Statistical study of energy and time costs of fault tolerance in Multilevel and EDCR protocols

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***Abstract*— Wireless Sensor Networks (WSNs) are composed usually of a huge number of sensor nodes capable of collecting and transmitting environmental data in an autonomous manner to a remote user's computer where the information may be viewed by a human, further processed and stored, or otherwise acted upon. They are generally deployed in harsh environments, where sensor nodes are prone to several failures out of which their energy depletion is the most present. Thus, the failure of a small number of nodes must not influence the network functioning. For this, including fault tolerance property in WSN routing protocols is of utmost importance. The choice of the fault tolerant protocol, and subsequently the type or the types of tolerated failures is imposed by the target WSNs application. This fault tolerance has energy and time costs that remain little studied in the scientific literature. Hence, this paper aims at studying the effect of failures density and surface density on the energy and time costs in the Multilevel and Energy aware Distributed partitioning detection and Connectivity Restoration (EDCR) protocols.**

Keywords*— *Energy and time costs, Failures and surface densities, Fault tolerance, Wireless sensor networks.

I. INTRODUCTION

A WSN is composed usually of a huge number of nodes either placed in specific locations or randomly deployed often through the air using airplanes or helicopters. The sensor nodes must be reliable and able to withstand to the most extreme conditions dictated by their environment of deployment (e.g. fire or water). As well as the energy limitation presents the major factor which causes the WSNs dysfunction. In fact, a WSN cannot survive if the loss of sensor nodes is too important because this causes losses of communication due to the large distance occurring between the remaining functional sensor nodes. Therefore, it is very important for a routing protocol to support fault tolerance functionality, in order to ensure the continuity of network service despite of failures.

We distinguish two types of faults in WSNs: Permanent Loss of Link (PLL) which is due to the physical destruction of a node, the depletion of its energy, etc., and Temporary Loss of Link (TLL) which is due to the network congestion (caused by the traffic overload) or severe conditions of the deployment environment (bad weather for example) [1]. Numerous solutions of Fault Tolerant Routing Protocols (FTRP) for WSNs have been developed, among them there are protocols that tolerate the type PLL and TLL of failures (e.g. ENFAT-AODV [2], HAFMS [3], Directed Diffusion [4] and IHR[5]) and protocols that tolerate a single type of failures (e.g. BPA-CRP[6], EDCR [7], CAF [8] and Multilevel [9]).

Since the energy depletion is the primary source of nodes failures and after that the WSN's failure, some FTRPs treat only this type of failures, it is the case of the Multilevel and EDCR protocols. Our study of these protocols has focused on the effect of failures and surface densities on their performances. For this purpose, we followed the energy and time costs depending on failures and surface densities using the WSNs simulator Castalia [10] developed by National ICT Australia in 2006. This simulator is founded on the basis of OMNET++ platform [11] and it is an open source simulator designed for energy-constrained networks namely WSNs and body area networks. Castalia is used by researchers and developers aiming at testing their proposals in real wireless communication modules having a realistic behavior especially radio layer's access. Additionally, Castalia computes the power consumption from one to another of radio states which are sleep, transmission, and reception. Also, it is largely used by an active users' community [12, 13, 14, 15].

The rest part of this paper is structured as follows: In Section II, we present the Multilevel and EDCR protocols. Section III is dedicated to the presentation of simulations. Simulation results and discussion of these results are provided in Section IV. Finally, Section V concluded the paper.

II. PRESENTATION OF MULTILEVEL AND EDCR PROTOCOLS

A. Multilevel

Multilevel protocol models the WSN into various levels on the basis of the hop count (*H*) a source node is away from the sink. Hence, the sink has the level 0 and each sensor node has a level *H*. The data transmission flow is oriented from a node having level *H* to its parent node having level *H-1*. A timer for receiving an acknowledgement (ACK) is triggered for the sent data to be sure of its successful reception. So, if the timer expires and the ACK is not received, the source node retransmits its data to its respective parent node. Otherwise, the packet of data is automatically dropped.

A node is declared faulty when its residual energy goes below a predefined value. In this case, the diffusion of "EnergyLow" message is required to allow child nodes to find new parent nodes. Upon receiving this message, the child nodes broadcast a "Hello" message to discover their new parents. Neighbouring nodes respond with a "Neighbour" message. It may happen that some nodes will update their levels because of the reception of "EnergyLow" message. Hence, the node that changes its level broadcasts a "LevelChange" message to its child nodes, if they exist, so that they change their levels.

Consider the Fig. 1, where the faulty node 0 diffuses an "EnergyLow" message. Accordingly, the nodes 1 and 9 receive this message and in their turn they diffuse a "Hello" message in order to search new parents nodes. Nodes 8 and

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24 receive this message and send a "Neighbour" message to nodes 1 and 9 respectively. On the receiving of this message, nodes 1 and 9 set nodes 8 and 24 as their parent nodes respectively. There is no need to diffuse a "LevelChange" message by the node 1 because it has not updated its level. Also, nodes 9 and 24 have the same level, thus it is required for the node 9 to update its level but it does not need to diffuse the "LevelChange" message.

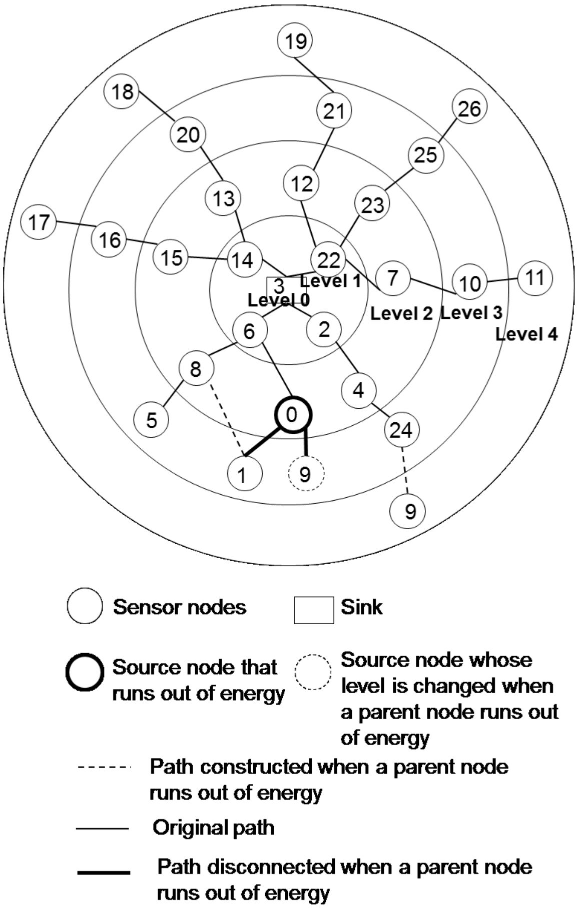

Fig. 1. Illustration of a failure recovery

B. EDCR

EDCR employs two types of nodes which are critical and non-critical. A node is assumed to be critical if its neighbours can be divided to at least two partitions. Otherwise, a sensor node is assumed to be non-critical if its neighbours remain connected without it. The critical nodes called also primary nodes select and designate a suitable neighbour as a backup to recover their possible failures.

Once the remaining energy of a critical node dips under a predefined value, its neighbours and its backup are informed through a notification message. Once neighbour nodes are aware of the critical node failure, they buffer critical sensed data to avoid their loss. Also, after the primary's failure detection, the backup node triggers its recovery. In the failures recovery three scenarios can take place:

1) When the backup node is not the primary node, it moves to the failed primary' position and in turn it nominates its new backup. If critical nodes exist at the old position they will be informed about the movement of backup node so as to look for another backup node.

2) In the situation when the backup node is itself a primary node, it informs its backup node so as to have a connected network. This situation is illustrated in Fig. 2. When the backup node 2 detects the failure of node 3 (Fig. 2.a) it will replace it and the node 1 which is the backup of node 2 will replace its primary node (Fig. 2.b).

3) There exists also the situation where the failed primary and its backup are critical nodes and in the same time they are backups one for the other. This situation is illustrated in Fig. 3. The failed node 1 and its backup node 2 are assumed to be critical nodes and in the same time they are considered as backups one for the other (Fig. 3.a). Then, the node 2 selects another node 3 as backup (Fig. 3.b). The node 2 diffuses a control message due to its movement and replaces the position of the faulty node 1. This triggers a series of movements of other nodes i.e. the node 3 moves to the position of 2 and the node 4 moves to the position of node 3. The node 5 is selected as backup of node 4 (Fig. 3.c).

When the backup node replaces its primary, it informs the neighbour nodes through a "DONERECOVERY" message. Upon receiving this message, these nodes resume routing of their buffered data packets.

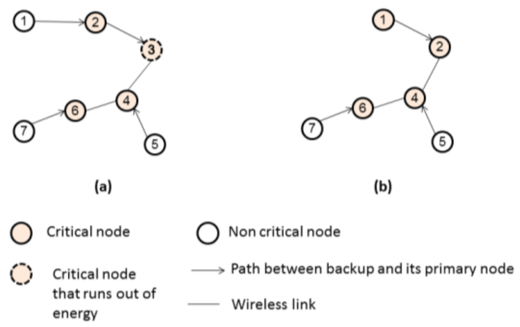

Fig. 2. The fault recovery if the backup is a critical node; (a) the node 2 recognizes the malfunction of primary 3 and (b) node 2 replaces node 3 and node 1 replace node 2

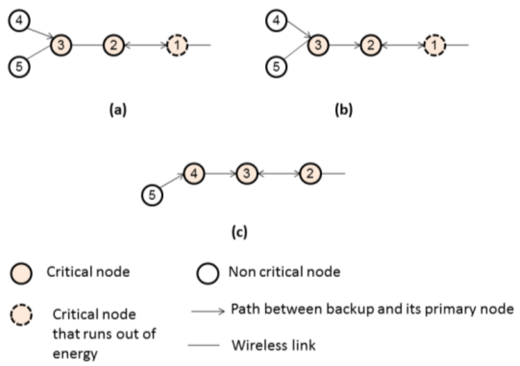

Fig. 3. The fault recovery if two sensor nodes are in the same time backup and primary one to another; (a) node 2 detect the failure of node 1, (b) node 2 select another backup, (c) node 2 moves to the position of node 1, node 3 replace node 2, node 4 replace node 3 and node 5 is selected as backup of node 4

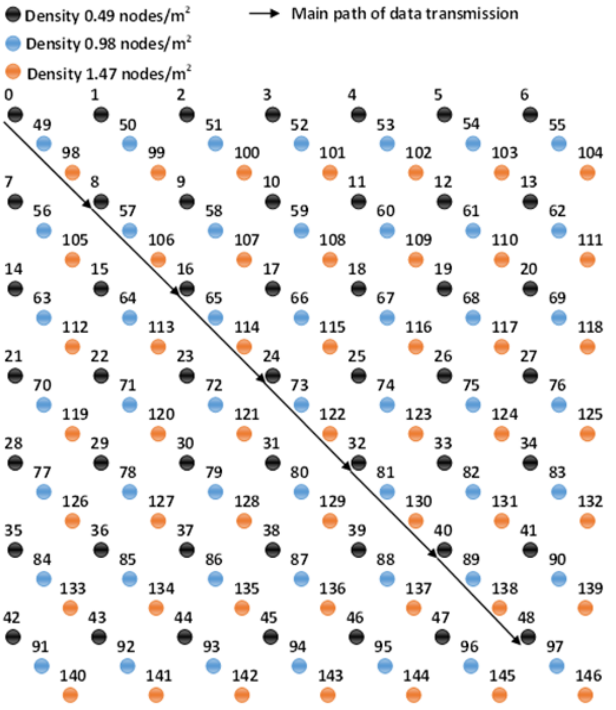

Fig. 4. The topology of the studied network

III. SIMULATIONS PRESENTATION

A. *Evaluation criteria and simulations parameters*

The performance of Multilevel and EDCR protocols is studied using Castalia simulator [10]. Indeed, to study the energy and time costs of failures recovery in the Multilevel and EDCR protocols, we choose to follow the evolution of energy and time costs based on i) the failures density: failed nodes' number on the total number of sensor nodes within the path of data transmission between the source and the sink. The path composed of nodes [0, 8, 16, 24, 32, 40, 48] (Fig. 4), is constructed by the protocols before reporting failures, will be later called "main path". ii) The surface density: number of nodes per m^2. With i) the energy cost: the energy required for the failures recovery, is the overall energy dissipated by the nodes participating to recover the failures. ii) the time cost: failures recovery time, is the time between the announcement of the failure by the node that runs out of energy and the failure recovery ending.

In all simulations, the remaining energy is set for the nodes that will fail to 400J and for the other nodes to 29160J, and we have used an ideal radio having 46.2 mW (-5dBm) for the transmitting power. At the beginning of each run, the nodes are uniformly deployed in the field. For different simulations the node with an ID 48 represents the sink and the node with an ID 0 is the source. These two nodes form the longest path in the network, the path that simulates the most of failures.

The table I summarizes the various parameters used in our simulations and their values.

TABLE I. SIMULATIONS PARAMETERS

Parameters		Values
Simulated surface (m^2)		10000
Initial energy (J)	of nodes that may fail	400
	of other nodes	29160
Source		Node 0
Sink		Node 48
Radio		IDEAL
Transmission power (dBm)		-5

B. *Deployment scenarios*

To study the effect of nodes density on the energy and time costs, we deployed three densities (0.49, 0.98 and 1.47 nodes / m^2) in a surface area of 10000 m^2. In the first density, 49 nodes have been deployed, the nodes numbered from 0 to 48 (Fig. 4). For the second density (0.98 nodes / m^2), 49 numbered nodes from 49 to 97 were inserted between the nodes of the first density. Similarly for the third density where the numbered nodes from 98 to 146 were inserted between the nodes of the second deployment.

Nodes that will fail are selected from the main path, the backup path is the path built after reporting failures. Furthermore, we assume that the nodes of the main path have the same history, so the nodes that may fail are declared "EnergyLow" at the same time in both protocols Multilevel and EDCR. Therefore, the maximum number of failures is 5. Thus, the possible densities of faulty nodes are 1/5, 2/5, 3/5, 4/5 and 5/5.

IV. SIMULATION RESULTS AND DISCUSSION

The position of faulty nodes on the main path influences on the simulations results. In fact, the energy and time costs depend on the number of neighbouring nodes of the faulty node which are involved in the construction of the backup path. To overcome this problem, we used a statistical average of the measures repeated three times. So, a script allowing to indicate in a random way the nodes to be faulty in the main path was developed. Table II illustrates this method, the example is given for Multilevel and EDCR protocols in the surface density of 0.49 nodes/m^2 and the number of nodes that will fail is 2 (failures density 2/5). This is repeated for the measures of Figs. 5 and 6 where we present, respectively, the costs of energy and time depending on the surface density and failures density. These figures show that the energy and time costs to recover faults increase with the surface density and the failure density. This is due to the communication of parent node with child nodes and these latter with the other neighbouring nodes during the failures recovery to find their new parent nodes in Multilevel. Also, for EDCR this is because the notification sent, if it is necessary, due to mobility and the notification sent in regards with energy low. Moreover, while the gap of time recovery between failures densities in Multilevel and EDCR remains practically constant from failures density to another, the gap of dissipated energies to recover failures in Multilevel and EDCR evolves in a remarkable way, in Fig. 5 it passes in Multilevel from 297,459J for the failures density 1/5 to 1590,945J for the failures density 5/5 and in EDCR from 11,459J for the failures density 1/5 to 45,945J for the failures density 5/5. The evolution of the gap in each protocol is explained by the fact that the energy cost is the sum of the consumed energies by the nodes involved in the failures recovery. Besides, this can be justified by the number of nodes that contribute to the recovery of failures that increases with the couple (failures density, surface density) in Multilevel. Also this can be explained in EDCR by the fact that the recovery is limited only to notification message, if it is required, due to mobility and the number of neighbouring nodes of critical node, that will receive notification message about energy dropping below a certain threshold, which increases with the aforementioned densities. This effect is not present in the failure recovery time, since the time cost is the difference between the time of failure announcement and the time of failure recovery ending.

TABLE II. THE STATISTICAL AVERAGES REGARDING THE COSTS OF ENERGY AND TIME OF 2 FAULTS RECOVERY IN THE SURFACE DENSITY OF 0.49 NODES/M^2 IN MULTILEVEL AND EDCR PROTOCOLS

		Energy of failures recovery (J)	Time of failures recovery (ms)
Multilevel	1st measure	65,800	6,756
	2nd measure	91,014	7,204
	3rd measure	81,302	9,400
	Statistical average	79,372	7,787
EDCR	1st measure	9,372	4,110
	2nd measure	8,831	5,900
	3rd measure	9,914	5,320
	Statistical average	9,372	5,110

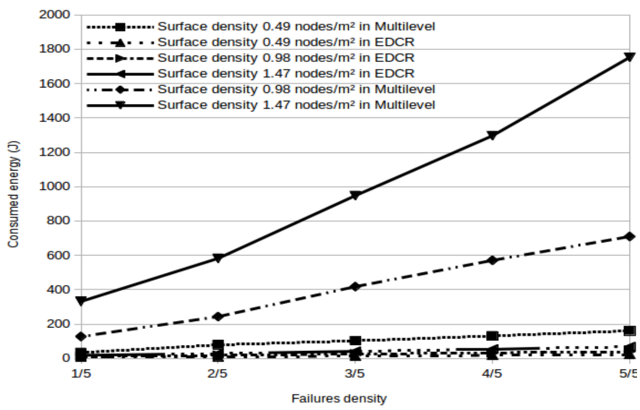

Fig. 5. The energy costs of the failures recovery depending on of the failures density and the surface density in Multilevel and EDCR

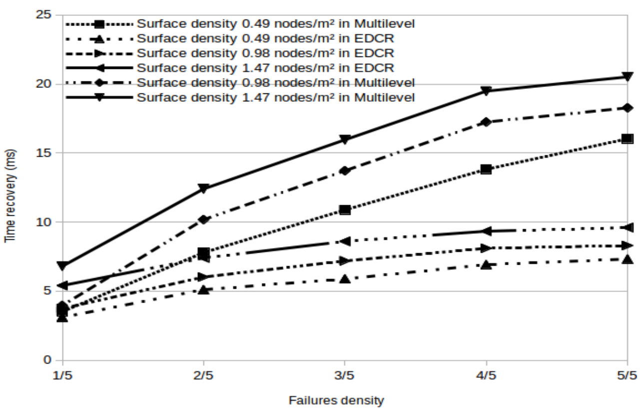

Fig. 6. The time costs of the failures recovery depending on of the failures density and the surface density in Multilevel and EDCR

V. CONCLUSION

In this work, we studied the energy and time costs to recover failures depending on the failures density and the surface density in the Multilevel and EDCR protocols. According to our assessments, we found that the energy and time costs increase with the increase of failures and surface densities. It was shown also that the redundancy of the nodes if it does not increase the failures recovery time when the number of failures in the path of data transmission is increased, it can significantly reduce the network lifespan when the failures number is quite significant. Hence the need to find, within the application constraints, the optimal point of the couple (desired maximum density of failures, surface density to deploy). On the other hand, EDCR provides better performance than Multilevel in terms of energy and time needed for failures recovery.

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