# Optimal $p$-persistent MAC algorithm for event-driven Wireless Sensor Networks

J. Vales-Alonso*, E. Egea-López, M. V. Bueno-Delgado, J. L. Sieiro-Lomba, J. García-Haro
Department of Information Technologies and Communications,
Polytechnic University of Cartagena, Spain.
* Corresponding author. Address: Campus Muralla del Mar, 30202, Cartagena, Spain.
phone: +34 968 326 588, fax: +34 968 325 973, e-mail: javier.vales@upct.es

***Abstract*—In event-driven wireless sensor networks nodes transmit information only if the monitored physical magnitude levels have triggered an alarm. In these networks, traffic exhibits a high spatial correlation, since it is likely that neighbor nodes detect and try to notify the same events. Thus, the probability of packet collision raises up, as well as notification delay, just as opposite as required. In this work we propose to use a $p$-persistent mechanism in the access control layer. The aim is reducing collisions and saving energy. We compute the optimal $p$ for a coherent network deployment and describe the experimental implementation of our proposal. Theoretical computations predict a notable improvement, specially in terms of energy, and experiments reveal that our proposal achieves up to 67% of energy saving compared against a perfect (collision-free) mechanisms.**

***Index Terms*—Wireless sensor networks, MAC protocols, delay sensitive, persistent**

## I. INTRODUCTION

Wireless Sensor Networks (WSN) are *ad-hoc* networks devoted to data gathering based on low cost and low transmission range (usually, less than 100 meters) sensor devices. Data are transmitted by means of multi-hop routing from sensing nodes to special nodes, called *sinks*, which process them. In WSN networks, mainly two kinds of traffic are usually considered [1]: (1) *periodic data* traffic, sensed data samples are periodically transmitted by each sensor to the sink(s), and (2) *event-driven* traffic, in this case the physical environment is continuously monitored, and if the sensed magnitude fulfills a qualifying condition (*e.g.* temperature is greater than 300 Kelvin degrees, pressure is lower than 100 kilo-pascal, etc.) an "event" is triggered, that is, an alarm is transmitted (a "notification") to the sink(s). Event-driven networks are usually associated with delay-sensitive applications, which require short notification delays.

Besides, a major constraint in WSN is still the battery lifespan, which determines, in most cases, the protocols operation. At Medium Access Control (MAC) level, sensor devices must turn on radios only when strictly necessary, to avoid unnecessary energy waste. Indeed, avoidance of idle listening and putting devices to sleep are the most widely used approaches to reduce power consumption. That is, nodes coordinate their operation in active/sleep periods (see figure 1), which yields to *time-slotted* activity. There are several proposals for MAC contention protocols adapted to this kind of operation, *e.g.* [2], [3], [4]. In this case, data exchange can only take place in the active periods. Within this period, before starting data transmission, nodes perform some anticollision mechanism. For CSMA/CA (the most common approach), the mechanism is as follows: backlogged nodes randomly select a number of contention micro-slots[1] $k = 1, \ldots, K$, and start transmission if medium keeps idle after that number of micro-slots. Transmission lasts until the end of active period. A collision occurs if more than one node select the same initial micro-slot.

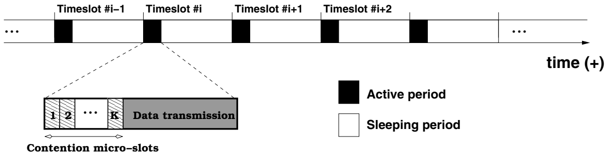

Fig. 1. Nodes coordinate themselves in activity/sleep periods, which result in time-slotted operation

If traffic shows an independent pattern among nodes (a classical hypothesis in the literature), time-slotted operation notably reduces consumption and provides a flexible access scheme. However, in networks where traffic is event-driven, transmissions exhibit a *high spatial correlation*, that is, it is very likely that several nearby nodes capture the same event and, consequently, try to simultaneously notify it. Since time-slotted operation groups communications in the active part of the frame, the probability of packet collision raises up, as well as notification delay, just as opposite as required.

In this paper we propose a modification of activity-slotted contention protocols to minimize the average latency of event notification and reduce energy consumption. Our modification is based on the introduction of a $p$-persistent algorithm at the MAC layer. That is, at each time-slot, backlogged nodes decide to wake up (with probability $p$) or to keep on sleeping (probability $1 - p$). We analyze the optimal persistence $p$, which minimizes the delay of the first notification of the event. In fact, the desired effect is twofold, because nodes that decide to keep on sleeping consume less energy. For example, consider an event sensed by 15 nodes, in the best case (with a successful transmission at the first trial) 15 nodes consume

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[1] We use the term *micro-slot* for a carrier sensing slot to distinguish from the active period slot

the energy of an idle listening activity period, whereas using $p$ persistence, on average only $15 \times p$ of the nodes wake up and consume energy. For a low value of $p$, a considerable saving of energy can be obtained. In fact, as we will show later, the saving is greater as the number of backlogged nodes increases. A computational feasible method for computation of $p$ is provided, as well as different analytic results that demonstrate the outperforming operation (in terms of energy and latency) of the proposed algorithm versus the classical 1-persistent approach.

The remainder of this work is organized as follows: Section II highlights related works for WSN. In Section III the optimal $p$ is computed as a function of the number of nodes present. Section IV describes the theoretical results in terms of time and energy of protocols using the optimal persistence. In section V the results of an experimental implementation of the p-persistent mechanism over S-MAC and MICA2 motes is discussed. Finally, Section VI presents the main conclusions of this work.

**Note:** Hereafter the following notation and conventions are used:

- Probabilities are denoted as $prob\{\text{Event}\}$.
- Random variables (rv) are denoted as $\boldsymbol{x}$.
- Average values are denoted as $\overline{\boldsymbol{x}}$.

## II. RELATED WORK

The number of MAC protocols for Wireless Sensor Networks which have been proposed in the last years shows the interest this field has acquired. Most of them mainly focus on energy saving, which is often achieved by trading-off for packet delivery latency, usually considered of secondary importance.

WSN MAC protocols can be classified into the classical categories of contention based protocols and time division protocols. Classical contention based protocols are simple, scalable and flexible but at the expense of high idle listening time, that is, high waste of energy. WSN protocols based on Carrier Sense Multiple Access (CSMA) are designed with mechanisms to avoid overhearing and idle listening and, thus, decrease energy consumption. The most used approach is to make nodes turn off their radio during inactivity. S-MAC protocol [2] is the first which propose to organize nodes in periodic cycles of activity and sleep (listen/sleep), This mechanism makes nodes activate for a short time interval (listening time) and put them to sleep (turn off the radio) during the rest of the time (sleep time). The ratio of the listen time and sleep time is called duty cycle. Decreasing duty cycle results in a reduction of the energy consumption. Nodes coordinate sleep time with their neighbours by means of a synchronization broadcast packet (SYNC packet). This packet is periodically rebroadcasted to maintain synchronization. Therefore, the activity period is split into two subperiods: synchronization and data exchange. During data exchange, nodes use a variation of the CSMA/CA procedure of IEEE 802.11: the contention window is fixed. In addition, RTS/CTS packet avoid hidden node problems. SMAC reduces energy waste considerably, but the constant sleep and listen periods increase the latency under variable traffic load.

Minimizing latency has also been the focus in [5], where authors propose to use a non-persistent CSMA but selecting the carrier sensing micro-slots with a nonuniform probability distribution function ($\boldsymbol{f}$) which maximizes the probability of success when $N$ nodes become simultaneously backlogged. Namely, $prob\{\text{“Start transmission in microslot } j\text{”}\} = f(j)$. The distribution ($\boldsymbol{f}$) also minimizes latency of a successful transmission. However, this optimal distribution requires the knowledge of the real number of contenders ($N$), which is usually unknown. To avoid this problem, the authors provide an approximation to the optimal distribution, called Sift distribution.

Our mechanism is suboptimal in comparison with $\boldsymbol{f}$ in terms of collision probability. However, in our case, not all nodes that sense an event will contend in the activity period. This property notably reduces power consumption as we will show.

## III. ANALYSIS

In this section we compute the optimal $p$ for the $p$-persistent mechanism described in Section I, that minimizes the delay of the first notification. That is, the time elapsed since the physical event takes place until the notification of the event reaches the sink node.

Before carrying out this analysis, it is necessary to assume a network model, since the optimal $p$ depends on the expected number of nodes sensing a triggering event. This model provides a way to estimate the number of nodes needed to cover an interest area with a required quality. That is, the number of nodes to be deployed to ensure that the probability of loosing an event of interest is below some target limit.

### A. *Network model*

- The network is formed by $n$ sensor nodes, densely and randomly deployed in a large area (of size $A$), since we consider that events occur equiprobably in the area $A$. Therefore the number of nodes that capture each event is given by a random variable $\boldsymbol{N}$, taking values on $[0, 1, \ldots, n]$. Let us consider an uniform node distribution into the target area. To compute $\boldsymbol{N}$, we assume that events are received by nodes within a certain radio $r$ from the point where the event takes place, and that the radio communication coverage radius is $R$. The size of the area where the event is sensed is given by $a = \pi r^2 \ll A$. Provided that $r < R$, all the nodes that receive the event content for its simultaneous transmission towards the sink. Then, the probability mass function of $\boldsymbol{N}$ is given by equation (1).

$$\begin{aligned} prob\{\boldsymbol{N} = i\} &= \binom{n}{i}\left(\frac{a}{A}\right)^i\left(1-\frac{a}{A}\right)^{n-i} \approx \\ &\approx \frac{(n\frac{a}{A})^i e^{-n\frac{a}{A}}}{i!} \\ &\Rightarrow \boldsymbol{N} \approx \boldsymbol{Poisson}\{n\frac{a}{A}\} \end{aligned} \tag{1}$$

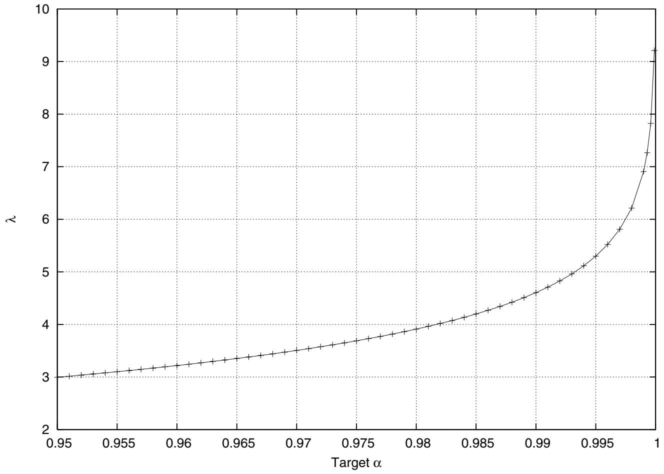

Fig. 2. $\lambda$ versus target $\alpha$

In the former equation we have employed the Poisson approximation for the binomial distribution. This approximation is correct if $\frac{a}{A} \ll n\frac{a}{A} \ll n$, which is clearly fulfilled in WSNs since $n$ is expected to be very large and the ratio $\frac{a}{A}$ very low. Based on the Poisson distribution nomenclature, let us define $\lambda = n\frac{a}{A}$. Therefore, in our model $\lambda$ can be interpreted as the *average number of nodes that receives each event*.

In addition, there is a relationship between $\lambda$ and the event coverage probability ($\alpha$) that is, the probability that at least one sensor captures an event,

$$1-\alpha = prob\{\boldsymbol{N}=0\} \Rightarrow \alpha = 1-e^{-\lambda} \Rightarrow \\ \Rightarrow \begin{cases} \lambda = -ln(1-\alpha) \\ n = -\frac{A}{a}ln(1-\alpha) \end{cases} \tag{2}$$

For instance, in a deployment in an area A of one kilometer square, if the event capture radio is 20 meters, for a event loss probability of $1-\alpha = 0.001$, we get $\lambda = 6.9$, and $n \approx 5500$ nodes. With this numerical example we can verify that $\frac{a}{A} = 0.00126 \ll n\frac{a}{A} = 6.9 \ll n = 5500$, and therefore the Poisson approximation holds.

Hence, for a given coverage probability target we can compute the number of sensors to be deployed, and the $\lambda$ associated to such network configuration. Figure 2 shows the $\lambda$ value *versus* a coverage probability target from 95% to almost 100%.

- The maximum notification time is much less than the inter-event time. This assumption implies that when a new event occurs the network is "empty" of notifications from other events. That is, we do not need to take into account the effect of simultaneous physical events in our study.
- There exists a preemption mechanism that allows forwarding nodes to acquire the channel without contention. This assumption is added to avoid contention from nodes in the route to the sink. The inclusion of such mechanism is sound since delay is minimized if a node that receives a notification packet, and must forward it towards the sink, immediately wins the channel and relay it. Let us notice that such a preemption mechanism is easily achieved by means of a variable delay before carrier sensing like the SIFS and DIFS delays in IEEE 802.11 or S-MAC adaptive sleeping. In this case, minimizing the delay in the first transmission is equivalent to minimizing end-to-end delay.

### *B. Average notification time*

At the beginning of each activity period, all the nodes ($N$) that have received an event contend to access the channel and transmit its notification. Let $K$ be the number of contention micro-slots, and let $\boldsymbol{q}$ be the random variable which selects the initial contention micro-slot for node $i = 1, \ldots, N$. Since contention micro-slots are usually chosen uniformly, $\boldsymbol{q} = \boldsymbol{Uniform}\{1, K\}$ for all nodes. Let us denote $q_k = prob\{\boldsymbol{q} = k\} = \frac{1}{K}$ for every $k \in [1, \ldots, K]$.

The probability of success in contention (one node wins) is a function of the number of competing nodes (N). Obviously, for $N = 1$ the probability is 1, and for $N \geq 2$ is given by (see [5]):

$$\pi(N) = N\sum_{s=1}^{K-1} q_s(1-\sum_{r=1}^{s} q_r)^{(N-1)} = \\ = \frac{N}{K}\sum_{s=1}^{K-1}(1-\frac{s}{K})^{(N-1)} \tag{3}$$

Now, let us consider persistence in the MAC algorithm, in this case the probability of success is computed in expression (4).

$$\pi(N,p) = \sum_{c=1}^{N} \pi(c)\binom{N}{c}p^c(1-p)^{N-c} \tag{4}$$

For a given number of contending nodes ($N$), we can define the random variable $\boldsymbol{T}_N$ representing the "number of time-slots until one of the $N$ nodes wins the channel and transmits". The mass probability function of $\boldsymbol{T}_N$ is given by equation (5).

$$prob\{\boldsymbol{T}_N{=}j\} = \pi(N,p)(1-\pi(N,p))^{j-1} \tag{5}$$

for all $j \geq 0$.

In the last expressions we have considered the parameter $N$ as a constant. However, as we previously discussed, it is in fact a random variable $\boldsymbol{N}$. From equations (1) and (5) we can compute the average number of time-slots until a node wins contention ($\overline{\boldsymbol{T}}$), for a random number of contenders $\boldsymbol{N}$. Namely,

$$\overline{\boldsymbol{T(p)}} = \sum_{i=1}^{n} \overline{\boldsymbol{T_i}} prob\{\boldsymbol{N} = i\} \tag{6}$$

Let us notice that the previous expression gives the average number of time-slots required for the transmission of the first notification.

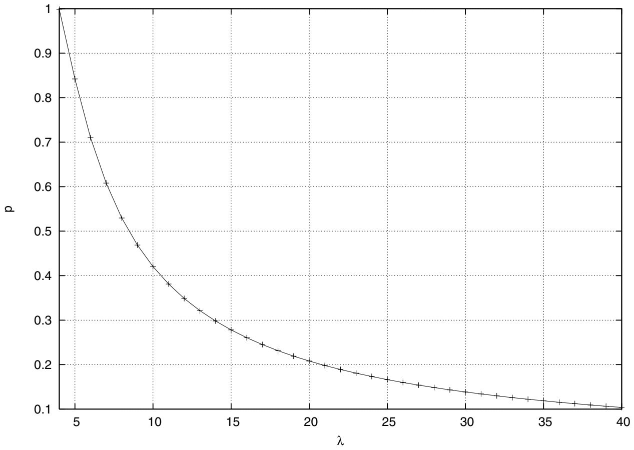

Fig. 3. Optimal $p$ versus $\lambda$

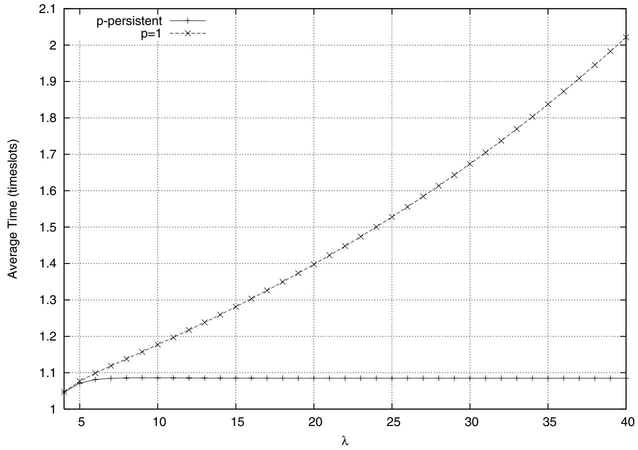

Fig. 4. $\overline{\boldsymbol{T(p)}}$ versus $\lambda$ for the optimal $p$

### C. *p optimization*

From the previous analysis we can express our minimization criterion as,

$$p = \arg\min_p \left\{\overline{\boldsymbol{T(p)}}\right\} =$$

$$= \arg\min_p \left\{ \sum_{i=1}^{n} \overline{\boldsymbol{T_i}} prob\{\boldsymbol{N}=i\}\right\} =$$

$$= \arg\min_p \left\{ \sum_{i=1}^{n} \left( \sum_{j=1}^{\infty} j prob\{\boldsymbol{T}_i = j\}\right) prob\{\text{N=i}\}\right\}$$

Simplifying,

$$\overline{\boldsymbol{T(p)}} = \frac{1}{p}\sum_{i=1}^{n}\left(\frac{1}{\sum_{c=1}^{i}\pi(c)\binom{i}{c}p^{c-1}(1-p)^{i-c}}\frac{\lambda^i e^{-\lambda}}{i!}\right) = \frac{f(p)}{p} \tag{7}$$

Deriving the previous equation and equalling to zero to compute the minimum, we obtain,

$$\frac{d\overline{\boldsymbol{T(p)}}}{dp} = \frac{d(f(p)/p)}{dp} = 0 \Rightarrow p = \frac{f(p)}{f'(p)} = g(p) \tag{8}$$

From equation (8) the optimal $p$ can be computed using the Banach's fixed point theorem [6]. This theorem states that for a contraction mapping $g(x)$ from a closed subset F of a Banach space E into F there exists a unique $x$ in F such that $g(x) = x$. In our problem the contraction mapping is $g(p) = \frac{f(p)}{f'(p)}$. In addition, the theorem provides a constructive method to find out the fixed point: setting an arbitrary initial $p_0$ we compute $p_{i+1} = g(p_i) = \frac{f(p_i)}{f'(p_i)}$. Eventually, the succession $p_i$ converges to the optimal $p$. Furthermore, since the theorem guarantees that the solution is unique this point is the minimum we look for.

## IV. RESULTS

Figure 3 shows the optimal $p$ obtained using the fixed point theorem. For values of $\lambda$ lower than 3.5 we obtain a $p > 1$, which has no physical meaning. In these cases, we have to select $p = 1$ to achieve the best performance. That is, the mechanism behaves as a 1-persistent algorithm. However, notice that in any practical deployment the number of nodes must be selected so that the probability of loosing events is low enough (usually target values should be less than 1%). Looking at figure 2, we get that in this case that $\lambda > 4$. For these values of $\lambda$ we obtain $p < 1$, and the use of the p-persistent approach makes sense.

Figure 4 shows the average number of activity periods (time-slots) required for the event notification respectively for the $p$-persistent and 1-persistent (i.e., no persistence mechanism used) variant of the protocol. As it is shown, the use of persistence controls and adjusts contention, keeping the notification delay almost constant. On the contrary, with 1-persistence, delay increases as the number of contenders raises (higher $\lambda$). In fact, the increase may be higher, depending on the size of the contention window, that is, the available number of micro-slots (these results have been computed for $K = 32$).

Finally, the energy saving can be approximated as follows. Let us assume some energy consumption per awake node and activity period: $G$. If no persistence is employed, the energy consumed for the transmission of a notification is $E_{p=1} \approx \overline{\boldsymbol{T(1)}}\lambda G$ (let us recall that $\lambda$ represents the average number of nodes sensing an event). Whereas if p-persistence is used the energy consumed is $E_p \approx p\overline{\boldsymbol{T(p)}}\lambda G$. Let us notice that the average time $\overline{\boldsymbol{T(p)}}$ is different in each case. Thus, the benefit is twofold since energy is reduced because of both the aslept nodes and the fewer number of time-slots needed. As shown in figure 5, using $p$-persistence the energy consumed can be as just a 5% of the energy wasted by the common approach for very high density networks. For a more realistic scenario, as the one provided in section III-A, with $\lambda = 6.9$, savings are around 50%.

## V. EXPERIMENTAL SET-UP

We have implemented our $p$-persistent approach over a slotted operation MAC (the S-MAC protocol) using a common WSN hardware (the MICA2 platform). Our goal was to demonstrate the feasibility of implementing the persistence

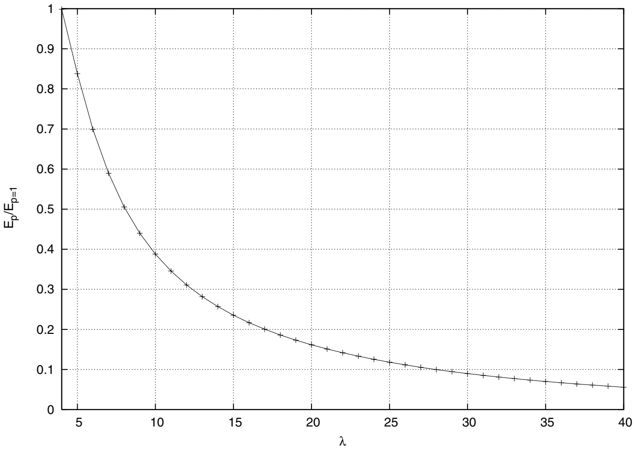

Fig. 5. Ratio of energy consumption by $p$-persistent and no persistent protocols versus $\lambda$ for the optimal $p$

mechanism in actual WSN equipment. Indeed, the network model used is different from the one discussed in the previous section, since it is not possible to reproduce such a big network in a lab environment. On the contrary, we aim at testing the mechanism reliability and its potential as a energy saving procedure.

As stated in II, SMAC [2] is a WSN MAC protocol that coordinates nodes in a time-slotted fashion of active/sleep periods. S-MAC uses a fixed contention window of $K = 32$ micro-slots selected uniformly, which allows seamless implementation of a $p$-persistent modification. MICA2 motes are a widely distributed hardware solution for WSN developed by Crossbow Inc. MICA2 are based on Chipcon CC1000 radio module which operates in the 868/916 MHz band. In our experiments (depicted in figure 6) we have:

- One mote (*coordinator*) which acts as sink and which triggers events in the network. Coordinator incorporates a MTS300 sensing board, which among other capabilities, has a tone buzzer and a tone detector hardware both at 4 KHz.
- Up to 8 sensing nodes, incorporating also MTS300 sensing boards.

The experiments proceed as follow:

1) The coordinator emits a tone at 4 KHz.
2) All sensing nodes detect it with the tone detector.
3) All sensing nodes start contention to notify the sound detection to the coordinator using the $p$-persistent approach.
4) When the first notification correctly reaches the coordinator it set up a flag in the next SYNC period (in our modification of SMAC all nodes keep listening during SYNC periods) to avoid further notifications.

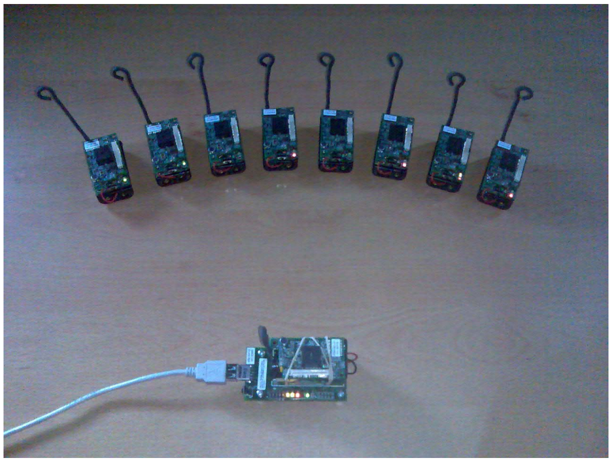

Fig. 6. Experimental set-up contains one sink node (bottom) and up to 8 nodes capturing acoustic events (top)

| | $p$ = 0.2 | | $p$ = 0.5 | | $p$ = 0.8 | |
|---|---|---|---|---|---|---|
| | Delay | Saving | Delay | Saving | Delay | Saving |
| N = 2 | 2.67 | 46.6% | 1.32 | 34% | 1.06 | 15.2% |
| N = 4 | 1.63 | 67.4% | 1.14 | 43% | 1 | 20% |
| N = 8 | 1.63 | 67.4% | 1.05 | 47.5% | 1 | 20% |

TABLE I
EXPERIMENTAL AVERAGE NOTIFICATION TIME (IN TIME-SLOTS) AND ENERGY SAVING

Figure 6 shows our setup. We performed this experiment for different number of nodes ($N = 2, 4, 8$). Let us remark that in this case all the nodes capture each event, and so traffic cannot be shaped as a Poisson pattern, and the formulas derived in the last section can not be directly used. We tested the mechanism performance for different persistence levels ($p = 0.2, 0.5, 0.8$). For each configuration we have gathered 30 samples of the notification delay (measured in time-slots). The average value is shown in table I. Indeed, we also depict the expected energy saving for each configuration, compared to a perfect access mechanism which is collision free. In this case, savings can be computed as $1-pT$, being $T$ the average notification delay (in time-slots) and $p$ the persistence level. As can be seen in table I, considerable saving can be achieved also in this configuration by means of the $p$-persistent mechanism.

## VI. CONCLUSIONS

A feasible modification for WSN MAC protocols that includes a persistence mechanism has been analyzed in this paper as a solution to reduce notification delays and save energy. The $p$-persistent approach notably reduces energy consumption since: (i) the number of collisions is minimized, and (ii) nodes do not wake up in all the activity periods. The optimal persistence ($p$) according to the expected number of nodes sensing events has been computed by means of a numerical algorithm based on the fixed point theorem, for different realistic network configurations. Both analytical and experimental results show a remarkable improvement, in the order of 50%, in terms of energy saving.

As a future work, we intend to extend our analysis to other environmental and operational conditions, for instance, considering non-uniform node distributions.

## VII. ACKNOWLEDGEMENTS

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## REFERENCES

[1] I. F. Akyildiz, I. H. Kasimoglu. Wireless sensor and actor networks: Research challenges, *Ad Hoc Networks*, Elsevier (forthcoming).

[2] W. Ye, J. Heidemann, D. Estrin. Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks, *ACM/IEEE Transactions on Networking*, vol. 12, pp. 493–506, 2004.

[3] T.V. Dam and K. Langendoen An Adaptative Energy-Efficient MAC Protocol for Wireless Sensor Networks *1st ACM Conf. Embedded Networked Sensor Sys.* Los Angeles, CA, Nov. 2003

[4] C.C. Enz et al. WiseNet: An Ultralow-Power Wireless Sensor Network Solution IEEE Comp., vol. 37, n0 8, Aug. 2004

[5] Y.C. Tay, K. Jamieson and H. Balakrishnan, Collision-Minimizing CSMA and Its Applications to Wireless Sensor Networks IEEE Journal on Selected Areas in Communications, Vol. 22, No. 6, August 2004

[6] Debnath, L. and Mikusinski, P. Introduction to Hilbert Spaces with Applications San Diego, CA: Academic Press, 1990.