A Comparative analysis with validation of NSGA-III and MOEA/D in resolving the 3D indoor redeployment problem in DL-IoT

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Abstract **Compared to the two-dimensional one, the three-dimensional deployment in WSNs (wireless sensor networks) is more complex and real. In this paper, the problem of 3D positioning of nodes is studied while minimizing the number of nodes and the consumption of energy; and maximizing the coverage area and the localization rate. Indeed, the aim is to choose the ideal 3D positions in which new nodes are added while optimizing the mentioned objectives. The proposed approach is based on two evolutionary algorithms (MOEA/D and NSGA-III). The simulation model takes into account the implementation of a 433 MHz physical layer, a non-coordinated IEEE 802.15.4 CSMA/CA access method, and a reactive AODV based protocol for routing layer. The obtained results of the simulations with OMNeT++ are presented to prove the effectiveness of the proposed approach.**

Keywords 3D indoor deployment, coverage, hybrid localization, WiNo nodes, RSSI, FER, simulation, MOEA/D, NSGA-III.

I. PROBLEM OF 3D INDOOR DEPLOYMENT IN WSNS

WSNs are commonly used in the majority of the applications having specific monitoring needs such as intelligent buildings, environmental or military applications. The effectiveness of an RCSF is strongly influenced by the deployment process and the positioning of the sensor nodes. In a WSN, deploying nodes is a strategy that aims to define the number of nodes, their positions and the network topology. Different problems are discussed during the deployment of the nodes.

A WSN is said to be three-dimensional if the variation in the height of the deployed sensors is not negligible with respect to the length and the width of the RoI (Region of Interest). Indeed, the 2D model loses its relevance for submerged, airborne or terrestrial networks. Although the existence of different research which has focused on resolving issues for three-dimensional deployment, there still many research challenges in three-dimensional spaces that have not yet been explored as much as for two-dimensional networks.

The type of the deployment depends on the application. Indeed, there are applications where it is possible to choose the locations where to place the sensor nodes. This type of deployment is called deterministic. In some other applications, due to the inability to access the terrain, a large number of nodes are scattered over the RoI from an aircraft or a helicopter. This type of deployment is called non-deterministic or random. In this paper, the initial deployment is improved by adding a set of nodes in a deterministic way. Coverage is the most important objective to optimize when deploying a WSN. It is an essential subject in the design of a WSN. Coverage is generally interpreted as how a network of sensors will supervise the area of interest. Indeed increasing the number of sensors cannot always provide total coverage, and it is also costly to maintain high-density networks. As a result, other approaches need to be applied to avoid these problems and to improve coverage after the initial random deployment.

Moreover, the localization of the sensors is the most important factor which is related to the coverage. Localization is important when there is uncertainty about the exact position of some nodes. Indeed, the localization information is crucial especially when an unusual event occurs. In this case, the sensor node that detected this event needs to locate it and then report the location of that event to the base station.

Different objectives were considered for the optimization: the number of nodes, the coverage of the network, the localization, and the energy consumption. For most deployment formulations, the problem of optimal placement of sensor nodes is proved NP-hard **[1]**. Therefore, for large-scale instances, this problem cannot be solved by deterministic methods.

For this, an optimization approach based on the MOEA/D **[2]** and NSGA-III **[3]** is proposed to solve the coverage problem after an initial random deployment. Despite the different challenges in WSNs, most researches have focused only on post-deployment issues such as sensor locations, MAC efficiency or routing. Our proposed model is different from the existing models since it integrates the deployment of the sensor nodes, and the localization in a single model.

The problem of deployment in WSNs is related to another recent area of research which is the interconnection of objects in the internet of things (IoT). The IoT refers to the interconnection of embedded computing devices that are uniquely identifiable within the existing infrastructure. The idea of IoT was developed following the WSN concept. The objects can be buildings, industrial devices, aircrafts, cars, machinery, or specific parts of a larger system for humans, animals and plants. Since these connected objects do not support a specific communication technology, wireless communication technologies will play a major role, in many applications and industries. The small and inexpensive WSN sensors allow the IoT to integrate the smallest objects which can be installed in any environment at a reasonable cost.

This paper is an extension of our work in **[4]**, **[5]** and **[6]** where different algorithms such as the NSGA-III are modified and hybridized with other algorithms to solve the 3D indoor deployment problem.

The rest of the paper is organized as follows: in Section II, the used network protocols are discussed. In Section III, the simulation tests of the network are presented. Finally, a discussion is established in section IV, and a conclusion and perspectives are listed in section V.

II. Modeling of the network protocols

A. Modeling the 3D localization

Although 3D localization is more realistic and accurate than the 2D one, most existing localization systems focus on the 2D plane. Like 2D localization, two types of localization can be distinguished in 3D environments: Range-Free localization and Range-Based localization, which uses measurements of distance and related to radio signals angles to locate the nodes. Range-Based localization algorithms impose a certain hardware requirement for radio nodes. Therefore, they are more expensive to implement in practice. The Landscape 3D algorithm **[7]**, for example, is a 3D localization-based algorithm. Different Range-Free 3D localization algorithms exist like the 3D DV-HOP algorithm **[8]**, the 3Dcentroid algorithm **[9]** and the 3D MDS-MAP **[10]**.

In order to combine the advantages of the two types of localization, a protocol based on RSSI exchanges, hybridized with the DV-HOP protocol is implemented. Indeed, this hybrid localization method is based on the combination of the average distance per hop and the RSSI data for the 3D localization. This system improves the 3D DV-HOP localization technique by introducing an RSSI value to correct this distance by hop. First, the 3D DV-HOP protocol uses the network connectivity information to estimate the nodes locations in 3D space. Then the RSSI value can be easily collected to correct the distances between the nodes found by the DV-HOP as a function of the signal strength. The RSSI value is measured in both directions: from the mobile node, the received RSSI value of other nodes (fixed, nomad or mobile) is measured; then from each fixed, nomad or mobile node, the RSSI value received from the mobile node is measured. The final value of the RSSI between the mobile node and each other node corresponds to the highest value of the two values already mentioned. The 3D DV-HOP algorithm does not require three neighbor anchors per node as required by other classical localization algorithms. In our proposed model (3D DV-Hop + RSSI), four nodes (not necessary anchors) are required: three nodes of the 2D plane and one node for the height. Figure 1 shows the locations using the 3D DV-Hop + RSSI algorithm with a network topology with three anchors and four ordinary nodes. A_1, A_2, A_3 are anchors while N_1, N_2, N_3 and Nx are ordinary nodes.

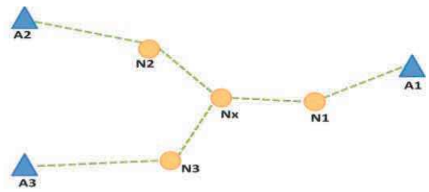

Fig. 1. Localization with the 3D DV-HOP + RSSI protocol

The RSSI value may be influenced by various factors other than distance, such as node movement, or energy level. Therefore, detailed modeling of the physical environment, LLC radio links, MAC and routing, greatly improves obtaining a precise distance from the RSSI value.

B. Physical layer (radio)

In our simulations, the physical layer uses a frequency set at 433 Mhz. Other parameters are initialized with significant values. Some values are fixed according to the used standard protocol such as 802.15.4 and some are derived from the empirical values of our experiments **[11]**. The following parameters are considered:

- Transmission power = 60 mW
- Reception gain = 50 mA
- Operating temperature = 25° c
- Bit rate = 256 kbps
- RSSI = initially (140)
- Bit Error Rate = initially (0.01)
- Indoor Range = 15m
- Maximum number of nodes = (by default 65000 as in the 802.15.4 protocol)
- Power supply = 3.6 v

C. MAC sublayer of the data link layer: CSMA/CA of 802.15.4

IEEE 802.15.4 is considered as a major technology of the WSN, and a great number of researches have been carried out to study the method of carrier multiple access with collision avoidance (CSMA/CA) in 802.15.4. When more than one station at a time attempts to emit a frame, a collision occurs, and eventually all data can be damaged. The CSMA-based algorithms attempt to break the synchronizations of faulty transmissions restarted at the same time, using exponential backoff random procedures. While wired devices can listen during their own transmissions and use CSMA with collision detection (CSMA/CD), wireless stations cannot listen to their own broadcasts and hear other collision transmissions at the same time, which consequently cannot be detected. Therefore, wireless devices use CSMA/CA. However, for the data link layer, a problem of access priority to the channel always arises if two nodes in range are speaking simultaneously. The 802.15.4 CSMA/CA protocol is modeled in our simulations.

D. Routing Layer: Reactive AODV

To model the routing layer, the reactive AODV (Ad-hoc on request Distance Vector) protocol is used. The AODV is a routing protocol for ad-hoc networks. It is designed to self-start in an environment of mobile nodes. In each node, AODV maintains a routing table. The entry of the routing table for a destination contains three essential fields: the next hop, a sequence id, and a hop count. In AODV, nodes discover roads in demand-response cycles. A node requests a route to a destination by broadcasting a RREQ message to all its neighbors. When a node receives a RREQ message but does not have a route to the requested destination, it transmits in turn the RREQ message. This node also remembers a path inversion to the requesting node, which can be used to transmit subsequent responses to this RREQ. This process is repeated until the RREQ reaches a node that has a valid route to the destination. This node (which may be the destination itself) responds with a RREP message. This RREP is a unicast along the reverse routes of the intermediate nodes until it reaches the originating node. Thus, at the end of this request-response cycle, a bidirectional path is established between the requesting node and the destination. When a node loses connectivity to its next hop, this node cancels its route by sending an RERR to all nodes that have potentially received its RREP.

In our case, each node, when receiving a RREQ, returns it to all its neighbors, including even the source that absorbs it. A TTL is also used which represents the maximum time (or number of hops) at the end of which a new RREQ with a higher sequence number is sent if no response is received from the destination node or from a node that knows a valid path to the destination. The destination receiving the RREQ chooses a new source from these neighbors. This destination node becomes the source and starts a new cycle by sending a new RREQ message. In our simulations, this process of request-response cycles stops after 4280 seconds of simulations (~72 minutes).

E. Energy modeling and network lifetime

A deployed active sensor dissipates energy during transmission, detection, reception of a message; or a period of inactivity. Therefore, energy efficiency is an essential key in designing a WSN. To model the energy consumption in our simulations, an initial energy indicator (***Eo***) is used in each node. According to the protocol 802.15.4, reception is more expensive than sending. Thus, E_0 will be reduced by i units if sending a message, and by 2*i units if a message is received. The equation (6) which models the energy consumption is used in the implemented energy model.

The energy consumption is linked to another indicator which is the lifetime of the network. Typically, the lifetime of the WSN is represented by the time after which the first node is out of service. Thus, for each optimization algorithm, the time corresponding to the lifetime of the network is measured in order to have an idea of the influence of the choice of the added nomad nodes locations over the lifetime of the network.

III. NETWORK SIMULATIONS WITH OMNET ++

In our simulations, the 3D case is considered. Four objectives were gradually considered (two objectives, then three, then four ones): the cost of deployment, the coverage, the localization, and the optimization of the energy consumption.

To validate the simulation, it is compared to the experiments carried out in our works in **[11]**. The same network architecture is used. It is based on 30 fixed nodes with known positions. The number of nomad nodes to be added is set to six. Their positions are determined by the used algorithms. Similarly for mobile nodes, only one node is used as trigger for the first message. The positions of the initially deployed fixed nodes are chosen according to the distribution law used by OMNet++ which tries to distribute uniformly the nodes from the center of the RoI. This leads to the non-coverage of certain zones at the borders if the number of fixed nodes is too small.

The execution scenario is as follows: an initial message is sent from the mobile node to a random destination d. Once d is found by the AODV protocol, it becomes the source and a new destination is chosen ... etc. This cycle is repeated until a stop condition is met, including a maximum simulation time.

To assess the connectivity in this scenario, a matrix of connectivity between the nodes is used. This matrix is deduced from the real results of our experimental observations in **[11]**. Thus, the same connectivity links of the experiments are used initially. Subsequently, in order to model the dynamism of the network, these connectivity links are subjected to a disturbance which enables varying the initial connectivity links. This perturbation concerns the calculation of the RSSI rates between the nodes. Indeed, a matrix of the RSSI rates which extracted from experiments is initially used. Then, this matrix is subjected to a perturbation (+/- 30 for each value) in order to have new connectivity relations between the nodes.

A. Working environment

Two main tools are used:

- OMNeT ++ 4.6 **[12]** is a free platform for the simulation and development of network protocols. OMNeT ++ IDE is based on the Eclipse platform and contains a simulation kernel library, a topology description language called NED, and a graphical user interface for running simulations. It provides a component architecture for C ++ programmed modules.

- JMetal 4.5.2 **[13]** is a java object-oriented platform that aims to develop experiment and study different meta-heuristics to solve multi-objective optimization problems. Using this platform, the proposed algorithms are implemented.

Figure 2 shows an example of the distribution of the nodes according to the OMNet++ interface in the simulations.

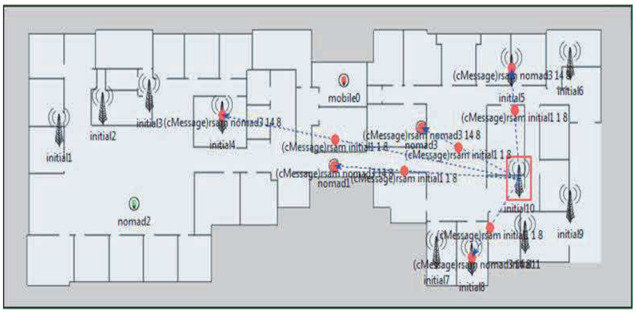

Fig. 2. The simulation Scenario

B. Variations in RSSI rates

To measure the localization, the RSSI metric is used, since the localization model is based on hybridization between the RSSI and the DV-Hop protocol. Therefore, the higher the RSSI, the more accurate the distance. Thus, the better the receptions, and the better the localization. A neighbor can be inserted into the neighbor table of a node only if the RSSI value of the detected node is greater than a predefined threshold. The theoretical value of this threshold is set at 100 in our simulations. Initially, the RSSI rates are based on the empirical values of the experiments **[11]**. Afterwards, to ensure the dynamism within the network, a disruption of the RSSI value is introduced via a random function (+/-30).

Figure 3 represents, for different number of objectives, the average of the RSSI rates which is measured for all the nodes in connection with the mobile node. In order to test the effect of increasing the number of objectives on the performance of the tested algorithms, our algorithms are tested with two objectives (number of nodes, coverage), then with three objectives (number of nodes, coverage, localization), then with four objectives (number of nodes, coverage, localization, energy consumption).

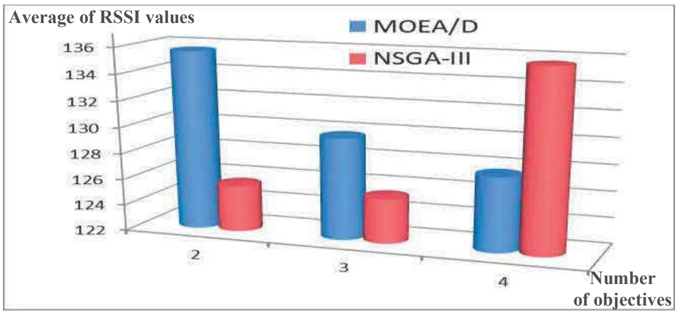

Fig. 3. Average RSSI rates during simulations

C. Variations in FER rates

To measure the coverage, the frame error rate (FER) is used as a measure to evaluate the quality of links between nodes. As a result, the lower the FER, the better the coverage. Although the values of the FER are less variable than those of the RSSI, we take, for each pair of nodes (node i - node C); i ∈ [1, 14], an average value which is extracted from four values taken with an interval of 10 seconds between the two nodes. Initially, the FER rates are based on the empirical values of the experiments **[11]**. Then, to guarantee a dynamism and realism within the network, a disturbance of the value of the FER is introduced via a random function (+/-0.04 to +/- 0.2). Figure 4 represents the average of the FER rates measured for all the nodes in connection with the mobile node.

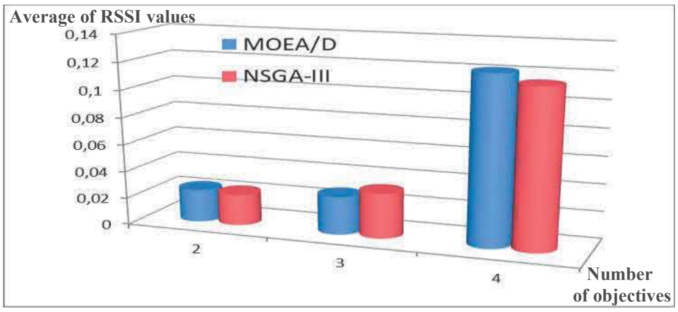

Fig. 4. Average of FER rates in simulations

D. Variations in the number of neighbors

To assess the network connectivity, the number of neighbors of the target is measured. Figure 5 represents the average of the number of neighbors of the mobile node per objective.

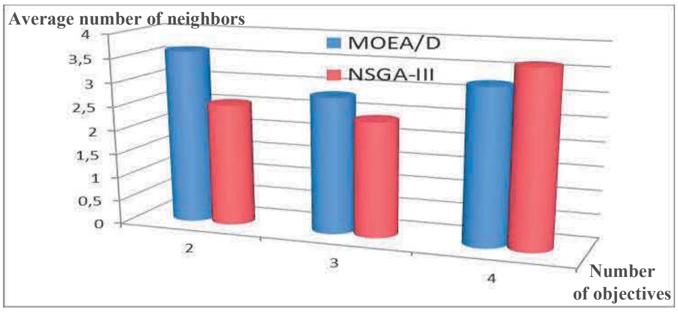

Fig. 5. Average number of neighbors in simulations

E. Variations in energy and network lifetime

Figures 6 and 7 represent the variations of the energy level of the network in the simulations over the time, for different number of objectives. For the two tested algorithms, an average of the energy indicator of the nodes is measured after the addition of the nomad nodes, according to the number of fixed nodes.

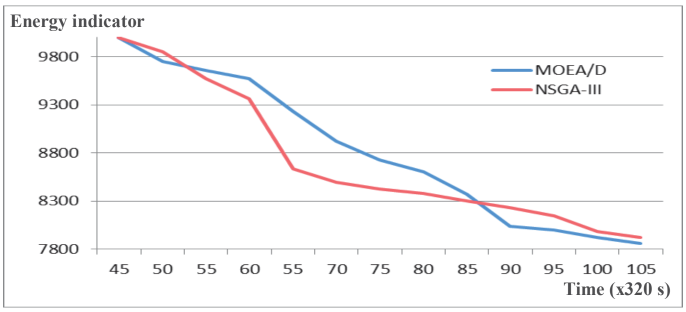

Fig. 6. Variation of energy in relation to the number of fixed nodes, for 2 objectives

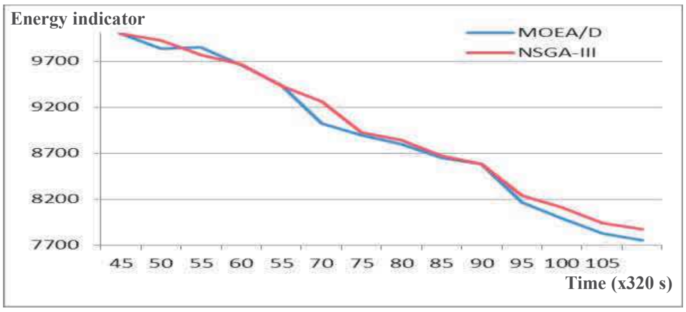

Fig. 7. Variation of energy in relation to the number of fixed nodes, for 4 objectives

Figure 8 shows the time (in seconds) beyond which the first node of the network is extinguished, for different number of objectives, which gives us an idea of the lifetime of the network.

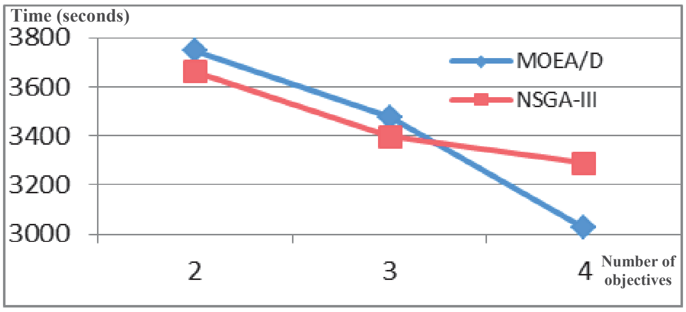

Fig. 8. Variation of the lifetime vs the number of nodes

IV. Discussion and Interpretations

In our simulations, the 3D case is considered. Four objectives were gradually considered (two objectives, then three, then four ones): the cost of deployment, the coverage, the localization, and the optimization of the energy consumption.

After analyzing the simulations, different interpretations can be envisaged.

- In some cases, lower RSSI averages are recorded after adding the nomad nodes. Despite this decrease indicating that the RSSI rates of the new (nomad) nodes are lower than the RSSI rates of the installed (fixed) nodes, the location rate, the coverage rate and the number of neighbors are improved. Given the objectives set by our approach, this decrease in RSSI averages is understandable. Indeed, adding a node to an x1 location makes it close to several nodes with a lower RSSI value. Thus, it's better to add it to a place x2 with a higher RSSI value but a smaller number of neighbors.

- The simulation results (Figures 4, 5 and 6) show conformity with the results of experimentations during the day **[11]**, in terms of the increase in coverage and localization rate, which proves the consistency of the simulation models and the effectiveness of the proposed approach in different contexts.

- By comparing the efficiency of the two proposed algorithms (MOEA/D and NSGA-III), the simulation results show that this efficiency is relative to the number of objectives to be met. For example, Figures 6 and 7 show that if the number of objectives is less than three, the MOEA/D is more efficient, while the NSGA-III is more efficient if the number of objectives exceeds three. This is explained by the fact that the MOEA/D is dedicated to multi-objective problems, whereas the authors of the NSGA-III propose it for many objectives problems.

To sum up, our work is a proof by simulations and experimentation of the observations of the MOEA/D and NSGA-III authors which has been proved only by tests on theoretical problems instances (benchmarks).

V. Conclusion and Perspectives

This paper aims to provide a 3D deployment scheme in indoor wireless sensor networks while satisfying different objectives. The objectives taken into consideration are the minimization of the number of nomad nodes to be added, the maximization of the coverage area, the maximization of the accuracy of the localization as a function of the signal detection based on a DV-Hop algorithm corrected by the RSSI, and the minimization of the energy consumption. An approach based on two algorithms is proposed: the MOEA/D and the NSGA-III. Our contributions are tested with simulations carried out using the OMNeT ++ simulator. For the many-objective case, the NSGA-III shows a significant improvement in the coverage quality and the localization accuracy. In the future, several issues can be investigated. The proposed strategy can be improved to ensure the deployment while considering various other objectives, such as lifetime and network connectivity. Moreover, it is interested to intensify the deployed network by adding new nodes in order to better satisfy the localization constraint imposing four neighbors for each target. The experiments will be repeated to study the influence of the network density on the results. Other research directions can be investigated such as considering the existence of obstacles in the 3D space, and implementing a more realistic energy model with OMNeT ++ based on the management of BO and SO values **[14]** of the 802.15.4 CSMA/CA protocol.

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