IMPACT OF THE SIMULATION PARAMETERS ON THE QUANTITATIVE RESULTS OF PROTOCOLS FOR WSNS.

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***Abstract*—Many protocols for wireless sensor networks are proposed in the literature. In most of this work, comparisons are made with existing protocols to show that the proposed protocol provides better overall performance without precise specifications of the simulation environment. In this paper we show that for a given propagation model, the value of its main parameters retained in the simulation process has very significant effects on the quantitative results. To do this, we use an asynchronous MAC protocol that we proposed which was compared with the reference MAC protocol specified in the standard IEEE 802.15.4 in beacon enabled mode. We use a realistic propagation model like log-Shadowing and we modify the parameters of this model. In this contribution, we also vary the capture threshold. We intuitively known that the asynchronous MAC protocol will ensure a better overall performance than the standard, we will try to show the diversity of results by intensive simulations. To the best of our knowledge, there are existing studies that show the impact of different propagation models on simulation results. However, no studies have shown this impact with such an important level of detail. From this study we estimate that when two communication protocols are compared, it is important to associate the performance curves with the precise and detailed conditions used for the simulation and to assess the global influence. According to this influence, a vigilance can be reported on the accuracy of results.**

Index Terms— WSNs; QoS; performance evaluation; radio propagation model; simulation parameters impact

I. Introduction

Wireless sensor networks are a promising solution for the implementation of environmental monitoring applications such as the rapid detection of disasters as forest fires and floods [1], [2], or the understanding of natural phenomena as volcano eruptions [3] and landslides [4]. That explains the many research studies carried out in this field. In most of these studies, comparisons are made with existing protocols to show that the proposed protocol provides overall better performance. In this paper we show that we must step back from the quantitative simulation results when comparing communication protocols. We used energy-saving MAC protocols for wireless sensor networks dedicated to environmental monitoring as an example. These MAC protocols are 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. The lower the value of the node duty cycle, the more this node saves energy. At the moment, the design of MAC protocols with very low duty cycles are still a challenge. Many MAC protocols based on the duty cycle mechanism are proposed in the literature and compared with other protocols. They can be classified into two main categories: synchronous and asynchronous duty cycle MAC protocols. In synchronous duty cycle MAC protocols the nodes agree on a common schedule for their activity and sleep periods. This is the case of the standard IEEE 802.15.4 [5] in beacon enabled mode, LO-MAC [6], D-MAC [7], and TreeMAC [8]. In asynchronous duty cycle MAC protocols, nodes do not have a common calendar for their activity and sleep periods. This is the case of X-MAC [9], OSX-MAC [10], RI-MAC [11], HKMAC [12], AaaMAC [13] and SlackMAC [14], [15]. In these protocols quantitative results of simulations comparing them with other existing protocols are given. However, the comparison conditions are not fully defined. The detail level used in the comparison of simulation results is much more specific than the detail level used to describe the simulation process. We show in this paper that it is important and even necessary to associate the performance results with the precise and detailed conditions used for the simulation. Few articles specify how the topologies used for the simulations are generated and how the radio links range is regulated. Most commonly, the propagation model is evoked but the justification of the values of its parameters is often missing. Likewise, the transmission power, the sensitivity and

the capture threshold are sometimes missing. This makes the simulation reproducibility quite difficult. To the best of our knowledge, there are existing studies that show the impact of different propagation models on simulation results as in [16] and [17]. However, no studies have shown this impact with such an important level of detail. We show, for instance that the value of the capture threshold and the main parameters (path loss exponent and the standard deviation) of a realistic propagation model as log-shadowing have significant effects on the quantitative results. To do this, we use an asynchronous MAC protocol that we proposed SlackMAC [14], [15] which was compared with the reference synchronous MAC protocol specified in the standard IEEE 802.15.4 [5] in beacon enabled mode. This choice is justified by the fact that we intuitively know the result of this comparison, we will try to show the diversity of results by intensive simulations. The remainder of this paper is organized as follows. In section II, we perform a comparative study of a synchronous and asynchronous MAC protocol with precise and detailed conditions. In section III, we show simulation results from this comparative study. Finally, we conclude our work in the section IV.

II. Comparative study

In this section we first describe the operating mechanism of the reference synchronous MAC protocol described in the standard IEEE 802.15.4 [5] in beacon enabled mode and the asynchronous MAC protocol SlackMAC [14],[15]. Then we give the technical details of the implementation of our comparative study.

A. 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. Figure 2 shows an example of the activity and sleep mechanism in the standard IEEE 802.15.4 with a duty cycle of 10% ($\frac{SD}{BI} \times 100$) for four nodes (n_1, n_2, n_3 and n_4) 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. Unlike the standard in SlackMAC, initially all nodes choose their activation times uniformly at random in the cycle. Figure 2 shows an example of activity cycle for four nodes (n_1, n_2, n_3 and n_4) in range with a duty cycle of 10% ($\frac{a}{c} \times 100$) in

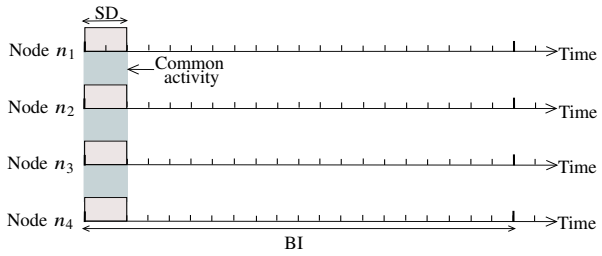


Fig. 1. Example of activity cycle of four nodes n_1, n_2, n_3 and n_4 in range, with a duty cycle of 10 % in the standard IEEE 802.15.4.

SlackMAC. It is noted that the activity of the nodes can

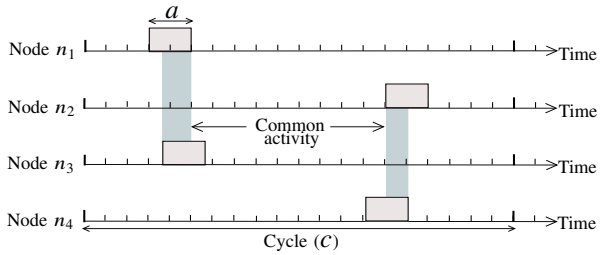


Fig. 2. Example of activity cycle of four nodes n_1, n_2, n_3 and n_4 in range, with a duty cycle of 10 % in SlackMAC.

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 [15]. 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 is the diversity of the quantitative values of these performance sets according to the chosen simulation parameters.

B. Technical details on the comparison implementation

In addition to the type of simulation model and its associated parameters, it is important to give the rules that allowed to generate the topology used for the simulation. In this paper and by way of example, the generated reference topologies have the following particularity:

- they are composed of N nodes;
- all the nodes of this kind of topology have at least one neighbor which is located less than 30 meters away
- all the neighbors of a node are located at least one meter away from one another.

Once a reference topology is generated it is also important to specify the transmission power used. This one combined with the receiver sensitivity parameter will give us a notion of range and with the interference threshold parameter will give the notion of the size of interference zone (this particular point is out of the scoop of this paper). The range is defined from the set of points around the transmitter such as:

$$Pr = Sensitivity\ Threshold = P_{min} \qquad (1)$$

The received power (Pr) depends on the transmission power, the distance that the signal travels and the transmission medium role which will be represented by the retained simulation model. The sensitivity threshold depends on the characteristics of receiver node radio transceiver. In our contribution this value is set to -85 dBm.

The realistic log-shadowing propagation model is often used in the literature. It is possible to add a random component to the path loss in order to take into account the diversity of measurements for the same path length. The log normal shadowing path loss model is formally expressed as follow:

$$PL_{dB} = PL_{dB}(d_0) + 10n\log_{10}\frac{d}{d_0} + X_\sigma \qquad (2)$$

Where d_0 is the reference distance, n is the path loss exponent, $PL_{dB}(d_0)$ is the path loss at the reference distance d_0 and X_σ a rule that produces the random correction. This random correction can increase or decrease the radio range. It is produced from a general Gaussian distribution of zero mean and standard deviation which is according to the diversity of measurements we want to represent (a few dB in general). When a random correction is associated to a propagation model, it is necessary to agree on what becomes the range. This raises the following question: for a given propagation conditions (represented by the model and its parameters) how does one adjust the transmission power so that a radio link between a transmitter and a receiver located at the range limit remains operational?

Maintaining a radio link always operational means that regardless of the value of random correction, the received power can exceed the sensitivity threshold. To simplify, it's necessary to consider that the most negative random corrective values ensure that the received power is equal to the sensitivity threshold. For a Gaussian distribution, this greatest negative value can be defined using a confidence interval of 95% (99.997%, respectively). This involves to take a safety of 2 standard deviations (3, respectively) relative to the mean value. For a low standard deviation of $3dB$ this leads to adding $6dBm$ ($9dBm$, respectively) to the transmission power. This increase leads to a power waste and a congestion which affects transmitter carrier spatial reuse. The notion of outage probability was introduced to make a good trade-off based on the distribution method used. A link is operational if the receiver receives statistically $X\%$ times of the cases with enough power (greater than the sensitivity threshold). $(1-X\%)$ represents the probability of failure. For these cases, the LLC layer of the WSNs will make the retransmission, thus the probability of non-reception will then be $(1-X\%)^2$. Having an operational link in 95% of the cases leads to admit that 5% of the Gauss curve surface allows a received power below the threshold sensitivity. The use of the distribution function attached to a reduced centered normal law, it is possible to determine the minimum necessary power that allows the reception threshold to be reached or exceeded in 95% of the cases.

We remain in this contribution at the level of principles. The justification of the computations needed to evaluate the transmission power is given in the literature on outage probability as in [18] [19].

These principles can be summarized as follows.

Let $Q(Z)$ the probability that a random variable X obtains a value of Q greater than Z, thus $1-Q(Z)$ is the probability that Q be less than Z.

Consider that: $Z = \frac{P_{min}-P_t-PL_{dB}(d)}{\sigma}$ (3)

Where σ is the standard deviation.

(1) $\implies$ $p(P_r(d) \leq P_{min}) = 1 - Q(Z)$ (4)

We thus obtained: $Q(Z) = 1-p(P_r(d) \leq P_{min})$ (5)

There is a K such as: $Q(K) = 1 - p(P_r(d) \leq P_{min})$ (6)

(5) and (6) $\implies$ $Z = K$ ie, $K = \frac{P_{min}-P_t-PL_{dB}(d)}{\sigma}$

whence, $P_t = P_{min} - PL_{dB}(d) - K * \sigma$ (7)

This relation (7) allowed us to complete the table II.

Moreover, the value set for the capture threshold, which represents the minimum power ratio in dB which enables the receiver in case of simultaneous reception to decode the strongest signal correctly, is sometimes missing. In this paper we also evaluate the impact of this parameter.

III. Comparison results

We carried out several simulations to show the results of this comparative study. We first describe the simulation environment and then compare the two MAC protocols in three different scenarios.

A. Simulation parameters

Our simulations are performed using the network simulator NS-2 [20]. Global simulation parameters are given in Table I. We use 10 random topologies of 100 nodes, with a maximum hops of 7. 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 located at one corner of the network. 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 are averaged over 10 repetitions per topology of the 10 topologies.

B. Simulation results

We compare the standard IEEE 802.15.4 [5] in beacon enabled mode which is the main synchronous duty cycle

Table I
GLOBAL SIMULATION PARAMETERS

Topologies area	170 m x 170 m
Maximum distance between nodes	30 m
Minimum distance between nodes	1 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 model
Data traffic	Constant-bit rate (CBR)
Data frame size	30 bytes
Data traffic period	60 seconds
Maximum send queue size	20 frames
Number of repetitions per topology	10
Simulation duration	3600 seconds

MAC protocol with the asynchronous MAC protocol SlackMAC [14],[15] in three different scenarios. In the first scenario, we evaluate the impact of the capture threshold, then in the second one the shadowing path loss exponent impact and finally the impact of shadowing standard deviation.

We opted for a simulation process driven by a constant radio range (not by a constant transmission power) to ensure the maintenance of the links. Thus, for a given value of shadowing path loss exponent (which is 2.0, 2.5, or 3.0) and a given value of shadowing standard deviation (which varies from 2 dB to 8 dB), we determined the associated transmission power using the outage probability method described in section II-B. Table II, contains the various parameters with the associated transmission power (in dBm) to allow a stability of the radio links ensuring 95% of the reception between two nodes with transmission range of 30 m.

Table II
TRANSMISSION POWER (Pt) IN DBM FOR CONSTANT RANGE

Path L. E. / Standard D. (dB)	2.0	2.5	3.0
2	-11.677	-4.291	3.093
4	-8.397	-1.011	6.373
6	-5.117	2.268	9.653
8	-1.837	5.548	12.933

1) Scenario 1: Capture threshold impact: In this scenario we vary the value of capture threshold from 2 dB to 10 dB and set the shadowing standard deviation to 4 dB then we perform the tests for a shadowing path loss exponent of 2.0 and 3.0.

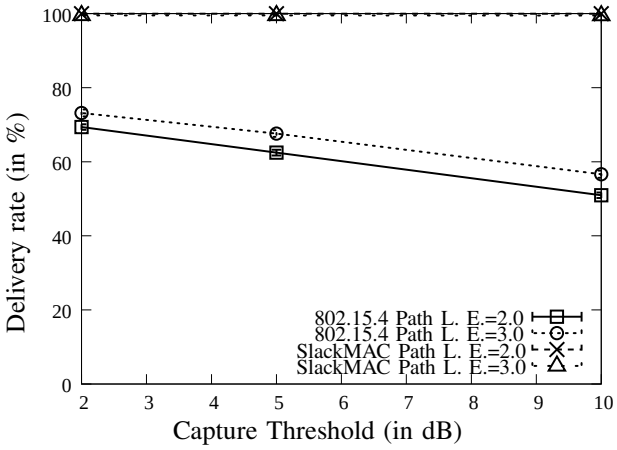


Fig. 3. Delivery rate as a function of the capture threshold with shadowing standard deviation of 4 dB for IEEE 802.15.4 and SlackMAC, when shadowing path loss exponent equal to 2.0 and 3.0.

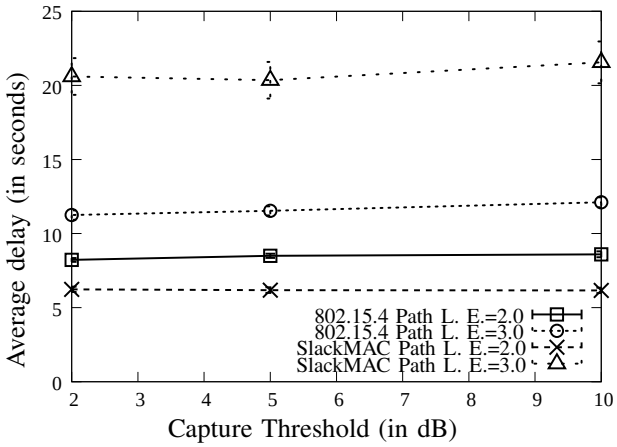


Fig. 4. Average delay as a function of the capture threshold with shadowing standard deviation of 4 dB for IEEE 802.15.4 and SlackMAC, when shadowing path loss exponent equal to 2.0 and 3.0.

Figures 3 and 4 show the delivery ratio and the end-to-end delay of data frames, respectively, as a function of the capture threshold (from 2 dB to 10 dB) with shadowing standard deviation of 4 for IEEE 802.15.4 and SlackMAC, when shadowing path loss exponent equal to 2.0 and 3.0.

For IEEE 802.15.4, the delivery ratio decreases from 69% to almost 51% for a shadowing path loss exponent of 2.0 and decreases from 73% to almost 56% for a shadowing path loss exponent of 3.0. The average delay remains around 8 s for a shadowing path loss exponent

of 2.0 and between 11 s and 12 s with a shadowing path loss exponent of 3.0.

For SlackMAC, the delivery ratio is 99.9% both for a shadowing path loss exponent of 2.0 and 3.0 regardless of the capture threshold. The average delay remains around 6 s for a shadowing path loss exponent of 2.0 and between 20 s and 21 s with a shadowing path loss exponent of 3.0.

The average delay varies little with the capture threshold for a given shadowing path loss exponent value with both protocols. The high delay in both protocols when the shadowing path loss exponent is equal to 3.0 is explained by the fact that when the value of shadowing path loss exponent increases, the interference area is reduced and the network becomes less meshed. This will require more hops to route data toward the sink, increasing the average end-to-end delay. Although the results of SlackMAC in terms of delivery ratio are generally better than those of the standard, these results can be compared with a difference of nearly 20% according to the capture threshold value set. The results in terms of delivery ratio of the standard are better when the capture threshold is low and less important when this value is high, this is due to the collision rates induced by a high capture threshold. This parameter has shown an important impact on the results of one of the two protocols, whereas its value is almost never mentioned in the simulations carried out comparing protocols in the literature.

2) Scenario 2: Shadowing path loss exponent impact: In this scenario we vary the value of shadowing path loss exponent from 2.0 to 3.0 and the shadowing standard deviation still set to 4 dB then we perform the tests for a the capture threshold of 2 dB and 10 dB.

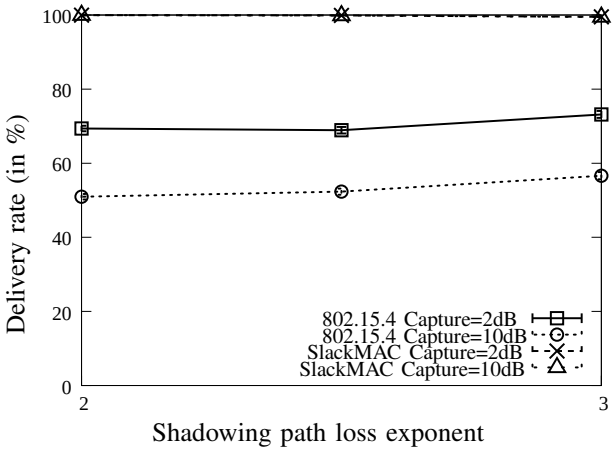


Fig. 5. Delivery rate as a function of the shadowing path loss exponent, with shadowing standard deviation of 4 dB for IEEE 802.15.4 and SlackMAC, when the capture threshold equal to 2 dB and 10 dB.

Figures 5 and 6 show the delivery ratio and the end-to-end delay of data frames, respectively, as a function of the shadowing path loss exponent, with shadowing standard deviation of 4 dB for IEEE 802.15.4 and SlackMAC, when the capture threshold equal to 2 dBm and 10 dBm.

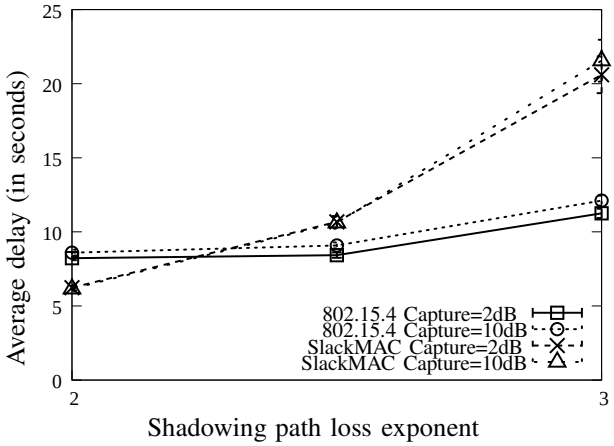


Fig. 6. Average delay as a function of the shadowing path loss exponent, with shadowing standard deviation of 4 dB for IEEE 802.15.4 and SlackMAC, when the capture threshold equal to 2 dB and 10 dB.

For IEEE 802.15.4, the delivery ratio increases from 69% to 73% for a capture threshold of 2 dB and increases from almost 51% to 56% with a capture threshold of 10 dB. The average delay increases from 8 s to 11 s for a capture threshold of 2 dB and from 8 s to 12 s with a capture threshold of 10 dB.

For SlackMAC, the delivery ratio decreases from 99.9% to 99.5% for a capture threshold of 2 dB and increases from 99.9% to almost 99.5% with a capture threshold of 10 dB. The average delay increases from 6 s to 20 s for a capture threshold of 2 dB and from 6 s to 21 s with a capture threshold of 10 dB.

We note that, for both protocols the delivery ratio varies little with the shadowing path loss exponent. For the standard, the delivery ratio remains higher for a low capture threshold than when it's high. The average delay increases for both protocols according to the shadowing path loss exponent, as in previous scenario. This is also due to the fact that when the value of the shadowing path loss exponent increases, the network is less meshed and requires more hops to route data toward the sink. There is also a reversal of performance in terms of average delay beyond the shadowing path loss exponent of 2.25 between the two protocols, the delay of the standard is better than in SlackMAC.

3) Scenario 3: Shadowing standard deviation impact: In this scenario we vary the value of the shadowing standard deviation from 2 dB to 8 dB and set the shadowing path loss exponent to 2.5 then we perform the tests for a the capture threshold of 2 dB and 10 dB.

Figures 7 and 8 show the delivery ratio and the end-

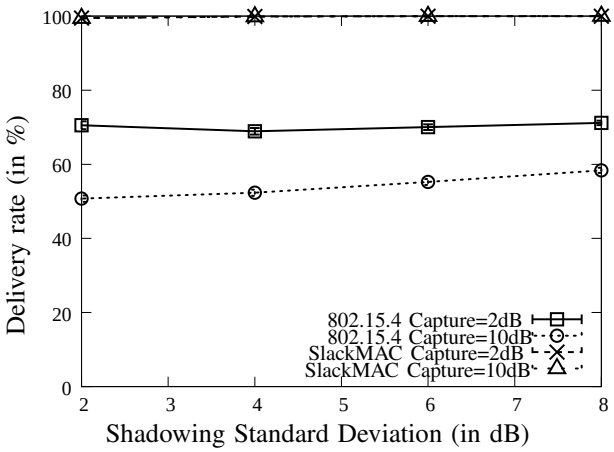


Fig. 7. Delivery rate as a function of the shadowing standard deviation, with shadowing path loss exponent of 2.5 for IEEE 802.15.4 and SlackMAC, when the capture threshold equal to 2 dB and 10 dB.

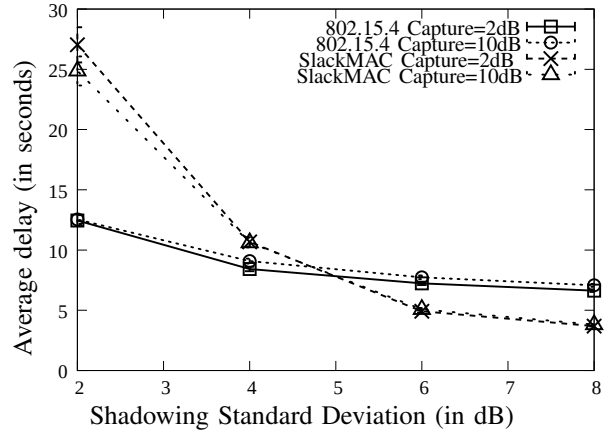


Fig. 8. Average delay as a function of the shadowing standard deviation, with shadowing path loss exponent of 2.5 for IEEE 802.15.4 and SlackMAC, when the capture threshold equal to 2 dB and 10 dB.

to-end delay of data frames, respectively, as a function of the standard deviation, with shadowing path loss exponent of 2.5 for IEEE 802.15.4 and SlackMAC, when the capture threshold equal to 2 dB and 10 dB.

For IEEE 802.15.4, the delivery ratio increases from 69% to 71% for a capture threshold of 2 dB and increases from 51% to almost 58% with a capture threshold of 10 dB. The average delay decreases from 12 s to 6 s for a capture threshold of 2 dB and from 12 s to 7 s with a capture threshold of 10 dB.

For SlackMAC, the delivery ratio increases from 99.4% to 99.9% for a capture threshold of 2 dB and increases from 99.4% to 99.9% with a capture threshold of 10 dB. The average delay decreases from 27 s to almost 4 s for a capture threshold of 2 dB and from 24 s to almost 4 s with a capture threshold of 10 dB.

We observe that, for both protocols the delivery ratio varies little with the shadowing standard deviation. For the standard, the delivery ratio remains higher (with a difference of almost 20%) when the capture threshold is low as in the scenario 2. Unlike scenario 2, here the average delay decreases for both protocols as a function of the shadowing standard deviation. This is due to the fact that when the value of the shadowing standard deviation is large, the fugitive existence of a link beyond the reference area is more probable, which reduce virtually the number of hops to route data toward the sink. As in scenario 2, there is also a reversal of performance of the two protocols when the shadowing standard deviation is greater than 5, the delay of SlackMAC is better than in the standard.

Through the results of scenarios 1, 2 and 3, it can be noted that, if we just allocate values to the simulation parameters, we can have a limited analysis. For example, if the value of the shadowing path loss exponent is set to 2.5, the standard deviation to 4 dB and the capture threshold to 10 dB, SlackMAC has a delivery ratio of 99.85% and the average delay is 10.6 seconds. While for the same parameters the standard has a delivery ratio of 52.32% and an average delay of 9.08 seconds. It will be concluded that the performance of SlackMAC is globally better compared to the standard. However, with another set of parameters as the value of the shadowing path loss exponent is 3.0, the standard deviation still set at 4 dB and the capture threshold set at 2 dB, the standard has a delivery ratio of 73.17% and an average delay of 11.25 seconds. While for the same parameters, SlackMAC keeps almost the same delivery ratio (ie 99.5%) and an average delay of 20.6 seconds. We observe the large differences in performance as a function of a simple set of parameters. While very often in the studies which are carried out comparing protocols proposed to those of the existing it is found that:

- not only, the main simulation parameters we have specified in this paper are not defined enough;
- but the variance between the performances are often less important than those shown in this paper.

IV. Conclusion

In this work, we carried out a comparative study of two protocols according to different simulation parameters to show the need to clearly specify the simulation environment when comparing protocols. We used an asynchronous MAC protocol with the reference MAC protocol specified in the standard IEEE 802.15.4 in beacon enabled mode. We knew intuitively that the asynchronous MAC protocol would provide better overall performance than the standard. However, we showed the diversity of the quantitative values of the performances according to the chosen simulation parameters. We evaluated the impact of different parameters such as shadowing path loss exponent, shadowing standard deviation and capture threshold. In each scenario, we

modified one parameter and fixed the others. The results show that for different values given to the main parameters of the shadowing propagation model and also to the capture threshold, there is a significant impact on simulation results. From this study we estimate that when two communication protocols are compared, it would be more insightful to specify the parameters used and to justify the choice of their value. It is imperative to reconcile the results with the parameters used in the simulation in order to judge their accuracy and also to allow their reproducibility. In this study we considered a simulation process for topologies using constant length of radio links. We intend to present a complementary analysis to this work which will be based on a simulation process with constant range vs constant transmission power.

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