Noname manuscript No.
(will be inserted by the editor)

An optimized and Power Savings protocol for Mobility Energy-Aware in Wireless Sensor Networks

Papa Dame BA · Ibrahima NIANG · Bamba GUEYE

Received: date / Accepted: date

Abstract Mobility management in Wireless Sensor Networks (WSNs) is a complex problem that must be taken into account in all layers of the protocol stack. But this mobility becomes very challenging at the MAC level in order to do not degrade the energy efficiency between sensor nodes that are in communication. However, among medium access protocols, sampling protocols reflect better the dynamics of such scenarios. Nevertheless, the main problem, of such protocols, remains the management of collisions and idle listening between nodes. Previous approaches like B-MAC and X-MAC, based on sampling protocols present some shortcomings. Therefore, we address the mobility issue of WSNs that use as medium access sampling protocols.

Firstly, we propose a mobile access solution based on the X-MAC protocol which remains a reference protocol. This protocol, called MoX-MAC, incorporates different mechanisms that enables to mitigate the energy consumption of mobile sensor nodes. Furthermore, we extend our former work [3] by evaluating the lifetime of static nodes with respect to MoX-MAC protocol, as well determine the degree of depletion of static nodes due to the presence of mobile nodes.

Keywords Wireless Sensor Networks · Mobility · MAC layer · Performance

Papa D. BA · I. NIANG · B. GUEYE
University Cheikh Anta Diop, Faculty of Science and Technology, Department of Mathematics and Computer Science, Dakar, SENEGAL
E-mail: papadam83.ba@ucad.edu.sn

I. NIANG
E-mail: iniang@ucad.sn

B. GUEYE
E-mail: bamba.gueye@ucad.edu.sn

1 Introduction

Recent advances in miniaturization of electronic systems have given rise to low power, low cost and multi-functional devices: wireless sensors. The organization of such sensors, in a network in order to cooperatively accomplish a task, takes the name of Wireless Sensor Network (WSN) [19,12]. In fact, Sthapit et al., in [16] define a WSN as a network of self-organizing low-powered devices having sensing and communication capabilities. However, WSNs are often deployed in hostile environments where optimization of the energy consumption of sensor nodes becomes crucial for the network lifetime [2]. In fact, to cover large extensions and areas with difficult access, there are certain technical limitations that require an exhaustive network design, and study, to choose the appropriate communication algorithm and a good network topology because one of the main concerns is the whole network power consumption because devices are powered with batteries, and low maintenance is desired [7].

Nowadays, the distributed robotics and low embedded systems have led to a new class of Mobile Sensor Networks (MSNs) that can be used for a wide range of other applications. MSNs have a same architecture with respect to WSN where sensors are fixed.

MSNs consist of a collection of sensor nodes that can move on their own and interact with the physical environment. Mobile nodes have the ability to sense, compute, and communicate like static nodes. A key difference is mobile nodes have the ability to reposition and organize itself in the network. A MSN can start off with some initial deployment and nodes can then spread out to gather information. Information gathered by a mobile node can be communicated to another mobile node when they are within range of each other. Challenges in MSNs include deployment, localization, self-organization, navigation and control, coverage, energy, maintenance, and data process.

MSNs applications include but are not limited to environment monitoring, target tracking, search and rescue, and real-time monitoring of hazardous material. For environmental monitoring in disaster areas, manual deployment might not be possible. With mobile sensor nodes, they can move to areas of events after deployment to provide the required coverage. In military surveillance and tracking, mobile sensor nodes can collaborate and make decisions based on the target. Mobile sensor nodes can achieve a higher degree of coverage and connectivity compared to static sensor nodes. In the presence of obstacles in the field, mobile sensor nodes can plan ahead and move appropriately to obstructed regions to increase target exposure [19].

Therefore, MSNs are constrained by the same energy and processing limitations, but they are supplemented with implicit or explicit mechanisms that enable these devices to move in space (e.g. motor or sea/air current) over time. Among numerous advantages that they have over the static WSNs (sensors are fix), MSNs need an efficient handling of mobility in all layers with respect to the sensor network protocol stack. The requirement to handle mobility adds another dimension to sensor network protocols, in addition to conservation of energy and computation resources [17].

Through a comparative study, we note that the sampling protocols (protocols that send a preamble before sending the data) [4,11,9] remain the most adaptable category for dynamic scenarios. Nevertheless, in this category, the solution proposed in [9], which is based on the *B-MAC* protocol [11], does not provide an effective mechanism against nodes' overhearing [5] caused by the use of a long preamble.

In the literature, *X-MAC* protocol [4] is a reference protocol in terms of energy efficiency according to sampling protocols. In this paper, we highlight the problems that it faces in dense and dynamic networks. To overcome these shortcomings, we propose a new protocol called *MoX-MAC*. Our protocol is based on a well known protocol called X-MAC which is designed for static WSNs.

The MoX-MAC protocol is able to deal with static sensors as well those that are in movement. Therefore, it enables to reduce the collisions during communication between mobile and static nodes while maintaining the performance of X-MAC. In addition, we address the problem of mobility in WSNs, and we focus on the *MAC* (Medium Access Control) layer. We explore in particular the main existing categories of MAC protocols in WSNs, and afterwards we identify the problems caused by mobility, and expose the most significant existing solutions.

Notwithstanding, the main contributions of this paper with respect to [3] are twofold:

- We perform several simulations in order to have different percentile levels of average energy consumption, average energy packet loss, and average medium access delay for a given mobile node.
- By using mathematical analysis, we evaluate the maximum degree of depletion of a given static node when it starts a communication with a given mobile node.

The remaining of this paper is organized as follows. Section 2 presents the background and related work on MAC protocols for WSNs and mobility challenges. In Section 3, we introduce our hybrid medium access protocol and point out the contributions of MoX-MAC in contrast to previous approaches. Following that we present results obtained through extensive simulation. Finally, we conclude and present some research perspectives in Section 4.

2 Background

Medium access control is critical for enabling successful network operation in order to avoid collision meanwhile to fairly and efficiently share the bandwidth resources among multiple nodes. According to the underlying control mechanisms such as collision avoidance, medium access, MAC protocols can be typically classified into three main categories: sampling protocols, slotted protocols and hybrid protocols [19].

In sampling protocols [4,11,9], nodes send a preamble before sending data. Each node in the network periodically switches its radio and listens the medium. If no signal is detected, the node turns off its radio. In contrast, if a preamble is detected, the node stays awake to receive the subsequent data. The preamble thus serves to synchronize a set of nodes to ensure they are ready to receive data sent by the transmitter of the preamble.

B-MAC [11] is the most famous protocol in this category. However, B-MAC suffers from node's "Overhearing" caused by the sending of a long preamble. The phenomena of Overhearing is due to the fact that a node receives packets that are destined to other nodes [5]. In contrast, X-MAC [4], overcomes this problem by splitting the long preamble used in B-MAC into small ones.

In slotted protocols [18,15], nodes are organized around a common timetable. Time is divided into slotted intervals, which are used by nodes to send or receive data, or to turn off their radios [9]. S-MAC [18] is the most famous protocol based on this principle.

Hybrid protocols [14,19] combine the strength of the slotted access (*TDMA*) and random access (*CSMA*) while offsetting the weaknesses of both access methods. For instance, the *Z-MAC* protocol [14] can be characterized as a hybrid protocol.

2.1 Mobility challenges in MAC solutions

In addition to the five main sources of energy consumption that are: overhearing, collisions, over-emitting, idle listening, the control-packet overhead [5], mobility in WSNs brings some new challenges in the design of MAC protocols, including managing the scheduling, transmission and packet resolution. MAC protocols such as sampling, slotted, and hybrid described in Section 2 may present several shortcomings when they are used in dynamic networks.

Slotted protocols can hardly integrate mobile nodes in their communication scheduling algorithms. Sampling protocols may however face synchronization problems between mobile and fixed nodes. In fact, when a node receives a preamble either with B-MAC or X-MAC, and afterwards it becomes mobile, it can happen that when the data arrives the node is far away to signal radio. Therefore, the data will be lost.

Such issue may happen when a mobile node transmits a preamble while moving. Furthermore, sending preambles reduces the channel availability and therefore increases the competition among the nodes. According to the frequency of the data collection in the network, the performance of mobile nodes can rapidly decrease [9].

Hybrid protocols seem to have a good adaptability to traffic conditions, but suffer in contrast to the problem of complexity of the control-packet overhead that leads to a high energy consumption.

Due to different issues illustrated above, our MoX-MAC protocol proposed here is based on a sampling approach.

2.2 Brief overview on sampling protocols

Following B-MAC [11] approach, the sender should send the entire preamble even though the receiver was woken up during the starting of the preamble's transmission. It is worth noticing that the goal of the preamble is to synchronize the sender and the receiver, as well to freeze the transmission of other nodes that hear this preamble. In so doing, the preamble mitigates the risk of collision.

The entire preamble needs to be sent before every data transmission because there is no way for the sender to know that the receiver has woken up. The Figure 1 illustrates a comparison of the use of a preamble with respect to X-MAC [4] and B-MAC [11] protocols.

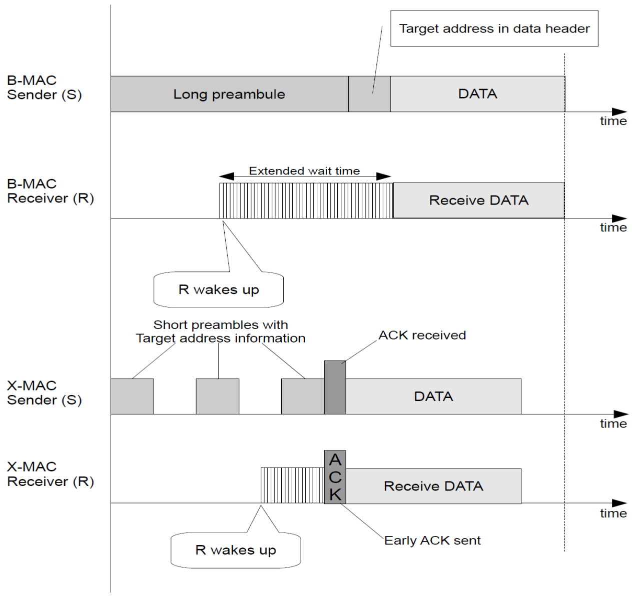

Fig. 1 Comparison of the communication architectures between B-MAC and X-MAC protocols.

According to B-MAC Sender (Figure 1), the data are transmitted after the entire preamble was sent. In contrast, for X-MAC, the preamble is splitted in short preambles with target information [4]. Therefore, as soon as that a short preamble is received by the receiver, it sends an "ACK", and thus, the sender stops the transmission of the remaining short preambles (Figure 1). Afterwards, the transmission of data can start. Put simply, one can have a higher probability to transmit firstly its data according to X-MAC compared to B-MAC (see Figure 1).

We have other shortcomings with respect to the transmission of a long preamble. After the first sender begins its preamble's transmission, subsequent transmitters stay awake and wait until the channel is free. Therefore, a sender can send a preamble in order to wake up a node that is already woken up by preamble sent previously.

In addition to shortening the preamble by the use of acknowledgement (ACK), X-MAC also addresses the problem of multiple transmitters sending the entire preamble even though the receiver is already awake. In X-MAC, when a transmitter is attempting to send, but detects a preamble, it waits until the channel is free. However, if during its listening, the node hears an acknowledgement (frame) that comes from the node that it wishes to communicate later, the transmitter starts a backoff (*ie.*, waits a random amount of time). After its backoff, the transmitter sends its data to this given node without a preamble [4].

2.3 Related work on mobility-based MAC solutions

MS-MAC is a slotted protocol proposed by Huan et *al.* in [10]. It is an improved version of the S-MAC [20] protocol in order to handle mobility. MS-MAC uses a simple mobility estimation algorithm to estimate the mobility in a neighbourhood.

As discussed in [17], one disadvantage of running the synchronization algorithm very often leads to higher energy consumption. Therefore, MS-MAC leads to high energy consumption in order to maintain connections between nodes during their mobility.

MMAC is a slotted protocol proposed by Ali et *al.* in [1]. MMAC is an improvement of the *TRAMA* [13] protocol by adding a mobility adaptive algorithm to overcome the problems encountered by TRAMA under mobile scenarios. TRAMA is a scheduled based protocol, however under mobility, the two-hop topology information becomes inconsistent. Furthermore, TRAMA uses a fixed time frame, which makes the mobile node to wait longer to join the network.

MMAC has an adaptive mobility algorithm which addresses these problems by adjusting the frame size according to the mobility status in the network.In fact, the basic idea is if a large number of nodes are expected to enter or leave the two-hop neighbourhood of a node, the frame time is reduced and vice versa. As discussed in [17], the disadvantages of MMAC are the highly complex scheduling algorithm to calculate the transmitter of each slot in a frame time. Note that the control overhead is high due to the explicit transmission of scheduling packet. MMAC consider also a duty cycle which is also high due to the use of a random access period and huge amount of collisions following the mobility of nodes.

CFMA (Collision Free Mobility Adaptive)is a slotted protocol proposed by Khan et *al.* in [8]. CFMA has a mobility adaptive algorithm that resolves the problem of collision by allocating delay to each node joining the network rather than choosing the delay randomly. This results in a significant improvement in throughput as well as reduction in energy due to the significant reduction in the number of retransmissions. Furthermore CFMA decreases the association time for the nodes which are moving from one cluster to another considerably without incurring energy losses and computational complexities. The protocol can be subdivided into two major phases which are the Initialisation and Running phases respectively.

The initialisation phase is performed by nodes that enter the network for the first time. The new joining nodes send their request to join the network along with their data priorities to the coordinator. If a node is mobile and receive signal from adjacent cluster coordinator it will monitor the signal strength. As the signal strength continues to be strong the node requests the current cluster coordinator to allocate the delay from the adjacent cluster. Upon receiving the request from the node the coordinator selects the appropriate delay values on the basis of the priority information sent by the node to the coordinator and the available delay value from the delay allocation table as well as initiate the request from the adjacent cluster coordinator for the delay to be allocated to a mobile node moving towards that cluster. The nodes after acquiring the respective delay from the coordinator wait for the data packet to be arrived in the buffer.

In the running phase, a node upon receiving the data packet in the buffer undergoes backoff delay which it receives from the coordinator during the initialisation phase. As the node finishes backoff delay, it starts to sense the channel for any ongoing activity, if it finds the channel available it uses the RTS/CTS mechanism to send its data to the coordinator. In this way the nodes can conserve the energy as well as the problem of collision due to hidden node is resolved. Upon completion of the data delivery the coordinator sends the acknowledgement signal to the node along with the new delay value in order to maintain the fairness in the network, so that all the nodes will be able to communicate towards the coordinator.

MACHIAVEL, a sampling protocol proposed by Kuntz et *al.* in [9], reiterates the sampling protocols principles. Therefore, the preamble is followed by a short "SYNC" message, sent by a static node, that enables the neighbourhood to prepare the reception of the trailing data. MACHIAVEL makes the mobile nodes benefit from this synchronization work.

When a mobile node wishes to emit data, it first samples the medium. If it does not detect any signal, it follows the standard procedure: it sends a preamble, a SYNC and then the data. If it detects a preamble, it is allowed to take possession of the medium at the end of the current preamble and SYNC being sent by a static node. For that purpose, MACHIAVEL specifies a delay (MIFS, MACHIAVEL Inter-Frame Space) that static nodes have to observe between the SYNC and their data. The value of the MIFS delay may vary according to the time that a node should take to sample the channel.

MEMAC (Mobility aware and Energy efficient Medium Access Control), proposed by Yahya et *al.* in [17], is a hybrid protocol. MEMAC uses a hybrid approach of both scheduled (TDMA) and contention based (CSMA) medium access schemes. MEMAC differentiates between data and control messages; long data messages are assigned scheduled TDMA slots (only those nodes, which have data to send are assigned slots), while short control messages are assigned random access slots. This technique limits message collisions and reduces the total energy consumed by the radio transceiver. Furthermore, MEMAC uses a dynamic frame size to enable the protocol to effectively adapt itself to changes in mobility conditions. Mobility prediction through the use of the first order auto-aggressive moving average model is used to dynamically adjust the frame size and control the channel access in an efficient way according to the mobility conditions.

3 MoX-MAC: a mobile access scheme for X-MAC

3.1 Architecture and description

As specified in [9], sending a preamble, in sampling protocols, reduces channel availability and thus increases the competition between the nodes. This problem is especially highlighted when a node sends preambles while moving, it might put in overhearing situation all nodes within range of its radio. This is a shortcoming according to X-MAC.

Therefore, we also take as hypothesis that the mobile nodes do not send preamble. Moreover, in MACHIAVEL, a mobile node sends its data to the static receiver node (preamble receiver). Nevertheless, in X-MAC, this receiver has the possibility to communicate with other static nodes after its first communication. In so doing, its lifetime will be reduced if it communicated in addition with mobile nodes.

3.1.1 Communication architecture in presence of mobile node

The main assumption in MoX-MAC is that mobile nodes should send their data to static nodes that should route these data towards the sink. Put simply, any communication initiated by a mobile node should go towards a static one.

As illustrated in Figure 2, we use a scenario similar to X-MAC: a series of short preambles sent by a static node in order to make ready node's neighbourhood to receive data; the node (recipient of data) that receives one of these short preambles, automatically sends an acknowledgement frame (ACK) to the issuer of the preambles to say that it is ready to receive data.

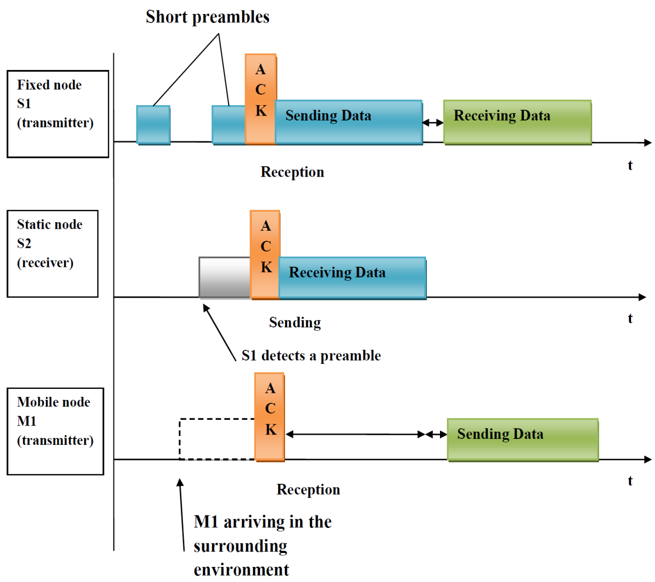

Fig. 2 Communication between mobile and static nodes following MoX-MAC protocol.

MoX-MAC uses this ACK frame for the benefit of mobile nodes.

When a mobile node wants to send data, it samples the medium in the hope of receiving an ACK. If it detects no signal, it follows the standard procedure of X-MAC (sending short preambles and data). If it detects an ACK, it waits until the end of the originally scheduled transmission of this ACK. Afterwards, it can send its data to the static node that has transmitted the preambles previously (receiver of the ACK). Figure 2 depicts this algorithm.

A mobile node waits a random time (backoff) before sending its data toward a static node (see Figure 2). The main reason is due to the fact that more than one mobile node can become potential transmitters. By doing this we mitigate the risk of contention. In other words, this backoff prevents collisions between competitive nodes.

Therefore, the static transmitter node remains awake after any initially scheduled transmission to eventually receive data (this period equals to the maximum of backoff period of the mobile node).

3.1.2 Communication architecture without mobility

In the case where no mobile node occupies the medium, the behavior of static nodes is very similarly to nodes in X-MAC, except the backoff performed by the static node's transmitter before returning to sleep as illustrated by the node $S1$ in Figure 3.

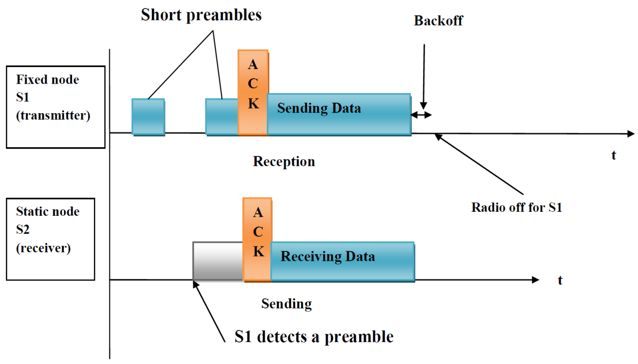

Fig. 3 Communication between static nodes without mobility.

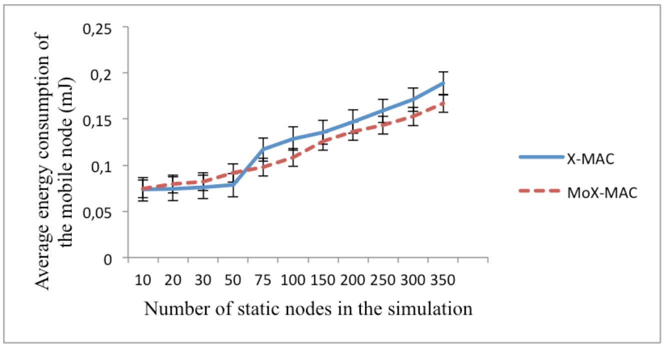

Fig. 4 Average energy consumption of a given mobile node.

Table 1 Simulation parameters

Simulation parameters	Values
Topology	Square (150mx150m), mobile and static nodes are distributed randomly for each simulation
Number of sensors considered during each simulation	10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 350
Mobility model	Random Way Point
Min speed of a mobile node	1.0 m/s
Max speed of a mobile node	4.0 m/s
Radio model	Chipcon CC2420 IEEE 802.15.4
Data size	16 Bytes
Duration	100 seconds

3.2 Performance analysis and validation

Using *COOJA*, a simulator integrated to *Contiki OS* [6] which implements the X-MAC protocol, we performed extensive simulations to check the performance of a given mobile node that uses our protocol. Simulations parameters are presented in Table 1.

To compare the performance between MoX-MAC and X-MAC, it is convenient to measure some metrics for the mobile node: the average energy consumption, the average packet loss, the average medium access delay. To do so, we performed 10 simulations.

3.2.1 Average energy consumption

The Figure 4 depicts the average energy consumption of a given mobile node with respect to other static nodes in the overall network. Note that the number of static nodes varies from 10 to 350. The x-axis show the number of given static nodes during each simulation and the y-axis the average energy consumption, in millijoule, of a given mobile node. It should be noted that during our extensive simulations, one node is mobile with respect to the remaining nodes. Error bars in figures 4, 5, and 6 indicate the minimum and the maximum value obtained for a given mobile node according to our different simulations.

As illustrated in Figure 4, up to 50 static nodes MoX-MAC and X-MAC have the same trend. Nevertheless, X-MAC outperforms a little bit MoX-MAX. The main reason is due that we have a low density nodes. Following MoX-MAC, the mobile node needs to hear ACK messages before transmitting its message. Since there is a limited number of nodes in the network we should wait a long time in order to hear an ACK. In so doing, it consumes its energy.

In contrast, when the mobile node uses X-MAC, since there is few nodes in the network, we have less probability that nodes experience collisions. Hence, the mobile node sends its data rapidly, and thus still awakes during less time.

Afterwards, with a number of static nodes upper than 50 the energy consumption of the mobile node when it uses MoX-MAC decreases compared to X-MAC (Figure 4). With X-MAC protocol, the number of collisions increases when the number of nodes augment. Therefore, nodes use more frequently this battery. Following MoX-MAC, when the number of static nodes increase (high density), the probability that the mobile node hears an ACK message is high. Therefore, it will be not necessary that the mobile node sends a preamble before the transmission of its data (as illustrated in Figure 2). Since collisions and idle listening are the main sources of energy consumption according to sampling protocols, it means that our approach gives better results compared to X-MAC. Indeed, following MoX-MAC, the mobile node hears more frequently ACK messages and sends faster its data.

3.2.2 Average packet loss

The Figure 5 depicts the average packet loss of a given mobile node with respect to other static nodes in the

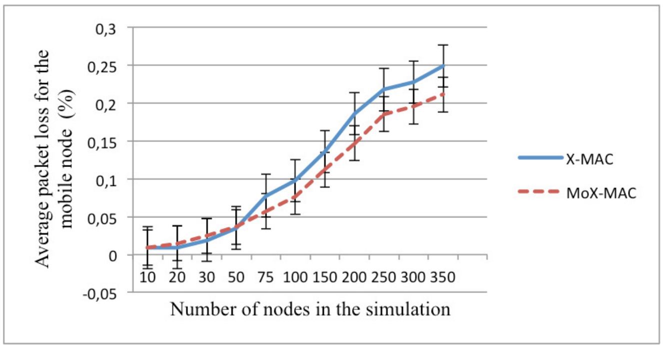

Fig. 5 Average packet loss of a given mobile node.

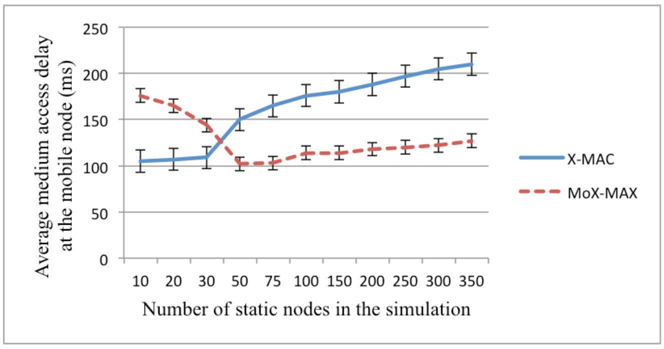

Fig. 6 Average medium access delay for a given mobile node.

overall network. Note that the number of static nodes varies from 10 to 350. The x-axis show the number of given static nodes during each simulation and the y-axis the average packet loss of a given mobile node.

MoX-MAC and X-MAC present the same trend when the number of static nodes is less than 50 nodes. In this case, the mobile node has the same percentage of packet loss. The percentage of packet loss is roughly equals to 0.05. In contrast, when the number of nodes is upper than 50 nodes, the percentage of packet loss for the mobile nodes is less when it uses the MoX-MAC protocol (Figure 5).

Furthermore, we note a gap between MoX-MAC and X-MAC from 50 to 350 nodes. In such interval, MoX-MAC outperforms the X-MAC protocol. For instance, for 350 static nodes the percentage of packet loss experienced by a given mobile node is roughly 0.25 and 0.20 respectively for X-MAC and MoX-MAC. It is worth noticing that when the node is moving the probability to lose data is high. It's the reason why the gap between both curves (Figure 5) is reduced. Nevertheless, in high density, Figure 5 exhibits clearly that MoX-MAC outperforms X-MAC.

3.2.3 Average medium access delay

The Figure 6 illustrates the average medium access delay of a given mobile node with respect to other static nodes in the overall network. It is worth noticing that the number of static nodes varies from 10 to 350. The x-axis show the number of given static nodes during each simulation and the y-axis the average medium access, in millisecond, of a given mobile node.

A high medium access delay can saturate the queue of packets of a mobile node. As illustrated in Figure 6, below 50 nodes, X-MAC protocol has a higher efficiency compared to MoX-MAC but beyond 50 nodes our approach outperforms the X-MAC. The reason why X-MAC outperforms MoX-MAC in low density is due to the fact that a mobile node using X-MAC protocol, has the advantage to automatically send a preamble after a listening of the channel. Indeed, in low-density there is less communication in the network and thus the channel is less busy.

In contrast to MoX-MAC, before sending its data the mobile node should hear an ACK. Therefore, since the number of nodes is reduced, the probability to hear an ACK is reduced, and thus, the node should listen the channel more time. Nevertheless, when the number of nodes is upper than 50 nodes, *ie.* high density, the time that the mobile node should wait according to X-MAC is very important. Indeed, we have more competitive transmissions.

Following MoX-MAC, the mobile node has a high probability to hear an ACK, and thus send its transmission to the potential receiver when it finishes its early transmission. The gap noticed in Figure 6 is more important compared to gap that Figures 4 and 5 illustrated. It should be noted that when the access delay is low it means that when a given wants to send its data it spends less time in the network, and thus consumes less power.

In summary, according to Figures 4, 5, and 6 we argue that MoX-MAC is able to reduce considerably the energy consumption of a given mobile node as well the average packet loss and the average medium access.

3.2.4 Supplementary cost of mobile nodes over static nodes

MoX-MAC has a supplementary cost over static nodes in the network since it increases their duty cycle. Since multiple mobile nodes can send their data to only one given static node, it is necessary to know how long a given static node can stay succinctly in communication with mobile nodes without ending its energy.Thus, when the medium of a given static node is accessed by N mobile nodes, we calculate the time T_m needed for this static node to stay awake in order to receive data from all mobile nodes susceptible to enter in communication with him. T_m is estimated according to:

- T_e: necessary time for the given static node to sample the channel when it wakes up;
- T_p: necessary time to send all preambles after the sampling period (we consider that the node sends all its preambles before receiving an ACK in order to maximize our results);
- T_a: necessary time for the node to receive the ACK;
- T_0: backoff time;
- $Data$: necessary time to send or receive data.

Thus, the necessary time T_m is given by the following expression:

$T_m = T_e + T_p + T_a + Data + N * T_0 + N * Data$

Therefore, we have:

$$T_m = T_e + T_p + T_a + N * (T_0 + Data) \quad (1)$$

Thus, the equivalent time in X-MAC is T_x such that:

$$T_x = T_e + T_p + T_a + Data \quad (2)$$

Thus, the supplementary cost C_s generated by mobile nodes over any static node with whom they enter in communication is given by the following formula [9]:

$$C_s = \frac{T_m - T_x}{T_x} \quad (3)$$

Hence:

$$C_s = \frac{N * (T_0 + Data)}{T_e + T_p + T_a + Data} \quad (4)$$

In case the medium of a static node is accessed by any mobile node, we have the following expressions :

$$T_m = T_e + T_p + T_a + Data + T_0$$

$$T_x = T_e + T_p + T_a + Data$$

$$C_s = \frac{T_m - T_x}{T_x} = \frac{T_0}{T_e + T_p + T_a + Data} \quad (5)$$

Using the simulation parameters, we can perform the calculation of the supplementary in order to determine the degree of depletion of static nodes by mobile nodes when they are in communication, in other words the necessary degree to limit the number of mobile nodes that can access the channel of a static node.

The parameters used in our extensive simulations are as follow:

- $T_e = 1ms$: necessary time to sample the channel;
- $T_p = 13ms$: necessary time to send all preambles;
- $T_a = 0.26ms$: necessary time to receive the ACK;
- $T_0 = 0.52ms$: backoff time;
- $Data = 1ms$: necessary time to send data.

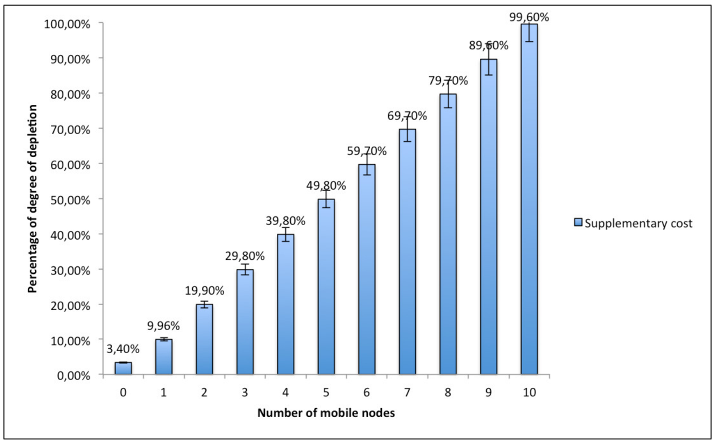

Fig. 7 Supplementary cost of mobile nodes' data transmission over a given static node.

Figure 7 depicts the maximum degree of depletion of a given static node when it enters in communication with mobile nodes in the overall network. Note that the number of mobile nodes varies from 0 to 10 because when 10 mobile nodes send their data to only one static node, the percentage of degree of depletion of this last one is close to 100%. The x-axis shows the number of given mobiles nodes during each estimation for the supplementary cost and the y-axis the percentage of degree of depletion of a given static node.

In summary, we can say that any static node, when it wakes up, should communicate with a limited number mobile nodes in order to maintain its lifetime in the network. As shown in figure 7, if 5 nodes communicate succinctly with one static node, their supplementary cost over this one is around 50%, what is enough for such static node in order to not decrease its energy for its future communications. In fact, since data are routed towards the sink in a WSN, when a static node is in communication with a mobile node, it should transmit data collected from this mobile node to other static nodes; thus, it should have a certain amount of energy in order to perform this data transmission with other static nodes.

4 CONCLUSION

Wireless Sensor Networks exhibit undoubtedly a major breakthrough for the future of human being in several application areas: medical, military, agricultural, domestic, etc. In this paper we were interested in handling mobility at the MAC layer of WSNs.

We proposed a mobile access scheme to overcome the limitations of X-MAC protocol. Our proposed solution, called MoX-MAC, allows specific channel access to mobile nodes while maximizing energy efficiency. The simulation results were satisfying with respect to the mobility of nodes. According to our MoX-MAC protocol, we are able to improve the energy consumption, to reduce the average packet loss and to mitigate the medium access delay of a given mobile node. The evaluation of MoX-MAC has shown its benefits, especially in dense networks where packet loss rate is significantly reduced for the mobile node.

As perspectives, we investigate to evaluate MoX-MAC on other aspects. Firstly, we plan to study the protocol behavior when the ratio of mobile nodes increases in the network. Moreover, the impact of mobile node's speed also seems to be an important consideration. Secondly, we plan to compare MoX-MAC with other mobility aware MAC protocols.

References

1. Ali, M., Suleman, T., Uzmi, Z.: Mmac: a mobility-adaptive, collision-free mac protocol for wireless sensor networks. In: Performance, Computing, and Communications Conference, 2005. IPCCC 2005. 24th IEEE International, pp. 401 – 407 (2005). DOI 10.1109/PCCC.2005.1460597
2. Ba, M., Niang, I., Gueye, B., Noel, T.: Deterministic key management scheme for securing cluster-based sensors networks. In: IEEE International Workshop on Wireless Network Algorithm and Theory. Hong Kong SAR (2010)
3. Ba, P.D., Niang, I., Gueye, B., Noel, T.: Mox-mac: A low power and efficient access delay for mobile wireless sensor networks. In: Proc of IEEE WMNC. Toulouse, France (2011)
4. Buettner, M., Yee, G.V., Anderson, E., Han, R.: X-mac: A short preamble mac protocol for duty-cycled wireless sensor networks. In: in SenSys, pp. 307–320 (2006)
5. Demirkol, I., Ersoy, C., Alagöz, F.: MAC Protocols for Wireless Sensor Networks: a Survey. IEEE Communications Magazine **44**(4), 115–121 (2006)
6. Dunkels, A., Gronvall, B., Voigt, T.: Contiki - a lightweight and flexible operating system for tiny networked sensors. In: LCN '04: Proceedings of the 29th Annual IEEE International Conference on Local Computer Networks, pp. 455–462. IEEE Computer Society, Washington, DC, USA (2004). DOI http://dx.doi.org/10.1109/LCN.2004.38
7. Garcia, M., Sendra, S., Lloret, J., Canovas, A.: Saving energy and improving communications using cooperative group-based wireless sensor networks. Telecommunication Systems pp. 1–14 (2011)
8. Khan, B., Ali, F.: Collision free mobility adaptive (CFMA) mac for wireless sensor networks. Telecommunication Systems pp. 1–16 (2011)
9. Kuntz, R., Noel, T.: Machiavel: Accessing the medium in mobile and dense wsn. In: Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on, pp. 1088 –1092 (2009). DOI 10.1109/PIMRC.2009.5449815
10. Pham, H., Jha, S.: Addressing mobility in wireless sensor media access protocol. In: Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004. Proceedings of the 2004, pp. 113 – 118 (2004). DOI 10.1109/ISSNIP.2004.1417447
11. Polastre, J., Hill, J., Culler, D.: Versatile low power media access for wireless sensor networks. In: SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems, pp. 95–107. ACM, Baltimore, MD, USA (2004)
12. Pottie, G.: Wireless sensor networks. In: Information Theory Workshop (1998)
13. Rajendran, V., Obraczka, K., Garcia-Luna-Aceves, J.J.: Energy-efficient collision-free medium access control for wireless sensor networks. In: Proceedings of the 1st international conference on Embedded networked sensor systems, SenSys '03, pp. 181–192 (2003)
14. Rhee, I., Warrier, A., Aia, M., Min, J., Sichitiu, M.L.: Z-mac: a hybrid mac for wireless sensor networks. IEEE/ACM Transaction on Networking **16**(3), 511–524 (2008)
15. Riga, N., Matta, I., Bestavros, A.: A geometric approach to slot alignment in wireless sensor networks. In: GLOBECOM, pp. 817–822 (2007)
16. Sthapit, P., Pyun, J.Y.: Medium reservation based sensor mac protocol for low latency and high energy efficiency. Telecommunication Systems pp. 1–9 (2011)
17. Yahya, B., Ben-Othman, J.: An adaptive mobility aware and energy efficient mac protocol for wireless sensor networks. In: Computers and Communications, 2009. ISCC 2009. IEEE Symposium on, pp. 15 –21 (2009). DOI 10.1109/ISCC.2009.5202382
18. Ye, W., Heidemann, J., Estrin, D.: Medium access control with coordinated adaptive sleeping for wireless sensor networks. IEEE/ACM Trans. Netw. **12**(3), 493–506 (2004). DOI http://dx.doi.org/10.1109/TNET.2004.828953
19. Yick, J., Mukherjee, B., Ghosal, D.: Wireless sensor network survey. Computer Networks **52**(12), 2292 – 2330 (2008)
20. Zheng, J., Jamalipour, A.: Wireless Sensor Networks: A Networking Perspective. Wiley-IEEE (2009)