A Distributed Scheduling Algorithm to Improve Lifetime in Wireless Sensor Network based on Geometric Placement of Sensors with Coverage and Connectivity Constraints

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***Abstract* – Wireless Sensors Network (WSN) are generally used in hostile environment and have several resource constraints such as limited energy, limited memory, limited communication capacities, etc. These limitations can cause changes in topology, isolation of sensors nodes, network partitioning, and loss of communication links. The results are the reduction of network lifetime and the deterioration of the coverage and network connectivity. Therefore placement strategies of sensors nodes and sleep/wake-up policy should be planed in a way to improve their lifetime while maintaining full coverage of the monitored region and optimal network connectivity. This paper proposes a novel algorithm that reduces the energy consumption under coverage and network connectivity constraints. The obtained results show that sensors nodes can save up to 30% of their energy with respect to previous works.**

***Keywords* – Wireless Sensor Network; network lifetime; coverage; network connectivity.**

I. INTRODUCTION

WSN has inspired tremendous research in the scientific and industrial communities in recent years. Advances in wireless communication and microelectronic mechanical systems have enabled the development of low cost, low power, multi-functional, tiny sensor node which can sense the environment, perform data processing and communicate each other over short distances. A WSN is an ad hoc network composed of many sensors nodes deployed either randomly or deterministically over a geographical region of interest and communicating via wireless links. Theses sensors can also collect data from the environment, do local processing and transmit the data to a sink node or base station via multipath routing. A wide range of potential applications have been envisioned using WSN such as environmental conditions monitoring, wildlife habitat monitoring, security surveillance, industrial diagnostic, agricultural of precision, improve health care, etc. Given their small size, low cost and deployment generally in hostile or difficult access areas, the sensors have severe resource constraints such as a limited energy, so a network lifetime limited, limited memory, limited bandwidth, limited computation and communication capacities, etc. These effects generate changes in topology, isolation of nodes, network partitioning, etc., so that they can reduce the network lifetime and degrade the coverage of the monitored region, and the network connectivity. Many related works are proposed in recent years to address these issues. The most important concern issues for optimizing network lifetime, sensors placement, coverage, and network connectivity. Placement methods, coverage and network connectivity problem are primarily aimed at ensuring full or acceptable coverage and optimal network connectivity. The optimization of the network lifetime methods focalize more on the extension of the lifetime while minimizing the energy consumption in the network; and especially not allow at the same time to ensure a total coverage of the monitoring area and a network connectivity. However, issues for optimizing the network lifetime, guaranteeing full coverage of the monitored region, and maintaining optimal network connectivity are usually conflicting in many applications of WSN such as security surveillance, agricultural of precision, habitat monitoring, etc. These applications require full coverage of the monitored region and optimal network connectivity while maximizing the network lifetime.

We propose in this paper a Distributed Scheduling Medium Access Control (DSMAC) algorithm to optimize the network lifetime while maintaining a full coverage of the monitored region and optimal network connectivity. First, we propose a novel network placement method which minimise the number of require sensors to ensure: the entire coverage of the monitored region and optimal network connectivity. Then, based on the geometric properties of our placement method, we implement a sleep/wake-up policy to improve the network lifetime while saving the full coverage of the monitored region and the optimal network connectivity. Our proposal is based on duty cycle techniques, redundancy of sensing coverage and beacon frames sent by each source node before the transmission of its data packets. Firstly, we present the analytical proof of the full coverage and the network connectivity. Secondly, we validate our proposal by simulations and compare it with the "*TunableMAC*" protocol [12]. The simulation results show that with DSMAC the nodes save about 30% of their energy and the received packets by the Sink node is improved relative to TunableMAC protocol.

The remaining of this paper is organized as follows. Section II surveys the related works. Section III presents our geographic placement method based on grids. Section IV presents the DSMAC algorithm and the analytical evaluation. Section V presents the validation of the DSMAC algorithm by simulations. Finally, Section VI concludes the paper and discusses future works.

II. RELATED WORKS

Network lifetime, placement methods, coverage, and network connectivity problem are critical issues in WSN. A lot of works have been done in recent years by the researchers for addressing these issues.

Akewar et al. [1] discuss the different deployment strategies such as forces, computational geometry and pattern based deployment. However, they don't address the lifetime issues in their study. With the same goal, Ankur et al. [2] present different placement strategies of sensors nodes in WSN taking into account the lifetime issues. They note that the most objective of placement techniques have focused on increasing the area coverage, obtaining strong network connectivity and extending the network lifetime. A more study of coverage and connectivity issues in WSN are presented in a survey by Khou et al. [3]. In this survey, the authors motivate their study by giving different use cases corresponding to different coverage, connectivity, latency and robustness requirements of the applications considered. They present also a general and detailed analysis of deployment problems in WSN. In their analysis, different deployment algorithms for area coverage, barrier coverage, and coverage of points are studied and classified according to their characteristics and properties. Note that, this survey is good references to have an overall view of coverage and connectivity issues in WSN. However, note that in their survey the network lifetime problem are not addressed while this problem is often in conflict with the coverage and connectivity problems. Zhu et al. [4] address the issues of coverage, connectivity, and lifetime in WSN; and they distinguish two coverage problems: static coverage and dynamic coverage. After the study of coverage problem, they propose a scheduling mechanism for sensors activities in order to reduce the energy consumption in the network and they analyze at the same time the relationship between coverage and network connectivity. Nevertheless, note that placement problem is not study and take account in their proposal. With the same goal, another approach which take account the sensors placement method based on territorial predator scent marking behavior is proposed by Abidin et al. [5]. The main goals of their proposal are: to achieve maximum coverage, to reduce the energy consumed and to guaranty network connectivity. However, note that in their approach the full coverage of the monitored region is not guaranteed. Also in this context, Mulligan et al. [6] present different coverage protocols that try to maximise the number of sensor which put into sleep mode while guaranteeing k-coverage and network connectivity. Singaram et al. [7] present also a recent study in which they propose a self-scheduling algorithm that extends the network lifetime while minimizing the number of active sensors. Note that in these two studies, connectivity issues are also not addressed by these authors. A recent survey for sensors lifetime enhancement techniques in WSN is presented by Ambekar et al. [8]. Nevertheless, as some previous authors in the related works, coverage and connectivity issues are not addressed by these authors.

With the same goal for optimizing the network lifetime in WSN by scheduling the sensors activities, more energy efficient MAC protocols based on duty cycle are developed. In fact, the duty cycle approach is the main feature of synchronous and asynchronous MAC protocols where any node can alternate between active and sleep states in order to save its energy. In this approach, nodes can only communicate when they are in active state. Several MAC protocols such as "S-MAC", "T-MAC", "B-MAC", and "X-MAC" based on duty cycle approach were proposed respectively by Kaur et al. [9], Kakria et al. [10], and Ullah et al. [11]. In the S-MAC protocol, nodes alternates between active and sleep periods. During active periods, the node radios are turned ON to communicate and during sleep periods the node radios are turned OFF to save energy. However this protocol has some limitations. Firstly, nodes broadcast their schedule to all neighbor nodes using the synchronization packet; so that this mechanism is not efficient in energy consumption. Another limitation of this protocol is that, all the border nodes incorporate the schedules and keep their radios ON during all their active periods. T-MAC extends S-MAC and provides several improvements. In T-MAC, the S-MAC limitations were overcome by including an adaptive duty cycle where the length of the active period is varied according to traffic. Therefore, this protocol significantly increases the network lifetime by downsizing the length of the active periods. However, such as S-MAC, in this protocol nodes broadcast their schedule to all communication neighbors using the synchronization packet. Thus, this mechanism is not efficient in energy consumption and is not suitable in a network with redundancy coverage. B-MAC is a MAC protocol which adopts the LPL (Low Power Listening) technical. In this technical, the nodes periodically switches between active and sleep periods. The active period is usually very short, just allows the node to sense the channel. B-MAC provides good energy efficiency. Nevertheless, since this protocol uses CSMA/CA (Carrier Sense Multiple Access/with Collision Avoidance) for the medium access, it suffers flow problem at the high load due to the collisions and the random backoff periods. Another problem of B-MAC is the over-listening of the preamble by all neighbor nodes because even if the packet is intended only for a particular node (next hop), all other neighbor nodes must still active to listen the preamble. X-MAC is another MAC protocol based on duty cycle approach. This protocol is an improvement of B-MAC to solve the over-listening problem. Instead of transmitting a long preamble, X-MAC divides it into a series of small packets preamble, each of them containing the receiver's address packet to be transmitted. Compared to B-MAC, X-MAC improves energy efficiency and reduces the time using the shortcut preamble. However, X-MAC may choose only one next hop (router) to move the packet to its destination, even if there are multiple paths in the network whose exploitation could make robustness in the transmission. Another limitation of X-MAC is the low flow problem. Indeed, when the load is high this remains no resolved due to the use of CSMA/CA mechanism for the medium access.

Furthermore, Boulis [12] proposes the TunableMAC protocol based also on the duty cycle approach. As in other MAC protocols note that, in TunableMAC the CSMA/CA mechanism is used for the medium access. It is worth noticing that with his protocol all the nodes are not aligned in their active period, so that each sender transmit an appropriate train of beacon frames to wake up potential receivers before transmitting each data packet. Thus, with respect to this mechanism all neighbour that act as potential receivers of a given sender will be awakened when they received the beacon frame from the sender. Therefore, a lack of efficiency is noted in term of energy consumed. However, TunableMAC is very flexible and can be used to make comparisons with new distributed MAC algorithms developed for WSN.

III. GOEGRAPHIC PLACEMENT OF SENSOR NODES

A. Asymptions and notations

We represent the WSN by a graph $G = (V, E)$ where V represents all vertices (nodes of the network) and $E \subseteq V^2$ represents the set of edges giving all possible communications. There is an ordered pair $(u, v) \in E^2$ if the sensor node u is physically capable to transmit messages to the sensor node v. In this case, sensor node v is located in the communication range of sensor node u. Thus, each node has its key communication range noted R_C that allows it to communicate with others sensor nodes. We assume that all sensor nodes have equal communication ranges. Each sensor node also has a sensing range noted R_S that allows it to sense and capture data from the environment. We also assume that all sensor nodes have the same sensing ranges. All the sensor nodes v located inside the communication range of a given sensor node u are called neighbour nodes of sensor node u and are noted $N(u)$. A bidirectional wireless link exists between a sensor node u and every neighbour $v \in N(u)$ and is represented by the directed edges (u,v) and $(v,u) \in E$. Note that all the neighbour nodes can communicate directly each other. In the following we note $M = \{S_1, S_2, ..., S_M\}$ the set of sensor nodes in the WSN. We note also $\mathrm{N} = |\mathrm{M}|$ the cardinality of the set M that also represents the number of sensor nodes in the WSN. In other hand, we assume in our study that all the sensor nodes transmit their captured data to a Sink node which is the only receiver.

In this part, we will give the modelling of the wireless channel. The performances of a wireless communication system are determined based on the communication channel in which it operates. In a WSN, modelling of communication is very difficult because the sensor nodes communicate in low power, and therefore radio links nodes are very unreliable. The unit disk model is the simplest deterministic model of communication that illustrates a unidirectional link between two sensor nodes. This model assumes that each sensor node is able to transmit its data to any sensor node being in its communication range. The communication range of each sensor node varies depending on the level of its transmission power. Therefore, we can say that two sensor nodes u and v can communicate each other if and only if the Euclidean distance noted $d(u,v)$ between the two sensor nodes is less than the communication range R_C of these two sensor nodes. Thus, two nodes $u, v \in M$ can communicate if:

$$d(u,v) \le R_C$$

Regarding the modelling of coverage, we consider in this paper coverage of point and coverage of area (region). Thus, we say that a sensor node S_i covers a point $q \in A$ if and only if:

$$d(S_i, q) = R_S$$

A coverage of surface (sensing coverage) means the total surface lying below the range of capture of data at least of a given sensor node. Let $S_i \in M$ a sensor node and note $C(S_i)$ the surface cover by the sensor node S_i, then:

$$C(S_i) = \left\{ q \in A \middle| d(S_i, q) \le R_S \right\}$$

The surface covered by a subset of sensor nodes $S_C = \{S_1, S_2, ..., S_C\} \subseteq M$ is then:

$$C(S_C) = \bigcup_{i=1}^{|S_C|} C(S_i)$$

For the coverage of area, we say that a sensor node S_i covers a region A if and only if for each point $q \in A$ then:

$$d(S_i, q) = R_S$$

We finish this part for the modelling of network connectivity. Two sensor nodes are said to be connected if and only if they can communicate directly (one-hop connectivity) or indirectly (multi-hop connectivity) [3]. In WSN, the network is considered to be connected if there is at least one path between the sink and each sensor node in the considered area. Thus, connectivity essentially depends on the existence of routes. It's affected by topology changes due to mobility, the failure of nodes, the attacks, etc. The results are the loss of communication links, the isolation of nodes, the network partitioning, thus the coverage of the monitored area can be degrade and/or the network lifetime can be decrease. Therefore, understanding the network connectivity of a WSN allows adapting the communication mechanisms to ensure the smooth running of applications. To study it, we will use the following notations and definitions. The neighbourhood $N(u)$ of a sensor node u represents the set of neighbour nodes that are within the communication range of node u. It is defined by:

$$N(u) = \left\{ (u,v) \in V^2 \middle| u \ne v \wedge d(u,v) \le R_C \right\}$$

A graph is called k-connected if there are at least k disjoint paths between two nodes of this graph. Coverage is often related to connectivity in WSN. In order to satisfy the conditions of coverage and connectivity, we consider in this paper that the communication range R_C is twice the sensing range R_S .

B. Sensors placement model based on grids

We consider the following placement method.

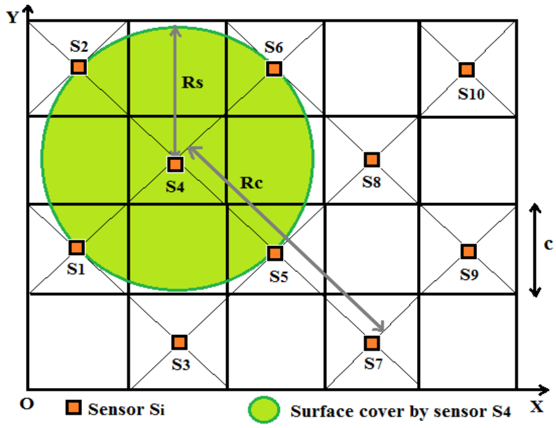

Figure 1. Sensor placement model in the monitoring region

According to the deployment of sensors described in the Figure 1, the geographical area is partitioned into contiguous square grids having the same dimensions that equal to c . The sensor node S_i is placed at a given area of a grid such that the entire area of the monitoring region is covered and the number of necessary sensors is minimized. Our geographic placement of sensors presents the following advantages:

1. The number of sensor nodes required to cover the whole area is minimized;
2. The position and the surface cover by each sensor node are known and can be respectively determined by its coordinates (X, Y) and/or its sensing range R_S .
3. A full coverage and optimal network connectivity are ensured;
4. There are redundancies on the sensing coverage which will be exploited by our proposal for scheduling sensors activities.

Now, the optimal length of c to ensure full coverage and network connectivity of our network placement model can be determined based on the sensing range R_S . This sensing range depends on the communication range R_C based on our assumptions. Furthermore, R_C is determined by the transmission power noted *TX power* and others parameters of the radio communication model. Based on geometric properties of squares and the placement model in Figure 1, the sensing range R_S can be computed using the following equation:

$$R_S^2 = c^2 + c^2 \Rightarrow R_S = c\sqrt{2} \Rightarrow c = \frac{R_S}{\sqrt{2}}$$

Now, let $M = \{S_1, S_2, ..., S_M\}$ the set of sensor nodes in the WSN and note that each sensor node S_i has (X, Y) coordinate in the coordinate system (O, X, Y) as shown in the Figure 1, where O is the originate of this coordinate system and X, Y represent respectively the X axis and the Y axis of the coordinate system. For instance:

$S_1\left(\frac{c}{2}, \frac{3c}{2}\right)$, $S_2\left(\frac{c}{2}, \frac{7c}{2}\right)$, $S_3\left(\frac{3c}{2}, \frac{c}{2}\right)$, and $S_4\left(\frac{3c}{2}, \frac{5c}{2}\right)$.

We show that, according to our placement method an area may be covered by many sensor nodes at the same time; this is due to overlapping coverage areas of neighbour sensor nodes. To optimize the energy consumption in the network, it is necessary to apply sleep/wakeup strategies by scheduling sensor nodes activities while maintaining the full coverage of the monitored region and optimal network connectivity to ensure robustness in the communication.

IV. PRESENTATION OF DSMAC AND ANALYCAL EVALUATION

A. Overview of DSMAC algorithm

DSMAC algorithm (Algorithm 1) includes the placement method described in Figure 1 and a sleep/wakeup policy based on duty cycle approach. It enables to minimize the energy consumed by the overall network while maintaining a full coverage and network connectivity with respect to all sensors. The DSMAC algorithm exploits the redundancy of sensing coverage due to our geographic placement method. Indeed, according to TunableMAC protocol, each sender should transmit a train of beacons frames in order to wake up its entire neighbourhood before sending any data packets. However, according to our DSMAC deployment of sensor nodes, where we have sensing coverage redundancies due to our placement strategy of sensor nodes, we do not need to wake up all a given sensor's neighbourhood. It is worth noticing that in TunableMAC, the set of sensor nodes has equal sleep interval and equal listening interval. Put simply, DSMAC wakes up only few sensor nodes among a well-chosen sensor's neighbourhood in order to reduce the energy consumed during transmission and reception as well as mitigates the number of collisions between sensor nodes.

According to DSMAC, each sensor node uses a neighbourhood's table that contains the ID of neighbour's nodes which is determined by the communication range R_C . Also, the sensor nodes have different sleep and listening intervals. DSMAC addresses the following two issues noted in previous studies:

(i) The set of sender's neighbours that should wake up according to its neighbour's table;

(ii) The scheduling of sleeping and listening intervals according to the parameters of the duty cycle.

In order to choose the best possible neighbours of a sensor node that enable to minimize the energy consumption during transmission while guaranteeing full coverage and network connectivity, to taking into account the two issues raised above, we consider two types of neighbours for each sensor node: "*close neighbours*" located at a maximum distance of $c\sqrt{2}$ from the sender and "*remote neighbours*" located at a distance strictly greater than $c\sqrt{2}$. For a given sender, its neighbour's receivers are only its remote neighbours. Therefore, remote neighbours must be woken up and all the remaining sensor nodes within its close neighbourhood must be set in sleeping mode (line 8 to line 14 of Algorithm 1). If they receive other beacons frame, they can decide whether they should wake up again to relay packets. Thus, our algorithm enables the following benefits:

1. Save the energy consumed in the network, so that the network lifetime will be improved;
2. Ensure full coverage and network connectivity;
3. Balance energy consumption in the network;
4. Reduce collisions that may be due to the CSMA/CA mechanism, so that the rate of received packets will be improved.

The Algorithm 1 above describes the DSMAC algorithm in pseudo code.

```
Inputs:
  "c" represents the length c of a given grid
  "d(X,Y)" represents the Euclidean distance between X and Y
  "Neighbor_Table" represents the node's neighbours table
  "ID" represents the ID of a given sensor node
  " $B_i$ " represents the beacon frame sent by the source $S_i$
Output:
  A set of active sensor to relay packets and a set of sensor in
  Sleep mode to save energy
1: for each sensor node $S_i \in M$ do
2:   for each sensor node $S_j \in M \wedge S_j \neq S_i$ do
3:     if $d(S_i,S_j) \le 2c\sqrt{2}$ then
4:       $Insert(ID\_S_j, Neigbor\_Table[S_i])$
5:     end if
6:   end for
7: end for
8: for each sensor $S_i \in M$ which broadcast a beacon $B_i$ do
9:   if $S_j \in M$ receives $B_i$ and $ID\_S_j \in Neigbor\_Table[S_i]$ then
10:    if $d(S_i,S_j) \le c\sqrt{2}$ then
11:      Make $S_j$ in sleep state until it receive a next beacon $B_k$
12:    end if
13:  end if
14: end for
```

Algorithm 1. DSMAC algorithm

As shown in the Algorithm 1 that describes the DSMAC algorithm, the lines 1 to 7 of this algorithm enable to compute the neighbour table for each sensor node $S_i \in M$ by inserting all the *ID* of its sensors neighbour $S_j \in M \wedge S_j \neq S_i$. After this step, each sensor node $S_j \in M$ neighbour of a given sender $S_i \in M$ will decide if it will be switched in Active or Sleep mode based on the beacon frame received by this sender (which precede the data transmission of the source) and its neighbour table (lines 8 to 14). Therefore, the sensor nodes will alternate in Sleep and Active mode to save their energy; so that the network lifetime will be improved. Note that the full coverage and network connectivity will be preserved during all the network lifetime. We will give in the following part the analytical proof of the full coverage and the network connectivity.

B. *Analysis of the full coverage and network connectivity in DSMAC*

In this part, we will present respectively the mathematical proof of the full coverage and the network connectivity regarding to DSMAC algorithm.

Consider a sender $S_i(x,y) \in M$. As we mentioned in the previous sections, before this source S_i transmits its data packets, then it broadcast a train of beacon frames noted respectively $B_{i1}, B_{i2}, ..., B_{ik}$ to wake up all the nodes S_j belonging to its neighbour table and located at a distance strictly greater than $c\sqrt{2}$. These nodes are all the remote neighbours of the sender $S_i(x,y)$. According to the placement method described in the Figure 1 and the illustration of remote/close neighbour described in the Figure 2, then the coordinate of these remote neighbours of $S_i(x,y)$ are the nodes of the following coordinate:

$$(x,y-2c),(x,y+2c),(x-2c,y-2c),(x-2c,y),$$
$$(x-2c,y+2c),(x+2c,y-2c),(x+2c,y),(x+2c,y+2c)$$

The coordinate of other close neighbour of the sender $S_i(x,y)$ which must be making in sleep mode are the nodes of the following coordinates:

$(x-c,y-c),(x-c,y+c),(x+c,y-c),(x+c,y+c)$.

Let us consider the sensor node $S_7(x,y)$ shown in Figure 2. Its neighbourhood's table contains *ID* of the set of the following sensor nodes:

$\{S_1,S_2,S_3,S_4,S_5,S_6,S_8,S_9,S_{10},S_{11},S_{12},S_{13}\}$.

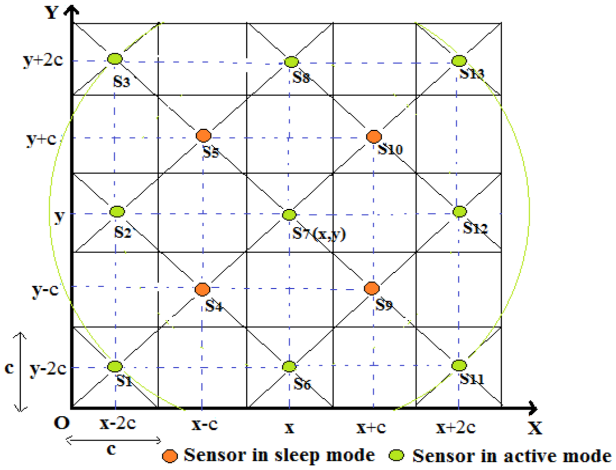

Figure 2. Illustration of close and remote neighbours of $S_7(x,y)$

If the sensor node $S_7(x,y)$ wants to transmit, then the set of sensors located to its neighbourhood table which must wake up after receiving the beacon frames sent by the sensor node S_7 are: $\{S_1, S_2, S_3, S_6, S_8, S_{11}, S_{12}, S_{13}\}$ and the following sensor nodes $\{S_4, S_5, S_9, S_{10}\}$ should be put in sleep mode. According to the Figure 2, the sensor nodes S_4, S_5, S_9 and S_{10} are in sleep modes at the same time whereas other sensor nodes belonging to S_7's neighbour table are in active mode and maintain the full coverage of the network. We show that the areas covered by the following sensor nodes S_4, S_5, S_9, S_{10} which are in sleep mode, and the one covered by the four active sensor nodes located at the vicinity of these sleeping sensors are fully covered by the active sensors. Let us consider the sensor node S_4 which is in sleep mode (Figure 2), then according to the definition of the sensing coverage of this sensor node noted $C(S_4)$, we have:

$$C(S_4) = \left\{ q \in A \middle| d(S_4, q) \le c\sqrt{2} \right\} \qquad (1)$$

According to the active sensor nodes S_1, S_2, S_6 and S_7 which are around the sensor node S_4, the sensing coverage of each of them is:

$$C(S_1) = \left\{ q \in A \middle| d(S_1, q) \le c\sqrt{2} \right\} \qquad (2)$$

$$C(S_2) = \left\{ q \in A \middle| d(S_2, q) \le c\sqrt{2} \right\} \qquad (3)$$

$$C(S_6) = \left\{ q \in A \middle| d(S_6, q) \le c\sqrt{2} \right\} \qquad (4)$$

$$C(S_7) = \left\{ q \in A \middle| d(S_7, q) \le c\sqrt{2} \right\} \qquad (5)$$

Note $S_C = \{S_1, S_2, S_7, S_6\}$. Based on the coverage area described in Section III, we have:

$$C(S_C) = C(S_1) \bigcup C(S_2) \bigcup C(S_7) \bigcup C(S_6) \qquad (6)$$

On the other hand, if we compute the Euclidean distance between the sensor node S_4 and the sensor nodes S_1, S_2, S_6 and S_7, then we have:

$$d(S_4, S_1) = d(S_4, S_2) = d(S_4, S_7) = d(S_4, S_6) = c\sqrt{2} \qquad (7)$$

Based on the sensing coverage of the sensor nodes S_4, S_1, S_2, S_6, S_7 described respectively in (1), (2), (3), (4), (5), and based in (6), (7), we have:

$$C(S_4) \subset C(S_1) \bigcup C(S_2) \bigcup C(S_7) \bigcup C(S_6) \qquad (8)$$

Hence based to (8), then the sensor nodes S_1, S_2, S_6 and S_7 provide a full coverage with respect to the area covered by the sensor node S_4. Similarly, we can show that sensors S_2, S_3, S_8 and S_7 (resp. Sensors S_6, S_{11}, S_{12} and S_7) provide a full coverage according to the area covered by the sensor S_5 (resp. sensor S_9). Finally, sensors S_8, S_{13}, S_{12} and S_7 provide a full coverage with respect to the area covered by sensor S_{10}. Since the sensor $S_7(x, y)$ is chosen randomly, we can conclude that the network remains fully covered when running the DSMAC algorithm.

In fact, two sensors S_U and S_V are connected if and only if:

$$d(S_U, S_V) \le 2c\sqrt{2} \qquad (9)$$

In order to prove the network connectivity, it is sufficient to show that all active neighbours of a given sender $S_i(x, y)$ will be connected to this sender during the execution of the DSMAC algorithm. The remote neighbours of the considered sender $S_i(x, y)$ are:

$$\mathrm{Re}mote\_Neigbor\_S_{X,Y} = \{S_{N1}(x, y-2c), S_{N2}(x, y+2c),$$
$$S_{N3}(x-2c, y-2c), S_{N4}(x-2c, y), S_{N5}(x-2c, y+2c),$$
$$S_{N6}(x+2c, y-2c), S_{N7}(x+2c, y), S_{N8}(x+2c, y+2c)\}$$

If we compute the Euclidean distance between $S_i(x, y)$ and each of sensor nodes $S_j \in \mathrm{Re}mote\_Neigbor\_S_{X,Y}$, we have:

$$d(S_i, S_j) \le 2c\sqrt{2} \qquad (10)$$

For instance:

$$d^2(S_i, S_{N1}) = (x - x)^2 + (y - (y - 2c))^2 = (2c)^2$$

$$\Rightarrow d(S_i, S_{N1}) = \sqrt{(2c)^2} = 2c \le 2c\sqrt{2}$$

Therefore, from (10) and based to (9) which illustrates the connectivity condition between two sensor nodes, then all sensors $S_j \in \mathrm{Re}mote\_Neigbor\_S_{X,Y}$ are connected to the sensor node $S_i(x, y)$. Since the sensor $S_i(x, y)$ is chosen randomly, then all active sensors will be connected during the execution of DSMAC algorithm. In addition, according to the definition of a graph which is k-connected and according to Figure 2, the network is at least 4-connected; therefore, there is an optimum routing topology. However, we will not discuss the routing aspect in this paper.

V. EVALUATION OF DSMAC ALGORITHM

We validated our proposal by extensive simulations done with "*Castalia.3.0"* framework [12]. Castalia is a WSN simulator for Body Area Networks (BAN) and generally networks of low-power embedded devices. It is based on the OMNeT++ platform.

A. *Experimental setting*

We consider a field of size equal to (200x200) m^2. The deployment type is static. We run four simulations scenario with respectively 40, 80, 120, 160, and 200 sensors that send their packets to a given Sink. The simulation time is set to 400 seconds. We used the "*CC2420*" radio type. The "*TX power*", the "*communication range*", the "*sensing range*", and the "*grid length*" are respectively set to 0dB, 20m, 10m, and 7m. For the application test, we considered "*ThroughputTest*" [12] to send constant data payload of 2000 bytes with a rate of 5 packets per second to the Sink. Note that in our simulation, all nodes are the same "*initial energy*" equal to 18720 Joules (J) corresponding of 2 piles AA.

B. *Simulation results*

We compared DSMAC and TunableMAC according to different metrics such as the energy consumed, the number received packets by the sink and the application level latency. We performed extensive simulations by considering the same scenarios and the same parameters.

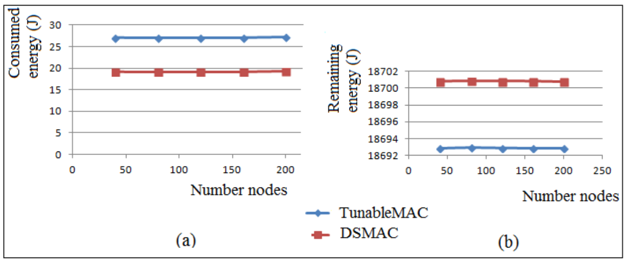

Figure 3. Energy-awareness between DSMAC and TunableMAC

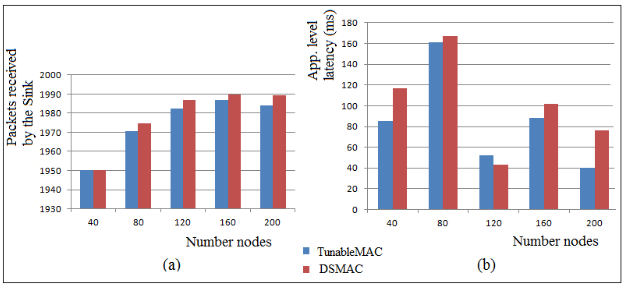

Figure 4. Evaluations of received packets and level latency in DSMAC and TunableMAC

The curves illustrated in Figure 3a and Figure 3b show respectively the average of energy consumed and the average of remaining energy in J for the both algorithms. DSMAC outperforms TunableMAC with respect to the energy consumed. Indeed, with DSMAC only few senders' neighbours are awakened in contrast to TunableMAC where the entire set of a node's neighbours are awakened. Therefore, more actives nodes exist and thus the energy consumed is increased. The average of energy consumed in the network is roughly equal to 19.18 J (resp. 27.09 J) for DSMAC (resp. TunableMAC). According to DSMAC sensors can save up to 30% of their energy compared to TunableMAC.

Figure 4a (resp. Figure 4b) show the average packets received by the Sink (resp. the average application level latency in ms). Figure 4a illustrates that DSMAC outperforms TunableMAC according to the number of packets received by the Sink. The main reason is due to the fact that DSMAC algorithm mitigates the number of collisions. Furthermore, Figure 4b shows the average application level latency. As shown in this figure the performance of TunableMAC is lightly upper than DSMAC but the upper level latency in these two algorithms is less than 166.9 ms, thus the level latency is reasonable in DSMAC regarding to the most applications for WSN.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a distributed scheduling algorithm based on a geometric placement model in order to improve the network lifetime while maintaining full coverage and network connectivity. After the implementation of DSMAC, we proved analytically that coverage and network connectivity are ensured at every time of the network lifetime during the execution of our algorithm.

Simulation results show that DSMAC outperforms the TunableMAC protocol with respect to network lifetime and the average of received packets by the Sink

In future work, we investigate a more realistic modelling of the communication channel, taking into account the path loss and temporal variations. We also intend to make new proposals with respect to routing in WSN based on our sensor placement model.

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