DSMAC: Constraints-based Coverage and Connectivity for Optimizing the Network Lifetime in Wireless Sensor Networks

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Abstract- In this paper, we propose a Distributed Scheduling Medium Access Control (DSMAC) algorithm for optimizing the network lifetime of sensor nodes. The geographic distribution of sensor nodes takes in to account coverage and network connectivity constraints. The optimal placement of sensors, based on square grids, and the ON/OFF scheduling approaches based on duty cycle techniques enable to reduce the energy consumed by sensors. Furthermore, DSMAC algorithm allows a full coverage of the monitoring area. Firstly, we design and validate DSMAC analytically. Secondly, by extensive simulations we show that DSMAC significantly reduces the number of powered ON sensors, and thus the energy consumed during data transport by up to 30%.

Keywords-Wireless Sensor Network; network lifetime; coverage; connectivity.

I. INTRODUCTION

A Wireless Sensor Networks (WSN) [2, 3] 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 in military, industrial diagnostic, agricultural of precision, improve health care. Nevertheless, sensors have resource constraints such as a limited energy, limited memory, limited bandwidth, etc. These limitations can lead to the isolation of sensors nodes by loosing network connectivity due to the fact that some sensor's neighbourhood have no power. Previous studies [2, 3, 4] try to increase the lifetime of sensors nodes. They do not take into account if the monitoring area is full covered. Since, many applications of WSN such as security surveillance, agricultural precision, habitat monitoring, a full coverage of the monitoring area is mandatory as well an energy-awareness network lifetime.

In this paper, we propose a MAC algorithm that enables: an optimal geographic placement of sensors which reduces the required number of sensors to cover a given area; and a scheduling mechanism based on duty cycle techniques in order to optimize the lifetime of sensor nodes ("SN") while providing a full coverage and a network connectivity of all SN.

The remainder of the paper is organized as follows. In Section II, we survey the different studies related to energy-efficiency. Section III describes the proposed geographic placement method of sensors based on grids. Next, Section IV illustrates and evaluates analytically our DSMAC algorithm. Section V evaluates the proposed DSMAC algorithm by simulations. Finally, Section VI concludes the paper and outlines our future work.

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.

The authors of [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, other authors in [2] present different placement strategies of SN in WSN taking into account the lifetime issues. Note that, the most objective of their proposal is to increase the area coverage, to obtain strong network connectivity and to extend the network lifetime. In [3], the authors propose a deterministic static SN placement based on territorial predator scent marking behavior. Their goal is to achieve maximum coverage and reduce the energy consumed and guaranty network connectivity. However, note that the full coverage is not guaranteed in their proposal. Another approach which tries to maximise the number of SN put into sleep mode while guaranteeing k-coverage and connectivity are proposed in [4]. Nevertheless, these protocols do not take into account the local area problem connectivity. A recent study which proposes a self-scheduling algorithm that extends the network lifetime while minimizing the number of active sensors is proposed in [5]. Nevertheless, connectivity issues are also not addressed by these authors.

Several energy efficient MAC protocols based on duty cycle such as "S-MAC", "T-MAC", "B-MAC", and "RI-MAC" are proposed in [6, 7, 8]. 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. Note that in this approach nodes can only communicate when they are in active state. Even if these MAC protocols are efficient in term of energy consumption, they suffer some common limitations. Indeed, in all these protocols, the nodes broadcast their schedule to all neighbor nodes using the synchronization packet; so that a lack of efficiency is noted in term of energy consumed. Note also that these scheduling approaches are not suitable in a network with redundancy coverage. Furthermore, the author of [9] proposes the "TunableMAC" protocol based also on the duty cycle approach. Such as the previous duty cycle protocols, it is worth noticing that with TunableMAC 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 also noted in term of energy consumed. However TunableMAC is very flexible and can be used to make comparisons with new MAC modules developed for WSN.

A. Asymptions and notations

We represent the WSN by a graph $G=(V,E)$ with V designating all vertices (nodes of the network) and $E \subseteq V^2$ the set of edges giving all possible communications. There is an ordered pair $(u,v) \in E^2$ if the node u is physically capable to transmit messages to the node v. In this case, node v is located in the communication range of node u. It's said that these two nodes are communication neighbours. Thus, each node has its key communication range noted R_C. We assume that all nodes have equal communication ranges. Each node also has a sensing range noted R_S. We also assume that all nodes have the same sensing ranges. In the following we denote *M* the number of SN in the WSN and *A* the surface where these SN are deployed.

In a WSN, modelling of communication is very difficult because the nodes communicate in low power, and therefore radio links nodes are very unreliable. The unit disk model is the simplest deterministic models of communication that illustrates a unidirectional link between two SN. This model assumes that each node is able to transmit its data to any node being in its communication range. The communication range of each node varies depending on the level of its transmit power. Therefore, two nodes u and v can communicate each other if and only if the Euclidean distance between these two nodes is less than the communication range R_C of these two nodes. Thus, two nodes $u,v \in M$ can communicate if $d(u,v) \le R_C$.

Also, a sensor S_i covers a point $q \in A$ if and only if $d(S_i,q)=R_S$, where R_S represents the sensing coverage of a given SN. Indeed, the sensing coverage means the total surface lying below the range of capture of data at least of a given SN. Let $S_i \in M$ a SN and $C(S_i)$ denotes the area covered by this SN 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 sensors nodes $S_C=\{S_1,S_2,...,S_C\} \subseteq M$ is: $C(S_C)=\bigcup_{i=1}^{|S_C|} C(S_i)$. According to the covered area, we say that a sensor S_i covers a region A if and only if for each point $q \in A$ then $d(S_i,q)=R_S$.

A SN is connected if and only if there is at least one route between each pair of nodes. The connectivity essentially depends on the existence of routes. It is affected either by the topology changes due to mobility of SN, or the failure of sensors nodes, or malicious sensors nodes, 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.

The neighbourhood $N(u)=\left\{(u,v) \in V^2 \middle| u \ne v \wedge d(u,v) \le R_C\right\}$ of a node u represents the set of neighbour's nodes that are within the communication range of the node u. A graph is called k-connected if there is an at least k disjoint path 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. Grids-based sensor nodes placement

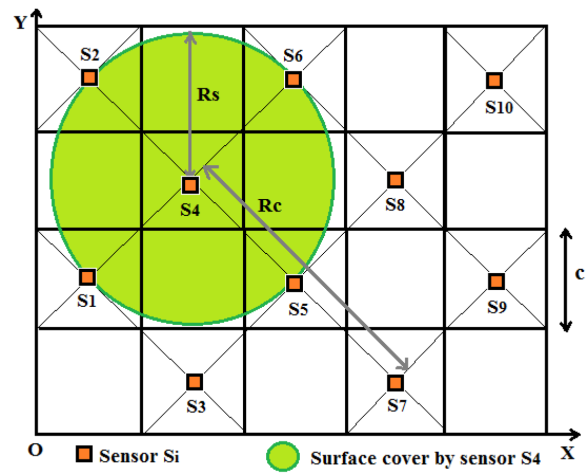

Fig. 1: Sensors placement model within the monitoring area

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 SN 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 SN presents the following advantages:

1. The number of sensors needed to cover the whole area is minimized;
2. The position and the surface cover by each SN are known and can be respectively determined by its coordinates (X, Y) and/or its sensing range R_S.

3. A full coverage and an optimal network connectivity are ensured;
4. It exist an overlapping area with respect to the sensing coverage of sensors that will be exploited by DSMAC for ON/OFF scheduling of SN.

Afterwards, the optimal length of c to ensure full coverage and network connectivity of our network 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, and R_C is determined by the transmission power and others parameters of the radio communication model. Based on the geometric properties of the obtained squares and the diamonds formed by the position of SN (Fig. 1), the sensing range R_S can be computed with the following formula: $R_S^2 = c^2 + c^2 \Rightarrow R_S = c\sqrt{2} \Rightarrow c = \frac{R_S}{\sqrt{2}}$.

Assume that $M = \{S_1, S_2, ..., S_M\}$ the set of SN and each sensor S_i has (X, Y) coordinate in the coordinate system (O, X, Y) as shown in the Fig. 1 where O, (OX) and (OY) denote respectively the origin, the X axis and the Y axis of this coordinate system. For example in this coordinate system $S_1\left(\frac{c}{2}, \frac{3c}{2}\right)$, $S_2\left(\frac{c}{2}, \frac{7c}{2}\right)$, and $S_3\left(\frac{3c}{2}, \frac{c}{2}\right)$ .We show that according to our placement method, an area may be covered by many sensors at the same time; this is due to overlapping coverage areas of neighbour sensors.

III. PRESENTATION OF DSMAC

A. *Overview of DSMAC algorithm*

DSMAC algorithm (Algorithm 1) considers our geometric placement and is a distributed scheduling mechanism for SN. It enables to minimize the energy consumed by the overall network while maintaining a full coverage and network connectivity with respect to all SN. 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. However, according to our DSMAC deployment of SN, where we have a sensing coverage redundancy due to our placement strategy of SN, we do not need to wake up all a given SN's neighbourhood. It is worth noticing that in TunableMAC, the set of SNs have equal sleep interval and equal listening interval. Put simply, DSMAC wakes up only few nodes among a well-chosen SN's neighbourhood in order to reduce the energy consumed during transmission and reception as well as mitigates the number of collisions between SN.

According to DSMAC, each SN uses a neighbourhood's table that contains the ID of neighbour's nodes which is determined by the communication range R_C . Also, the SN have different sleep listening interval. 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 time according to the parameters of the duty cycle.

In order to select the best potential neighbours that enable to minimize the energy consumption during transmission while guarantying full coverage and network connectivity, to taking into account the two issues raised above, we consider two types of neighbours for each 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 (lines 7 to line 11 of Algorithm 1). Therefore, remote neighbours must be woken up and all the remaining nodes within its close neighbourhood must be set in sleeping mode. If they receive other beacons frame, they can decide whether they should wake up again to relay packets (lines 15 and 16 of Algorithm 1). Therefore, with this sleep/wake-up policy, a full coverage and optimal network connectivity will be guaranteed at any given time of the network lifetime. Indeed, if we awakened only the close neighbour, the full coverage and network connectivity must be not guaranteed, this is due to our placement strategy.

Algorithm 1: *DSMAC Algorithm*

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

B. *Analytical evaluation of the DSMAC algorithm*

In this section, we give a proof of the full coverage of the area monitoring by our SN regarding to our placement method. Afterwards, we demonstrate that the network is connected and there is an optimum routing topology in this network.

Consider a sender $S_i(x,y) \in M$ before transmitting its data packets, it broadcasts a train of beacons frames $B_{i1}, B_{i2}, ..., B_{ik}$ in order 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 represent the sender's remote neighbours and their coordinates are expressed as follows: $(x, y-2c),(x, y+2c),(x-2c, y-2c),(x-2c, y),(x-2c, y+2c),$ $(x+2c, y-2c),(x+2c, y),(x+2c, y+2c)$ according to our placement method. The coordinates of other closest neighbours of the sender $S_i(x,y)$ that can be put in sleep mode are $(x-c, y-c),(x-c, y+c),(x+c, y-c),(x+c, y+c)$ (Fig. 2).

Let us consider the sensor node $S_7(x,y)$ shown in Fig. 2. Its neighbourhood's table contains the ID of the set of SN $\{S_1, S_2, S_3, S_4, S_5, S_6, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}\}$.

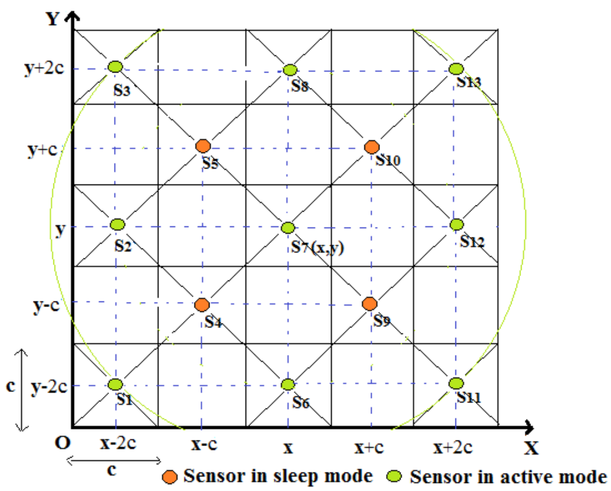

Fig. 2: Illustration of close and remote neighbours of $S_7(x,y)$

If the sensor $S_7(x,y)$ 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 SN S_7 are: $\{S_1, S_2, S_3, S_6, S_8, S_{11}, S_{12}, S_{13}\}$ and the following SN $\{S_4, S_5, S_9, S_{10}\}$ should be put in sleeping mode. According to the Fig. 2, S_4, S_5, S_9 and S_{10} are in sleeping modes at the same time whereas other SNs belonging to S_7's neighbour table are in active mode (powered ON) and maintain a full network coverage. We show that the areas covered by the following SN S_4, S_5, S_9, S_{10} which are in sleep mode, and the one covered by the four active SN located at the vicinity of these sleeping SN are fully covered by the active SN. Let us consider the SN S_4 which is in sleep mode (Fig. 2), then according to the definition of the sensing coverage of this sensor noted $C(S_4)$, we have $C(S_4) = \{q \in A | d(S_4, q) \le c\sqrt{2}\}$. According to the active S_1, S_2, S_7 and S_6 which are around the sensor S_4, the sensing coverage of each: $C(S_1) = \{q \in A | d(S_1, q) \le c\sqrt{2}\}$, $C(S_2) = \{q \in A | d(S_2, q) \le c\sqrt{2}\}$ $C(S_7) = \{q \in A | d(S_7, q) \le c\sqrt{2}\}$, $C(S_6) = \{q \in A | d(S_6, q) \le c\sqrt{2}\}$

Note $S_C = \{S_1, S_2, S_7, S_6\}$. Based on the area covered, we have

$$C(S_C) = C(S_1) \bigcup C(S_2) \bigcup C(S_7) \bigcup C(S_6) \qquad (1)$$

On the other hand, we have:

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

Based on the sensing coverage of SN S_1, S_2, S_6, S_7, Eq.1, and Eq.2, we see that: $C(S_4) \subset C(S_1) \bigcup C(S_2) \bigcup C(S_7) \bigcup C(S_6)$. Hence, S_1, S_2, S_6 and S_7 provide a full coverage with respect to the area covered by the S_4. Similarly, we can show that S_2, S_3, S_8 and S_7 (resp. S_6, S_{11}, S_{12} and S_7) provide a full coverage according to the area covered by S_5 (resp. S_9). Finally, S_8, S_{13}, S_{12} and S_7 provide a full coverage with respect to the area covered by S_{10}. Since the sensor $S_7(x,y)$ is chosen randomly, we can conclude that the network remains fully covered when our scheduling algorithm is run.

In fact, two SN S_U and S_V are connected if and only if,

$$d(S_U, S_V) \le 2c\sqrt{2} \qquad (3)$$

In order to demonstrate the network connectivity, it is sufficient to show that all active neighbours of a given sender $S_i(x,y)$ are connected to this sensor.

The remote neighbours of $S_i(x,y)$ 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 Euclidian distance between $S_i(x,y)$ and each of it's SN $S_j \in \mathrm{Re}mote\_Neigbor\_S_{X,Y}$, we have: $d(S_i, S_j) \le 2c\sqrt{2}$

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 Eq.3 which illustrates the connectivity condition between two sensors, all sensors $S_j \in \mathrm{Re}mote\_Neigbor\_S_{X,Y}$ are connected to SN $S_i(x,y)$. Since the SN $S_i(x,y)$ is chosen randomly, then all active sensors will be connected after the execution of our DSMAC algorithm. In addition, according to the definition of a graph which is k-connected, 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.

IV. EVALUATION OF DSMAC ALGORITHM

We validated our proposal by extensive simulations done with "*Castalia.3.0*" framework [9]. 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 and its default parameters. The "*TX power*", the " *power consumed in RX mode*", the "*power consumed in sleep mode*", the "*communication range*", the "*sensing range*" and the "*grid length*" are respectively equal to 0 dB, 62 mW, 1.4 mW, 20 m, 10 m, and 7 m. For the test application, we considered "*ThroughputTest*" [9] to send constant data payload of 2000 bytes with a rate of 5 packets per second to the sink node. Note that in our simulation, all nodes are the same initial energy equal to 18720 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 failed packets due to interferences. We performed extensive simulations by considering the same scenarios and the same parameters.

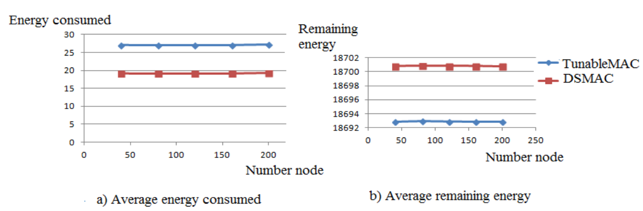

Fig. 3: Energy-awareness between DSMAC and TunableMAC

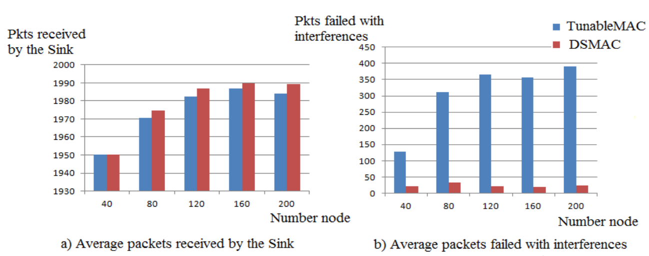

Fig. 4: Evaluation of received packets between DSMAC and TunableMAC

The curves illustrated in Fig. 3a and Fig. 3b show respectively the average of energy consumed in Joules (J) and the remaining average energy for both algorithms. DSMAC outperforms TunableMAC with respect to the energy consumed. Indeed, with DSMAC only few senders' neighbours woke up in contrast to TunableMAC where the entire set of 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 (resp. 27.09 J) for DSMAC (resp. TunableMAC). According to DSMAC SN can save up to 30% of their energy compared to TunableMAC.

Fig. 4a (resp. Fig. 4b) shows the average packets received by the Sink (resp. the average packets failed due to collisions). Fig. 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, Fig. 4b shows the average packets failed due to interferences. The gap between both algorithms is more important. Indeed, the average packets failed with interferences is roughly equals to 310.33 for TunableMAC and 24.21 for DSMAC.

V. CONCLUSION AND FUTURE WORK

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 demonstrated analytically that the full coverage and network connectivity are ensured at every time of the lifetime during the execution of our algorithm.

Simulation results show that DSMAC outperforms the TunableMAC protocol with respect to network lifetime, the number collisions and the average of received packets by the Sink. As future work, we plan to take into account the path loss and temporal variations of the wireless channel. We also intend to show that DSMAC enables an optimum routing based on given topology.

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