An Energy-Latency-Efficient MAC Protocol for Wireless Sensor Networks

Tahar Ezzedine, Mohamed Miladi and Ridha Bouallegue

Abstract—Because nodes are usually battery-powered, the energy presents a very scarce resource in wireless sensor networks. For this reason, the design of medium access control had to take energy efficiency as one of its hottest concerns. Accordingly, in order to improve the energy performance of MAC schemes in wireless sensor networks, several ways can be followed. In fact, some researchers try to limit idle listening while others focus on mitigating overhearing (i.e. a node can hear a packet which is destined to another node) or reducing the number of the used control packets. We, in this paper, propose a new hybrid MAC protocol termed ELE-MAC (i.e. Energy Latency Efficient MAC). The ELE-MAC major design goals are energy and latency efficiencies. It adopts less control packets than SMAC in order to preserve energy. We carried out ns-2 simulations to evaluate the performance of the proposed protocol. Thus, our simulation's results prove the ELE-MAC energy efficiency. Additionally, our solution performs statistically the same or better latency characteristic compared to adaptive SMAC.

Keywords—Control packet, energy efficiency, medium access control, wireless sensor networks.

I. INTRODUCTION

WIRELESS sensor networks present ad-hoc networks consisting of a large number of sensor nodes which collaborate to perform a shared mission. There is a wide range of promising applications for these networks, such as, environment monitoring, health-care and battlefield operations. Henceforth, due to the constrained deployment and the difficult environmental conditions of wireless sensor networks, they require to overcome many challenges. Energy efficiency in communication is one of the major challenges for designing the above described networks. For the obvious sake of network connectivity and availability, the sensor network life-time had to be maximized. Due to the fact that sensor nodes are generally battery-powered, the energy presents a very scarce resource. Accordingly, the objective of energy efficiency is addressed at the entire network components. In particular, at the MAC layer as it manages the radios' operating mode bearing in mind that radios systems are the most energy consumer in wireless communications. Recently, there has been substantial research on the design of energy efficient MAC protocols for wireless sensor networks. Thus, several new MAC protocols targeted specifically for wireless sensor networks have been proposed, but each protocol presents some advantages and suffers from some drawbacks. This motivates us to propose a

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new energy efficient MAC protocol which realizes both energy efficiency and improve the channel utilization compared to the already existed techniques. Toward this goal, we develop a hybrid MAC protocol termed ELE-MAC inspired by the adaptive SMAC scheme. In fact, we adopt a new control packet and we design a packet exchange sequence aiming to minimize the energy wasted by control packets and to decrease latency. The rest of the paper is organized as follows: section 2 reviews the related work. Section 3 summarizes the proposed protocol design, the simulation settings and our experimental results. Finally, section 4 collects some conclusions and presents our future work.

II. RELATED WORK

Over the past few years, a wide variety of MAC protocols were postulated to multi-hops wireless sensor networks. They have been proposed from both prototyping and simulation-based studies. MAC protocols targeted at wireless sensor networks provide: contention-based access, time division multiple access or hybrid approaches mixing both concepts of the first and the second schemes. A concise survey of several MAC protocol recently proposed for wireless sensor networks can be found in [1]. In this section, we first brief the basic ideas of the IEEE 802.11, the TDMA and the SMAC techniques as they present building blocs for most of the proposed schemes as well as for our protocol (i.e ELE-MAC). After that, we outline the wireless sensor networks MAC design requirements.

A. IEEE 802.11

IEEE 802.11 [3] is the standard MAC layer which is proposed for wireless local area networks. This scheme is a contention-based protocol which can be operated in ad-hoc mode. It employs RTS/CTS control packets in order to reduce collisions which may occur by hidden terminals. Otherwise, IEEE 802.11 uses both physical carrier sense and virtual carrier sense mechanisms. Also, it is worth to note that IEEE 802.11 includes a power-save mode in which individual nodes periodically listen and sleep. Since the IEEE 802.11 technique is based on the RTS/CTS exchange, it suffers from the energy inefficiency problem. The energy consumed by this protocol is considerable and can be explained by the long periods in which nodes are in the idle listening state. For this reason, several protocols based on this technique were proposed with the goal of mitigating the energy consumed across idle listening. Further, energy efficiency at the MAC layer has became a hottest concern when designing wireless sensor networks.

B. TDMA

The TDMA approach is based on the allocation of specific time slot to each node of the network. This allows nodes to enter inactive states when not scheduled for its own time slot. This mechanism is adopted in order to conserve energy. Thereby, TDMA-based protocols, in contrast to contention-based protocols, are very efficient at avoiding collisions and minimizing the idle listening times. However, using TDMA as it is in wireless sensor networks is not practical because of the following reasons. In TDMA, a cluster-head is required to manage time slot allocation which overcomes the sensor networks resources added to the deployment constraints. Also, TDMA doesn't take advantage that sensor data are directed for a single destination. As a matter of fact, it introduces synchronization overhead [2]. To better address the requirement of wireless sensor networks, with respect to energy efficiency, several MAC protocols combining the contention-based and the time-based concepts were proposed. In the next subsection, we will briefly describe the SMAC protocol as being a hybrid MAC protocol. In fact, it presents the most relevant scheme to our approach.

C. Sensor MAC (SMAC)

One of the famous and the well cited hybrid energy efficient MAC protocol in literature is SMAC [4]. This scheme is mainly based on three mechanisms. First, the reduction of overhearing by means of RTS/CTS packets like in IEEE 802.11. Second, the minimization of idle listening across the scheduling of periodic listen/sleep periods. Third, the adoption of a message passing mechanism with the aim to reduce the contention latency. In fact, the message passing approach allows the RTS packet to reserve the medium for transmitting the entire message instead of reserving it only for the first fragment as for IEEE 802.11. For the obvious sake of synchronization, SMAC uses SYNC packets for maintaining the same listen/sleep schedules among neighboring nodes. A recent SMAC enhancement is given in [5], where the authors proposed a new technique which is called adaptive listening. The main purpose of this technique is to reduce the sleep delay which is introduced by the periodic sleep of each node in case of a multi-hops network. Henceforth, with this technique each node which overhears a neighbor's transmission (i.e. by means of a CTS packet) wakes up for a short period at the end of this data transmission. So, if the node presents the next hop it will pass the data directly instead of waiting the next active period. For the rest of nodes which are woken up adaptively they go back to the sleep state.

D. Designing new MAC approaches

To date, the primary goal for wireless sensor networks in general and MAC in particular has been energy efficiency. The literature shows that these networks still require new MAC techniques since there are no energy efficient standard solutions [10]. Henceforth, the straightforward way to tackle the energy efficiency problem at the MAC layer is to adapt, optimize or merge the existing MAC schemes that present major weaknesses. This allows to design new approaches, able to seriously fulfill the wireless sensor networks' requirements.

III. THE ELE-MAC PROTOCOL

Having studied the ELE-MAC building blocs, we now focus our attention on the ELE-MAC design details as well as its power dissipation and latency characteristics.

A. ELE-MAC design Overview

The control packets effect on the network power consumption is significant [12]. This is can be explained by the control packet size which is comparable to the size of data packets in wireless sensor networks [2]. Therefore, the energy consumption can be greatly reduced by optimizing the exchanged control packets. This observation leads us to
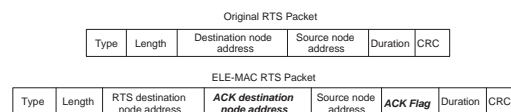

Fig. 1. The RTS control Packets

propose a new energy efficient MAC protocol that minimizes the exchanged control packets. In other words, the basic idea of ELE-MAC is to minimize the control packets exchanged in the adaptive SMAC protocol. At the same time, ELE-MAC should conserve the SMAC's benefits. In what follows, we describe the proposed control packets adopted in our scheme and its operating. The major difference between ELE-MAC and the adaptive SMAC protocol described in [5] is that we adopt a personalized RTS packet. Further, this packet provides two additional fields (i.e. $ACK destination Node Address$ and $ACK flag$) as it is shown in figure 1. The added fields allow the new RTS packet to play the role at the same time of an ACK and a RTS. This new packet will be exchanged only when data are sent adaptively (i.e. not at the scheduled listen time). Thus, no ACK packet will be emitted in that case. Else-where, the transmission is performed normally (i.e. at the scheduled listen time). In other words, each data packet received is followed by an ACK to the sender. Now we use an example to illustrate the ELE-MAC basic mechanisms. Referring to figure 2, node A has data to be transmitted to node B to end in node C which is the sink of the illustrated topology. As it is shown in this plot, our scheme starts the adaptive wake up period immediately after receiving the data packet instead of waiting for the ACK packet like for the SMAC adaptive listening mechanism. This modification is made for allowing a receiver to inform its neighbors about the data reception through the $ACK flag$ field. Also, this packet allows the receiver to mention its need to transmit the received data packet to the next-hop if it exists (i.e. send RTS). As it is stated in [6] and [7], the most common workload in sensor networks consists on small periodic data packets. Thus, ELE-MAC doesn't propose a fragmentation mechanism. Like IEEE 802.11 and SMAC, broadcast packets are sent only when virtual and physical carrier sense indicate that the medium is free. In addition, these packets will not be preceded by RTS/CTS and will not be acknowledged by their recipients.
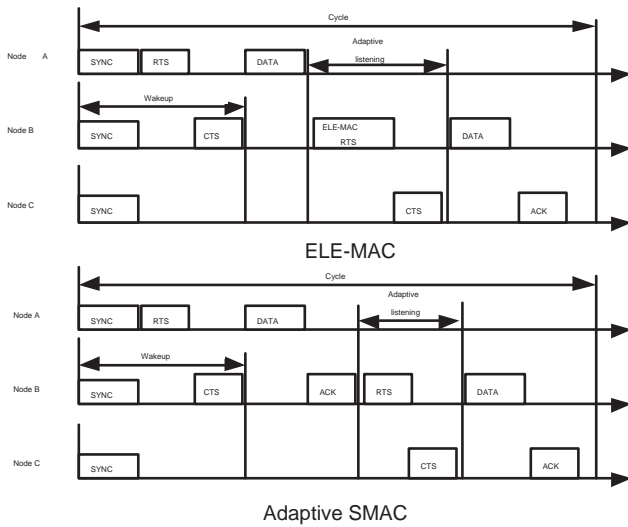
Fig. 2. Adaptive SMAC and ELE-MAC mechanisms

B. ELE-MAC Performance evaluation

In this section, we investigate ELE-MAC performances using simulations. By comparing with SMAC (in its two alternatives), we show the ELE-MAC energy as well as its end-to-end delay efficiency. To do this, we have implemented ELE-MAC in NS-2.28 [9] to perform our simulations. In fact, the adaptive SMAC implementation deployed in this NS's version doesn't provide us with the correctly nodes' energy consumption. Further, the problem resides in the implemented Energy Model. This is because it doesn't take into consideration the energy wasted by idle listening (i.e. doesn't drain energy in the sleep/wakeup methods). Henceforth, to enable the right tracking of the energy consumed by each node at any time, we tune the energy model and the SMAC sources. In what follows, we describe our simulation methodology, then, we present our results and findings.

1) Simulation model: In this sub-section, we describe the simulation settings that we have used for our experiments and we provide details about the specific configuration of the network nodes. In fact, for investigating the behavior of the proposed protocol when varying the traffic load and because of the limited transmission range of wireless network interfaces (i.e. multiple network hops may be required for one node to exchange data) a multi-hops environment is required.

Similar to the test bed realized in [5] for evaluating SMAC on a multi-hop networks, we set a linear topology composed from ten nodes with only one source and a sink which is chosen the later node in the multi-hops chain. This simple topology allows us to concentrate on the inherent properties of ELE-MAC and SMAC.

The routing protocol makes greedy forwarding decisions using information about a router's immediate neighbors in the network topology [13]. In fact, to let each node hear only its next neighbor, we put nodes distant by 200 meters taking into account that the transmission range in NS-2 is set to 250 meters. Also, note that no mobility is assumed

in our simulation scenarios. As the goal of our simulation is to compare the performance of SMAC with ELE-MAC, we choose our traffic source to be constant bit rate (CBR) source. Concerning the hardware settings, the radio system was set as the RFM TR3000 [8]. To make the performance evaluation fairly, we choose the same parameters for SAMC, adaptive SMAC as well as for ELE-MAC. The NS-2 ELE-MAC and SMAC simulation parameters are summarized in table I. With the aim to extract the useful traces and to compute the energy consumption as well as the latency we have used awk and bash scripts. Further, to provide significant statistical results, we run each experiment many times taking different seeds. Hence, we compute the average characteristics with 95% confidence intervals.

TABLE I
ELE-MAC/SMAC SIMULATION PARAMETERS

Simulation parameter	Value
NS version	NS-2.28
Routing protocol	GPSR
Control packet length	10 bytes
Data packet length	50 bytes
Transmission power	36 mW
Receiving power	14.4 mW
Idle power	14.4 mW
MAX NUM NEIGHBORS	20
DUTY CYCLE	10%
SYNC CW	31
DATA CW	63
BANDWIDTH	20 kbps

2) Simulation results: In this sub-section, we discuss our experimental results obtained for SMAC with and without adaptive listening and for ELE-MAC. Furthermore, we provide comparisons in terms of the used control packets, the entire energy consumed by the network, the realized end-to-end latency and finally the occurred collisions.

a) Control packets analysis: To analyze how ELE-MAC achieves energy and latency efficiencies, in the following we measure the average used control packets with different traffic rate sources. The control packets adopted by ELE-MAC and SMAC are illustrated in figure 3. From this plot, it is clear that ELE-MAC exchanges few control packets compared with SMAC.
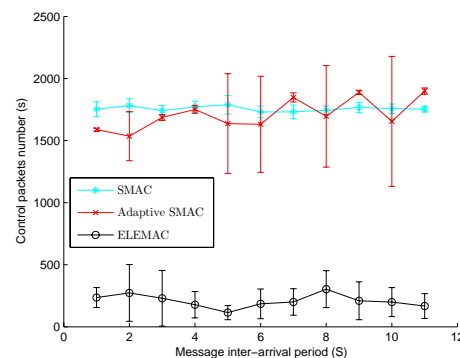

Fig. 3. Control packets number: : 95% confidence intervals are shown.

This allows to conserve the energy amount which would be lost by the control packets overhead. This advantage will be clearly seen in the energy analysis plot.

b) Energy analysis: Tseng et al. in [11] have proposed an analytical energy consumption model for SMAC. It is based on the energy model illustrated in [4]. It is worth to note that this model was validated by comparison with simulation's results. Considering this work, a sensor node energy consumption over a period of time denoted t can be expressed as follows:

$$E(t) = N_T(t)E_T + N_R(t)E_R$$
$$+T_S(t)P_S + T_I(t)P_I \qquad (1)$$

where the denotations are illustrated in table II.

TABLE II
ENERGY MODEL DENOTATIONS

Notation	Parameter
N_T	Number of times that a node transmits
N_R	Number of times that a node receives
E_T	Energy consumption when transmitting
E_R	Energy consumption when receiving
T_S	Times the node spending in sleep
T_I	Times the node spending idle
P_S	Power consumption for sleep mode
P_I	Power consumption for idle mode

Since our analytical approach goal is to provide equations that give insights into the energy efficiency of ELE-MAC, we ignore the energies which are in average similar for ELE-MAC and SMAC (i.e. $T_S(t)P_S$ and $T_I(t)P_I$). As it is refereed in [11], the energy consumption for transmitting a packet under a network running SMAC can be evaluated as:

$$E_T = P_{Tx}(t_{RTS} + t_{data}) + P_{Rx}(t_{CS} + t_{BO} + t_{SL} \qquad (2)$$
$$+t_{CTS} + t_{ACK} + 3t_{SIFS} + t_{DIFS})$$

Similarly, the expected energy for receiving a packet is given by:

$$E_R = P_{Tx}(t_{CTS} + t_{ACK}) + P_{Rx}(t_{RTS} + t_{data} \qquad (3)$$
$$+3t_{SIFS} + t_{DIFS})$$

where the used parameters are summarized in table III.

In the following, we are looking to calculate the required

TABLE III
ENERGY CALCULATION PARAMETERS

Notation	Parameter
P_{Tx}	Power consumption for transmitting
P_{Rx}	Power consumption for receiving
t_{RTS}	Time spent in sending RTS
t_{data}	Time spent in sending $data$
t_{CS}	Time spent in carrier sense
t_{BO}	Backoff delay
t_{SL}	Sleep delay
t_{CTS}	Time spent in sending CTS
t_{ACK}	Time spent in sending ACK
t_{SIFS}	$SIFS$ time
t_{DIFS}	$DIFS$ time

energy to forward only one packet and not the energy spent

during a period of time (i.e. t) like [11]. According to our network setting, the total energy for transmitting a packet from the source to the destination can be calculated for adaptive SMAC and ELE-MAC respectively as follows:

$$E_{SMAC} = 9(E_T + E_R) \qquad (4)$$
$$E_{ELE-MAC} = 5(E_T + E_R) + 4(E_{RA} + E_{TA}) \qquad (5)$$

where E_{RA} and E_{TA} denote respectively the ELE-MAC reception and transmission during adaptive listening periods.

$$E_{TA} = P_{Tx}(t_{ELE-MAC-RTS} + t_{data}) \qquad (6)$$
$$+P_{Rx}(t_{SL} + t_{CTS} + 2t_{SIFS})$$
$$E_{RA} = P_{Tx}(t_{CTS}) + P_{Rx}(t_{ELE-MAC-RTS} \qquad (7)$$
$$+t_{data} + 2t_{SIFS})$$

Using (4),(5),(6) and (7), we evaluate the economized energy when running ELE-MAC as :

$$E_{Economized} = 8P_{Rx}(t_{SIFS} + t_{DIFS}) \qquad (8)$$
$$+4(P_{Tx} + P_{Rx})(t_{ACK} + t_{RTS} - t_{ELE-MAC-RTS})$$

It is worth to note that the size of the ACK and the original RTS packet implementation is 16 bytes while the ELE-MAC-RTS packet size is 20 bytes. So, the value of the term

$$t_{ACK} + t_{RTS} - t_{ELE-MAC-RTS}$$

is the time required for transmitting 12 bytes. Note that the energy amount illustrated in (8) will be economized for each transmitted packet over the ten nodes linear networks.

Now we present simulation comparisons to validate the ELE-MAC energy performance. In figure 4, the total energy consumption of SMAC, adaptive SMAC and ELE-MAC protocols, is plotted by varying the message inter-arrival which impacts the traffic load (i.e. we vary the traffic load by changing the message inter-arrival on the source node). For this experiment, each node was initially given 150 Joules of energy. From the plotted results, we notice that the energy consumption fluctuates and remains on average constant for original SMAC. But it slowly increases, linearly, as the traffic load decreases (i.e. inter-arrival message increases) for adaptive SMAC. Also, it is clear that the lowest energy consumption is obtained when running ELE-MAC. In fact, it outperforms statistically adaptive SMAC with a factor of 1.36. This improvement can be explained by the reduced number of the used ACK to acknowledge the reception of the exchanged data packets. Regarding the ELE-MAC energy behavior with the traffic load variation, it follows the adaptive SMAC as it adopts the same mechanisms.

c) Latency analysis: Now, we tackle the end-to-end delay quantification from the simulation viewpoint. To do this, we illustrate in figure 5 the basic SMAC, the adaptive SMAC and the ELE-MAC realizations in terms of the total time required to transmit the generated data packets. As can be seen in this figure, ELE-MAC achieves statistically the same latency performance as adaptive SMAC or better. As it is mentioned earlier, this is because ELE-MAC uses the same adaptive listening approach proposed for SMAC. Now, comparing SMAC and its adaptive version, it is clear that the
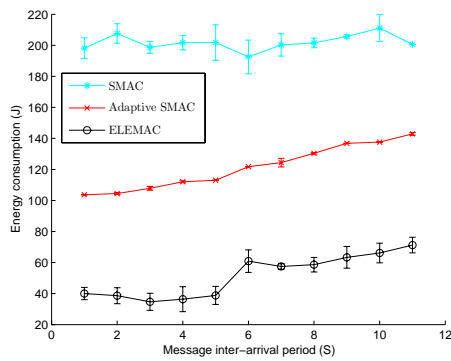
Fig. 4.   Total energy consumed on all nodes: 95% confidence intervals are shown.

latter performs better latency property than the original version under all traffic conditions. This improvement is introduced by the adaptive listening technique. To go further, since we set a multi-hops linear topology, in each hop, the receiver's next hop will adaptively wake up to pass data packet for the next hop directly instead of waiting its listen schedule. As a result, latency is significantly reduced.

In order to investigate the network hop's number effect on
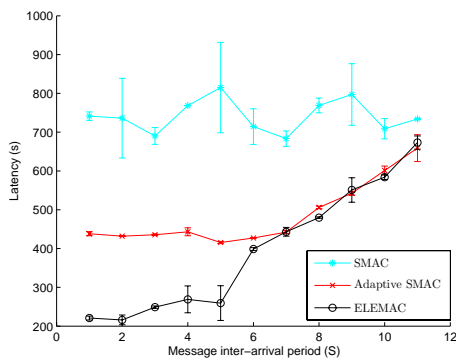

Fig. 5.   End-to-end latency as a function of the inter-arrival message: 95% confidence intervals are shown.

the ELE-MAC performance, we realized simulations of linear networks composed from a number of node varying between one and nine. In these experiments, the source traffic rate was constant bit rate with $1s$ inter-arrival message. The obtained results are presented in figure 6. The first thing to notice, is that ELE-MAC realizes the better end-to-end latency compared to SMAC and this for all the traffic rates greater than $3s$. For near $one-hop$ topologies, the adaptive SMAC approach slightly outperforms ELE-MAC. This is can be explained by the number of adaptive listening times which increases when the hop's number increase. In fact, as it is already stated in the ELE-MAC design section, our control packets will be used only in case of an adaptive listening transmission. Thus, ELE-MAC will be quite beneficial for the networks with a large hop's number.

The second observation is that the ELE-MAC end-to-end

characteristic is statistically constant and do not vary like the SMAC curves which increases exponentially with the hop's number. From this observation, we conclude that ELE-MAC is suitable for the applications where an independent delay is required under varying hop's number.
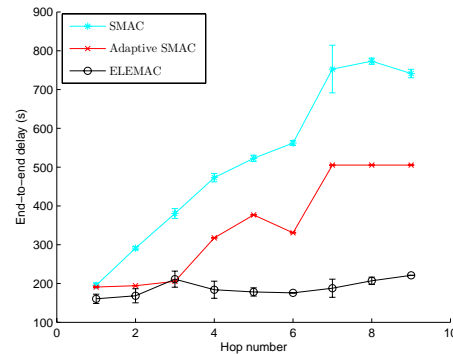

Fig. 6.   End-to-end latency as a function of the hop's number: 95% confidence intervals are shown.

d) Collision analysis: The data reception interference is known as collision. This phenomenon occurs when two nodes send a data packet at the same time which leads to the packets corruption. To resolve the manifested problem, a retransmission should be envisaged. As a matter of fact, the latency as well as the energy consumption will be increased. In this section, we quantify the collisions occurred when using ELE-MAC and SMAC in its two versions. In fact, the study of collision will allow us to argue the end-to-end delay and the energy collapse when the traffic load decreases. Figure 7 plots the amount of packet collisions over the simulation time according to various traffic loads.
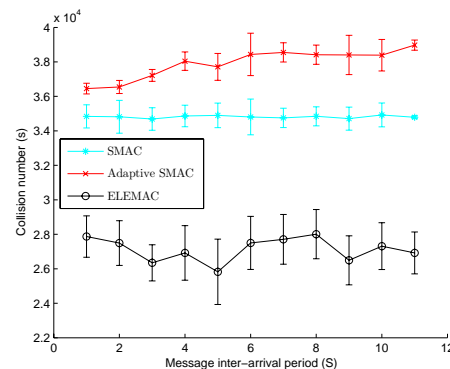

Fig. 7.   Collision's number: 95% confidence intervals are shown.

For ELE-MAC, the average gain in collision over the adaptive SMAC is 28.4%. In other words, for all source traffic rates, the ELE-MAC protocol performs better than the SMAC approaches.

IV. CONCLUSION AND FUTURE WORK

Wireless sensor networks have recently emerged as a major research topic. A key issue that needs to be addressed in

those networks is to minimize the energy consumption for extending the network lifetime and conserving a good latency performance. Henceforth, the focus on energy consumption requires special solutions since typical communication protocols for wireless networks are designed mainly to achieve high throughput, low latency and fairness. This has led the MAC layer energy property to become one of the highest topics for wireless sensor networks. There are multiple ways for a MAC protocol to achieve its energy efficiency and delay requirements. To conclude, this paper has presented a new energy efficient MAC layer inspired by the adaptive SMAC protocol and based on reducing the misused control packets. Through a set of simulations, we demonstrate that the proposed scheme (i.e. ELE-MAC) is better than the adaptive SMAC in terms of energy efficiency. It is worth to note, that ELE-MAC conserves an appropriate latency property which can be explained by the use of the SMAC adaptive listening technique. Collision and control packets results were provided to argue the ELE-MAC performances. Our MAC evaluation points to a number of critical areas for future work. The most serious is to tackle a network with high density of nodes to investigate the ELE-MAC behavior under realistic sensor network environments. Our future plan includes also, extending ELE-MAC by combining other control packets such as RTS and SYNC in order to provide a better solution.

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