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IMPACT OF SIMULATION ENVIRONMENT IN PERFORMANCE EVALUATION OF PROTOCOLS FOR WSNS.

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Abstract. Wireless sensor networks are increasingly used in many emerging applications. This type of network is composed of hundreds of low-cost sensor nodes, but with a limited budget batteries, low communication range, limited throughput, reduced computing power, low memory and low storage capacity. Communication protocols are proposed in the literature to deal with technical challenges coming from low intrinsic resources of sensor nodes. In most of these studies, simulations comparing a proposed protocol with other existing protocols are performed to show that the proposed protocol provides overall better performance. However, the environmental specification that made these comparisons is very often neglected or non-existent. In this study we show that it is essential to have the simulation environment very well defined before considering whether a protocol provides better performance than others. To do this we use two duty cycle MAC protocols, the standard IEEE 802.15.4 and SlackMAC (a protocol that we proposed). The aim of the paper is not to make an exhaustive comparison of protocols. We intuitively know that SlackMAC provides a better overall performance than the standard. What we are trying to show is the gap between performances according to simulation conditions. We will mainly focus on the topologies used and the capture effect. The results draw attention to the fact that it is essential to clearly define the simulation environment and also to reconcile the chosen conditions with the results when comparing the performances of two protocols.

Keywords: WSNS; QoS; performance evaluation; simulation conditions; topologies impact; capture effect impact

1 Introduction

Wireless Sensor Networks (WSNs) have attracted great interest in the last decade. This explains the rich and active research about communication protocols for WSNs in order to deal with technical constraints related to sensor nodes. In most of these studies, in

the absence of real conditions to validate the proposed protocols, many simulations are carried out to evaluate their performances. Mostly, these simulations are done with performance comparisons of proposed protocols compared to existing one to show that the new protocol provides better performance. However, sometimes the level of detail on the results surpasses the description of the simulation conditions used to obtain them.

In this paper we raise the curtain on this issue and we draw attention regarding the quantitative results of simulation when communication protocols are compared. Let us take the case of works that conduct to establish efficient mechanisms to ensure a long lifetime to the network. We take as examples energy-efficient MAC protocols based on sequences of active periods (during which the radio module is on) and sleep periods (during which it is off) called duty cycle. The duty cycle represents the proportion of the active period over the total duration of the cycle (active period + sleep period). The main energy-saving MAC protocol based on this mechanism is the standard IEEE 802.15.4 [1] in beacon-enabled mode. In this type of protocols nodes agree on a common calendar for their periods of activity and sleep. This category is called synchronous duty-cycle MAC protocols. Other categories based on an asynchronous mechanism are also proposed in the literature. In these second categories, nodes do not have a common calendar for their period of activity and sleep. Most of these protocols are proposed as improvements to some existing protocols. However, there is a lack of important information on simulation conditions such as: radio frequency, antenna, propagation model, transmission power, topology information, data traffic information, capture effect, etc.

These omission do not allow to judge the relevance of the results and also does not allow reproducibility. There are studies that show the impact of different propagation models and topologies on simulation results as in [2] and [3]. However, to the best of our knowledge, no studies have shown these impacts with such a high level of detail as that in this paper. We use two energy-efficient MAC protocols, the standard IEEE 802.15.4 [1] and SlackMAC [4,5] (a protocol that we have proposed). The aim of the paper is not to make an exhaustive comparison of protocols. We know intuitively that SlackMAC generally provides better performance than the standard. What we are trying to demonstrate through intensive simulations is the diversity in the performance gaps according to simulation conditions. Mainly, we will focus on the topologies used and the capture effect.

This paper is organized as follows. In section 2, we make a summary of duty cycle MAC protocols and take note of the levels of detail on the missing simulation conditions. In section 3, we analytically compare the two protocols that serve tests in our study and give the technical details of our study. In section 4, we show simulation results from this comparative study. Finally, we conclude our work in section 5.

2 State-of-the-art

The MAC protocols of the literature based on the duty cycle mechanism can be classified into two main categories such as synchronous duty cycle MAC protocols and asynchronous duty cycle MAC protocols.

2.1 Synchronous duty cycle MAC protocol

In synchronous duty cycle MAC protocols synchronization can be global or local.

In the case of global synchronization, all nodes share a common schedule for their periods of activity and inactivity. The main MAC protocol based on this mechanism is the standard IEEE 802.15.4 [1] in beacon enabled mode. This is also the case of protocol in [6] and LO-MAC (*Low Overhead MAC*) [7].

In the case of local synchronization, the nodes are synchronized by neighborhood, very often according to a tree topology as a function of their position relative to the sink. One of the first protocols based on this mechanism is S-MAC (*sensor-MAC*) [8] then D-MAC (*Data-gathering MAC*) [9] and TreeMAC [10]. Improvements of these protocols are proposed in ID-MAC [11], DW-MAC (*Demand Wakeup MAC*) [12], DSF (*Dynamic Switch-based Forwarding*) [13] and iCore [14].

2.2 Asynchronous duty cycle MAC protocol

In asynchronous duty cycle MAC protocols, nodes do not have a common calendar for their activity and sleep periods. A distinction can be made between sender-initiated and receiver-initiated MAC protocols.

In sender-initiated MAC protocols, most of the communication load is supported by sender nodes. The main protocol based on this principle is B-MAC protocol *Berkeley MAC*) [15]. In B-MAC, a sender sends a long preamble before sending data frame. X-MAC [16] is one of the first improvement of B-MAC. Many other protocols such as BoX-MAC [17] and OSX-MAC [18] have been proposed thereafter.

Unlike sender-initiated MAC protocols, in receiver-initiated MAC protocols, most of the communication load is supported by the receiver nodes. In receiver-initiated MAC protocols the receiver initiates the communication by sending a beacon frame to express its ability to receive data frame. RI-MAC [19] is the main protocol based on this mechanism. RIX-MAC (*Receiver-Initiated X-MAC*) [20], ERI-MAC [21], OC-MAC [22] and protocol in [23] are improvement of RI-MAC.

Other hybrid MAC protocols that are both sender-initiated and receiver-initiated have been proposed to balance the communication load on the sender and receiver nodes. This is the case of protocol in [24] and SlackMAC [4,5].

2.3 Overview of simulation conditions

In most of the protocols cited above comparisons by simulation on NS2 [25] are performed to show that the proposed protocols provide better overall performance than those of the existing. Table 1 gives a summary of simulation conditions description used in these comparisons. These simulation conditions essentially concern radio frequency, antenna (type, gain, height), propagation model, transmission power (noted TX power in table 1). It is also important to provide information about topology used (type, size, transmission range that provides connectivity, number of nodes, and sink position). Parameters such as receive power threshold and carrier sense threshold (noted RXThresh_ and CStresh_), and capture threshold (noted CPThresh_) are all equally important.

Traffic information such as type, size in byte and generation period of data packets are also required.

It can be seen from Table 1 that these important elements of simulation conditions are often not fully defined and sometimes non-existent.

Table 1: Overview on specification of NS2 simulation conditions

Simulation conditions / Protocols	DW-MAC [12]	LO-MAC [7]	ID-MAC [11]	DSF [13]	iCore [14]	OSX-MAC [18]	OC-MAC [22]	RIX-MAC [20]	[23]	ERI-MAC [21]	[24]	SlackMAC [5,4]
Radio Frequency	✓	✓	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗
Antenna: -type -gain -height	1/3	1/3	✗	✓	✗	✗	✗	1/3	✗	✗	✗	✗
Propagation model	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗	✓	✓
TX power	✓	✓	✓	✗	✗	✓	✗	✓	✗	✓	✓	✓
Topology: -type -size -TX range -number of nodes -sink position	✓	✓	✓	3/5	✓	1/5	✓	3/5	✓	✓	✓	✓
-RXThresh_ -CSThresh_	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗
Traffic: -type -size -period	✓	2/3	2/3	1/3	1/3	1/3	2/3	✓	2/3	2/3	2/3	2/3
Capture Threshold	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

3 Study framework

In this section we first describe the operating mechanism of the reference synchronous MAC protocol described in the standard IEEE 802.15.4 [1] in beacon enabled mode and the asynchronous MAC protocol SlackMAC [5,4]. Then we give the technical details of the implementation of our comparative study.

3.1 Description of the operating mechanism of IEEE 802.15.4 and SlackMAC

In the beacon enabled mode of the standard IEEE 802.15.4, the medium is accessed using the slotted CSMA/CA (Carrier-Sense Multiple Access with Collision Avoidance) algorithm. All nodes wake up periodically together and share a common activity throughout the SD (Superframe Duration) period and change to sleep mode the rest of the BI (Beacon Interval) period.

The left side of Figure 1 shows an example of the activity and sleep mechanism in the standard IEEE 802.15.4 with a duty cycle of 25% ($\frac{SD}{BI} \times 100$) for three nodes (n_1 ,

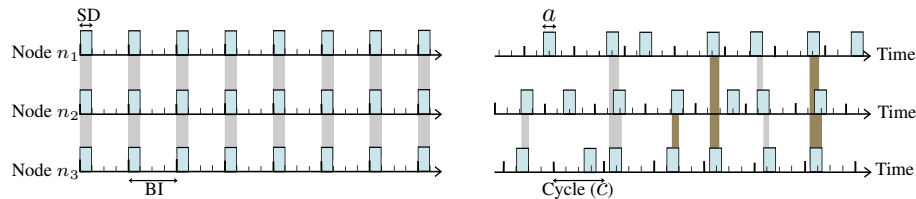


Fig. 1: Example of activity of three nodes n_1 , n_2 and n_3 in range, with a duty cycle of 25 % for respectively the standard IEEE 802.15.4 (left) and SlackMAC (right).

n_2 and n_3) in range. It can be seen that all the activity of the nodes is concentrated on the period SD . This reduces the communication time given to each node and increases the risk of collision depending on the number of nodes in competition to access the medium.

In SlackMAC, the medium is also accessed using the slotted CSMA/CA algorithm. The right side of Figure 1 shows an example of activity cycle for three nodes (n_1 , n_2 and n_3) in range with a duty cycle of 25 % ($\frac{a}{c} \times 100$) in SlackMAC. Unlike the standard in SlackMAC, initially all nodes choose their activation times uniformly at random in the cycle. When a node chooses a time that yields to successful communications (reception or transmission of a frame), it memorizes it and the probability to choose this time increases, as can be seen in darker towards the right of Figure 1. It is noted that the activity of the nodes can be distributed over the whole cycle unlike the standard. Indeed, on average there are few active nodes at the same time, which reduces the risk of collision and allows a higher communication time per nodes than the standard for the same duty cycle as shown in [4].

According to such conditions, it is intuitively known that SlackMAC will ensure overall better performance than the standard. However, what we are trying to show in what follows is the diversity in the performance gaps according to simulation conditions.

3.2 Technical details

In this part we detail the technical environment used for our simulations. We want to highlight the fact that in a deployment study and a priori evaluation of its performance by simulation of WSNs, it is essential to be attentive and precise on the description of simulation conditions. In a simulation process we know how the choice of the propagation model is important for the relevance of the results. In this paper we will consider that this choice has been made at best and we focus on the impact of the chosen type of topology and on the effects of the given value of capture threshold parameter, often neglected in literature. The topology (or distance between nodes), the propagation model, and the capture threshold are three elements concerned to distinguish a collision of a successful reception. In a first step we propose a small synthesis of the topologies usually exploited but not often justified and/or not sufficiently detailed. On the second hand we provide some clarification on why it is important to specify the capture effect.

Topology production strategy In addition to specifying the propagation model and its associated parameters, it is also important to give the rules that allowed to generate the topology (or topologies) used for the simulation. Generally, in the used WSNs topologies for communication protocol comparison tests, nodes are positioned according to a grid or randomly distributed over a given area.

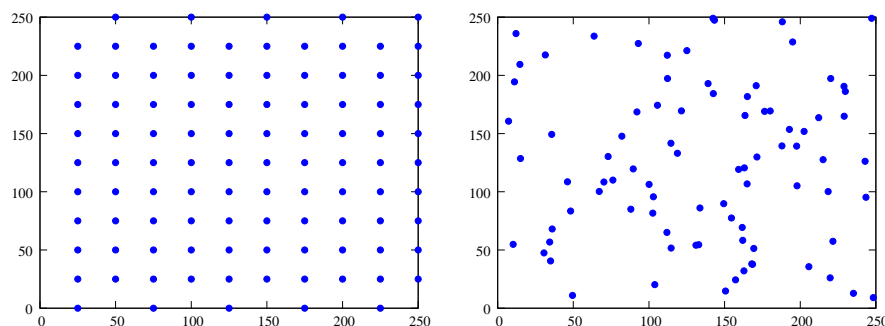


Fig. 2: Topology of 100 nodes on square area of 250 m x 250 m with respectively a grid positioning (left) and random positioning (right).

Figures 2 and 3 illustrate respectively the topologies in square and pseudo-linear, with in each case, one hundred nodes are positioned both in grid and randomly.

The random positioning is more closer to a realistic positioning. However, the concept of random position can change depending on how the placement is carried out. Indeed, to randomly place N nodes on a given area by hand, the person will try to cover the whole area and avoid nodes overlapping. For the same surface S and for the same number of nodes, the topologies obtained by a generator of random positions (x, y) lead to much greater diversity of solution but are not necessarily more representative for WSNs field. It can have less covered places than others, overlays and nodes that are too distant from others. To avoid the latter two situations, once the positions are

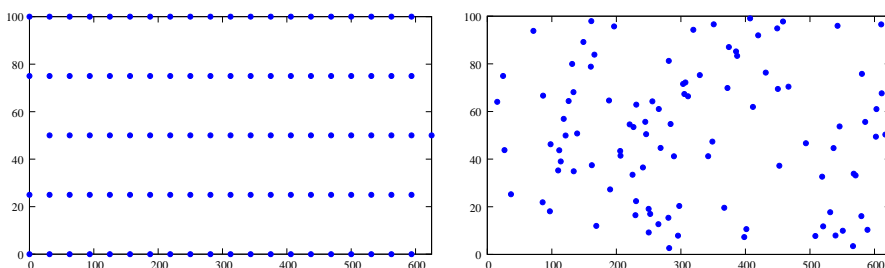


Fig. 3: Topology of 100 nodes on square area of 625 m x 100 m with respectively a grid positioning (left) and random positioning (right).

randomly drawn, we use two filters in the control of network connectivity by Prim's algorithm (developed by Robert C. Prim (1957)). We set a minimum value of 1 m and a maximum of 50 m between any neighbors nodes. The surface of the coverage area ($62500 m^2$), the propagation model, the data packets production, the total number of nodes and the percentage of source nodes are identical in each case. We consider two forms of topologies (square of size 250 m x 250 m and pseudo-linear of size 625 m x 100 m) and for each type, nodes are positioned both in grid and randomly. In any case, the sink is located at the top right corner of the area.

In this work, our field of investigation is thus reduced to simulations on these 4 types of topologies (see Figures 2 and 3) with different values of capture threshold.

Capture effect The capture effect relates to the simultaneous reception of several frames with power levels such that the reception of one of them is possible. When a frame f is received with a power P_f greater than or equal to the sum of the powers of the other k frames received at the same time plus a capture threshold fixed, the frame f is correctly decoded by the receiver. The capture threshold is the minimum power ratio in dB which enables the receiver in case of simultaneous reception to decode the strongest signal correctly. Therefore, if the difference between the power of a received signal and the sum of power of the other signals is greater than this threshold, reception is considered as a capture and the dominant signal is decoded correctly. Otherwise, the simultaneous reception will cause a collision and the signals can not be interpreted. This capture threshold has a direct impact on the collision rate of frames when the traffic subjected to the network becomes very significant.

4 Results

We carried out several simulations to show the diversity in the results as a function of simulation conditions for protocols SlackMAC [4,5] and the standard IEEE [1]. We first describe the simulation environment and then compare the two MAC protocols.

4.1 Simulation parameters

Our simulations are performed using the network simulator NS-2 [25]. Global simulation parameters are given in Table 2. We use 10 of each type of topology of 100 nodes described in section 3 (see figures 2 and 3). We generate a convergecast communication (from the nodes to the sink), for 30 source nodes located randomly in the network. These source nodes perform periodic measurements and route them via other nodes to the sink. Nodes have a duty-cycle of 1% and the global cycle is 5 s (that is, nodes are active during $A=50$ ms every $C=5$ s). The same gradient-based routing protocol is used to route packets hop by hop towards the sink for both MAC protocols. All presented results, in each case are averaged over 10 repetitions per topology for the 10 topologies. We compute transmission power (in dBm) using outage probability method (defined in [26,27]). For transmission range of 50 m and shadowing parameters defined in Table 2, the equivalent transmission power which can ensure stability of the radio links for 95% of the reception between two nodes is equal to 10.5342501084 dBm. This value is used as a transmission power in all simulations.

Table 2: Global simulation parameters

Topologies area	250 m x 250 m and 625 m x 100 m
Transmission range	50 m
Number of nodes	100
Number of source nodes	30
Radio frequency	2.4 GHz
Receive threshold (RXThresh)	-85 dBm
Carrier-sense threshold (CSThresh)	-92 GHz
System loss (L)	1
Antenna type	Omnidirectional
Antenna gain (Gt, Gr)	1
Antenna height (Z)	1.5 m
Propagation model: shadowing	path loss exponent = 2.5 shadowing deviation = 4.0 dB
Data traffic	Constant-bit rate (CBR)
Data frame size	30 bytes
Data traffic period	from 5 seconds to 60 seconds
Maximum send queue size	20 frames
Number of topology	10
Number of repetitions per topology	10
Simulation duration	3600 seconds

4.2 Simulation results

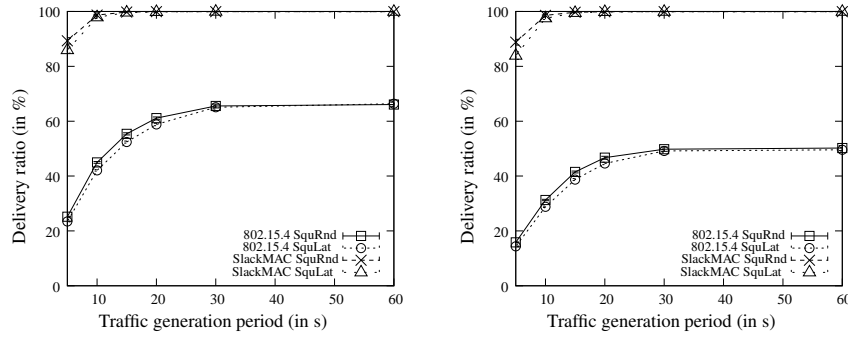


Fig. 4: The packets delivery ratio as a function of the traffic generation period with respectively the capture threshold of 2 dB (left) and 10 dB (right) for IEEE 802.15.4 and SlackMAC when square topologies are into grid and random.

Results with square topologies of size 250 m x 250 m In this first scenario, we perform tests using both a grid and random topologies (respectively noted SquLat and SquRnd). We vary the traffic generation period from 5 seconds to 60 seconds with capture threshold of 2 dB and 10 dB.

Figures 4 and 5 show respectively the delivery ratio and the end-to-end delay of data frames, as a function of the traffic generation period (from 5 s to 60 s) for IEEE 802.15.4 and SlackMAC, when square topologies are into grid and random.

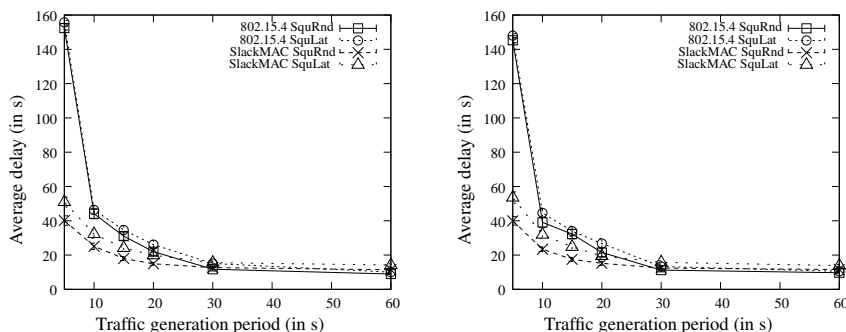


Fig. 5: Average delay as a function of the traffic generation period with respectively the capture threshold of 2 dB (left) and 10 dB (right) for IEEE 802.15.4 and SlackMAC when square topologies are into grid and random.

For IEEE 802.15.4:

- when nodes are positioned in a grid, the delivery ratio increases from 23.43% to 66.34% for the capture threshold of 2 dB and from 14.37% to 49.56% for the capture threshold of 10 dB. The average delay decreases from 155.75 s to 10.02 s for the capture threshold of 2 dB and from 148 s to 10.52 s for the capture threshold of 10 dB.
- when nodes are randomly positioned, the delivery ratio increases from 25.18% to 66.07% for the capture threshold of 2 dB and from 15.81% to 50.2% for the capture threshold of 10 dB. The average delay decreases from 144.69 s to 7.22 s for the capture threshold of 2 dB and from 145.28 s to 9.66 s for the capture threshold of 10 dB.

For SlackMAC:

- when nodes are positioned in a grid, the delivery ratio increases from 85.91% to 99.07% for the capture threshold of 2 dB and from 83.89% to 99.9% for the capture threshold of 10 dB. The average delay decreases from 59.09 s to 14.19 s for the capture threshold of 2 dB and from 53.52 s to 13.90 s for the capture threshold of 10 dB.
- when nodes are randomly positioned, the delivery ratio increases from 89.29% to 99.93% for the capture threshold of 2 dB and from 88.08% to 99.92% for the capture threshold of 10 dB. The average delay decreases from 40.14 s to 11.47 s for the capture threshold of 2 dB and from 39.96 s to 11.55 s for the capture threshold of 10 dB.

The results of this scenario show that for SlackMAC, whether the nodes are positioned in grid or randomly on a square area, the delivery ratio vary very little according to the traffic and the capture threshold. However, the average delay is better in the case of random positioning when the traffic varies regardless of the capture threshold. For the standard, the results also vary very little with the type of positioning. On the other hand, there is a difference of 16% in the delivery ratio between a capture threshold of 2

dB and 10 dB for the two types of positioning. The average delay also varies little, but remains better when the positioning is random.

Results with pseudo-linear topologies of size 625 m x 100 m In this second scenario, we perform tests using both a grid and random topologies (respectively noted StrLat and StrRnd). We also vary the traffic generation period from 5 seconds to 60 seconds with capture threshold of 2 dB and 10 dB.

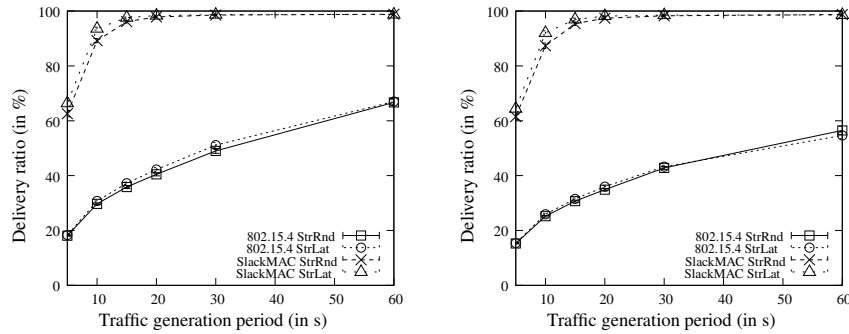


Fig. 6: The packets delivery ratio as a function of the traffic generation period with respectively the capture threshold of 2 dB (left) and 10 dB (right) for IEEE 802.15.4 and SlackMAC when pseudo-linear topologies are into grid and random.

Figures 6 and 7 show respectively the delivery ratio and the end-to-end delay of data frames, as a function of the traffic generation period (from 5 s to 60 s) for IEEE 802.15.4 and SlackMAC, when pseudo-linear topologies are into grid and random.

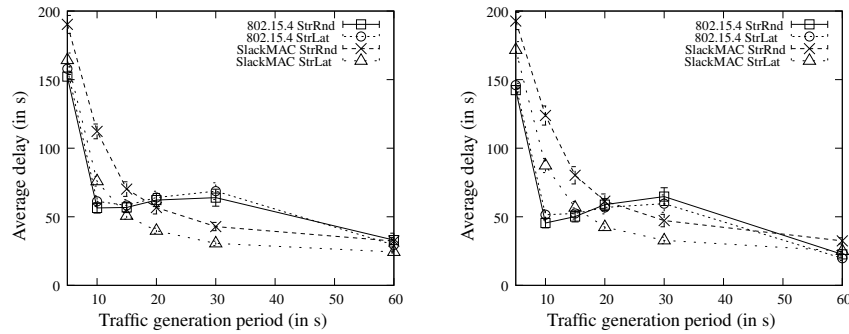


Fig. 7: Average delay as a function of the traffic generation period with respectively the capture threshold of 2 dB (left) and 10 dB (right) for IEEE 802.15.4 and SlackMAC when pseudo-linear topologies are into grid and random.

For IEEE 802.15.4:

- when nodes are positioned in a grid, the delivery ratio increases from 18.34% to 66.98% for the capture threshold of 2 dB and from 15.42% to 54.65% for the capture threshold of 10 dB. The average delay decreases from 157.94 s to 29.49 s for the capture threshold of 2 dB and from 145.99 s to 19.79 s for the capture threshold of 10 dB.
- when nodes are randomly positioned, the delivery ratio increases from 18.09% to 66.67% for the capture threshold of 2 dB and from 15.28% to 56.48% for the capture threshold of 10 dB. The average delay decreases from 152.20 s to 33.02 s for the capture threshold of 2 dB and from 142.32 s to 22.59 s for the capture threshold of 10 dB.

For SlackMAC:

- when nodes are positioned in a grid, the delivery ratio increases from 66.40% to 98.72% for the capture threshold of 2 dB and from 64.41% to 98.57% for the capture threshold of 10 dB. The average delay decreases from 164.26 s to 24.39 s for the capture threshold of 2 dB and from 171.67 s to 25.10 s for the capture threshold of 10 dB.
- when nodes are randomly positioned, the delivery ratio increases from 62.55% to 98.8% for the capture threshold of 2 dB and from 61.49% to 98.73% for the capture threshold of 10 dB. The average delay decreases from 190.27 s to 32.32 s for the capture threshold of 2 dB and from 192.74 s to 32.43 s for the capture threshold of 10 dB.

The results of this second scenario show that for SlackMAC, whether the nodes are positioned in grid or randomly on a square area, the delivery ratio vary very little according to the traffic and the capture threshold. However, unlike the square zone where the best average delay is obtained with a random positioning, that is not the case with a pseudo-linear zone in which the best average delay is with a grid positioning regardless of the capture threshold. For the standard, the results vary very little with the type of positioning for the delivery ratio and the average delay regardless of the capture threshold.

Effect of capture threshold In this last scenario, we perform tests using the two topologies area such as square and pseudo-linear. We set the traffic generation period to 60 seconds and vary the capture threshold from 2 dB to 10 dB.

Figures 8 and 9 show respectively the delivery ratio and the end-to-end delay of data frames, as a function of the capture threshold (from 2 dB to 10 dB) for IEEE 802.15.4 and SlackMAC.

For IEEE 802.15.4:

- when topology is square, the delivery ratio decreases from 66.34% to 49.56% for grid positioning and from 66.07% to 50.20% for random positioning. The average delay increases from 10.02 s to 10.52 s for grid positioning and from 8.93 s to 9.66 s for random positioning.
- when topology is pseudo-linear, the delivery ratio decreases from 66.98% to 54.65% for grid positioning and from 66.67% to 56.48% for random positioning. The average delay decreases from 29.49 s to 19.79 s for grid positioning and from 33.02 s to 22.59 s for random positioning.

For SlackMAC:

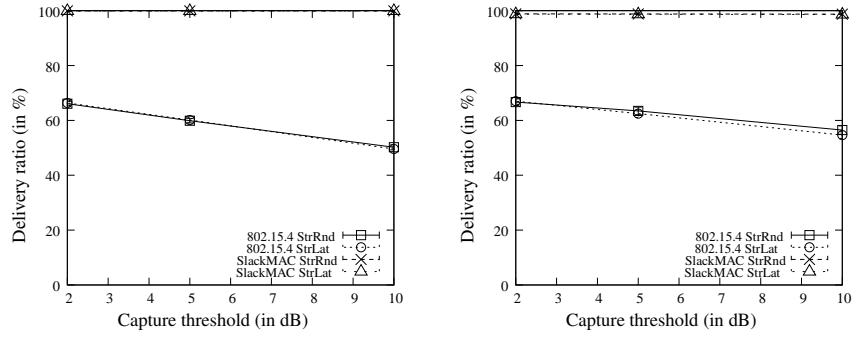


Fig. 8: The packets delivery ratio as a function of the capture threshold with respectively square topology (left) and pseudo-linear topology (right) into grid and random for IEEE 802.15.4 and SlackMAC when the traffic generation period is 60 seconds.

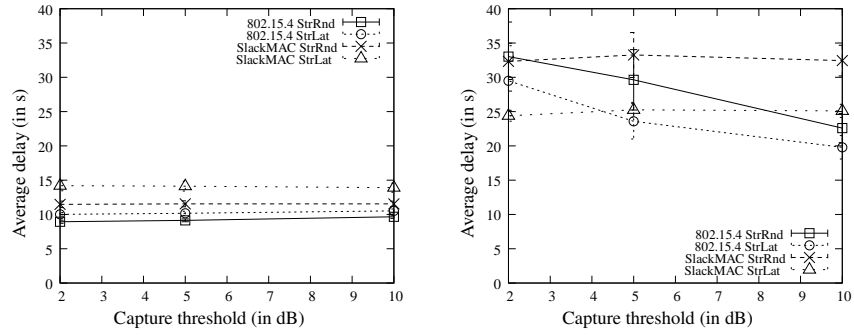


Fig. 9: Average delay as a function of the capture threshold with respectively square topology (left) and pseudo-linear topology (right) into grid and random for IEEE 802.15.4 and SlackMAC when the traffic generation period is 60 seconds.

- when topology is square, the delivery ratio is always around 99.9% for grid positioning and for random positioning. The average delay decreases slowly from 14.19 s to 13.9 s for grid positioning and always around 11 s for random positioning.

- when topology is pseudo-linear, the delivery ratio is always around 98.8% for grid positioning and for random positioning. The average delay decreases slowly from 24.39 s to 25.10 s for grid positioning and always around 32 s for random positioning.

The results of this last scenario show that for SlackMAC, whether the nodes are positioned in grid or randomly for the two zones of topology the delivery ratio varies little with the capture threshold. However, the average delay for a square zone is better for random positioning than grid positioning and for a pseudo-linear zone the better average delay is obtained with a grid positioning. Unlike SlackMAC, the delivery ratio in the standard decreases when the capture threshold increases regardless of the zone and the positioning. The average delay increases with the capture threshold for square zone and decreases with the capture threshold for pseudo-linear zone regardless of positioning.

5 Conclusion

In this work, we show the need to be attentive and precise about the description of the simulation conditions comparing the performance of communication protocols for WSNs. For a given and widespread signal propagation model we pointed out how the topology choice and the capture threshold value may impact simulations results. To do this we used an asynchronous MAC protocol SlackMAC and the reference MAC protocol specified in the standard IEEE 802.15.4 in beacon-enabled mode. The aim of the paper is not to make an exhaustive comparison of protocols. We knew intuitively that the asynchronous MAC protocol would provide better overall performance than the standard. What we have demonstrated with intensive simulations, is the diversity in the results when the simulation conditions change. The conditions we have dealt with are the topology types and the capture threshold used in a WSN simulation process : (i) grid or random topologies for squared or stretched areas and (ii) capture threshold varying from 2 dB to 10 dB. The results showed great diversity such as for example for the same form of topology (square or pseudo-linear), either one of the two protocols gives better performances when the positioning is in grid and the other one rather with a random positioning. These observations are also made for two different forms of topology. These results also showed a very significant impact of the capture threshold on one protocol than the other. These remarkable differences between performances when simulation conditions change, confirm that it is essential to clearly define the simulation environment and also to reconcile the chosen conditions with the results when comparing the performances of protocols.

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