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A MAC Scheduling Algorithm for Optimizing the Network Lifetime in Wireless Sensor Networks Based on Coverage and Connectivity Constraints

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Abstract: Wireless Sensor Networks (WSN) are kind of wireless networks including many sensors node which can be deployed rapidly and cheaply over a geographical region of interest, and thereby they can be used for different purposes such as environment monitoring, wildlife habitat monitoring, security surveillance, industrial diagnostic, agricultural of precision, improve health care, etc. Optimizing the network lifetime, minimizing the number of active nodes, maintaining full coverage of the monitored region, and providing optimal network connectivity are critical issues in WSN. These issues are usually conflicting and complementary in many WSN applications. In this paper, we propose a distributed Medium Access Control Scheduling Algorithm called MAC-SA to optimize these four issues simultaneously. Therefore, the geographic distribution of sensor nodes takes into 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 nodes. Furthermore, MAC-SA algorithm allows a full coverage of the monitored region and ensures optimal network connectivity. Firstly, we design and validate MAC-SA analytically. Secondly, by extensive simulations we show that MAC-SA significantly reduces the number of powered ON sensors, and thus the energy consumed during data transport by up to 30 %. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Wireless Sensor Networks, Placement strategy, Network lifetime, Coverage, Network connectivity.

1. Introduction

A Wireless Sensor Network (WSN) [1] 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 losing network connectivity due to the fact that some sensor's neighbourhood have no power. Previous studies [2, 5, 6] 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 target 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 Medium Access Control Scheduling Algorithm (MAC-SA) 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 2, we survey the different studies related to the sensors placement problem, coverage and network connectivity problem, and network lifetime problem. Section 3 presents the different definitions, notations and assumptions used in the paper. Section 4 describes the proposed geographic placement method of sensors based on grids. Next Section 5 illustrates and evaluates analytically our MAC-SA algorithm. Section 6 evaluates the proposed MAC-SA algorithm by simulations. Finally, Section 7 concludes the paper and outlines our future work.

2. Related Works

Network lifetime, placement methods, coverage, and network connectivity problem are important 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. These surveys are good references to have an overall view of coverage and connectivity issues in WSN. However, they don't address the lifetime issues in their study. With the same goal, Ankur, *et al.* [2] presents 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 maximize 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. In the same purpose, existing surveys introduce basic concepts related to coverage and connectivity. Ghosh, *et al.* [9] classify coverage problems as coverage based on exposure and coverage exploiting mobility. Area coverage, point coverage and barrier coverage is another classification proposed in detailed by respectively Fan, *et al.* [10] and Wang, *et al.* [11]. With the same goal, Zhu, *et al.* [12] distinguish two coverage problems: static coverage and dynamic coverage. They also propose a study of sleep scheduling mechanisms to reduce energy consumption and analyze the relationship between coverage connectivity. However, placement strategies of SN and lifetime problems are often missed in their surveys.

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. In so doing, several MAC protocols such as "S-MAC", "T-MAC", "B-MAC", "X-MAC" and "RI-MAC" based on duty cycle approach were proposed in [13-15] by respectively Kaur, *et al.*, Kakria, *et al.* and Ullah, *et al.*

In S-MAC (Sensor MAC) [13], 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. Nodes establish and maintain synchronization in order to choose common fixed active periods. The active period is divided into two sub-periods for exchanging synchronization packets (SYNC packets) and DATA packets. Each node is assigned a radio ON/OFF schedule. A node, after deploying, waits for one cycle of active and sleep period to receive existing network schedule. If a SYNC packet is found then it accepts the schedule carried by the SYNC packet otherwise it uses its own schedule. S-MAC saves energy by reducing idle listening with sleep schedules. However this protocol has some limitations. Firstly, nodes broadcast their schedule to all neighbor nodes using the SYNC packet; so that this mechanism is not efficient in energy consumption. Secondly, all the border nodes incorporate the schedules and keep their radios ON during all of the active periods. Thirdly, predefined and constant sleep and listen periods is a reason for reduced efficiency of S-MAC under variable traffic.

T-MAC (Time-out MAC) [13-14] extends S-MAC and provides several improvements. In T-MAC, the S-MAC limitations were overcome by including an adaptive duty cycle when the length of the active period is varied according to traffic. Each node predicts channel activity during an active period so that it can adjust the length of its current active period. Another improvement consists to maintain node in active state during a time-out in order the node can continue to transmit packets in a burst. T-MAC significantly increases the network lifetime by downsizing the length of the active periods and by using traffic indicators at the beginning of the active periods, nodes determine when to remain active or to switch in sleep period. However, such as S-MAC in this protocol nodes broadcast their schedule to all communication neighbors using the SYNC packet. Thus this mechanism is not efficient in energy consumption and is not suitable in a network with redundancy coverage. Another default of this protocol is the over-listening problem as a node, even if he is not involved in the communication must remain active for a period of time-out.

B-MAC (Berkeley MAC) [14] adopts the famous technical LPL (Low Power Listening). In this technical the nodes periodically switches between active and sleep state. The active state is usually very short, just allows the node to sampling the channel. When a node wakes up, he lights his radio and checks the state of the channel (CCA: Clear Channel Accessment). If there is no activity, then it goes back to sleep state. Otherwise, it remains active to receive packets. After the reception, the node returns to the sleep mode. For the transmitter, each transmission of a packet is preceded by the transmission of a long preamble. The size of the preamble should be longer than the wake up interval to make sure it can be detected by a receiver (next hop). In this way, the receiver is notified to receive the data packet. B-MAC provides good energy efficiency and the active period of each receiver may be adjusted depending on the load of the transmitter. It is therefore with dynamic duty-cycle and self-adapting to the change of the traffic. B-MAC also provides a high level interface for reconfiguring the sleep interval to find a good compromise between power and network throughput. Since B-MAC uses CSMA/CA for the medium access, it suffers flow problem at the high load due to the collisions and the random backoff periods necessary to avoid these collisions. Such as S-MAC, 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 preamble; so that, a lack of efficiency is noted in term of energy consumed.

X-MAC [15] 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. Time intervals are inserting between these packets preamble and thus allow the destination node to send an acknowledgment (ACK) when it receives one of these preambles packets. Once the transmitter receives the ACK, it knows that the next hop node is awakened and stops sending suites preamble packets and immediately sends the packet to the receiver. As B-MAC, X-MAC also provides self-adjustment of the sleep interval according to variation of the traffic. Compared to B-MAC, X-MAC improves energy efficiency and reduces the time using the shortcut preamble. However as explained above, 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.

In RI-MAC (Receiver-Initiated MAC) [14], it’s the receivers which initiate data transmission technique. In this transmission technique, the sender remains active and waits silently until the receiver explicitly signifies when to start data transmission by sending a short beacon frame. As only beacon frame and data transmissions occupy the medium in RI-MAC, with no preamble transmissions as in LPL technical used in B-MAC protocol; occupancy of the medium is significantly decreased, so that other nodes can exchange data. The receiver-initiated design in the RI-MAC not only substantially reduces overhearing, but also achieves lower collision probability and recovery cost. Therefore, RI-MAC significantly improves throughput and packet delivery ratio, especially when there are contending flows such as bursty traffic or transmissions from hidden nodes. In this protocol, the nodes are scheduled to wake up periodically to verify if any data packets are intended for them. They send out a beacon frame, which is picked up by an awakened sensor node that has pending data packets to send. After receiving the beacon the sender node starts transmitting the data packets. On the reception of these, the receiver node sends an ACK beacon. The ACK beacon plays a dual role; first to acknowledge the reception of the data packet and second to ask for more data packets if any from the same node. In RI-MAC, medium access control among senders that want to transmit data frames to the same receiver is mainly controlled by the receiver. This design of RI-MAC makes it more efficient in detecting collisions and recovering data frames that are lost than B-MAC and X-MAC where the senders are hidden to each other. As a receiver expects incoming data only RI-MAC reduces overhearing within a small window after beacon transmission. With the lower cost for recovering lost data frame and detecting collisions, RI-MAC has higher power efficiency even when the load of network increases. However, as the previous MAC duty cycle protocols presented, RI-MAC suffers some default. Indeed, where there are several transmitters, the collision can occur in this protocol.

Even if these MAC protocols are efficient in term of energy consumption, they suffer some common limitations. Indeed, in almost of 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 the scheduling approaches used in almost the MAC duty cycle protocols described above are not suitable in a network with redundancy coverage; due mainly to the broadcast of synchronization and data packets by the senders to all communication neighbors' nodes and the retransmission packets.

Furthermore, Boulis [16] 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 this 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 MAC algorithms developed for WSN.

3. Background Metrics

3.1. Network Model

We represent the WSN by a graph:

$$G = (V, E), \qquad (1)$$

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 u has its key communication range noted $R_C(u)$ that allows it to communicate with others sensor nodes. We assume that all sensor nodes have equal communication ranges noted R_C. Thus, for two given sensor nodes u and v such that $u \neq v$ which their communication ranges are respectively $R_C(u)$ and $R_C(v)$ we have:

$$R_C(u) = R_C(v) = R_C \qquad (2)$$

Each sensor node u also has a sensing range noted $R_S(u)$ that allows it to sense and capture data from the environment. We also assume that all sensor nodes have the same sensing ranges noted R_S. Therefore, for two given sensor nodes u and v such that $u \neq v$ which their sensing ranges are respectively $R_S(u)$ and $R_C(v)$ we have:

$$R_S(u) = R_S(v) = R_S \qquad (3)$$

The entire sensor node 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 node $v \in N(u)$ 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 respectively A and $M = \{S_1, S_2, ..., S_M\}$ the surface of the monitored region where the SN are deployed and the set of SN 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. On the 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 of the application packets.

3.2. Modeling the Wireless Communication

The performances of a wireless communication system are determined based on the communication channel in which it operates [23]. In WSN, modelling 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 is in correlation with its power transmission. 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 their communication range R_C. Thus, two nodes $u,v \in M$ can communicate if:

$$d(u,v) \le R_C \tag{4}$$

Therefore, the communication between SN is based on geometrical considerations. Note that even if the unit disk model is widely used for analytical models, it suffers some limitations. One of these limitations is that, this model is considered to be ideal as it assumes that the messages are still received with no mistake, i.e. it suppose the conditions of the MAC layer as ideal.

Another model which takes important aspect for the wireless channel is the log-normal shadowing model. This model enables to estimate the average path loss between two sensors nodes, or in general, two points in space. For WSN, where the separation of nodes is a few meters to a few hundred meters, this model is the most used to provide accurate estimates for the average path loss. The formula below enables to estimate the path loss in decibel (dB) depending on the distance between two nodes and other parameters described in the following [23].

$$PL_0(d) = PL(d_0) + 10\eta Log\left(\frac{d}{d_0}\right) + X_\sigma, \tag{5}$$

where $PL_0(d)$ is the path loss at a distance d that represents the Euclidean distance between the transmitter and the receiver. The parameter $PL(d_0)$ represents the path loss known at a reference distance d_0. This reference distance is generally equal to 1 meter (m) or 1 km. The parameter η is the exponent path loss depending in the environment and whose value is usually in the range [2~4]. The parameter X_σ is a random variable with mean zero Gaussian standard deviation σ.

The received signal power P_r at a distance d is the difference between the output power of the transmitter P_t and the path loss $PL_0(d)$, i.e.

$$P_r = P_t - PL_0(d) \tag{6}$$

In this formula all the powers are expressed in dB. With this formula, we can control and estimate the communication range of the SN.

We consider in this paper these two models.

Given the graph $G=(V,E)$ defined in the Section 3.1 and the communication range R_C of the SN, the unit disk model defines the set $E \subseteq V^2$ of edges which represent also the communication link between the SN by:

$$\mathrm{E} = \left\{(u,v) \in V^2 \middle| u \ne v \wedge d(u,v) \le R_C\right\}, \tag{7}$$

where $d(u,v)$ represent the Euclidean distance between two given nodes $u,v \in G$. Thus, based on Equation (6), we can determine all SN which are in the transmission range of another given SN by computing their communication ranges. In so doing, we use Equations (5), (6) and others radio parameter defined in [16] to compute the radio range (communication range) of SN. Afterwards, based on our assumptions, we can compute also the sensing range of SN and the grid length of our placement model.

On the other hand, we use the well-known IEEE 802.11 as MAC layer and CSMA/CA (Carrier-Sense Multiple Access/with Collisions Avoidance) as medium access protocol.

3.3. Modelling the Coverage

Coverage is an important performance metric in WSN, which reflects how well a sensing field is monitored [11]. We may interpret the coverage concept as a nonnegative mapping between the space points of a sensing field and the sensors of a WSN [17]. There exist many type of coverage: area coverage (coverage of region), barrier coverage, and coverage of points [3]. We consider in this paper the area coverage and coverage of points. Thus, we say that a sensor node S_i covers a point $q \in A$ if and only if:

$$d(S_i,q) = R_S \tag{8}$$

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:

$$C(S_i) = \left\{q \in A \middle| d(S_i,q) \le R_S\right\} \tag{9}$$

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

$$C(S_C) = \bigcup_{i=1}^{|S_C|} C(S_i) \tag{10}$$

An area is said to be covered if and only if each location of this area is within the sensing range of at least one active sensor node. 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:

$$d(S_i, q) = R_S \tag{11}$$

Area coverage is one of the fundamental problems in wireless sensor networks [11]. In the area coverage problem, the goal is to cover the whole area of the network. Depending on the application requirements, full or partial coverage is required. However, full coverage provides the best surveillance quality of the region [3]. There are two types of coverage: simple coverage and k-coverage defined as multiple coverage and depending on the degree of robustness required by the application [3]. Multiple coverage is defined as an extension of simple coverage. This type of coverage is suitable to applications such as security surveillance, distributed detection, mobility tracking, monitoring in high security areas, agricultural of precision, and military intelligence in a battlefield. In many kind of WSN related above, it is necessary to ensure full coverage of the monitored area, optimal network connectivity while deploying the minimum number of sensor nodes. This can be satisfied by covering every location in the field using at least one sensor node. Many studies aim to optimize the number of sensor nodes deployed while ensuring a high level of coverage and optimal network connectivity. So that, data captured in this location by the SN should be reported to the sink. The Fig. 1 and Fig. 2 below illustrate respectively the mechanisms of simple coverage and multiples coverage.

The problem of coverage area consists to apply scheduling mechanism of sensors activities to decide what sensor must be made in active mode (radio ON) or sleep mode (radio OFF) while maintaining a full coverage of the monitoring region. As we say below one degree of coverage is not sufficient for many applications of WSN related above. So that to schedule the sensors activities for these kinds of applications while ensuring full coverage of the monitored region, i.e. to ensure that if an event takes place at any geographic point of this area, it is detected by at least one sensor, it is necessary to guarantee multiple coverage when placing the SN in the interest region. In this case, an area may be covered by many sensors at the same time; this is due to overlapping coverage area of neighbour sensors. Therefore an event can be detected and reported by several sensors; this is inefficient in term of energy consumption, as some sensors will dissipate energy unnecessarily in the capture, processing and transmission. So that to reduce the energy consumption and optimize the network lifetime, it is necessary to apply scheduling strategies after planning optimal placement of SN; and while guaranteeing at the same time full coverage of the monitored region and optimal network connectivity. In this paper we will use distributed strategies based on an optimal placement of sensors to schedule the SN activities while maintaining full coverage and network connectivity. The following Fig. 3 illustrates a scheduling mechanism of SN activities in order to reduce the energy consumed in the WSN while ensuring the entire coverage of the monitored region and optimal network connectivity. This scheduling mechanism is based on ON/OFF scheduling approach and must allow to all SN which are in active mode (ON) to ensure the network functionally while maintaining full coverage of the monitored region and optimal network connectivity.

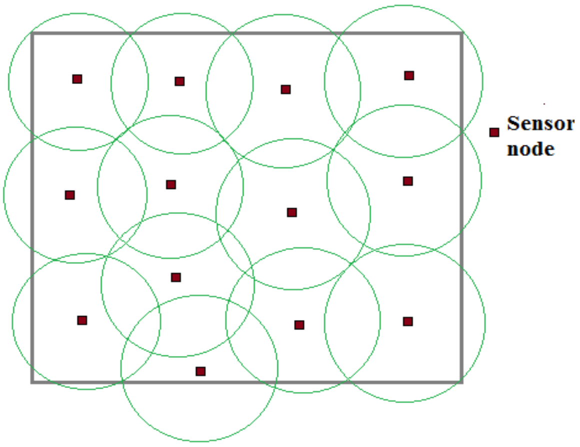

Fig. 1. Illustration of simple coverage.

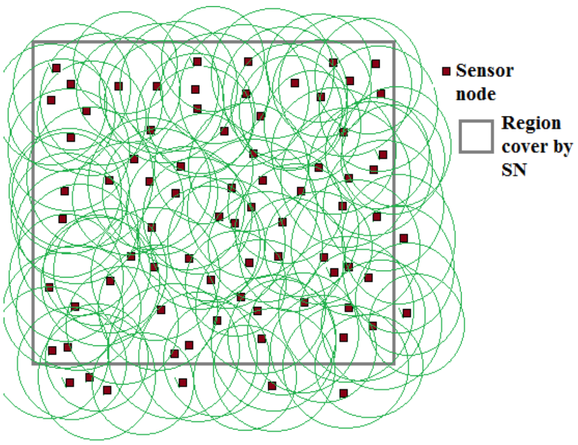

Fig. 2. Illustration of multiple coverage.

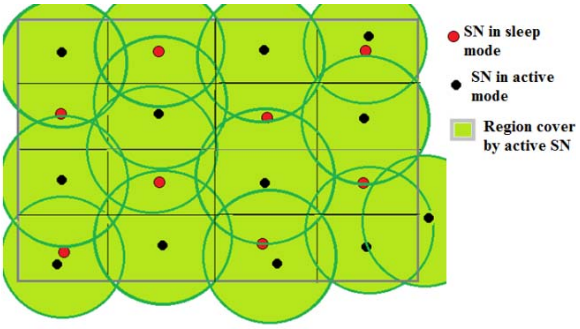

Fig. 3. Illustration of an ON/OFF scheduling mechanism to reduce energy consumed by SN while ensuring full coverage of a monitored region.

3.4. Modelling the Connectivity

Two SN 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. Connectivity is important issue in WSN. 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. Therefore, connectivity problem must be study and take into account in the design and the deployment of many WSN applications in order to guarantee coverage constraints and to ensure robustness in communication.

There are two types of network connectivity: full network connectivity and intermittent network connectivity [3]. Full network connectivity can also be either simple (1-connectivity) or multiple (k-connectivity). Full connectivity is said to be simple if there is a single path between any SN to the sink node; and it is said to be multiple if there are multiple disjoint paths between any SN and the sink node. In addition, full connectivity can be maintained during the deployment strategy of SN or it can be provided only when SN have been deployed in the monitored region. In the following, we use connectivity to represent full connectivity. Note that, in some WSN applications, it is not necessary to ensure full connectivity at any given time in the monitored region. For these WSN applications, it is sufficient to guarantee intermittent connectivity by using a mobile sink that moves and collects data from disconnected sensor nodes. There are two types of intermittent connectivity: the first one uses only one or several mobile sinks and the second uses a mobile sink and multiple throw boxes (Cluster heads).

In this paper, we consider static SN, so that we consider only full connectivity. As we say in previous sections connectivity is often conflicting and complementary to coverage for many WSN applications such as security surveillance, agricultural precision, habitat monitoring, etc. Thus, for these WSN applications, it is not enough to ensure coverage without considering connectivity. When a SN captures data from the environment, it must be transmit these data to a sink node. Consequently, it is necessary to ensure the connectivity between the SN and the sink in order to guarantee the transfer of information to the sink.

Referring to the definition of the connectivity of two SN, two sensor nodes u and v are connect if they can communicate directly. In this case we say that these SN are communication neighbour. So that the communication neighbour of a sensor node u noted $N(u)$ is define by:

$$N(u) = \left\{ v \in V \middle| v \neq u \wedge d(u,v) \leq R_C \right\} \tag{12}$$

A graph of a network which is connected is call a graph connected. Referring to this definition a graph is called k-connected if there is at least k disjoint path between two nodes of this graph. As we say above coverage is often related to connectivity in WSN. So that, to deal with the full coverage and the optimal network connectivity and to ensure the coverage and connectivity conditions, we consider in this paper that the communication range R_C is twice the sensing range R_S .

3.5. Modelling the Energy Consumption

The energy consumed by a sensor node is mainly due to the following: capture, processing and data communication [21].

The energy of capture is dissipated by the SN to perform the following tasks: sampling, A/D conversion and activation of the capture probe. The cost of this energy depends on the specific sensor types (image, sound, temperature, etc.) and previous tasks assigned to him. In general, the energy of capture represents a small percentage of the total energy consumed by a SN.

The processing energy corresponds to the energy consumed by a sensor node during activation of its data processing unit (operations, read/write in memory). It is divided in two parts: switching energy and leakage energy. The switching energy is determined by the supply voltage and the total capacitance switched at the software level (by executing software). The leakage energy is the energy consumed when the computer unit performs no processing. In general, the processing energy is low relative to that required for communication.

The energy of communication is divided into two parts: the reception energy (energy consumed in RX mode) and the transmission energy (energy consumed in TX mode). This energy is determined by the amount of data to be communicated and the transmission distance, as well as by physical properties of the radio module. The scope of transmission of a signal depends on its transmission power (TX power). When the TX power is high, then the signal will have a large scope and the energy consumed will be higher. Note that the energy of communication represents the largest portion of the energy consumed by a SN.

The cost of the energy consumed by a sensor node must also depend on the activity status of this sensor (TX, RX, Idle and Sleep). These activities modes (or states) represent the different modes of operation of a SN [22]. Note that in the idle mode the sensor node can listen to the wireless channel without accessing to this wireless channel, while in sleep mode, the radio module is OFF and no communication is possible. It should be added that the transition between these different modes induces a cost on energy consumption even if it is small compared to other costs of energy consumption in the other modes.

For a given SN, the cost of consumed energy respectively in the TX, RX, Idle, Sleep, and Transition (Sw) states are respectively noted: $E_{Tx}(k,P_{out}), E_{Rx}(k), E_{Idle}, E_{Sw}$ where k represents the message length in bytes and P_{out} represents the TX power. If the consumed energy is expressed in Joules (J), it's regarded as the product of the voltage in Volt (V) applied to the circuit, the intensity of the current in Ampere (A) following through it, and the elapsed time in seconds (s) to perform the operation. So that, the cost of consumed energy in the different states described above can be expressed by the following equations:

$$E_{Tx}(k,P_{out}) = k.C_{Tx}(P_{out}).V_B.T_{Tx}, \tag{13}$$

$$E_{Rx}(k) = k.C_{Rx}.V_B.T_{Rx}, \tag{14}$$

$$E_{Idle} = C_{Idle}.V_B.T_{Idle}, \tag{15}$$

$$E_{Sleep} = C_{Sleep}.V_B.T_{Sleep}, \tag{16}$$

$$E_{Sw} = C_{Sw}.V_B.T_{Sw}, \tag{17}$$

where V_B represents the tension provided by the battery. C_{Tx}, C_{Rx}, C_{Idle}, C_{Sleep}, and C_{Sw} represent respectively the intensity of the current in the four states: TX, RX, Idle, Sleep, and transition. T_{Tx}, and T_{Rx} denoted respectively the TX and the RX time for one byte (with $T_{Tx} = T_{Rx}$). T_{Idle} is the time between the end of one communication (TX or RX) and the beginning of the next communication. T_{Sleep} is the interval time spent by a SN in the Sleep mode, and T_{Sw} is the switching time between two different modes. In this paper, we will use the radio type CC2420 [20] for the validation of our proposal by simulations and we will consider only the TX, RX, and Sleep modes. The transition time (in ms) and the transition power (in mA) between the considered modes are respectively given by the Delay transition matrix (described in Table 1) and the Power transition matrix (described in Table 2).

Table 1. Delay transition matrix.

	RX	TX	Sleep
RX	-	0.01	0.194
TX	0.01	-	0.194
Sleep	0.05	0.05	-

Table 2. Power transition matrix.

	RX	TX	Sleep
RX	-	62	62
TX	62	-	62
Sleep	1.4	1.4	-

4. Geographic Placement Model of SN Based on Grids

We consider the sensor placement model described in the following Fig. 4.

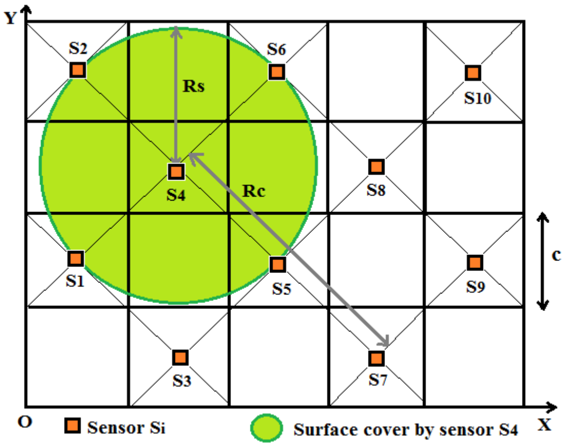

Fig. 4. Sensors placement model based on grids.

According to the deployment of sensors described in the Fig. 4 above, the geographical region of interest is partitioned into contiguous square grids having the same dimensions that equal to c. Each SN S_i is placed at a given area of a grid such that the entire area of the monitored region is covered and the number of necessary sensors is minimized. Our geographic placement model 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 its sensing range R_S.
3. A full coverage of the monitored region and an optimal network connectivity are ensured.
4. It exist an overlapping area with respect to the sensing coverage of SN that will be exploited by our MAC-SA algorithm for ON/OFF scheduling of SN.

Now, the optimal length c of the grid to ensure full coverage and network connectivity of our network model can be determined based on the sensing range R_S. The sensing range depends on the communication range R_C based on our assumptions. As we said in Section 3.2, we will use Equations (5), (6) and others radio parameter defined in [16] such as the TX output power, the pass lost ($PL(d_0)$), the reference distance (d_0), the exponential path lost (η) in order to compute the communication range R_C of the SN. Afterwards, based on our assumptions ($R_C = 2R_S$), we can compute also the sensing range R_S of the SN.

Finally, based on the geometric properties of the obtained squares and the diamonds formed by the position of SN (Fig. 4), the length c of the grid can be computed by using Pythagoras theorem. Thus, we can use the following equation to compute c:

$$R_S^2 = c^2 + c^2, \tag{18}$$

$$\Rightarrow R_S = c\sqrt{2}, \tag{19}$$

$$\Rightarrow c = \frac{R_S}{\sqrt{2}} \tag{20}$$

Based on our assumptions, we have:

$$R_C = 2R_S \Leftrightarrow R_S = \frac{R_C}{2} \tag{21}$$

Thus, according to (6.3), and (6.4), we have:

$$c = \frac{R_C}{2\sqrt{2}} \tag{22}$$

Note $M = \{S_1, S_2, ..., S_M\}$ the set of SN deployed according to our placement model described above in the Fig. 4. Note also that each SN S_i has (x, y) in the coordinate system (O, X, Y) as shown in the Fig. 4 where O, (OX) and (OY) denote respectively the origin, the X axis and the Y axis of this coordinate system. Thus, using this coordinate system and according to our placement model, we can express the coordinate (x, y) of each SN function of the length c of the grids. For example as shown in this figure:

$S_1\left(\frac{c}{2}, \frac{3c}{2}\right)$, $S_2\left(\frac{c}{2}, \frac{7c}{2}\right)$, $S_3\left(\frac{3c}{2}, \frac{c}{2}\right)$, $S_4\left(\frac{3c}{2}, \frac{5c}{2}\right)$, $S_5\left(\frac{5c}{2}, \frac{3c}{2}\right)$, $S_6\left(\frac{5c}{2}, \frac{7c}{2}\right)$, $S_7\left(\frac{7c}{2}, \frac{c}{2}\right)$, $S_8\left(\frac{7c}{2}, \frac{5c}{2}\right)$, $S_9\left(\frac{9c}{2}, \frac{3c}{2}\right)$, and $S_{10}\left(\frac{9c}{2}, \frac{7c}{2}\right)$.

Note $S_C = \{S_1, S_2, ..., S_C\} \subseteq M$ a subset of SN deployed in the WSN according to our placement model. Then referring to the definition of the surface covered by a subset of sensor nodes described in Equation (10), 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 area of neighbours sensor nodes. Therefore, to save energy consumed in the network and to maximize network lifetime, it is necessary after the final deployment to schedule sensor nodes activities by applying Sleep/wake-up strategies (e.g. redundant nodes for full coverage, useless nodes for partial coverage) while ensuring full coverage of the monitored region and optimal network connectivity.

Note that the scheduling activity for SN differs from deployment method of SN, because existing sensor nodes are only switched ON or OFF but are not moved. In the following section we'll present the MAC-SA algorithm which is based on our geographic placement method and which enables to schedule the SN activities and optimize the network lifetime while maintaining full coverage of the monitored region and network connectivity.

5. Presentation and Analytical Evaluation of MAC-SA

5.1. Overview of MAC-SA

MAC-SA algorithm (Algorithm 1) considers our geometric placement model and is a distributed scheduling mechanism for SN activities.

Algorithm 1. MAC-SA algorithm.

Inputs:
"c" represents the length c of a given grid
"d(X,Y)" represents the Euclidean distance between two given sensor nodes 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 a given source S_i

Output:
- A set of active sensor nodes to transmit packets and to ensure a full coverage of the monitored region and optimal network connectivity.
- A set of sensor nodes which are in sleep mode to save their energy.

```
for each sensor node $S_i \in M$ do
    for each sensor node $S_j \in M \wedge S_j \neq S_i$ do
        if $d(S_i, S_j) \leq 2c\sqrt{2}$ then
            Insert$(ID\_S_j, Neigbor\_Table[S_i])$
        end if
    end for
end for
for each sensor $S_i \in M$ which broadcast a beacon $B_i$ do
    if $S_j \in M$ receives $B_i$ and $ID\_S_j \in Neigbor\_Table[S_i]$ then
        if $d(S_i, S_j) \leq c\sqrt{2}$ then
            Make $S_j$ in sleep state until it receive a next beacon $B_k$
        end if
    end if
end for
```

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 MAC-SA 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 MAC-SA 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 SN has equal sleep interval and equal listening interval. Put simply, MAC-SA 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 MAC-SA, 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 has different sleeping and listening intervals. MAC-SA addresses the following two issues noted in previous studies:

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

2) The scheduling of sleeping and listening intervals 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 and reception modes while ensuring a full coverage and network connectivity, and 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. Therefore, remote neighbours must be woken up and all the remaining nodes within its close neighbourhood must be set in sleeping mode (line 8 to line 12 of Algorithm 1). If they receive other beacons frame, they can decide whether they should wake up again to relay packets. Our algorithm allows the following benefits:

1. Save the energy consumed in the network, so that the network lifetime will be improved;
2. Save full coverage and network connectivity at every time of the network lifetime;
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 by the Sink will be improved.

We will present in the following part the description of MAC-SA algorithm in pseudo code.

As shown in the algorithm 1, the lines 1 to 7 enable to compute the neighbour table of each SN $S_i \in M$ by inserting the entire ID of its neighbour $S_j \in M \wedge S_j \neq S_i$. After this step, each SN $S_j \in M$ 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 SN which will usually switch in Sleep mode will save more 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.

5.2. Analysis of the Full Coverage and Network Connectivity in MAC-SA

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.

Let us consider a sender $S_i\left(x,y\right) \in M$. As we said that in the description of our MAC-SA algorithm, before this SN transmits data packets, it broadcasts a train of beacons frames noted $B_{i1}, B_{i2}, ..., B_{ik}$ in order to wake up all the sensor nodes S_j belonging to its neighbour table and located at a distance strictly greater than $c\sqrt{2}$. Based on our placement model described in Fig. 4 above and according to the Fig. 5 below that illustrates the coordinate of remote and close neighbour for a given sender $S_i\left(x,y\right)$, the coordinate of this sender's remote are expressed as follows:

$$\left(x,y-2c\right),\left(x,y+2c\right),\left(x-2c,y-2c\right),$$
$$\left(x-2c,y\right),\left(x-2c,y+2c\right),\left(x+2c,y-2c\right),$$
$$\left(x+2c,y\right),\left(x+2c,y+2c\right).$$

According to Fig. 4 and Fig. 5, the coordinates of other close neighbours of the sender $S_i\left(x,y\right)$ that can be put in sleep mode are expressed as follows:

$$\left(x-c,y-c\right),\left(x-c,y+c\right),\left(x+c,y-c\right),\left(x+c,y+c\right)$$

Now, let us consider the sensor node $S_7\left(x,y\right)$ shown in Fig. 5. Its neighbourhood's table contains the ID of the set of the following SN:

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

If the sensor $S_7\left(x,y\right)$ 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: $\left\{S_1,S_2,S_3,S_6,S_8,S_{11},S_{12},S_{13}\right\}$, and the following SN: $\{S_4, S_5, S_9, S_{10}\}$ should be put in sleeping mode. According to the Fig. 5, S_4, S_5, S_9 and S_{10} are in sleeping modes at the same time whereas other SN 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. 5), then according to the definition of the sensing coverage of this sensor noted $C(S_4)$, we have:

$$C(S_4) = \left\{ q \in A \middle| d(S_4, q) \le c\sqrt{2} \right\} \tag{23}$$

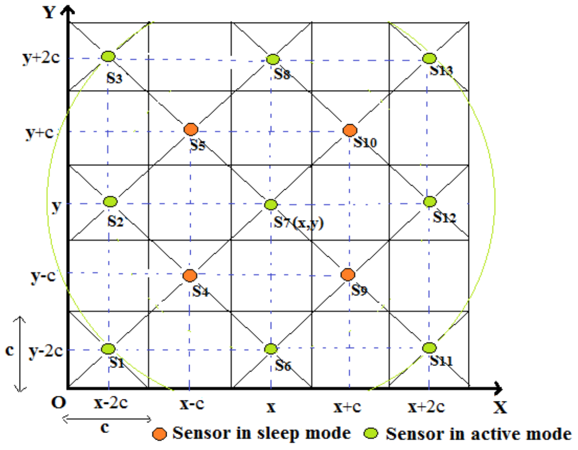

Fig. 5. Illustration of close and remote neighbours of $S_7(x, y)$.

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

$$C(S_1) = \left\{ q \in A \middle| d(S_1, q) \le c\sqrt{2} \right\} \tag{24}$$

$$C(S_2) = \left\{ q \in A \middle| d(S_2, q) \le c\sqrt{2} \right\} \tag{25}$$

$$C(S_7) = \left\{ q \in A \middle| d(S_7, q) \le c\sqrt{2} \right\} \tag{26}$$

$$C(S_6) = \left\{ q \in A \middle| d(S_6, q) \le c\sqrt{2} \right\} \tag{27}$$

Note $S_C = \{S_1, S_2, S_7, S_6\}$.

Based on the coverage area of a subset of SN described in (10), we have:

$$C(S_C) = C(S_1) \bigcup C(S_2) \bigcup C(S_7) \bigcup C(S_6) \tag{28}$$

On the other hand, if we compute the Euclidean distance between the SN S_4 and each SN $S_j \in C(S_C)$, we have:

$$\begin{aligned} &d^2(S_4, S_1) = \left[(x-c)-(x-2c)\right]^2 \\ &+\left[(y-c)-(y-2c)\right]^2 = 2c^2 \\ &\Rightarrow d(S_4, S_1) = c\sqrt{2}, \end{aligned} \tag{29}$$

$$\begin{aligned} &d^2(S_4, S_2) = \left[(x-c)-(x-2c)\right]^2 \\ &+\left[(y-c)-y\right]^2 = 2c^2 \\ &\Rightarrow d(S_4, S_2) = c\sqrt{2}, \end{aligned} \tag{30}$$

$$\begin{aligned} &d^2(S_4, S_7) = \left[(x-c)-x\right]^2 \\ &+\left[(y-c)-y\right]^2 = 2c^2 \\ &\Rightarrow d(S_4, S_7) = c\sqrt{2}, \end{aligned} \tag{31}$$

$$\begin{aligned} &d^2(S_4, S_6) = \left[(x-c)-x\right]^2 \\ &+\left[(y-c)-(y-2c)\right]^2 = 2c^2 \\ &\Rightarrow d(S_4, S_6) = c\sqrt{2} \end{aligned} \tag{32}$$

Thus according to (29), (30), (31) and (32), we have:

$$\begin{aligned} d(S_4, S_1) &= d(S_4, S_2) = d(S_4, S_7) \\ &= d(S_4, S_6) = c\sqrt{2} \end{aligned} \tag{33}$$

Based on the sensing coverage of SN S_1, S_2, S_6, S_7 described in (24), (25), (26) and (27); according to (28) and (33), we have:

$$C(S_4) \subset C(S_1) \bigcup C(S_2) \bigcup C(S_7) \bigcup C(S_6) \tag{34}$$

Hence, S_1, S_2, S_6, and S_7 provide a full coverage with respect to the area covered by the SN 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 during the execution of MAC-SA algorithm.

In fact, based on our assumptions and the modelling of the network connectivity presented in Section 3.4, two SN S_i and S_j are connected if and only if:

$$d(S_i, S_j) \le 2c\sqrt{2} \tag{35}$$

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 sender. The remote neighbours of the SN $S_i(x,y)$ noted $\mathrm{R}\_Neigbour\_S_{x,y}$ are:

$$\begin{aligned}&\mathrm{R}\_Neigbour\_S_{x,y} = \{S_{N1}(x,y-2c), S_{N2}(x,y+2c),\\ &S_{N3}(x-2c,y-2c), S_{N4}(x-2c,y), S_{N5}(x-2c,y+2c),\\ &S_{N6}(x+2c,y-2c), S_{N7}(x+2c,y), S_{N8}(x+2c,y+2c)\}\end{aligned}$$

If we compute the Euclidian distance between the sensor $S_i(x,y)$ and each of the sensor nodes $S_j \in R\_Neigbour\_S_{x,y}$, we have:

$$d(S_i,S_j) \le 2c\sqrt{2} \tag{36}$$

For instance:

$$\begin{aligned}&d^2(S_i,S_{N1}) = (x-x)^2 + (y-(y-2c))^2 = (2c)^2\\ &\Rightarrow d(S_i,S_{N1}) = \sqrt{(2c)^2} = 2c \le 2c\sqrt{2}\end{aligned}$$

Thus, $d(S_i,S_{N1}) \le 2c\sqrt{2}$

Therefore, according to (36) and based to (35) which illustrates the connectivity condition between two sensors, all sensors $S_j \in R\_Neigbour\_S_{x,y}$ 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 during the execution of our MAC-SA algorithm. In addition, according to the definition of a graph which is k-connected, the network is at least 4-connected; therefore, optimum routing topology exists in this network. However, we will not discuss the routing aspect in this paper.

6. Evaluation of MAC-SA by Simulation

We validated our proposal by extensive simulations done with "*Castalia.3.0*" framework [16]. 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 [19] and can be used by researchers and developers who want to test their distributed algorithms and/or protocols in realistic wireless channel and radio models, with a realistic node behavior especially relating to access of the radio.

6.1. Experimental Settings

We consider a field of size equal to 200 m×200 m. The deployment type is static and based on the coordinate (x, y) of each SN. We run four simulation scenarios with respectively 40, 80, 120, 160, and 200 sensor nodes that send their packets to a given Sink. The simulation time is set to 400 seconds. For the application test, we considered "ThroughputTest" [16] 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 J corresponding of 2 piles AA.

The Table 3 below shows the description of the different simulation parameters and setting.

Table 3. Simulation parameters and settings.

Parameter	Value
Field sixe	(200 × 200) m^2
Number of node considered during each simulation	40, 80, 120, 160, 200
Deployment type	Static
Simulation time	400 s
Radio range (R_C)	~20 m
Sensing range (R_S)	10 m
Grid range (c)	~7 m
Radio type	CC2420 [20]
Transmission power	0 dB
Power Consumed in TX, RX and Sleep modes	62 mW, 62 mW, 1.4 mW
Power Consumed per Sensing	0.02 mJ
Initial energy	18720 J
Data Rate	250 kbps
Modulation Type	PSK
Bit per Symbol	4
Bandwidth	20 MHz
Noise Bandwidth	194 MHz
Noise Floor	-100 dB
Sensibility	95 dB
Path Loss Exponent (η)	2.4
Initial Average Path Loss ($PL(d_0)$)	55
Reference distance (d_0)	1 m
Gaussian Zero-Mean Random Variable (X_σ)	4.0
Application Name	ThrouputTest [16]

6.2. Simulation Results

We compared MAC-SA and TunableMAC according to different metrics such as the energy consumed, the number received packets by the sink, the failed packets due to interferences and the application level latency. We performed extensive simulations by considering the same scenarios and the same parameters. The following figures show the simulation results.

The curves illustrated in Fig. 6 and Fig. 7 show respectively the average of energy consumed in Joules (J) and the average of remaining energy in J for the both algorithms. MAC-SA outperforms TunableMAC with respect to the energy consumed. Indeed, with MAC-SA 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 J (resp. 27.09 J) for MAC-SA (resp. TunableMAC). According to MAC-SA SN can save up to 30 % of their energy compared to TunableMAC. As shown that in Fig. 7 the average remaining energy in the network is roughly equal to 18700.803 J (resp. 18692.914 J) for MAC-SA (resp. TunableMAC).

Thus, the network lifetime time is improved in MAC-SA relative to TunableMAC.

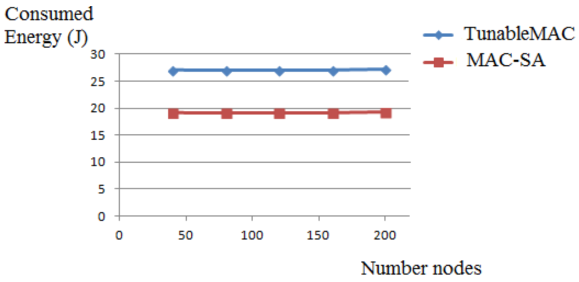

Fig. 6. Average consumed energy in MAC-SA and TunableMAC.

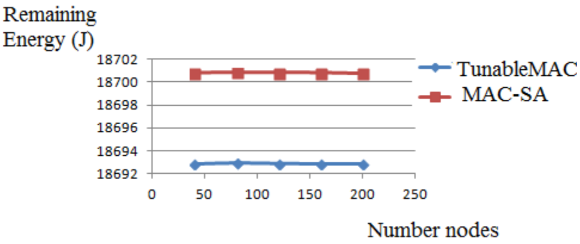

Fig. 7. Average remaining energy in MAC-SA and TunableMAC.

Fig. 8 (resp. Fig. 9) shows the average packets received by the Sink (resp. the average packets failed due to interferences). Fig. 8 illustrates that MAC-SA outperforms TunableMAC according to the number of packets received by the Sink. The main reason is due to the fact that MAC-SA algorithm mitigates the number of collisions.

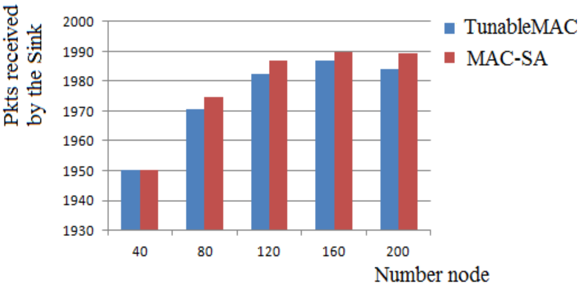

Fig. 8. Average packets received by the Sink in MAC-SA and TunableMAC.

Furthermore, Fig. 9 shows the average packets failed due to interferences. The gap between both algorithms is more important. Indeed, the average number of packets failed with interferences is roughly equals to 310.33 (resp. to 24.21) for TunableMAC (resp. MAC-SA).

Fig. 10 shows the application level latency for both algorithms. As shown in this figure the performance of TunableMAC is lightly upper than MAC-SA but the upper level latency in these two algorithms is less than 166.9 ms, thus the level latency is reasonable in MAC-SA regarding to the most applications for WSN.

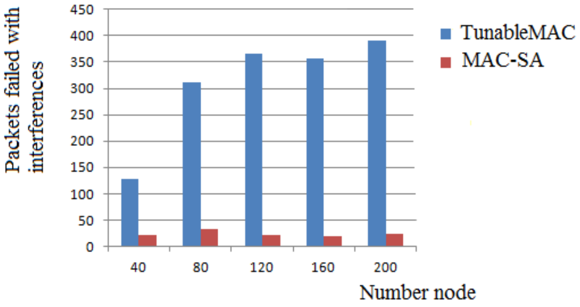

Fig. 9. Average packets failed with interferences in MAC-SA and TunableMAC.

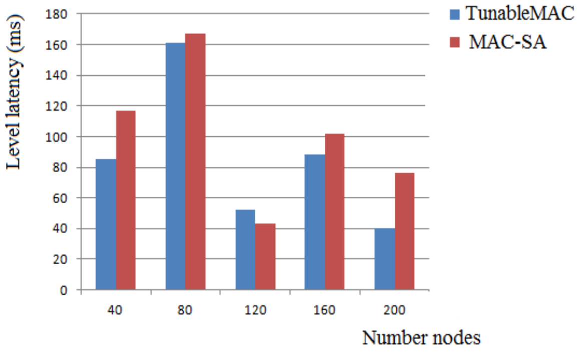

Fig. 10. Average application level latency in MAC-SA and TunableMAC.

7. 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 design and the implementation of MAC-SA, we demonstrated analytically that coverage and network connectivity are ensured at any given time of the lifetime during the execution of our algorithm.

Simulation results show also that MAC-SA 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 by proposing a more realistic modelling of the wireless communication. We also intend to show that MAC-SA enables an optimum routing based on given topology.

References

[1]. M. C. Akewar, N. V. Thkur, A Study of Wireless Mobile Sensor Network Deployment, *International Journal of Computer and Wireless Communication*, Vol. 2, No. 4, 2012, pp. 533- 541.

[2]. P. Ankur, M. A. Rizvi, Analysis of Strategies of Placing Nodes in Wireless Sensor Networks, *International Journal of Advanced Research in Computer Science and Software Engineering*, Vol. 4, Issue 2, February 2014, pp. 398-402.

[3]. I. Khou, P. Minet, A. Laouiti, S. Mahfoudh, Survey of Deployment Algorithms in Wireless Sensor Networks: Coverage and Connectivity Issues and Challenges, *International Journal of Autonomous and Adaptive Communications Systems*, 2014, pp. 1- 24.

[4]. C. Zhu, C. Zheng, L. Shu, G. Han, A survey on coverage and connectivity issues in wireless sensor networks, *Journal of Networks and Computer Applications*, Vol. 35, No. 2, 2012, pp. 619-632.

[5]. H. Z. Abidin, N. M. Din, N. A. M. Radzi, Deterministic Static Sensor Node Placement in Wireless Sensor Network based on Territorial Predator Scent Marking Behavior, *International Journal of Computer Network and Information Security*, Vol. 5, No. 3, December 2013, pp. 186-191.

[6]. R. Mulligan, Coverage in Wireless Sensor Networks: A Survey, *Networks Protocols and Algorithms*, Vol. 2, No. 2, 2010, pp. 35- 41.

[7]. M. Singaram, D. S. Finney, N. K. Sathish, V. Chandraprasad, Energy Efficient Self-Scheduling Algorithm For Wireless Sensor Networks, *International Journal of Scientifique & Technology Research*, Vol. 3, Issue 1, 2014, pp. 75-78.

[8]. D. V. Ambekar, A. D. Bhoi, R. D. Kharadkar, A Survey on Sensors Lifetime Enhancement Techniques in Wireless Sensor Networks, *International Journal of Computer Applications*, Vol. 107, No. 19, December 2014, pp. 22-25.

[9]. A. Ghosh, S. K. Das, Coverage and Connectivity Issues in Wireless Sensor Networks: A survey', *Pervasive and Mobile Computing*, Vol. 4, Issue 3, 2008, pp. 303-334.

[10]. G. Fan, S. Jin, Coverage Problem in Wireless Sensor Networks: A Survey, *Journal of Networks*, Vol. 5, No. 9, 2010.

[11]. B. Wang, Coverage Problem in Sensor Networks: A Survey, *ACM Computing Surveys*, Vol. 43 No. 4, 2011.

[12]. C. Zhu, C. Zheng, L. Shu, G. Han, A survey on coverage and connectivity issues in wireless sensor networks, *Journal of Network and Computer Applications*, Vol. 35, No. 2, 2012, pp. 619-632.

[13]. J. Kaur, T. C. Aseri, A. Kakria, A survey of locally synchronized MAC protocols in Wireless sensor network, *International Journal of Computer Applications*, Vol. 91, No. 11, April 2014, pp. 37- 41.

[14]. A. Kakria, T. C. Aseri, A Survey on Asynchronous MAC protocols in Wireless Sensor Networks, *International Journal of Computer Applications*, Vol. 108, No. 9, December 2014, pp. 19-22.

[15]. A. Ullah, G. Kim, J. S. Ahn, Performance Analysis of X-MAC protocol with Collision Avoidance Algorithm, in *Proceedings of the IEEE INFOCOM*, 2013, pp. 211-212.

[16]. A. Boulis, Castalia. A simulator for Wireless Sensor Networks and Body Area Networks, Version 3.2, *User's Manual*, March 2011.

[17]. H. Xu, J. Zhu, B. Wang, On the Deployment of a Connected Sensor Network for Confident Information Coverage, *Sensors*, Vol. 15, No. 5, 2015, pp. 11277-11294.

[18]. M. Varposhti, M. Dehghan, R. Safabakhsh, A Distributed Homological Approach to Location-Independent Area Coverage in Wireless Sensor Networks, *Wireless Personal Communications*, Vol. 83, No. 4, 2015, pp. 3075-3089.

[19]. OPNET Technologies, Inc. Opnet modeler wireless suite - ver. 15.0.A.PL1. http://www.opnet.com

[20]. Chipcon, CC2420 Data Sheet. http://www.chipcon.com

[21]. W. Heinzelman, A. Chandrakasan, H., Balakrishnan, Energy-Efficient Communication Protocol for Wireless Micro sensor Networks in *Proceedings of the 33rd Hawaii International Conference on System Sciences*, Vol. 8, January 2000, pp.8020-8030.

[22]. M. Younis, T. Nadeem, Energy efficient MAC protocols for wireless sensor Networks, Technical Report, *University of Mryland Baltimre County*, USA, 2004.

[23]. C. T. Kone, Design of the architecture for a large Wireless Sensor Network, Thesis Network and Tecommunications, *Henri Poincare University (Nancy I)*, 2011, pp. 27-31.

[24]. D. Ngom, P. Lorenz, B. Gueye, A Distributed Scheduling Algorithm to Improve Lifetime in Wireless Sensor Network based on Geometric Placement of Sensors with Coverage and Connectivity Constraints, in *Proceedings of the 9th International Conference on Sensor Technologies and Applications (SENSORCOMM' 15)*, Venice, Italy, 23-28 August 2015, pp. 57-63.