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MAC Mechanism for a Scalable Wireless Sensor Networks using Independent Duty Cycles

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Abstract—Wireless sensor networks (WSNs) are increasingly used in order to monitor the environment. It is important to ensure that protocols for WSNs are scalable (as WSNs can be composed of hundreds of devices) and energy-efficient (as they are designed to operate for years). In this paper, we show that in synchronized MAC protocols, synchronization requires a lot of energy, and in unsynchronized MAC protocols, it is difficult for neighbor nodes to communicate together in an energy-efficient manner (as they are not synchronized). We use a mathematical model to quantify the average communication delay for unsynchronized MAC protocols, and to compute the average probability that this delay is infinite. Then, we propose a distributed MAC mechanism, based on the beacon-enabled mode of IEEE 802.15.4, without the synchronization mechanism. Our mechanism greatly reduces the probability that the communication delay is infinite, allows nodes to communicate with their neighbors periodically (but not systematically), and ensures that the energy consumption is constant. Finally, we evaluate the performance of our mechanism by simulation, and conclude that it can be integrated into a scalable MAC protocol.

I. INTRODUCTION

Wireless sensor networks (WSNs) are composed of cheap devices that can sense the environment, perform some computations, and communicate together using wireless links. These advantages allow them to be used to monitor various environments, such as volcanoes [1], bridges [2], fields [3], and bird nests [4]. These applications often require a large number of network devices, and they have to run for a long period (usually, several years).

The IEEE 802.15.4 standard [5] has been proposed to enable low-power communications in personal area networks, including wireless sensor networks. It has two operational modes: the non beacon-enabled mode and the beacon-enabled mode. In the non beacon-enabled mode, most devices wake up only when they have data to transmit, and go back to sleep afterwards. This requires some devices to always remain awake in order to receive data, which consumes a lot of energy. In the beacon-enabled mode, all devices are synchronized: they all wake up at the same time in order to communicate, and go back to sleep at the same time in order to save energy. However, the synchronization of devices is often difficult to achieve, and does not scale well.

In this paper, we propose a distributed MAC mechanism for WSNs which aims at improving the connectivity and the scalability of the IEEE 802.15.4 standard, while having

a low energy consumption. Our mechanism is to remove the synchronization constraint of the IEEE 802.15.4 beacon-enabled mode by having devices use independent duty cycles. Our approach improves the connectivity as devices will eventually (with high probability) share a common activity period and be able to communicate, even though they are not synchronized. Similarly, our approach improves the scalability as synchronization is no longer necessary when nodes wake up. Note that our mechanism can be used as an essential building block of a MAC protocol.

The paper is organized as follows. Section II gives a detailed explanation of the IEEE 802.15.4 standard, which is the basis of this work. Section III presents how independent duty cycles can improve the connectivity and scalability of the network. Section IV describes our simulation results, and shows that we are able to achieve a similar energy efficiency as IEEE 802.15.4. Section V discusses how our proposition can be implemented as a distributed mechanism. Finally, Section VI summarizes our work.

II. STATE OF THE ART

Most energy-efficient MAC protocols are based on a periodic sequence of activities and inactivities, called duty cycle. Nodes communicate during the activity period, and can sleep during the inactivity period, which spares energy. Those MAC protocols can be divided into two categories, depending on whether they are synchronized or not.

A. Synchronized MAC protocols

The IEEE 802.15.4 protocol [5] in beacon-enabled mode is one of the most common energy-efficient MAC protocols. Each full-function device (FFD) sends a beacon regularly, with a period called BI (for beacon interval). When a reduced-function device (RFD) receives a beacon, it starts its activity period for a duration called SD (for superframe duration). The ratio SD/BI defines the duty cycle of the protocol. Note that all nodes share the same activity period, as they are synchronized by the beacon reception. The medium is accessed using the slotted CSMA/CA (carrier-sense multiple access with collision avoidance) algorithm.

In D-MAC [6], nodes are synchronized according to their depth on a collection tree. When nodes of depth d are in a transmission slot, nodes of depth $d + 1$ are in a reception

slot. In Z-MAC [7], a TDMA (time-division multiple access) approach is used to synchronize nodes. A slot is assigned to all nodes in the configuration phase, and is used in case of high contention. In case of low contention, all nodes access the channel simultaneously, with a contention access mechanism. In G-MAC [8], time is divided into three periods: a collection period (where the medium is accessed by CSMA/CA), a period of traffic indication (whose role is to maintain synchronization between nodes) and a distribution period (where the medium is accessed by TDMA). All nodes have simultaneous activities during the first and the second periods, and non-simultaneous activities during the third period. In S-MAC [9], each node propagates periodically its time schedule to its neighbors. Each node adapts its activity to the first schedule it receives. Thus, nodes can determine when to be active or inactive, depending on whether they have to communicate with a given neighbor or not. In [10], the authors show that higher performance can be achieved when different wireless personal area networks have disjoint activity periods. However, ensuring that activity periods are disjoint requires synchronization. In MC-LMAC [11] nodes are synchronized but, use multiple channels dynamically. MC-LMAC is based on the single-channel protocol LMAC [12]. MC-LMAC maximizes throughput of LMAC by using a plurality of channels for transmission. The principle in MC-LMAC is as follows, firstly, nodes try to find time slots following the rule of LMAC. Second, the nodes that have not been able to find time slots invite their free neighbors to listen on an agreed channel. The problem with MC-LMAC is that most of the difficulties of synchronizing all MAC protocols duty cycle synchronous, dynamic scheduling interface change requires the generation of a large number of control message.

B. Not-synchronized MAC protocols

The IEEE 802.15.4 protocol in non beacon-enabled mode allows nodes to communicate without requiring a synchronization mechanism. When an RFD has to send data to an FFD, it simply wakes up and transmits the data. This requires, however, the FFDs to be active all the time, which consumes energy. The medium is accessed using the non-slotted CSMA/CA algorithm. Although the non beacon-enabled mode allows nodes to have non-simultaneous activities, it cannot be used in practice due to its energy requirements.

In B-MAC [13], nodes are not synchronized but wake up periodically for a short duration. When a sender node has to communicate to a receiver node, the sender node sends a long preamble before its frame (which makes B-MAC a sender-initiated protocol). When the receiver wakes up, it detects the preamble and stays active until the end of the preamble and the reception of the frame. While this approach yields good performance, nodes have to stay awake frequently in order to receive frames, and therefore the energy consumption of B-MAC relies heavily on the traffic. In X-MAC [14], the same approach as B-MAC is used. Instead of using a long preamble, each sender sends several small frames, which allows the receiver to go back to sleep as soon as it has received the frame, rather than having to wait for the

preamble. WiseMAC [15], RI-MAC [16], ADB [17], PW-MAC [18], and EM-MAC [19] focus on a receiver-initiated approach. In WiseMAC, preambles are used, but their lengths is reduced by allowing the sender to wake up before the beginning of the activity period of the receiver. In RI-MAC, the receiver initiates the communication. RI-MAC is based on low power probing, where the receiver sends a beacon to express its ability to receive data packets. RI-MAC reduces channel occupation (as it does not require nodes to send preambles), but generates high energy consumption. The same authors proposed the protocol ADB, to provide essentially a broadcast service in RI-MAC protocol. And PW-MAC for reduce the listening time of the sender in RI-MAC, by having each node compute its awakening times according to a pseudo-random number generator rather than according to a fixed schedule. The drawback of PW-MAC is that sending the beacons before packet transmission generates overhead, and introduces a delay when listening the channel. As PW-MAC in EM-MAC, a node computing its moments of awakening using a pseudo-random generator. A node independently decides its wake-up time and exchange channel. The wake-up channel is not necessarily the same as the channel for exchanging data. In EM-MAC, the sender also knows the parameters of the pseudo-random generator and receiver wake-up channel. EM-MAC inherits the shortcomings of PW-MAC, and more, in EM-MAC, each node invokes twice a pseudo-random generator, hence, generation of additional overhead.

III. IMPROVING THE ENERGY EFFICIENCY OF A LOW DUTY CYCLE MAC PROTOCOL

We identified two main issues in IEEE 802.15.4. First, when the non beacon-enabled mode is used, several nodes cannot sleep and the energy consumption is high. Second, when the beacon-enabled mode is used, the required synchronization is difficult to achieve for a large number of nodes, and the fact that all nodes share the same activity cycle reduces the performance of the MAC protocol (since they all compete for the medium at the same time).

In the following, we show additional drawbacks of the existing approaches. Even in the case where nodes start their activity at different times (which increases the performance of the MAC protocol), some nodes might never have a shared activity, which is detrimental for the network. We also study the delay a node has to wait, on average, to meet another node.

A. Study of the probability of shared activities

Let us suppose that nodes have the same beacon interval but start randomly within the beacon interval. Let us denote by n_i each node, BI the duration of the beacon interval, and $\alpha \in [0; 1]$ the duty cycle (that is, each node is active during $SD = \alpha \cdot BI$). Without loss of generality, we can assume that n_1 starts at the beginning of its beacon interval (in this case, n_1 finishes its activity at $\alpha \cdot BI$).

First, we compute the probability $P_{disjoint}$ that n_1 and n_2 have disjoint activities. If $\alpha > 1/2$, $P_{disjoint} = 0$ as nodes are active during more than half of their beacon interval. Let

us now consider that $\alpha \leq 1/2$. $P_{disjoint}$ is equal to the probability that n_2 starts its activity duration after n_1 finishes its own, and that n_2 finishes its activity duration before n_1 starts its next one. Thus, $P_{disjoint}$ is the probability that n_2 starts in $[\alpha.BI; BI - \alpha.BI]$. This interval always exists since $\alpha \leq 1/2$ yields to $\alpha.BI \leq BI - \alpha.BI$. As we assume that the starting time of n_2 is uniformly distributed, we have $P_{disjoint} = (BI - 2\alpha.BI)/BI$, that is $P_{disjoint} = 1 - 2\alpha$. For instance, when $\alpha = 1/4$, $P_{disjoint} = 1 - 1/2 = 1/2$. When $\alpha = 1/8$, $P_{disjoint} = 1 - 1/4 = 3/4$. When the duty cycle is low, the probability that some nodes never share a common activity is high, which is an important drawback of existing methods.

Second, we compute the probability P_{all} that there is a time when n nodes are active simultaneously. Recall that all nodes have activity periods starting randomly (except for n_1). Since these activities are independently chosen, we can compute P_{all} as

$$P_{all} = \prod_i P(n_i \text{ is active}) = \prod_i \alpha = \alpha^n.$$

For instance, when $\alpha = 1/2$ and $n = 3$, $P_{all} = 1/8$. When $\alpha = 1/2$ and $n = 4$, $P_{all} = 1/16$. It can be seen that when the number of nodes n is large, the probability that all nodes share a common activity is very low, which is also an important drawback of existing methods.

B. Study of the delay before a shared activity

It is important to know the delay before two nodes can have a shared activity, in addition to knowing that they will eventually meet. We define the average delay between two nodes n_1 and n_2 as the average duration between any instant when n_1 is active, and the first instant when n_1 and n_2 are active. Note that sometimes, n_1 and n_2 never meet: these cases are not taken into account in the average delay, but the probability that this occurs is $P_{disjoint}$.

To compute the average delay, we examine two cases that are equally likely to occur. Case 1 is when n_2 starts within $[0; \alpha.BI]$, and Case 2 is when n_2 starts within $[BI - \alpha.BI; BI]$. These two cases are depicted on Fig. 1. Notice that it is not possible for n_2 to start at other times, as this would cause an infinite delay.

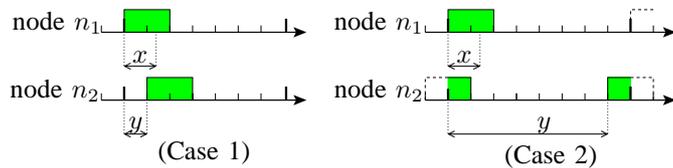


Figure 1. Two cases that can occur when two nodes n_1 and n_2 meet.

Let d_1 be the average delay for Case 1. Let us denote by x the instant within the activity of n_1 (over which the average is performed), and by y the starting time of n_2 . According to

Fig. 1, we have:

$$\begin{aligned} d_1 &= \frac{1}{\alpha^2.BI^2} \sum_{y=0}^{\alpha.BI} \left(\sum_{x=0}^{y-1} (y-x) + \sum_{x=y}^{\alpha.BI-1} 0 \right) \\ &= \frac{(\alpha.BI + 1)(\alpha.BI + 2)}{6\alpha.BI}. \end{aligned}$$

Let d_2 be the average delay for Case 2. Again, according to Fig. 1, we have:

$$\begin{aligned} d_2 &= \frac{1}{\alpha^2.BI^2} \sum_{y=BI-\alpha.BI}^{BI-1} \left(\sum_{x=0}^{y+\alpha.BI-BI} 0 \right. \\ &\quad \left. + \sum_{x=y+\alpha.BI-BI}^{\alpha.BI-1} (BI-x) \right) \\ &= \frac{\alpha(2\alpha-3).BI^2 - 3.BI - 2}{6\alpha.BI}. \end{aligned}$$

The average delay d is thus:

$$d = \frac{d_1 + d_2}{2} = \frac{(\alpha.BI + 1).(4 + 3.BI - \alpha.BI)}{12\alpha.BI}.$$

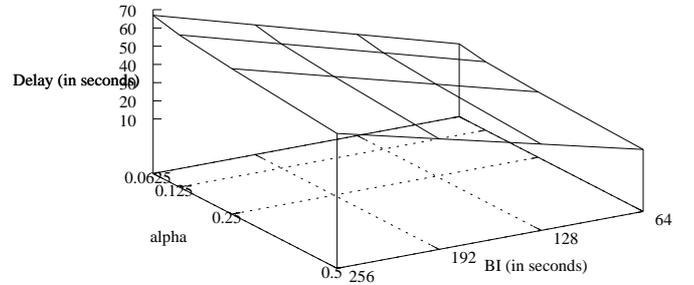


Figure 2. Numerical value of the delay d as a function of BI and α .

Figure 2 shows the delay d as a function of BI and α . It can be noticed that even when the delay is not infinite, the delay is relatively large. It reaches up to 70 s for $BI = 256$ and $\alpha = 6.25\%$.

C. Description of our proposition

Our proposition can be summarized by the following items:

- allowing nodes to start their activity at a random time within the beacon interval,
- forcing nodes to have different beacon intervals while maintaining a given duty cycle,
- removing the constraint that all the nodes of the network have to agree on when to send their beacons.

The first item ensures that all nodes are not always active simultaneously, which improves the performance of the MAC protocol. The second item ensures that nodes have a high probability to meet while maintaining the same energy-efficiency as the beacon-enabled mode. The third item allows our mechanism to be independent of the number of nodes in the network, which enables its integration into a scalable MAC protocol. In this way, our proposition benefits from the energy-efficiency of the beacon-enabled mode (as each node keeps the

same duty cycle), without having the drawbacks of a global synchronization (as each node keeps its own time schedule).

Figure 3 shows the activities of three nodes as a function of time, with a duty cycle of 25% and when nodes start their activities randomly within the beacon interval. To ease the description, we made two simplifying assumptions: there are only 8 backoff periods per cycle (that is, $BI = 8$), and the backoff periods are synchronized for all the nodes. In general, the number of backoff periods per cycle is much larger: for a beacon interval of $2^6 \times 15.36$ ms, which is about one second, there are 3072 backoff periods of $320 \mu\text{s}$ each. Backoff periods cannot be synchronized for all the nodes when there is no global synchronization, but the desynchronization only impacts one backoff period at most, out of all the backoff periods of the beacon interval. Periodically, nodes n_1 and n_2 share a common activity period (at the end of the activity of n_1 and at the beginning of the activity of n_2). However, in the example depicted here, n_3 never shares a common activity with neither n_1 nor n_2 .

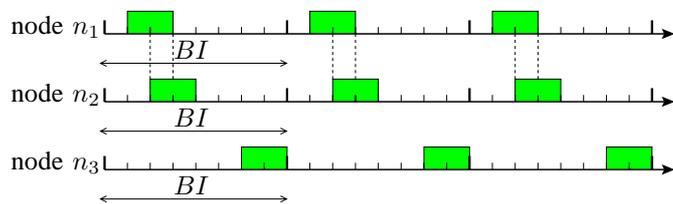


Figure 3. Activities of three nodes as a function of time, with a duty cycle of 25%, and when activities start randomly within the beacon interval. Node n_3 never shares a common activity period with n_1 nor n_2 .

Figure 4 shows the activities of three nodes as a function of time, for our proposition. Notice that for each node, the duty cycle is 25% (even if the beacon interval is different). Common activities between two nodes are no longer periodic: they appear depending on the beacon interval of each node. For instance, n_1 shares a common activity with n_2 at the beginning of the first activity period of n_1 , and at the end of its third activity period. Node n_3 shares a common activity with n_2 at the beginning of its first activity period, and a common activity with both n_1 and n_2 at the end of its second activity period.

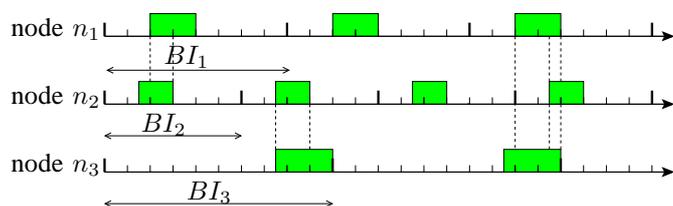


Figure 4. Activities of three nodes as a function of time, with a duty cycle of 25%, for our proposition. All possibilities of shared activities (n_1 and n_2 , n_1 and n_3 , n_2 and n_3 , and all three nodes together) happen in this short example.

The main advantages of our proposition are the following:

- it does not require synchronization,
- the duration of the activity period is never exceeded,

- the probability that a node is isolated from the other nodes in range is low (see $P_{disjoint}$),
- as few nodes are active simultaneously on average, contention access MAC protocols can achieve higher performance,
- there are times when all nodes are active, which enables to broadcast frames efficiently.

IV. SIMULATION RESULTS

In order to evaluate the performance of our proposition, we ran some simulations using a set of Perl scripts. As a basis for our comparison, we use a model similar to the one depicted on Fig. 3: BI has a constant value of 128 backoff periods, and each node chooses randomly the beginning of its activity within the period. Our proposition, depicted on Fig. 4, allocates a random BI to each node, such that each BI is within $[64; 256]$ and is a multiple of 4. The activity duration in our case varies for each node, but the duty cycle is constant for all nodes. Again, each node chooses randomly the beginning of its activity within its period. Each simulation lasts until a global periodicity is obtained (which happens after a number of backoff periods equal to the least common multiple of all the BI s). Note that all nodes are in range (that is, they are in the same cell). In the following plots, each point is averaged over 500 repetitions.

Figure 5 shows the average probability for all the nodes of a cell to be active simultaneously, as a function of the number of nodes. We evaluate two duty cycles: 50% and 25%, and we compare the probability when BI s are constant (which is denoted by BI is not random) and when BI s are different for each node (which is denoted by BI is random). For a given duty cycle, the probability that all nodes are active simultaneously decreases with the number of nodes, as expected. However, when BI s are random, the probability is much higher than when BI s are constant, and decreases linearly instead of exponentially. In all cases, our proposition yields a much higher probability than the state of the art. For instance, when the duty cycle is equal to 50% and for four nodes in a cell, the probability that they have a common activity is only 5% (out of active duration of nodes, which is only 50% of the time) when BI s are the same, while it exceeds 40% when BI s are random.

Figure 6 shows the average probability for several nodes in a cell to be active simultaneously, when the total number of nodes in the cell is seven. For instance, the probability that three nodes (out of seven) are active simultaneously for a duty cycle of 50% is about 60% when BI s are constant, and about 80% when BI s are random. The probability that six nodes (out of seven) are active simultaneously for a duty cycle of 50% is about 10% when BI s are constant, and about 40% when BI s are random. With our proposition, the probability that several nodes are active simultaneously decreases slowly.

Figure 7 shows the average delay (in backoff periods) as a function of the number of nodes in the cell. We compute here only the delay until two nodes are active simultaneously, without considering the MAC delay required for two active

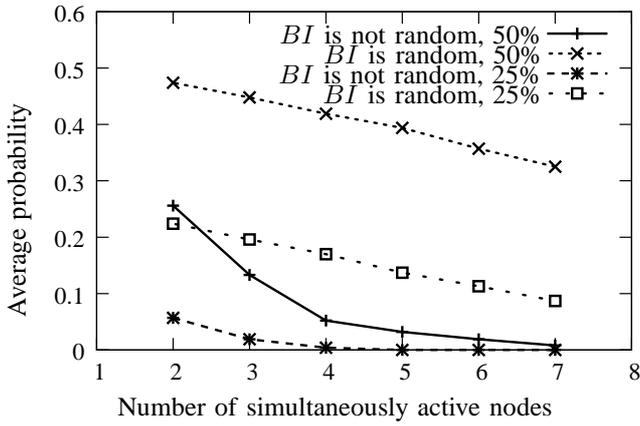


Figure 5. Average probability for all nodes in a cell to be active simultaneously. When BI is chosen randomly for each node, the probability that all nodes in a cell are active simultaneously at a given time is high and decreases slowly.

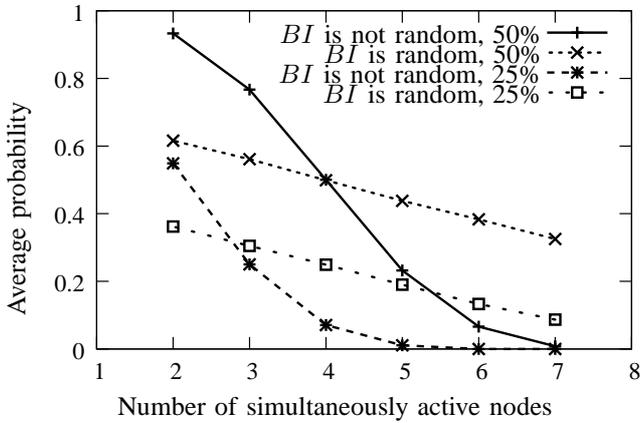


Figure 6. Average probability for several nodes to be active simultaneously, for a total of seven nodes in a cell. When BI is chosen randomly for each node, the probability that several nodes are active simultaneously decreases slowly with the number of active nodes.

nodes to communicate. The delay is averaged over all pairs of nodes, but does not take into account the infinite values. Notice that the percentage of infinite delays is very high when BI is not random, and very low when BI is random. For a duty cycle of 50%, the percentage of infinite delays varies between 0.5% and 1% when BI is not random, and is always 0% when BI is random (for our 500 repetitions). For a duty cycle of 25%, the percentage of infinite delays varies between 50% and 51% when BI is not random (which is very high), and varies between 1.5% and 2% when BI is random (which is very low). When BI is constant and the duty cycle is low, a large number of delays are infinite and are therefore omitted from the computation. When BIs are random, the delay is higher on average but only a small percentage of infinite delays are omitted.

V. IMPLEMENTATION AS A DISTRIBUTED PROTOCOL

In this section, we describe how to build a distributed and scalable protocol from our proposition.

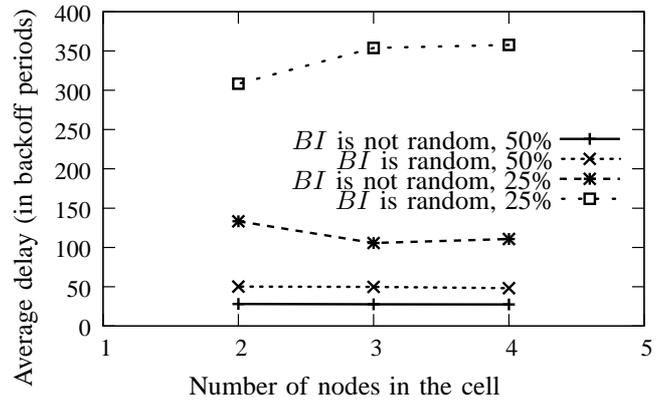


Figure 7. Average delay for two nodes in a cell to be active simultaneously. When BI is chosen randomly for each node, the average delay is approximately twice higher than when BI is not random. However, when BI is chosen randomly, the probability that delays are infinite is very low.

Algorithm 1 presents our protocol. Note that all nodes share the following values: Δ is a duration (generally large), BIs are chosen randomly within $[minBI; maxBI]$, and $dutyCycle$ is the fixed duty cycle for each node. We assume here that nodes start randomly and independently. Initially, each node chooses its own BI in $[minBI; maxBI]$ according to our proposition, and operates according to this BI . After Δ backoff periods, the node determines whether it has met any neighbor or not. If it has not, it draws a new BI and starts again. Otherwise, it keeps the same value for BI .

Algorithm 1 Scalable protocol using independent duty cycles.

Require: Δ , $minBI$, $maxBI$ and $dutyCycle$ are global constants

```

neighbors ← 0
repeat
  BI ← 4 · [rand(minBI, maxBI)/4]
  SD ← dutyCycle · BI
  repeat
    node is active during SD backoff periods
    new ← number of new neighbors discovered
    neighbors ← neighbors + new
    node is inactive during BI – SD backoff periods
  until Δ backoff periods have passed
until neighbors ≠ 0
while true do
  node is active during SD backoff periods
  node is inactive during BI – SD backoff periods
end while

```

When the first node joins the network, it keeps changing its BI as it does not meet any neighbor. When the second node joins the network, it is very likely that it will eventually meet the first (according to the results shown on Fig. 5). Even if it does not meet the first node with the current BI , the second node will eventually draw a new BI . The process continues in the same way for all nodes. The probability that two disjoint networks are created in the same cell is very low, as it would

require all the nodes of a set N_1 to have disjoint activities with all the nodes of a set N_2 .

Our protocol is scalable and distributed, as it does not require any knowledge about other nodes, or a large overhead in terms of control messages. However, its convergence can be slow, depending on the value of Δ and on the number of nodes in range.

VI. CONCLUSION

In WSNs, it is difficult to synchronize many nodes in an energy-efficient manner. Without synchronization, MAC protocols often require some nodes to remain active (which consumes energy) or to have disjoint activities (which forbids communications between nodes). In this paper, we proposed a distributed MAC protocol that guarantees that nodes share common activities (with a high probability) while having an energy consumption similar to the one of synchronized MAC protocols, but without the synchronization overhead. Our simulation results show that our mechanism achieves good performance in terms of percentage of shared activities. On average, the delay for our mechanism is larger than the delay of other protocols, but our mechanism has a very low probability of having infinite delays, contrarily to other protocols. Finally, our mechanism can be used as an essential building block of a MAC protocol.

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