt" strategies, the difference between WE3S and the analytical formulas is due to the overhead of the PHY and MAC layers: the analytical formulas do not take it into account, whereas WE3S does.

	Formulas	WE3S simulator	Difference
	DL slot		
UL throughput (Mbps)	5.00	4.98	0.38 %
Doze time (%)	85.50	81.11	5.13 %
	DL prompt		
UL throughput (Mbps)	5.00	4.99	0.21 %
Doze time (%)	90.00	82.42	8.43 %
	UL slot		
UL throughput (Mbps)	2.80	2.89	3.09 %
Doze time (%)	0	0	N/A
	UL prompt		
UL throughput (Mbps)	4.61	4.55	1.33 %
Doze time (%)	0	0	N/A

Table 3: Comparison between the analytical formulas and WE3S on four energy-saving strategies.

4 PERFORMANCE EVALUATION

In this section, we evaluate the performance of the energy-saving strategies described in Section 2 using two case studies inspired by real-life scenarios.

4.1 Configuring the energy-saving strategies

Every considered MAC energy-saving strategy involves a number of configuration parameters ranging from one (for the "DL prompt" and the "UL prompt" strategies) to six (for the "DL slot + UL slot" strategy). In this section, we explain how we configure the different MAC energy-saving strategies for all the STAs of the WLAN.

For the "DL slot" and the "UL slot" strategies, we assume that all STAs have the same inter-slot period. We use $T_{\text{inter-slot}}$ to denote this inter-slot period. Then, we subdivide $T_{\text{inter-slot}}$ as many times as the number of stations in time slots of equal size (this is in general agreement with [12]). Each STA is allocated a single slot whose position in the inter-slot period remains the same over the whole simulation. More formally, for each STA i implementing the "DL slot" or the "UL slot" strategies, we have:

$$\begin{aligned} T_{\text{DL/ULslot}}(i) &= T_{\text{inter-slot}} \\ \Delta t_{\text{DL/ULslot}}(i) &= \frac{T_{\text{inter-slot}}}{n_{\text{STA}}} \\ t_{\text{DL/ULslot}}(i) &= i \times \frac{T_{\text{inter-slot}}}{n_{\text{STA}}} \end{aligned} \tag{7}$$

The configuration of the "DL prompt" (resp. "UL prompt") strategy is simply determined by the periodicity at which DL (resp. UL) prompts are sent. We use the rate at which each STA generates its DL (resp. UL) traffic to set the periodicity of these prompts, namely $T_{\text{DLprompt}}(i)$ (resp. $T_{\text{ULprompt}}(i)$). To do that, we introduce a new parameter, denoted by P_{prompt}, which is a positive integer and can be viewed as a sampling factor. For instance, $P_{\text{prompt}} = 2$ leads STAs using the "DL prompt" strategy to send a DL prompt every 2 frame generations. More formally, for each STA i implementing the 'DL prompt" or "UL prompt" strategies we have:

$$T_{\text{DLprompt}}(i) = \frac{l_{\text{frame}}(i)}{\lambda_{\text{DL}}(i)} \times P_{\text{prompt}} \quad \text{or} \quad T_{\text{ULprompt}}(i) = \frac{l_{\text{frame}}(i)}{\lambda_{\text{UL}}(i)} \times P_{\text{prompt}} \tag{8}$$

To explore various configurations for the strategies restricting both downstream and upstream traffic (*i.e.,* combining the "DL slot" or the "DL prompt" strategy with the "UL slot" or "UL prompt" strategy), we do as follows. Since each component (*i.e.,* DL and UL) operate independently from the other, we configure each component separately, based on Eqs. (7) and (8).

To explore various configurations for each strategy in the three case studies, we consider the following set of values: $T_{\text{inter-slot}} = \{5, 10, 20, 50, 100\}$ ms and $P_{\text{prompt}} = \{1, 4, 8\}$. Considering multiple configurations for each strategy enables us to more accurately evaluate the actual efficiency of each strategy (given that their performance strongly depends on their configuration). Note that the WE3S simulator could also include other energy-saving strategies' configurations than the ones used in our study.

4.2 Case study 1: *"Public WLAN"*

Our first case study, called *"Public WLAN"*, aims to represent WLANs that can be found in public places (*e.g.,* train stations and shopping malls). The WLAN can frequently experience unfavorable conditions due to the large number of STAs associated with the AP. Through this case study, we investigate if certain energy-saving strategies may efficiently operate when the WLAN is more crowded.

For the sake of our analysis, we distinguish a so-called foreground STA, whose performance will be evaluated, from a number of background STAs, which compete for the radio resources but are not evaluated. Let $i_F \in \{1 \ldots n_{\text{STA}}\}$ be the index of the foreground STA. Its characteristics are: $r(i_F) = 100$ Mbps, $\lambda_{\text{DL}}(i_F) = \lambda_{\text{UL}}(i_F) = 5$ Mbps, $l_{\text{buffer}}(i_F) = 20$ frames and $l_{\text{frame}}(i_F) = 11,520$ bits.

On the other hand, background STAs characteristics are as follows: $n_{\text{STA}} = 15$ and $\forall i \in \{1 \ldots n_{\text{STA}}\} \setminus \{i_F\}$: $r(i) = 100$ Mbps, $\lambda_{\text{DL}}(i) = \lambda_{\text{UL}}(i) = 1$ Mbps, $l_{\text{buffer}}(i) = l_{\text{APbuffer}} = 20$ frames and $l_{\text{frame}}(i) = 11,520$ bits. Taken together the background STAs lead to a saturation of the medium close to 30% to which the workload of the foreground STA will be added.

Using our WE3S simulator, we obtain the throughput ($X_{\text{DL}}(i) + X_{\text{UL}}(i)$) and the energy consumption of the foreground STA for each energy-saving strategy and its configurations. The corresponding results are given in Figure 3. We start by analyzing the throughput performance. First, when making use of "No strategy", the WLAN is able to successfully handle all traffic (the location of the black star on the x-axis is at 10 Mbps, which corresponds to its workload). Second, if properly configured, the "UL slot" and "UL prompt" strategies enable the WLAN to attain the workloads, except for one configuration of the "UL slot" strategy. This good behavior mostly owes to the ability of these strategies at reducing the probability of collision when the number of competing STAs is large. Third, the other energy-saving strategies, except the "DL slot + UL slot" strategy, mostly struggle to meet the workload demands of the STA and manage to do so only with one of their configurations. Lastly, regardless of its configuration, the "DL slot + UL slot" strategy is never able to support the workload demands of the STA.

We now analyze for each strategy how it performs with regard to energy consumption. The "UL slot" and the "UL prompt" strategies consume as much as the "no strategy". This means that the retransmissions due to the high contention count for little to nothing in the energy consumption of the STA. Next comes the "DL prompt"

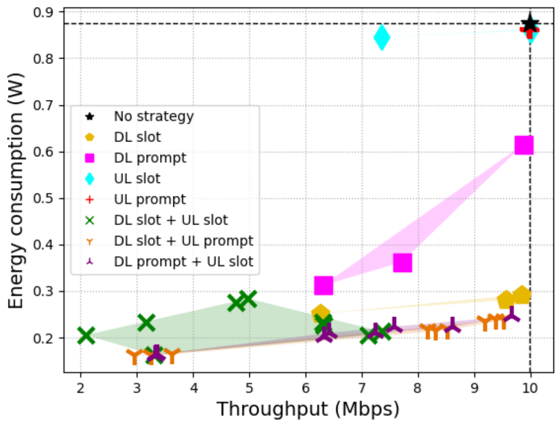


Figure 3: Case study 1. Performance of the energy-saving strategies for various configurations of their parameters.

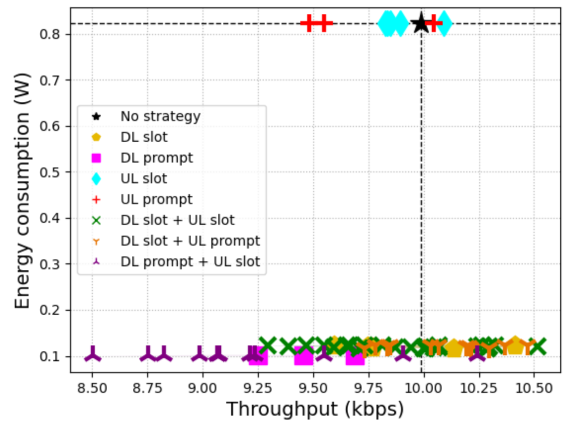


Figure 4: Case study 2. Performance of the energy-saving strategies for various configurations of their parameters.

strategy, which consumes between one third and one half of the "no strategy". In this case study, the time to access the medium is, in general, not immediate so the STA must wait before sending its frames, limiting its doze time. Despite these unfavorable conditions, the "DL prompt" strategy manages to decrease the energy consumption of the STA. All the other strategies manage to cut the energy consumption of the STA by around four.

4.3 Case study 2: *"WLAN for IoT"*

Our second case study, named *"WLAN for IoT"*, represents a WLAN that comprises only IoT devices, which exclusively communicate using the IEEE 802.11 standard. With this case study, we investigate the performance that can be reached when a large number of IoT STAs, each with a very low workload, use IEEE 802.11. We set $n_{\text{STA}} = 51$ and the characteristics of STAs as follows: $\forall i \in \{1 \ldots n_{\text{STA}}\}$: $r(i) = 100$ Mbps, $\lambda_{\text{DL}}(i) = 1$ kbps, $\lambda_{\text{UL}}(i) = 9$ kbps, $l_{\text{buffer}}(i) = l_{\text{APbuffer}} = 20$ frames and $l_{\text{frame}}(i) = 11,520$ bits. With these parameters, the workload of each STA includes in average one downstream frame and nine upstream frames every 10s.

Based on the results of WE3S, Figure 4 shows the throughput $(X_{\text{DL}}(i) + X_{\text{UL}}(i))$ and the energy consumption $(E(i))$ of any of the 51 (homogeneous) STAs for each energy-saving strategy and configuration. First, we observe that all the considered energy-saving strategies have at least one configuration that can successfully meet the throughput demands of STAs. Second, the levels of energy consumption, which is a key factor for IoT devices, widely vary across energy-saving strategies. While the "UL slot" and "UL prompt" strategies lead to similar levels as with "No strategy", all the other strategies, which share the feature of restricting the downstream traffic, consume just an eighth to that level.

4.4 Discussion

Through these case studies, we observe that most of the seven energy-saving strategies, provided they are correctly configured, manage to meet the throughput demands of STAs. The selected configuration also strongly influences the energy consumption of the strategies and may cut this consumption by a factor between 2 and 8.

Our results show that, for each case study, multiple strategies may drastically reduce energy consumption without trading off on the STA needs in throughput. Table 4 reports, for each case study, the strategies, along with their found configurations, that perform the best with regard to energy saving. To appear in this table, a strategy must obtain with one of its configurations the lowest possible value of energy consumption across all strategies (with a margin of tolerance of 0.1W) while reaching at least 90 % of the DL throughput and 90% of UL throughput obtained by the "No strategy". The "DL prompt + UL slot" strategy is not selected for case study 2 because, with this strategy, the STA cannot reach more than 90% of the DL throughput attained by the "No strategy".

It is worth noting that there seems to be no "one size fits all" strategies, as the efficiency of strategies appears to be very scenario-dependent. Note that, even if we explored different configurations by varying the parameter values, we certainly have missed some better configurations. In any case, this works underlines the need and the difficulty of developing efficient configuration methods.

Lastly, in this work, we focus only on the influence of energy-saving strategies on the STAs throughput and energy. Clearly, strategies should also be investigated with regard to their influence on the average delay experienced by frames. Exploring this other dimension would be the subject of future work.

5 RELATED WORK

In this paper, we focus on the IEEE 802.11 MAC energy-saving mechanisms. Several performance evaluation studies have contributed to the development of these MAC energy-saving mechanisms by analyzing their energy consumption and proposing solutions to their configuration. In [5], the authors propose an analytical model of the RAW mechanism (corresponding to our "DL prompt + UL slot" strategy). Using this model, the authors demonstrate how to configure the parameters of the RAW mechanism in a scenario where STAs have different requirements in terms of throughput and energy consumption. In [12], the authors compare different

	Best energy-saving strategies	Energy consumption
Case study 1 *"Public WLAN"*	**DL slot** ($T_{inter-slot}$=10 ms) **DL slot + UL prompt** ($T_{inter-slot}$=5 ms, P_{prompt}=1) **DL prompt + UL slot** (P_{prompt}=1, $T_{inter-slot}$=5 ms)	0.25 W (30 %)*
Case study 2 *"WLAN for IoT"*	**DL slot** ($T_{inter-slot}$=100 ms) **DL prompt** (P_{prompt}=1) **DL slot + UL slot** ($T_{inter-slot}$=100 ms for DL and UL) **DL slot + UL prompt** ($T_{inter-slot}$=100 ms, P_{prompt}=1)	0.1 W (15 %)*

Table 4: Performance and parameter configuration of the best energy-saving strategies per case study.
* **Percentage compared to the energy consumption with "No strategy".**

approaches to configure the different parameters of the TWT mechanism (corresponding to our "DL slot + UL slot" strategy). The authors implemented the main principles of the TWT mechanism in the ns-3 simulator to conduct their study. In [6], the authors study the S-APSD mechanism (corresponding to our "DL slot" strategy) and propose a fast scheduling of the DL slots to cope with variable traffic in WLANs. The authors show that their solution outperforms that presented in [8] in terms of complexity while being equally efficient with regard to energy consumption.

A number of papers compare two MAC energy-saving mechanisms. In [7], the authors compare the U-APSD and the S-APSD mechanisms, belonging to the "DL prompt" and the "DL slot" strategies, respectively. They use the OPNET simulator to evaluate the efficiency of each mechanism on a WLAN scenario with an increasing number of heterogeneous stations with different requirements. In [9], the authors compare the RAW mechanism and the TWT mechanism, corresponding to the "DL prompt + UL slot" strategy and the "DL slot and UL slot" strategy, respectively. To conduct their evaluation, they use the ns-3 simulator, which they expanded to include an energy life-cycle model and an implementation of the TWT mechanism. Their simulated results show that the TWT mechanism outperforms the RAW mechanisms with regard to energy consumption in their tested scenario. To summary, all these studies are dedicated to one or two IEEE 802.11 MAC energy-saving mechanisms and, unlike our paper, they do not provide a comparison of the different possible MAC energy-saving mechanisms.

6 CONCLUSIONS

While everyone would agree that computer networks must make their share in reducing energy consumption, the case of the IEEE 802.11 standard, which rules virtually all WLANs, has attracted relatively little attention. Nonetheless, multiple energy-saving mechanisms (*e.g.,* RAW, PS-Poll, TWP) have been standardized but in practice, they are rarely implemented and run by the APs and STAs.

In this paper, we evaluate and compare the overall merits of different approaches to energy saving. To do that, we abstract the rationale behind existing IEEE 802.11 energy-saving mechanisms and we formalize them into seven possible strategies. Then, we develop the discrete-event WE3S simulator, specially designed for evaluating these strategies, that delivers fair estimates for both throughput and energy consumption in WLANs.

Using two distinct case studies, inspired by real-life scenarios, we analyze and compare the different strategies. Overall, we observe that, provided an adequate configuration of their parameters, every strategy can meet the throughput demands of STAs. At the same time, the vast majority of these strategies can also lead to a significant drop in energy consumption (by a factor between 2 and 8). However, our numerical results show that there is no silver bullet when it comes to choosing strategies. It all depends on the considered scenarios. Furthermore, the selected configuration for each strategy is critical in determining its ability. This underlines the need of developing efficient methods to automatically configure the strategy parameters of STAs and APs.

In our future works, we intend to investigate the influence of these strategies on the average delay experienced by frames. While throughput and energy consumption are arguably the foremost performance metrics to evaluate the merits of an energy-saving strategy, the delay is also critical for many applications. [4]

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