Sum Minimum Cost Link Algorithm for Wireless Sensor Networks

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***Abstract*— A Wireless Sensor Network is a group of small sensor nodes which are used to cooperatively monitor physical or environmental conditions. Each node collects events or data from the field of interest, which seems inaccessible at the most time. By using the wireless communication capacities, sensor node sends its information to the remote base station where the end-user can access data. To deal with this, an appropriate energy-efficient routing algorithm is needed to the inherent characteristics of this kind of networks. The objective of our paper is to extend the whole network lifetime by applying two routing algorithms, one on the entire network and the other, on a special area called a hotspot, with the aim to tackle the problem of the isolation of the sink node caused by the depletion of the energy of sensor nodes surrounding it. The first protocol is based on residual energy and link distances, and aims seeking the optimal path from the sensor node transmitter to the sink node. The second protocol is based on the equitably distribution of the energy over all nodes located in the hotspot area and avoids the isolation the sink node from the rest of the network.**

Keywords-WSNs; Event detection probability; Route selection; Energy Consumption.

I. INTRODUCTION

Recent advances in technological developments at the micro-application, the radio communication and the integration of microprocessors, have made possible to develop a new range of small low-cost electronic devices. The latter may be deployed in large numbers to form an intelligent and autonomous Wireless Sensor Network (WSN) that can monitor specific areas. Each sensor node collects events or data from the field of interest, which seems the most time inaccessible, by using the wireless communication capacities. Then, sensors usually communicate with each other in a multi-hop manner and specific nodes send information to a remote Base Station (BS) or sink, where the end-user can access them [1]. Because of limitations on the energy supply, the available storage space and the computational capacity of the sensor nodes, the energy conservation is a critical challenge in a WSN [2].

The energy restrictions of sensor networks influence the design of every piece of the software running in the network. To increase energy saving, protocols might take advantage of network specific characteristics to optimize their operations, such as radius coverage, sensing coverage, event-driven operation, and node positioning [3]. Thus, to extend the whole network lifetime, protocols must interact only with nearby nodes to increase their scalability and efficiency; sensor nodes are more prone to failures and harsh communication conditions. If all sensors in a field of interest follow the nearest sink strategy, sensors around nearest sink, called hotspot, will exhaust energy early. It means that this sink is isolated from the network early and numbers of routing paths are broken. This task must be taken into account because when the sink node is isolated from the rest of the network, the WSN becomes useless [4].

The objective of this paper is to extend the whole network lifetime by applying two routing algorithms, one on the whole network and the other on a special area called a hotspot, in order to tackle the hotspot problem, the isolation of the sink node caused by the depletion of the energy of sensor nodes surrounding it.

The first protocol is based on residual energies and link distances, and aims to find the optimal path from the transmitter sensor node to the sink node.

The second protocol is based on the equitably distribution of the energy over all nodes located in the hotspot area and avoids the isolation of the sink node from the rest of the network; only nodes with residual energies greater than the network energy average will participate to relay the data parquets.

The remaining of the paper is organized as follows: In Section II, some related works are presented. Then, radio model and problem statement are reviewed in Section III. In Section IV, we describe the new proposed route algorithm, while in Section V, we present the simulation results and their analysis. Finally, conclusions are drown in Section VI.

II. RELATED WORK

In this article, we focus on the flat-based routing algorithms, in which all nodes are typically assigned equal roles or functionalities. In flat-based networks, each node typically plays the same role and sensor nodes collaborate to perform the sensing task. This is also called Multi-hop flat routing. In the next paragraphs we will give some examples of these protocols.

One of the flat-based routing techniques is SPIN (Sensor Protocols for Information via Negotiation) [5]. It is a source initiated protocol that uses a flat network structure and reactive routing. The SPIN protocol family is designed based on four basic messages that are:

- *ADV*: new data advertisement. This message is used by a node to inform other nodes that it has data to send; the actual data is sent only when acknowledged and requested by a node. Also, this massage contains only meta-data.
- *REQ*: request for ADV data. It is sent by the recipient to the sender node, if the recipient is interested in the actual data. Here also, it contains only meta-data.
- *DATA* : this is the actual data message.

In addition, the Directed Diffusion (DD) [6] is a data-centric (DC) and application-aware protocol in which data generated by sensor nodes is named by attribute-value pairs. In the DC protocol, data coming from different sources are combined and thus eliminating redundancy and minimizing the number of transmissions. It consists of four elements: (1) Interest: a task description which is named by a list of attribute-value pairs that describe a task, (2) Gradient: path direction, data transmission rate, (3) Data message, and (4) Reinforcement: to select a single path from multiple paths.

The MCFA (Minimum Cost Forwarding Algorithm) [7] consists in finding a path with the minimum of intermediate sensors nodes to reach the remote Sink; each node maintains the least cost estimated from itself to the Sink. Source node will forward the message to its neighbors, which is nearest to the Sink. This process repeats until the Sink is reached. Besides, the MTE (Minimum Transmission Energy) [8] proposed protocol is based on selecting route that uses the least amount of energy to transport data from the source node to the Sink. Assuming that the energy consumption is proportional to square distance between nodes, the intermediate nodes, which operate as routers, are chosen for minimizing the sum of squared distances over the path. Thus, if a node A transmits data to a node C, the node B will participate to the route only if (d_{xy} is the distance between x and y):

$$d_{AC}^2 > d_{AB}^2 + d_{BC}^2 \tag{1}$$

Furthermore, xMREPsum (Sum Maximum Residual Energy Path) [9] is another route technique. Here, the authors propose a cost function that represents the reciprocal of the residual energy at node N_i after the route will have been used by a packet, and uses an exponential parameter P. This function is given by the next equation:

$$f(c_{ij}) = \left(\frac{1}{E_{ri} - e_{ij}}\right)^P \tag{2}$$

where E_{ri} is the residual energy of the node N_i and e_{ij} is the energy expenditure per bit transmission across the link (N_i, N_j). This last energy is defined as follows:

$$e_{ij} = max\left(0.01, \frac{d_{ij}}{E_i}\right) \tag{3}$$

where E_i is the initial energy of the node i, and d_{ij} is the distance between the two nodes N_i and N_j.
Then, the shortest path is obtained by using the conventional BellmanFord [10] equation given by:

$$D_i^{n+1} = min\left(min\left(f\left(c_{ij}\right) + D_j^n\right), D_i^n\right) \tag{4}$$

III. RADIO MODEL AND PROBLEM STATEMENT

We consider a simple model for the radio hardware energy dissipation where the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics. This model is the one used in [11] and illustrated in Fig. 1.

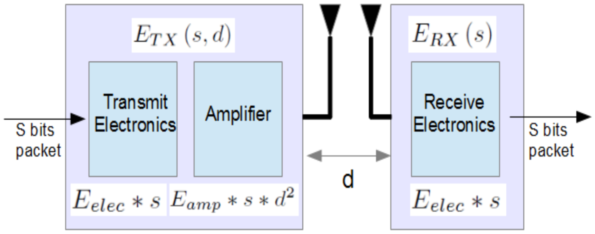


Fig. 1. Radio energy dissipation model.

The transmitted and received energy costs for the transfer of an s bit data message between two nodes separated by a distance d, is given by the following equations:

$$\begin{aligned} E(s,d) &= E_{TX}(s,d) + E_{RX}(s) & (5)\\ E_{TX}(s,d) &= E_{elec} * s + E_{efs} * s * d^2 if d \leq d_0 & (6)\\ E_{TX}(s,d) &= E_{elec} * s + E_{amp} * s * d^4 if d > d_0 & (7)\\ E_{RX}(s) &= E_{elec} * s & (8) \end{aligned}$$

where E_{elec} is the energy dissipated per bit to run the transmitter E_{TX} or the receiver E_{RX} circuit. The E_{elec} depends on many factors such as the digital coding, the modulation, and the spreading of the signal. E_{amp} is the transmitter amplifier while E_{efs} is the transmitter in free space, d is the distance between the sender and the receiver, and $d_0 = \sqrt{\frac{E_{efs}}{E_{amp}}}$ is the minimal distance. As a conclusion, the total energy consumption E_k in the selected route P_k which source node sends s bits packet to the Sink is as below:

$$E_k = \sum_{i=0}^{D-1} E_{i,i+1} \tag{9}$$

where D is the number of nodes along the route of source destination pair.

The basic function of a routing algorithm is to select the path from a set of paths, which is the most effective on the basis of specific criteria [12][13]. Intuitively, to maximize the lifetime of WSNs, the path that achieves the minimum energy consumption while ensuring energy field between individual nodes must be used [14][15]. Flat multi-hop routing algorithms are excellent in terms of their capability of using power-aware metrics to choose minimum power consuming paths. Our proposed routing protocol is combined between two criteria, the first is the shortest path, because data from sensor networks are usually time sensitive; so it is important to receive data as soon as possible; the second criteria is the residual energy of nodes, which distributes equitably the energy over all nodes.

The isolation of the sink node is caused by the depletion of the energy of sensor nodes surrounding it (the hotspot problem). It means that this sink is isolated from network early and numbers of routing paths are broken, so the WSNs becomes useless [16]. To avoid the isolation of the sink node, we aim to suggest a new strategy which distributes equitably the energy over all nodes of a WSN.

Another challenge of the WSNs is the efficient deployment of the required coverage [17]. Specifically, given a monitoring region, how can we guarantee that every point in the region is covered by the required number of sensors? In other words, we need to recognize which areas are covered by enough sensors. This problem is challenging due to the limitations of wireless sensors. In the next section, we will define sensing coverage and will formulate the maximum sensing coverage region problem.

IV. PROPOSED ROUTE ALGORITHM

To reduce the energy consumption in WSNs, we propose a protocol architecture to ensure good routing of data between nodes and the BS. We adopt a sensing model probability in dense networks. A sensor can detect any events located in the area sensing, so we can identify the redundant nodes that will change their operating modes between sleep and active ones. In this section we will give more details of the different components of our proposal MCLsum (Sum Minimum Cost Link) algorithm.

A. Event detection probability

WSNs are characterized by random network topology where all nodes are randomly deployed in field of interest. Our objective in this section is to define the optimal number of the nodes used in an area and sensing coverage. To achieve this objective, we study the sensing model probability that is generally coupled closely with the specific sensor application and the type of sensor device used [18][19]. We adopt a sensing model probability where a sensor can detect any events located in the area sensing. All sensor nodes are assumed to be homogeneous, and have the same sensing coverage (R_s).

For a uniformly distributed sensor network with node density λ [20], we denote the number of sensors covering the location by n. The sensing model probability follows a Poisson distribution as given by the next formula:

$$P(n=k)=\frac{(S\lambda)^k}{k!}e^{(-S\lambda)} \tag{10}$$

P is the probability that an event can be immediately detected by k sensors located within the area of interest, each sensor covering an area of $S=\pi R_s^2$. Hence, the previous probability can further be represented as:

$$P(n=k)=\frac{(\lambda\pi R_s^2)^k}{k!}e^{(-\lambda\pi R_s^2)} \tag{11}$$

Therefore, the probability that no sensor in an area of interest can detect an event is $\overline{P}=e^{(-\lambda\pi R_s^2)}$. Then, the complement of $\overline{P}$ is the probability that there is at least one sensor which detects an event. This sensing model probability can be represented as:

$$P=1-\overline{P}=1-e^{(-\lambda\pi R_s^2)} \tag{12}$$

P is determined by the node density and the sensing range, while increasing the sensing coverage and the number of nodes, the detection probability increases and all events that happen in the network, will be covered. The optimal values that must be considered to totally cover an area are obtained by the simulation of the formula event detection probability.

B. Availability of nodes and redundant nodes

We can efficiently reduce the energy consumption in most of the WSNs applications, and extend the whole network lifetime, when sensor power can be put on/off periodically. Thus, it is appropriate to take into account the node availability rate p in our analysis. Each sensor node can decide whether to become active with probability p or move to the sleep mode with probability $1-p$ witch means to be off in every sensing period. Thus, the probability that the event can be immediately detected once it appears in an homogeneous WSNs with node density λ, sensing range R_s and node availability p, can be given determined by:

$$P=1-\overline{P}=1-e^{(-p\lambda\pi R_s^2)} \tag{13}$$

In a dense network, the sensing areas of different nodes may be similar to their neighbor nodes and nodes will transmit redundant information. This will increase the total energy consumption of the WSN. Therefore, it is important to place or select the effective number of sensor nodes to cover the same monitored area as much as possible without diminishing the overall field coverage. Thus, we must identifies the redundant nodes denoted by probability $1-p$ in a dense networks and changes their operating mode between sleep and active modes.

1) The overlapped area and redundant nodes in WSNs: Consider two nodes N_i and N_j location at (x_{Ni}, y_{Ni}) and (x_{Nj}, y_{Nj}) respectively. The node N_i covers the S_{Ni} area and the other node covers the S_{Nj} area. Let us note d_{ij} the distance between nodes N_i and N_j.

The overlapped area S_{ol} of nodes N_i and N_j is defined as the intersection region between S_{Ni} and S_{Nj} areas, that is formulated by the next equation:

$$S_{ol}=S_{Ni}\cap S_{Nj} \tag{14}$$

An example of S_{ol} is represented in Fig. 2.

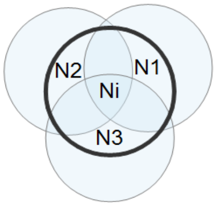


Fig. 2. Example of redundant node N_i totally overlapped by nodes N_1, N_2, and N_3.

As in [17], S_{ol} can obtained by the follow result:

$$S_{ol} = R_s^2 \times \left(\theta - \frac{d_{ij}}{R_s} \sqrt{1 - \left(\frac{d_{ij}}{2R_s} \right)^2} \right) \tag{15}$$

with θ is the central angle of the overlapped area given by the next equation:

$$\theta = \arccos \left(\frac{d_{ij}}{2R_s} \right) \tag{16}$$

We can note that each point located in S_{ol} can be covered by both N_i and N_j nodes.

2) Operation modes of nodes: Due to the fact that the deployment of node in the network is random, many redundant nodes may be detected [21]. As discussed above, a redundant node is a node where its entire sensing region is covered by the sensing region of other nodes. Hence, we run our algorithm to determinate this kind of nodes. Assume that each node knows positions of its neighbours, it is possible that all of them have the capability to define their state (redundant or not). If the node is redundant, it powering-off both the sensing and the communication units. Here, we note that the node is operating in the sleep mode, but from time to time it powering-on only the radio module to listen if data is coming from its neighbours during a listening time T_{listen}. Consequently, the remaining energy is saved and the whole network lifetime is extended. But, how long should a redundant node remain in a sleep mode? To response to this question, we apply the following approach based on the minimum residual energy threshold parameter. Node N_i participating to cover a part of one redundant node and having residual energy E_{ri} greater than threshold Θ_{Eng}, will broadcast continually a short message during a period $T_{broadcast}$ with a radio range equal to R_s. The objective of these transmissions is to inform the redundant node that its remaining energy will be exhausted soon. Indeed, the sufficient and necessary conditions to wake-up the redundant node are:

$$T_{broadcast} > T_{listen} \tag{17}$$

$$E_{ri} > \Theta_{Eng} \tag{18}$$

Thus, the redundant nodes verifying the two last conditions, can switch from the sleep mode to the active one. Therefore, a large part of energy will be saved and the redundant transmissions will be efficiently reduced. Consequently, the whole network lifetime will be extended.

C. Routing inside Hotspot area

We suggest a new protocol to select nodes that will participate to the data transmission path in the hotspot area. It is based on a strategy which distributes equitably the energy over all nodes located in the hotspot area and avoids the sink node isolation from the rest of the network. Sink defines the radius of hotspot area by broadcasting a short message, and requesting the residual energy for each node located in hotspot area. In order to compute the energy average of the hotspot area, each node sends a short message to the sink containing the residual energy; only nodes with residual energy greater than the network energy average will be selected by the Sink to participate to relay the data packets, as expressed by the next equation:

$$Er_i \geq Emean : i \in B \tag{19}$$

where Er_i is the residual energy of the node i, $Emean$ is the energy average of hotspot area, and B is the node set located in hotspot area.
The diagram in Fig. 3 shows more details and resumes all these steps.

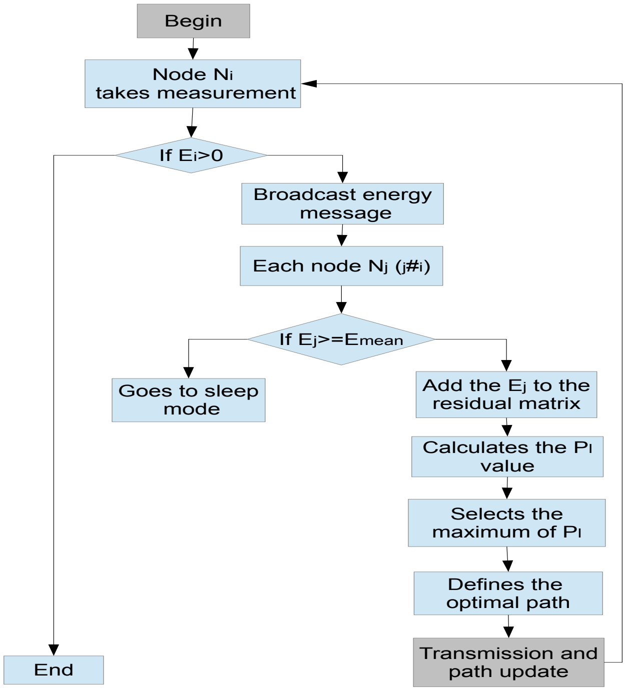


Fig. 3. Routing inside Hotspot area flow chart.

D. Selecting an optimal route

It consists to select paths with maximum residual energy and squared distances. So, energy consumption is balanced among all nodes with the aim to minimize the sum of squared distances over the path. More specifically, cost function that represents the link c_{ij} is:

$$f\left(c_{ij}\right) = \frac{d^2}{Er_j} = \frac{\mid N_i - N_j \mid^2}{Er_j} \tag{20}$$

where Er_j is the residual energy of the node j and the distance $\mid N_i - N_j \mid$ is defined as the length of the line segment connecting N_i and N_j; this Euclidean distance must be less than the coverage radius R_c of node i. The total cost for a route l of length D is computed by the following equation:

$$P_l = \sum_{i=0}^{D-1} f\left(c_{i,i+1}\right) = \sum_{i=0}^{D-1} \frac{\mid N_{i+1} - N_i \mid^2}{Er_{i+1}} \tag{21}$$

Using the Dijksta algorithm, the optimal route with the minimum P_l can be fixed. As a conclusion, the selected route P_k is the one that satisfies the following property:

$$P_k = min\{P_l : l \in A\} \tag{22}$$

where A is the set of all the possible routes. Our proposed scheme, routing inside hotspot area is shown in Fig. 4.

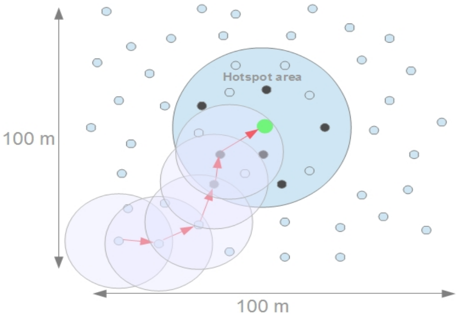


Fig. 4. Wireless sensor networks.

V. SIMULATION RESULTS

In this section, we evaluate the performance of our architecture protocol using MATLAB software. We consider a random wireless sensor network composed of n static sensor nodes and one sink node. These static sensor nodes are independent and distributed uniformly on an area $100m \times 100m$. Each sensor node sends its acquired data to the sink node located at the center of the sensor field. Moreover, we run our simulation using the radio model presented in Fig. 1 with simulation parameters shown in Table I.

TABLE I
SIMULATION PARAMETERS

NODES	100
INITIAL ENERGY E_r	5 J/node
TRANSMITTER ELECTRONICS E_{elec}	50 nJ/bit
E_{efs}	10 nJ/bit
E_{amp}	100 nJ/bit
DEAD NODES	< 0.1 J
DATA PACKET SIZE	4000 bytes
ENERGY MESSAGE SIZE	200 bytes

A. *Optimal node number with sensing coverage for an area*

The results illustrated in Fig. 5 shows that the event detection probability P is determined by the node density and the sensing range. Event detection may need a large sensing range or a high node density, thus increasing the WSN deployment cost. Fig. 5(a) shows the simulation results of the formula event detection probability. On the other hand, we can obtain the same results given in Fig. 5(b). By running simulations, we change the node density by varying two parameters, the sensing range R_s from $0m$ to $20m$, and the node number n from 1 to 100. We assume that an event occurs randomly in a given location on the network and we compute the probability to detect this event. For given values of R_s and n, we run 10000 simulations and we calculate the percentage of detection. We can note that if we increase the lasts parameters the probability to cover an event happens in the network increases to. However, for a given value of R_s or n we can see that this percentage of coverage is constant and attend 100%. Indeed, increasing more n or R_s will not affect the robustness of detection. Consequently, for a given value of R_s, we can find the optimal node number which can be deployed to cover efficiently the controlled region and reciprocally. This node number and sensing range will be the optimal values, which must be used to totally cover an area.

B. *Node availability*

We set the node number to 100 and the sensing coverage to 20. we run our algorithm to determinate redundant nodes.

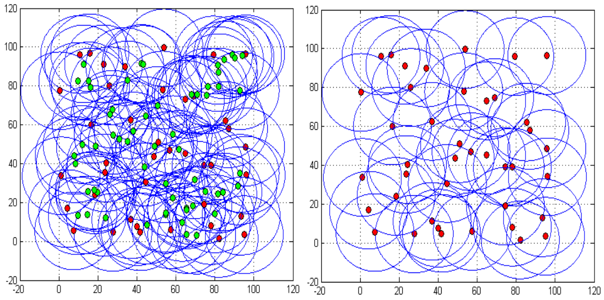


Fig. 6. Redundant nodes for a $100m \times 100m$ network area.

Fig. 6 shows the redundant node location determined in the WSN area. We note that there are approximately 35 redundant nodes expressed by the green color dispersed over the network. Moreover, we see that only 65 nodes can cover efficiently the total region. So, 65 is the optimal node number which can be deployed to cover the region.

We can express the efficient number of nodes which can be deployed to cover the area of interest by node availability rate p as a variable in event detection probability P.

$$P = 1 - e^{(-p\lambda\pi R_s^2)} \tag{23}$$

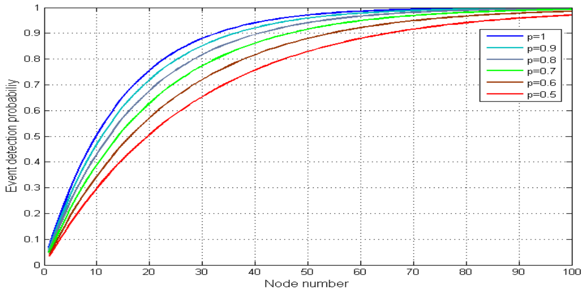
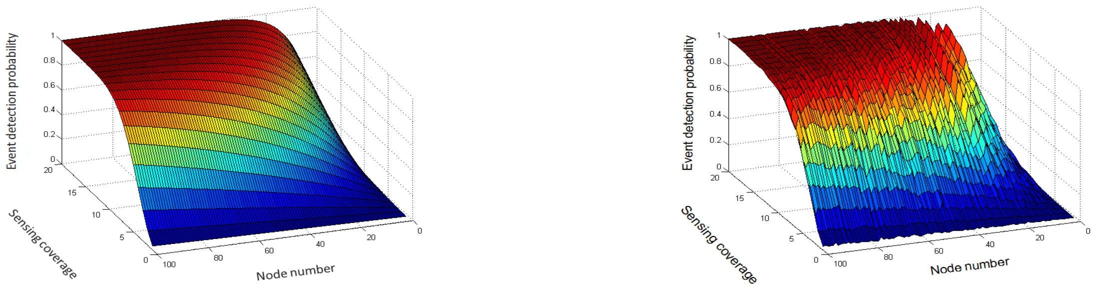


Fig. 7. Node availability.



(a) (b)

Fig. 5. Event detection probability, (a) Sensing model probability (b) Simulation.

Fig. 7 shows the curves of event detection probability model according to different values of node availability rate. It is obvious that if node availability rate p increases the event detection probability P increases too.

In the next subsection, we will evaluate the performance of our routing protocol MCLsum by taking into account that redundant nodes switch from sleep mode to active one, and vice versa.

C. Performance evaluation

We give the comparisons between MCLsum, the MTE and the xMREPsum algorithms. The evaluations are discussed in terms of energy stored, number of nodes still alive, and number of messages received at the sink.

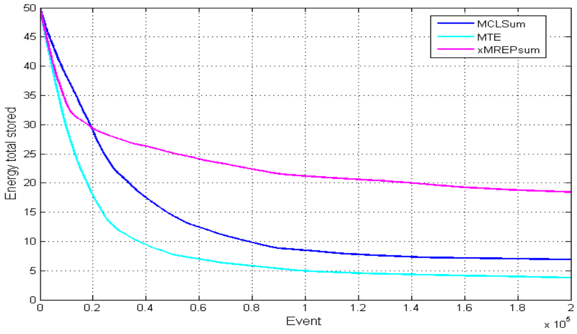


Fig. 8. Total energy stored (Joule).

In each round, we assume that an event occurs randomly in a given location on the network. During the simulation, the network nodes die randomly in the supervised area. We then give the simulation results of the three compared approaches.

Fig. 8 gives the total network remaining energy in every sensing round. The network remaining energy decreases rapidly in the Direct transmission and xMREPsum protocols.

We can see that, in the $0.1 * 10^6$ first events, approximately 45% of the total network energy is consumed in the MTE and 35% in xMREPsum protocol. Whereas, the MCLsum consumed only 20% of the total energy of the network. From the $0.2 * 10^6$ first events, rate event detection for protocol xMREPsum is reduced compared to two other protocols MTE and MCLsum, which explains low energy consumption.

As shown in Fig. 9, we represent the number of data messages that are correctly received by BS. We can notice that the total number of these messages is substantial for the MCLsum protocol. This means that MCLsum is more efficient than MTE and xMREPsum protocols.

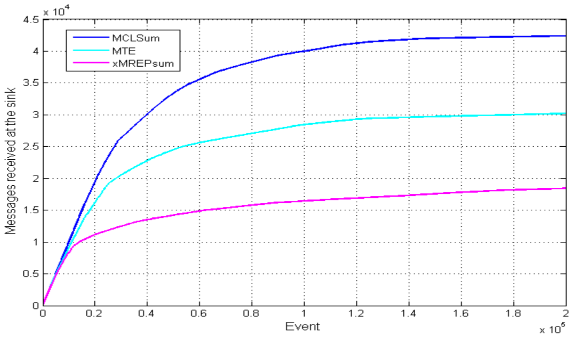


Fig. 9. Number of data messages correctly received at the Sink.

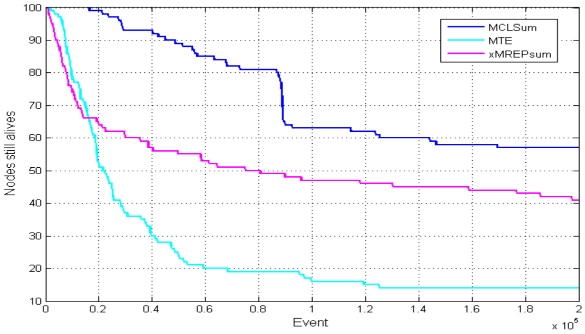


Fig. 10. Number of nodes still alive.

Fig. 10 shows the variation in the total number of sensors that are still alive. We observe that in MTE protocol, the first node die appears in the 1800th event, in xMERPsum it happens in the 900th event and in MCLsum it comes in 16300th event. So, our protocol increases the whole network lifetime. Moreover, our MCLsum protocol is approximately 2x better than MTE in term of node death, and better about 3x than xMREPsum. Taking in consideration the residual energy, square distance between nodes, and average network energy in hotspot area, our protocol presents more efficiency and more robustness. Consequently, the MCLsum enlarges substantially the lifetime of the whole network related to the others algorithms.

VI. CONCLUSION

In this paper, we presented a novel routing protocol for WSNs by taking into account the hotspot problem. The proposal provides better solution for routing protocol of WSNs. It is based on residual energy and link distances of nodes, and aims to seek the optimal path from a transmitter sensor node to a sink node. The hotspot problem is solved thanks to our strategy which equitably distributes the energy over all nodes located in the hotspot area and avoids the isolation of the sink node from the rest of the network. The simulation results show that, compared to the MTE and the xMREPsum protocols, best results are obtained by the MCLSum protocol. Thus the whole WSNs lifetime is significantly extended by the last approach.

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