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MX-MAC: a mobile access scheme for X-MAC protocol

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RÉSUMÉ. L'évolution continue de l'électronique et des technologies de communication sans fil ont conduit à créer des dispositifs de captage à faible coût, de faible puissance, et multifonctionnels. L'émergence de ces types de capteurs a conduit à la création des réseaux de capteurs sans fil(RCSF), où les nœuds capteurs sont répartis dans l'espace pour réaliser de manière coopérative une tâche. Les RCSF opèrent en environnements contraints. Aux limitations en termes d'énergie, de mémoire et de capacité de calcul des nœuds s'ajoute la récente perspective d'utiliser des capteurs mobiles. Toutefois, parmi les protocoles d'accès au médium, les protocoles par échantillonnage prennent mieux en compte la dynamique de tels scénarios, où la problématique principale demeure la gestion des collisions et de l'écoute oisive entre les nœuds. La seule solution de mobilité proposée dans ce type de protocole se base sur le protocole B-MAC qui, cependant, présente des insuffisances par rapport à son homologue X-MAC. Dans ce mémoire, nous abordons la problématique de la mobilité sur la couche MAC des RCSF basée sur les protocoles par échantillonnage qui restent la catégorie de protocole la plus adaptable aux scénarios dynamiques. Après une étude comparative des protocoles par échantillonnage, nous proposons une solution d'accès mobile pour le protocole X-MAC qui demeure le protocole de référence dans cette catégorie. Cette proposition, appelée MX-MAC, intègre les mécanismes permettant d'atténuer la consommation énergétique des nœuds capteurs mobiles. A travers une validation théorique et expérimentale, nous montrons les gains que peut apporter notre contribution par rapport à X-MAC.

ABSTRACT. Continuous developments in electronics and wireless communications technologies have led to create low cost, low power, and multifunctional sensor devices. The emergence of such sensors has led to the invention of Wireless Sensor Networks (WSNs), where nodes are spatially distributed to cooperatively achieve a task. WSNs operate in constrained environments. In addition to the limitations in terms of energy, memory and computation, the use of mobile sensors has recently been contemplated. However, among medium access protocols, the sampling protocols reflect better the dynamics of such scenarios, where the main problem remains the management of collisions and idle listening between nodes. The only mobility solution proposed in this protocol is based on the B-MAC protocol, however, has shortcomings compared to its counterpart X-MAC. In this paper, we address the mobility issue on the MAC layer of WSNs based on sampling protocols which remain the most adaptive protocols to dynamic scenarios. After a comparative study of sampling protocols, we propose a mobile access solution for the X-MAC protocol that remains the reference protocol used in this category. This proposal, called MX-MAC, incorporates mechanisms to mitigate the energy consumption of mobile sensor nodes. Through a theoretical and experimental validation, we show the gains that can make our contribution with respect to X-MAC.

MOTS-CLÉS : Réseaux de capteurs sans fil, mobilité, couche MAC, X-MAC, performances.

KEYWORDS : Wireless Sensor Networks, mobility, MAC layer, X-MAC, performances

1. Introduction

Continuous developments in micro-electro-mechanical systems, digital electronics, and wireless communications technologies have led to create low cost, low power, and multifunctional sensor devices, which can observe and react to changes in physical phenomena of their surrounding environments. The emergence of such sensors has led to the invention of Wireless Sensor Networks (WSNs). A WSN is an ad hoc network of autonomous low-powered sensors that are spatially distributed and communicate wirelessly to cooperatively achieve a task.

The improvements in stationary WSNs in along with the continues advances in distributed robotics and low power embedded systems have led to a new class of Mobile Wireless Sensor Networks (MSNs) that can be used for air, ocean exploration and monitoring, automobile applications and a wide range of other applications. MSNs have a same architecture to their stationary counterparts, thus 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. Additionally, MSN devices might derive their coordinates through absolute (e.g. dedicated Geographic Positioning System hardware) or relative means (e.g. localization techniques, which enable sensing devices to derive their coordinates using signal strength, time difference of arrival or angle of arrival).

There are numerous advantages of MSNs over the static WSNs. In particular, MSNs offer : i) dynamic network coverage, by reaching areas that have not been adequately sampled ; ii) data routing repair, by replacing failed routing nodes and by calibrating the operation of the network ; iii) data muling, by collecting and disseminating data/reading from stationary nodes out of range ; iv) staged data stream processing, by conducting in-network processing of continuous and ad hoc queries ; and v) user access points, by enabling connection to handheld and other mobile devices that are out of range from the communication infrastructure.

These advantages of MSNs necessitate an efficient handling of mobility in all layers of 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. To be effective in both stationary and mobile scenarios, we need protocols that can work efficiently in terms of saving energy for sensor nodes when they are stationary, and at the same time those protocols need to provide acceptable performance level when sensors are mobile. Such protocols need to be mobility-aware and adaptive to mobile sensors' speeds.

Energy consumption has been considered as the single and important design key in sensor networks, hence, the most recent work on medium access control (MAC) protocol for sensor networks focused on energy efficiency, where MAC protocols play a crucial role in controlling the usage of the radio unit. The radio transceiver unit is the major power consumer unit in the sensor node. For most MAC protocols designed for WSNs, it is assumed that the sensor nodes are stationary, which causes performance degradation when these protocols are applied in mobile environments [1].

In this paper, we address the problem of mobility in WSNs, and more particularly what it means at the MAC layer. We will explore in particular the main existing categories of MAC protocols in WSNs and then we will identify the problems caused by mobility, and expose the most significant existing solutions. Through a comparative study, we note that the sampling protocols remain the most adaptable group to dynamic scenarios. However, in this category, the solution proposed in [2], which is based on the B-MAC protocol [3], does not provide an effective mechanism against nodes' overhearing caused by use of a long preamble. Noticing the X-MAC protocol [4] as a reference protocol in terms of energy efficiency in sampling protocols, we will also highlight the problems faced by the latter in dense networks and dynamic.

In this context, we developed the MX-MAC protocol, a new medium access method for mobile sensors in X-MAC. MX-MAC allows to reduce collisions during communication between mobile and static sensors while maintaining the performance of X-MAC.

The remaining of this paper is organized as follows. Section *2* presents the background and related work on MAC layer design for sensor networks, and mobility handling issues. Section *3* presents at first detailed design of the new MX-MAC and secondly discusses the theoretical and experimental validation. Section *4* concludes the paper with its main contribution and the future work.

2. Related work

2.1. Main existing MAC protocols categories

Among the various functions of a MAC layer, scheduling has been the domain of many improvements. The main idea is to turn off the radio as much as possible while ensuring connectivity between the sensor nodes. To satisfy this, three main categories of protocols have emerged : sampling protocols, slotted protocols and hybrid protocols.

The sampling protocols use sending a preamble before the data. Each node in the network periodically switches its radio and listens to the medium. If no signal is detected, the node turns off his 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 issuer of the preamble. B-MAC and X-MAC protocols are the most popular based on this idea.

The slotted protocols 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. CSMA-based protocols such as S-MAC and IEEE 802.15.4, and the TDMA-based protocols (eg TRAMA) fall into this category.

Hybrid protocols combine the strength of the TDMA and CSMA while offsetting their weaknesses.Z-MAC belongs to this category.

2.2. Mobility-based MAC solutions

MS-MAC, a slotted protocol proposed by Huan et *al.* dans [5], is an improved version of the S-MAC [6] to handle mobility. MS-MAC uses a simple mobility estimation algorithm to estimate the mobility in a neighborhood. In MS-MAC, the mobility of nodes is detected by the change in received signal level of the SYNC message from the neighbor. The nodes store the received signal strength values of the SYNC messages received from each neighbor. If the change in the received signal level exceeds a minimum threshold, the nodes assume that there is a movement in the neighboring node themselves. From the change in the received signal level, a node further detects whether its neighboring is moving and at what relative speed it is moving. The SYNC message is modified to include this mobility information, in addition to transmission schedules. If there are multiple mobile nodes in the neighborhood, the maximum speed is included in the SYNC notification. Nodes that gather this mobility information forms an active area around the mobile node, and run the synchronization algorithm more often than the default value. This lets the mobile node expedite the connection process in a new cluster without losing all the neighbors and thereby the connectivity. One disadvantage of running the synchronization algorithm very often leads to higher energy consumption. Therefore, MS-MAC trades high energy for avoiding broken connections in the event of mobility [1].

MMAC, a slotted protocol proposed by Ali et *al.* in [7], is an improvement of the TRAMA protocol by adding a mobility adaptive algorithm to overcome the problems encountered by TRAMA under mobile scenarios. Because TRAMA is a scheduled based protocol, then under mobility the two-hop topology information becomes inconsistent. As well, TRAMA uses a fixed time frame, which makes the mobile node to wait longer to join the network. MMAC has a mobility adaptive algorithm which addresses these problems by adjusting the frame size according to the mobility status in the network. The disadvantages of MMAC are the highly complex scheduling algorithm to calculate the transmitter of each slot in a frame time. The control overhead is high because of the explicit transmission of scheduling packet. The duty cycle is also high because of the random access period and increased collisions due to mobility [1].

Machiavel, a sampling protocol proposed by Kuntz et *al.* in [2], reiterates the principles of sampling protocols : the preamble followed by a short SYNC message sent by a fixed sensor allows the neighborhood to prepare for the reception of the trailing data. Machiavel makes the mobile sensors 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 (sending of a preamble, 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 fixed node. For that purpose, Machiavel specifies a delay (MIFS, Machiavel Inter-Frame Space) that fixed nodes have to observe between the SYNC and their data. The value of the MIFS delay may vary according to the time a sensor node takes to sample the channel. In order to minimize the risk of collisions with other sensors, the mobile node draws a random time T_0 between 0 and MIFS. Upon the expiration of this delay, it samples the medium again, and sends its data if the channel is still free. The sensor that initially emitted the preamble, as well as all the other sensors located in the shared neighborhood of the mobile node, receive the data. All of the recipients know that more data will follow as long as the source address of the received data does not match the one of the SYNC message. Before being able to switch off their radios, they thus wait a delay at least equal to MIFS. During this period, other mobile nodes may send their own data following the same scheme as previously explained. In order to avoid that too many mobile sensors monopolize the medium, the fixed sensor may restrict how many could consecutively take possession of it. For that purpose, it may not wait for the MIFS delay after receiving data from a mobile sensor. If no other mobile emits data upon expiration of the MIFS delay, the fixed sensor which initially owned the medium can send its data. On reception, all of the recipients can switch off their radio. Fixed nodes behave in a very similar way as a classic sampling protocol, besides the MIFS delay between the SYNC message and their data.

MH-MAC (Mobility Adaptive Hybrid MAC Protocol), proposed by Raja et *al.* in [8], uses a hybrid design motivated by the fact that a mobile network has a mix of static and mobile nodes, and each node requires a channel access method best suited for it. For static nodes, the protocol provides a schedule-based approach ; the rationale being the consistency in two-hop neighborhood that eases the calculation of a schedule. For mobile nodes that are dynamic in nature, the protocol uses a contention-based approach. Thus, on entering a neighborhood, mobile nodes do not have to wait for a long time to get the schedule.

In order for the nodes to determine the type of channel access mechanism that it can use, we use a mobility estimation algorithm to determine the mobility type of a node. Also, a mechanism to disseminate the mobility type of a node to its neighbors is used. To respond to different levels of mobility in the network, MH-MAC dynamically adapts the ratio between static and mobile slots and the frame time accordingly. However, communication between both types of sensors does not seem possible (as each uses a different part of the window), unless a cluster topology is used with one sensor continuously listening to the medium [2].

MEMAC (mobility aware and energy efficient medium access control), proposed by Yahya et *al.* in [1], is a hybrid protocol. MEMAC utilizes 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), whilst 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.

2.3. Mobility and MAC protocols

In addition to the five main sources of energy consumption that are : overhearing, collisions, overemitting, idle listening, the control-packet overhead [9], mobility in WSNs brings some new challenges in the design of MAC protocols, including managing the scheduling, transmission and resolution of packet. Both categories of protocols identified in this paper may face several problems when used in dynamic networks. First, slotted protocols can hardly integrate mobile sensors in their communication scheduling algorithms. Secondly, sampling protocols may however face synchronization problems between mobile and fixed nodes. When a sensor is not continuously in range of the node that emits the preamble, it may not detect any signal when sampling the channel. As a result, its radio may be switched off when the correspondent sends the data. 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 performances of mobile sensors can rapidly decrease [2]. Finally, hybrid protocols seem to have a good adaptability to traffic conditions, but suffer in contrast to the problem of complexity of the header control-packet overhead that leads to a high consumption of energy.

3. MX-MAC : a mobile access scheme for X-MAC

3.1. X-MAC in a nutshell

Using an extended preamble and preamble sampling allows for low power communications, yet even greater energy savings are possible if the total time spent transmitting preambles is reduced. In traditional asynchronous techniques, the sender sends the entire preamble even though, on average, the receiver has woken up half way through the preamble. 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. This is one case where more time is spent sending the preamble than is necessary, as illustrated by the extended wait time in Figure 1. Another case occurs when there are a number of transmitters waiting to send to a particular receiver. After the first sender begins transmitting preamble packets, subsequent transmitters will stay awake and wait until the channel is clear. They will then begin sending their preamble, and this occurs for every subsequent sender. Consequently, each sender transmits the entire preamble when in fact the receiver was woken up by the first transmitter in the series. In the development of X-MAC, we provide solutions for both of these cases. Instead of sending a constant stream of preamble packets, as would most closely approximate traditional LPL, we insert small pauses between each packet in the series of short preamble packets, during which time the transmitting node pauses to listen to the medium. These gaps enable the receiver to send an early acknowledgement packet back to the sender by transmitting the acknowledgement during the short pause between preamble packets. When a sender receives an acknowledgement from the intended receiver, it stops sending preambles and sends the data packet.

This allows the receiver to cut short the excessive preamble, which reduces per-hop latency and energy spent unnecessarily waiting and transmitting, as can be seen in Figure 1. Since the sender quickly alternates between a short preamble packet and a short wait time, we term this approach a strobed preamble.

In addition to shortening the preamble by use of the acknowledgement, 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 and is waiting for a clear channel, the node listens to the channel and if it hears an acknowledgement frame from the node that it wishes to send to, the transmitter will backoff a random amount and then send its data without a preamble. The randomized backoff is necessary because there may be more than one transmitter waiting to send, and the random backoff will mitigate collisions between multiple transmitters. Also, the backoff is long enough to allow the initial transmitter to complete its data transmission. To enable this technique, after the receiver receives a data packet it will remain awake for a short period of time in case there are additional transmitters waiting to send. The period that a receiver remains awake after receiving a data packet is equal to the maximum duration of the senders backoff period, to assure that the receiver remains awake long enough to receive any additional transmitters data packet. Together, these two techniques greatly reduce excessive preambles, result in the reduction of wasted energy, and allow for lower latency and higher throughput. In addition, both of these techniques are broadly applicable across all forms of digital radios, including packetized and bit stream, because the short time gaps, early acknowledgements, and random backoff can all be implemented in software [4].

3.2. Architecture operating of MX-MAC

As specified in Machiavel, 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 his radio. This problem decreases greatly with X-MAC, but remains a problem for him. Therefore, we also take as hypothesis that the mobile nodes do not send preamble. Moreover, in Machiavel, a mobile node sends its data

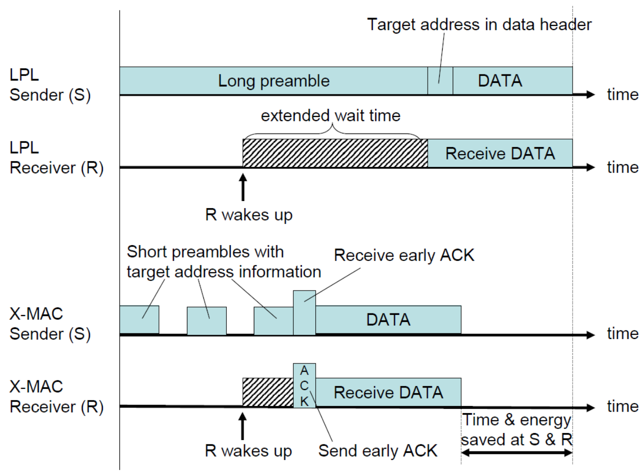

Figure 1. *Comparison of the timelines between LPL's extended preamble and X-MAC's short preamble approach.*

to the static receiver node(preamble receiver), but in X-MAC, this one may possibly be in communication with other static nodes after its first communication, so his life duration would be reduced if it communicated in addition with a mobile node.

3.2.1. Scenario of our protocol in case of mobility

In MX-MAC, we take the principle of the sampling protocol X-MAC : a series of short preambles sent by a static sensor can prepare the neighborhood to receive data ; the node recipient of data that receives one of these short preambles, automatically sends an acknowledgment frame (ACK) to the issuer of the preambles to say that he is ready to receive data. MX-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 will wait until the originally scheduled transmission of this ACK to send its data to the static node that transmitted the preambles(receiver of the ACK).

In Machiavel, data of the mobile node are sent to static node receiving the preamble, but in MX-MAC data are sent to the static node transmitting preambles. Note that a mobile node performs a random time before sending its data to the static node. Indeed, this random time is required because more than one one mobile node may be waiting to transmit and this will prevent collisions between them.

Therefore, the static transmitter node remains awake after any initially scheduled transmission to eventually receive data (period equal to the maximum of backoff period of the mobile node). The operation scheme is summarized in Figure 2.

3.2.2. Scenario of our protocol in no presence of mobile nodes

In the case where no mobile node appropriates the medium, static nodes behave very similarly to the sampling protocol X-MAC, except the backoff performed by the static transmitter node before returning to sleep as shown in Figure 3.

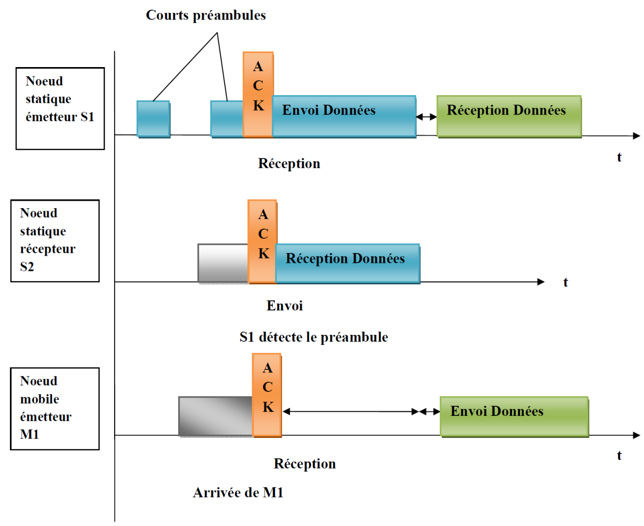

Figure 2. *The MX-MAC protocol*

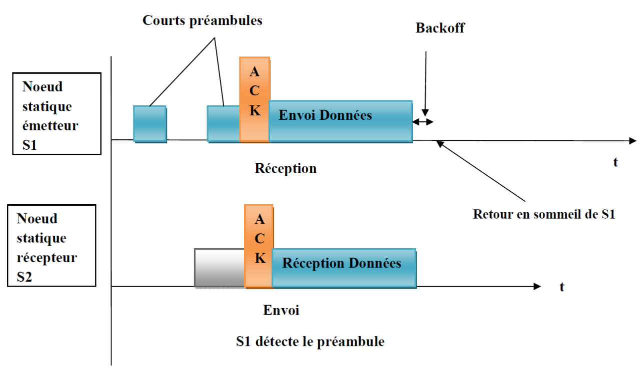

Figure 3. *MX-MAC : operation where no mobile node accessess to the channel*

3.3. Theoretical validation

Machiavel brings mobility to B-MAC protocol. However, B-MAC has a problem of overhearing with the nodes receiving preambles that addresses the X-MAC protocol. Thus, compared to sources of energy consumption(collisions, overhearing, over-emitting, control-packet overhead and idle listening), the MX-MAC protocol, in addition to reduce the overhearing problem, decreases collisions between static and mobile nodes. In fact, our reorganization of the communication between static and mobile nodes highly reduces competition in the channel access. Table 1 shows a comparison between Machiavel and MX-MAC with the sources of energy consumption at the MAC layer.

As MX-MAC is based on X-MAC, or in this latter collisions are reduced compared to B-MAC with the use of the ACK, this parameter is also reduced in MX-MAC for the static

Source of energy consumption	**Machiavel**	**MX-MAC**
Overhearing	Yes	No
Idle listening	Yes	Yes
Collisions	Yes	reduced
Control-packet overhead	No	No
Overemitting	No	No

Tableau 1. *Theoretical comparison between Machiavel and MX-MAC*

nodes. In conclusion, MX-MAC theoretically outperforms Machiavel in terms of energy efficiency.

3.4. Experimental validation

For the experimental validation, we used *COOJA*, a simulator integrated to Contiki OS [10]. Before running the simulations, we have to adjust some parameters which are presented in Table 2.

Simulation parameter	**Values**
Topology	Square (150mx150m), mobile and fixed sensors are distributed randomly for each simulation
Number of sensors	10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 350, 400
Mobility model	Random Way Point
Radio model	Chipcon CC2420
Data seize	16 Bytes
Duration	100 seconds

Tableau 2. *Simulation parameters*

To compare the performances between MX-MAC and X-MAC, it is convenient to measure some metrics for the mobile node are that are : the average energy consumed, the average packet loss, the average medium access delay

3.4.1. Average energy consumed

As illustrated in Figure 4, the energy consumption of the mobile node decreased with MX-MAC compared to X-MAC. This result is logical since our proposal promotes avoidance of packet collisions of the mobile node. Since collisions and idle listening are the main sources of energy with the sampling protocols, it remains that our approach is considerable given that collisions are greatly reduced with X-MAC for the static nodes and MX-MAC follows the same principle as X-MAC for the static static.

3.4.2. Average packet loss

As illustrated in Figure 5, the average packet loss for the mobile node also decreased with MX-MAC. This reflects the fact that our approach reorganizes the communication

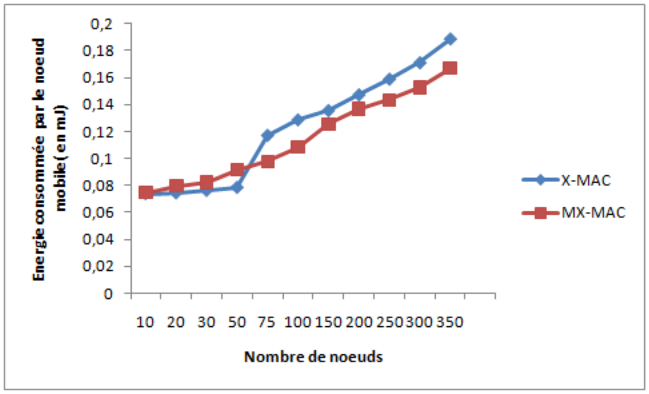

Figure 4. *Average Energy consumed by the mobile node*

period of mobiles nodes relative to the static nodes in contrast with X-MAC protocol where static and mobile nodes are in competition for the channel access. Thus the small decrease in the rate of packet loss for MX-MAC compared to X-MAC is explained by the fact that a moving node has a high probability of data loss during communications due to synchronization errors that result.

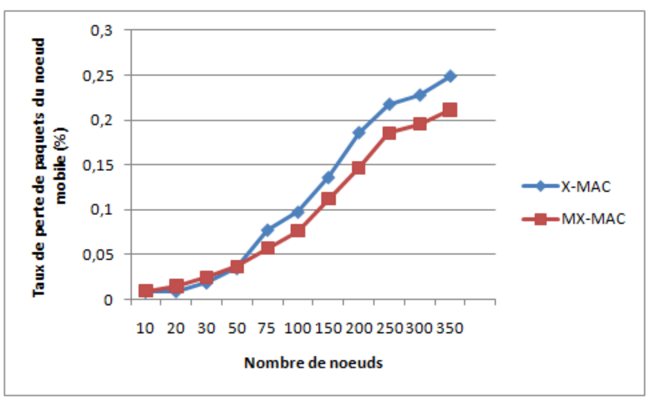

Figure 5. *Average packet loss of the mobile node*

3.4.3. Average medium access delay

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 MX-MAC but beyond 50 nodes our approach is much better than X-MAC. This is explained by the fact that a mobile node using X-MAC in low-density, has the advantage of automatically send a preamble after sampling the channel to detect a possible neighbor while in MX-MAC listenning to any eventual ACK (which would be rare in low-density network) before continuing the classical communication of X-MAC. However, as these ACKs are common in high density, mobile nodes become more efficient in using MX-X-

MAC than X-MAC.

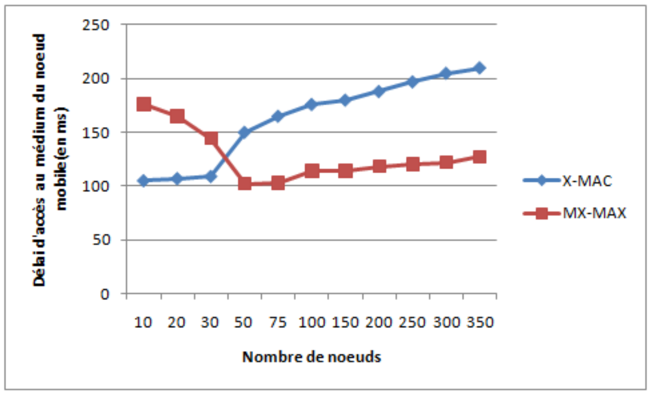

Figure 6. *Average medium access delay of the mobile node*

4. CONCLUSION

WSNs 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 the problem of mobility at the MAC layer of WSNs. Thus, we proposed a mobile access scheme for the X-MAC protocol. The proposed solution, called MX-MAC, allows specific channel access to mobile nodes while maximizing energy efficiency. The simulation results were satisfying for mobile nodes : their performances were improved on energy consumption, average packet loss and the medium access. This evaluation of the protocol allowed us to demonstrate its benefits, especially in dense networks where packet loss rate is significantly reduced for the mobile node. As perspectives, we wish to evaluate MX-MAC on other aspects. First, we wish 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. We have yet evaluated the MX-MAC protocol at one hop, it would be interesting to know its impact in multi-hop. Then, an experimental comparison with other protocols such as Machiavel seems also be necessary.

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