Machiavel: Accessing the Medium in Mobile and Dense WSN

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***Abstract*—Wireless sensor networks 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, only a few medium access control protocols consider the dynamic of such scenarios. In this paper, we present potential problems that could arise with nowadays protocols operating in mobile environments. We particularly focus on the synchronization issues between fixed and mobile sensors, as well as congestion in dense networks. For that purpose, we introduce Machiavel, a new method to access the medium. Machiavel allows mobile sensors to capture the channel even in networks with high contention, while guaranteeing the synchronization with their peers. An evaluation by simulation demonstrates the benefits of our contribution compared to the B-MAC protocol.**

I. Introduction

During the last decade, Wireless Sensor Networks (WSN) have been contemplated as a promising technology for prevention, monitoring or tracking purposes. The constraints induced by such networks in terms of energy, memory or computation have naturally attracted the interest of the research community. A number of improvements at different levels of the communication stack have been proposed [1], and several successful deployments have already been reported. For example, the glacier monitoring detailed in [2] has contributed in the modelling of a micro-climate to monitor and prevent floods.

Recent progresses in embedded systems and communication protocols have stimulated the elaboration of more complex scenarios. They target dense and dynamic networks with the use of mobile sensors or multiple data collection schemes. Especially, mobility in WSN can be employed to extend the network coverage and connectivity, as well as improve the routing performances [3]. The use of body sensors in a medical environment as detailed in [4] also illustrates these possibilities. However, these new scenarios raise novel difficulties when designing protocols, especially at the Medium Access Control (MAC) level.

In this paper, we will further study which issues mobility brings in WSN, specifically at the MAC layer. Therefore, we first remind in Section II the main MAC protocol schemes existing in WSN. We then identify the issues raised by the mobility and expose the most significant contributions in this field. In particular, we discuss how synchronization and congestion issues in dense and dynamic networks can severely impact the performance of a moving node.

The role of a mobile sensor can be crucial in some scenarios, such as intrusion detection or target tracking. It may be necessary to give more importance to the data it emits. For that purpose, we have developed the Machiavel protocol, a new medium access method for mobile sensors. In particular, Machiavel guarantees a better synchronization of the neighborhood while reducing the delay to access the medium. Principles of this protocol are presented in Section III. We will study the advantages of this solution in Section IV and compare its performances to the B-MAC protocol [5]. Perspectives and concluding remarks will follow in Section V.

II. Accessing the Medium in Mobile WSN

A. Background

The constraints induced by the WSN have motivated researchers to propose new schemes to access the medium. Especially, achieving low power communication has been the major challenge in the last decade (in contrast with delay improvements or fairness in traditional wireless networks). Collisions, overhearing, idle listening and control packet overhead have been identified as the main sources of energy wastage [6]. In order to address these problems, MAC scheduling has especially been the field of several enhancements. The main idea is to put the radio in the sleep mode as often as possible while ensuring the link connectivity among the sensor nodes. In order to meet this requirement, two main schemes came up: the sampling protocols and the slotted protocols.

Sensor nodes that employ sampling protocols always send a preamble followed by a synchronization (SYNC) message before the plain data. Every node in the network periodically wakes up its radio and samples the medium. If no traffic is detected, the node switches its radio back to sleep. If a preamble is perceived, the sensor remains awake to receive the trailing data. The preamble thus synchronizes the neighboring nodes and ensures that they will be ready to receive the data. The preamble length must indeed be longer than the medium sampling period on the nodes. B-MAC [5] is one of the most famous protocol based on this idea. Slotted protocols organize the nodes around a common schedule. Time is divided into discrete slots distributed among the sensors, and used to send or receive data, or to power off the radio. Slotted CSMA protocols such as S-MAC [7] or IEEE 802.15.4, as well as TDMA protocols (e.g. TRAMA [8]) belong to this category.

Yet, various issues can emerge when using these protocols in a mobile environment. We will detail them further in the next section, along with the most significant solutions.

B. Mobility issues and existing solutions

Both categories of protocols identified in Section II-A may face several problems when used in dynamic networks. First, slotted protocols can hardly integrate mobile sensors in their communication scheduling algorithms. For example, the periodic synchronization which is essential in S-MAC [7] may prevent a mobile node to send or receive data if it does not know the period used in the virtual cluster where it is located. To solve this, MS-MAC [9] extends S-MAC and suggests to adjust the synchronization period according to the speed of the mobile sensor. In practice, the received signal level used as a mobility indication does not provide a fair accuracy.

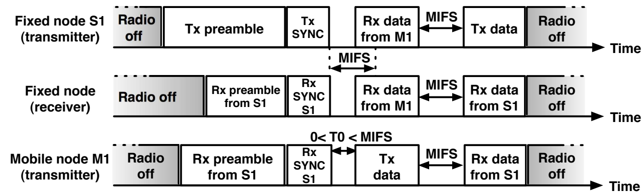
TDMA protocols can barely adapt to the arrival of new sensors in the neighborhood. Indeed, they have to compute and distribute again the timeslots every time a new sensor wishes to participate in the communication. In order to alleviate this problem, EMACs [10] allows sensors to offer momentarily to other nodes the timeslots they own. The number of timeslots in the communication window being bound, such proposal remains hardly scalable to a large number of nodes. Sampling protocols do not suffer from such limitations: in theory, every node may be able to emit at anytime on the medium. They are thus more suitable in scenarios where the topology is subject to change. In the remaining of this paper, we will thus focus on this second category of protocols.

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. Both issues will be further demonstrated in Section IV. The hybrid protocol MH-MAC [11] thus proposes to divide the communication window in two parts: one for the fixed nodes, with a medium access controlled by a TDMA protocol, and one using a CSMA protocol for the mobile sensors. Still, 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.

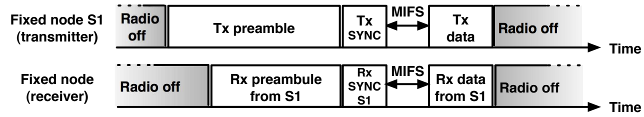
In order to alleviate both the synchronization issues and the difficulties for a mobile node to access the medium in a dense network, we propose the Machiavel protocol.

III. The Machiavel Medium Access Control

We will first describe how Machiavel operates at one hop in Section III-A, followed by the multi-hop operations in Section III-B.



(a) A mobile wants to emit and takes possession of the medium



(b) No mobile node takes possession of the medium

Fig. 1. The Machiavel protocol.

A. First-hop operations

Machiavel is a sampling protocol: 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 (Figure 1(a)). 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 this paper, we use a value of one millisecond for MIFS. In order to minimize the risk of collisions with other sensors, the mobile node draws a random time *T0* 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. We will further evaluate this aspect in Section IV-B2. 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.

Figure 1(b) illustrates the situation when no mobile node takes possession of the medium. Fixed nodes behave in a very similar way as a classic sampling protocol, besides the MIFS delay between the SYNC message and their data.

B. Multi-hop operations

The first-hop operation as described in the previous section would allow to reduce synchronization and congestion issues at the mobile node. However, in a multi-hop topology, the data emitted by a mobile node and forwarded by the fixed nodes towards the sink may still suffer from congestion. According to the number of hops, the gain obtained at the first hop may thus become negligible. Therefore, a bit in the Machiavel MAC header indicates whether the data initially comes from a mobile node. When a fixed node has to forward such data, it stores it in a priority packet queue. A fixed node always checks first in this queue when it is ready to forward data. When trying to access the medium to send such priority packet, the fixed node is allowed to take possession of the channel in the same way as a mobile node. As a result, packets initially emitted by a mobile node can be forwarded faster to the sink.

However, this scheme does not guarantee that the next routing hop will be synchronized and ready to receive data. Indeed, it may not be in range of the node that initially sent the preamble. For that reason, fixed nodes may only take possession of the medium when it is owned by a node located in the shared neighborhood with its next routing hop.

IV. Evaluation of our Proposal

A. Simulation environment

In order to shed some light on the synchronization and congestion issues that we outlined in Section II-B, as well as evaluate our proposal, we have used the WSNet software [12]. WSNet is a wireless sensor network simulator that offers various interference and modulation models, as well as the possibility to configure the radio medium accurately. We have compared our proposal to B-MAC [5]. We made our choice for this protocol because it is certainly the major sampling protocol in WSN: the possibility to configure some parameters (such as the preamble length or the use of acknowledgments) makes it a suitable protocol for a number of scenarios. Furthermore, it has already been used successfully in real deployments, such as detailed in [13]. Also, the mobile-oriented protocols presented in Section II-B are not appropriate for our hypothesis of dense networks. We have thus implemented B-MAC and Machiavel for WSNet.

The simulation scenario consists in a mobile sensor moving in a network whose density and data communication frequency of the fixed nodes are gradually increasing. The details of our simulation environment are exposed in Table I. We have first performed these simulations with all the nodes using B-MAC, then using Machiavel. Every pair in *(number of fixed sensors, data sending period)* has been simulated 20 times. The results outlined in the next sections are an average of the overall data collected on the set of simulations. The 95% confidence interval in Table II denotes the reliability of our measures.

B. Results and analysis

First, we evaluate the benefits of Machiavel from the mobile point of view. We then expose its cost on the fixed sensors. Finally, we analyze its performances in a multi-hop scenario.

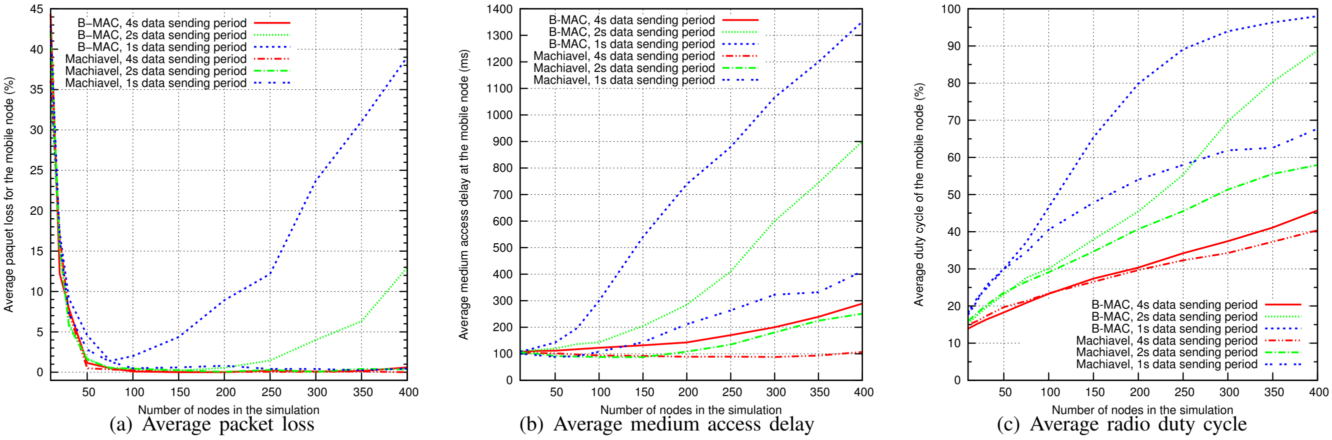
TABLE I
SIMULATION PARAMETERS

Simulation parameter	Value
Topology	Square (20x20m), mobile and fixed sensors distributed randomly for each simulation
Number of fixed sensors	10, 20, 30, 50, 75, 100, 150 200, 250, 300, 350, 400
Data sending period	Mobile sensor: 1s
	Fixed sensors: no data sent, 4s, 2s, 1s
Data size	18 Bytes
Mobility model	Billiard, 1m/s, random initial direction
MAC layer	B-MAC or Machiavel (preamble: 100 ms)
Radio model	Half-duplex, bandwidth: 15 kB/s
Antenna model	Omnidirectional
Radio propagation model	Friis, 868 Mhz, pathloss: 2 (range: 4m)
Modulation model	BPSK
Duration	100s

1) Benefits for the mobile sensors: We have computed the packet loss of a mobile sensor, i.e. the percentage of packets sent by the mobile at the application layer and received by none of its neighbors at the end of the simulation. It is depicted according to the number of sensors in the simulation on Figure 2(a). We notice a packet loss rate above 10% for both B-MAC and Machiavel when the number of nodes is low (10 to 30 nodes). Such loss is also experienced by B-MAC when the density is high (200 to 400 nodes) and communications are frequent in the network. In such case, Machiavel significantly decreases the losses: they are close to zero.

Various reasons can explain why packets from the mobile sensor are not received by peers. The main ones are summarized in Table II. In the first case, it turns out that the network density is not high enough to guarantee that the mobile sensor will be in the surrounding of other sensors when it emits its data: packets are obviously lost. In this paper, we will not focus on the lowly dense networks. The use of a preamble divided in short messages such as suggested by X-MAC [14] could limit these losses by sending the data packet only when one of such messages is acknowledged. In the second case, we notice that most of the packets not received at the end of the simulation with B-MAC are actually still in its packet queue. However, when Machiavel is used, losses are close to zero. It means that a large majority of the packets originated from the mobile sensor have been received by at least one neighbor.

Figure 2(b) illustrates why Machiavel performs better than B-MAC in a dense network. It depicts the average delay per packet to access the medium. As a reference, the case where fixed nodes do not send any data during the experiment gives us the lower bound of this delay. For B-MAC, it is equivalent to 106 ms, that is the sum of the backoff period (5 ms in average), the preamble and SYNC message (100 ms), and the channel sampling period (1 ms in average). When B-MAC is used, we notice that the medium access delay can exceed the data sending period of the mobile node at the application layer (1s in our environment). The high level of competition on the channel is the cause of such delay. As a consequence, data packets at the mobile sensor are pushed in the communication queue faster than they are sent on the medium. According to the size of the queue, packets may be either dropped or greatly



(a) Average packet loss (b) Average medium access delay (c) Average radio duty cycle

Fig. 2. Benefits of Machiavel for the mobile node compared to B-MAC, when the network density increases

TABLE II
MAIN REASONS WHY PACKETS FROM A MOBILE NODE ARE LOST, WHEN THE DATA SENDING PERIOD IS 1S.
THE 95% CONFIDENCE INTERVAL DENOTES THE RELIABILITY OF OUR MEASURES.

Number of sensors	*Percentage of packet loss and 95% confidence interval*		*Main reasons (% of the packet loss)*							
			No neighbors		*In queue*		*Collisions*		*Radio off*	
	B-MAC	*Machiavel*	*B-MAC*	*Machiavel*	*B-MAC*	*Machiavel*	*B-MAC*	*Machiavel*	*B-MAC*	*Machiavel*
10	36.1 (± 6.2)	42.9 (± 5.42)	95.4	95.4	0.0	0.0	0.8	0.2	2.1	2.57
50	4.6 (± 2.1)	2.8 (± 1.54)	31.9	37.5	1.1	0.0	15.2	5.2	24.0	32.29
100	2.0 (± 0.9)	0.5 (± 0.42)	0.0	0.0	15.0	0.0	15.3	19.6	31.7	37.50
300	23.7 (± 5.3)	0.4 (± 0.24)	0.0	0.0	63.2	62.5	6.5	6.4	2.5	1.97
400	39.0 (± 6.4)	0.4 (± 0.32)	0.0	0.0	74.6	100.0	4.8	0.0	0.8	0.0

delayed. As an example, our network with 400 sensors shows a packet loss of 39% at the mobile node, in which nearly 75% correspond to packets that are still in its queue at the end of the simulation. With Machiavel, the medium access delay is greatly reduced. By allowing the mobile sensor to take possession of the medium, Machiavel gives it the opportunity to emit its data even though the level of competition on the channel is high. The mobile may succeed in sending its own data right after the first preamble sampled, which results in delays smaller than the lower bound calculated for B-MAC. However, this is not always the case, as we can also observe that delays may be longer than the preamble length. If the medium is occupied during the MIFS delay (e.g. when a collision between two fixed nodes occurs), the mobile node does not send its data and waits for a later opportunity.

Table II also exposes other causes to the losses observed for B-MAC. Collisions are mainly due to the hidden node problem (we do not use RTS/CTS mechanism in our simulations). Switched off radio illustrates the synchronization issues between the mobile node and its neighborhood, as exposed in Section II-B. With Machiavel, even though a few losses due to congestion or synchronization issues can be noticed, they are negligible if we confront them to the total of packets lost.

Another interesting aspect to measure is the radio duty cycle of the mobile sensor. It is depicted on Figure 2(c). In case the competition on the channel is high, the 30% threshold is exceeded with B-MAC even in lowly dense networks. The main reasons are that the mobile constantly has data packets in its queue, and needs to send a preamble for each of them. With Machiavel, we can observe a reduction of almost 30 points compared to the duty cycle percentage obtained for B-MAC in the most dense networks.

2) Cost for the fixed sensors: Yet, it is obvious that Machiavel has a cost for the fixed nodes and increases their duty cycle. We depict in Figure 3 the delay before a fixed node can emit its own data when Machiavel is used, according to the number of mobile nodes that successively take possession of the medium. This delay is computed from the moment the fixed node starts to send its preamble.

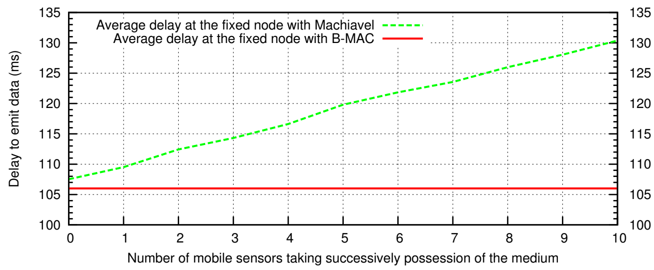


Fig. 3. Average delay to emit data for a fixed node

When no mobile node takes possession of the medium, this delay is around 107 ms for the fixed node. Compared to B-MAC (106 ms), the overhead is equivalent to the MIFS delay (1 ms) which represents an increase of 0.94%. When ten mobile sensors access successively to the medium that was initially owned by the same fixed node, this delay is equal to 130 ms, which represents a 22.6% overhead compared to B-MAC. This highlights the need to limit the number of time the medium can be possessed successively by mobile sensors,

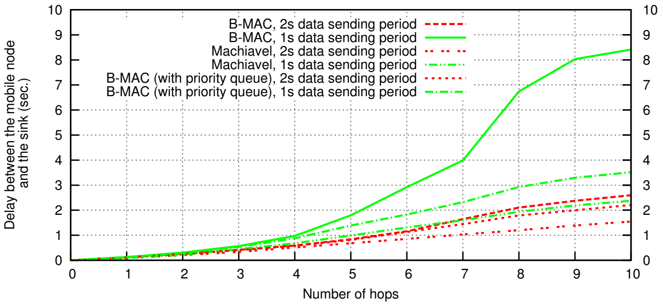


Fig. 4. Delay from the mobile node to the sink in a multi-hop scenario

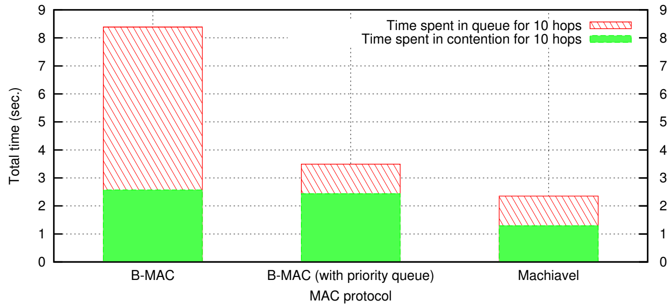


Fig. 5. Time spent in contention and in queue over 10 hops

as we discussed already in Section III-A. For example, such limit could be dynamically adjusted by the node according to its remaining battery. In return, we can raise that mobile nodes do not need to send a preamble anymore. For example, data from all the ten mobiles can be sent within 130 ms. With B-MAC, it would take more than a second (as each would need to capture the medium, send a preamble and its data).

3) Multi-hop operations: In order to evaluate how Machiavel behaves in a multi-hop scenario, we have added static routing towards the sink in our simulation environment. We have evaluated the end-to-end delay between a mobile sensor and a sink according to the number of hops between both, when using B-MAC or Machiavel. Results are depicted in Figure 4. We can observe a sudden increase after the seventh hop for B-MAC with a 1s data sending period. This is due to the funnelling effect which causes the packet queues of the nodes to be filled up along with the number of hops. The use of a priority queue that we raised in Section III-B can alleviate this problem. As this idea is not new, we have also implemented this mechanism in B-MAC. This allows to better compare the gain offered by our contribution. Still, Machiavel performs better than B-MAC by allowing the fixed nodes to take possession of the medium when forwarding data originating from a mobile node.

In order to illustrate how this plays a role in the overall latency, we represent in Figure 5 the average time spent in queue and in contention for a packet travelling through 10 hops. We can notice that Machiavel greatly decreases the time spent in contention. The priority queue in combination with our protocol reduces the overall delay by a factor of 3.6 compared to B-MAC, and 1.5 compared to B-MAC with a priority queue.

V. Conclusion

Mobile sensors have been recently contemplated in a variety of scenarios in WSN, in order to increase the network coverage or for target monitoring purposes. The dynamic aspect of such scenarios raises however multiple issues when trying to access the medium. In this paper, we have particularly focused on the synchronization failures between fixed and mobile nodes, as well as the channel congestion problems in dense networks.

In order to alleviate these issues, we have proposed the Machiavel protocol. Unlike standard sampling protocols, Machiavel guarantees a mobile node that its neighbors are synchronized when emitting data. Machiavel also reduces the delay to access the medium, hence avoids the mobile to saturate its packet queue. When operating over several hops, the combination of the medium borrowing with a priority queue allows to report data faster to the sink. An evaluation of our proposal has demonstrated significant reduction in packet losses and end-to-end delays in dense networks.

As Machiavel relies on a fixed sensor infrastructure, we will investigate further its behaviour when the ratio of mobile nodes increases in the network. Studying the effect of different node speeds and mobility models is also part of our future work. We will also consider a comparison with other protocols than B-MAC. On the protocol side, we would like to extend our contribution to the communications between mobile sensors.

The testbed deployed within the Senslab project [15] (1024 sensors envisioned) will provide us the means to validate our protocol in a real and large-scale environment.

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