Intelligent Wireless Sensor Network Deployment for Smart Communities

Francisco Luna, Juan F. Valenzuela-Valdés, Sandra Sendra, and Pablo Padilla

The authors introduce the concept of intelligent WSNs. In order to outfit the WSN of a huge amount of possibilities to route and control the different nodes, their nodes incorporate the possibility of transmitting and receiving signals from/ to several nodes jointly through beamforming. In their approach, this latter technique is intelligently applied to allow the deployment of new WSNs to be able to react and to adapt its features depending on the environmental conditions.

ABSTRACT

Smart Communities demand a huge amount of data to monitor different human activities. Until now, wireless sensor networks (WSNs) have provided these data with a low cost and low intelligence networks. However, the constraints and the required baseline performance of WSNs have increased exponentially, and there is a lack of a global proposal to satisfy the demand of Smart Communities. There are several approaches regarding efficient WSN deployments to maximize network lifetime and performance. The vast majority of those proposals try to separately address several inherent constraints and limitations related to energy and node lifetime. In fact, they typically provide efficient management approaches based on existing solutions, but they do not propose new tools or algorithms to afford them. To tackle this problem in a global manner, we introduce the concept of intelligent WSNs. In order to outfit the WSN with a huge amount of possibilities to route and control the different nodes, our nodes incorporate the possibility of transmitting and receiving signals from/to several nodes jointly through beamforming. In our approach, this latter technique is intelligently applied to allow the deployment of new WSNs to be able to react and to adapt its features depending on the environmental conditions, maintaining QoS and enlarging network lifetime. This is the main goal of our proposal.

INTRODUCTION

The demand for communication services in very diverse scenarios is becoming a challenging issue, in particular in those related to Internet of Things (IoT) and Smart Communities. The later concept goes beyond those such as smart cities, covering a wider area (such as a city, its surrounding area and regional neighborhood), combining both urban areas and rural areas [1]. In such smart scenarios, wireless sensor networks (WSNs) have the potential to provide a ubiquitous network of connected devices, enabling support to information, sensing and communication systems. As a consequence, Smart Communities are one the most promising scenarios to use WSNs, although our approach can also be applied to other scenarios such as, for example, precision agriculture (Fig. 1), and monitoring mountain roads or coastal lagoons (an underwater WSN).

A smart community is usually implemented in a distributed manner due to the particular and independent necessities of users in their relation with their immediate environment and the complete community. Thus, a decentralized approach is commonly adopted to implement the networking infrastructure of such communities, for recruiting information from sensors, engaging citizens equipped with their smart devices, or providing cloud computing capabilities and data analytics, among others. For this type of distributed and diverse communication scenario, WSNs have arisen as a real, effective solution that provides proper performance at the lowest cost. The necessity of autonomous support for a variety of potential applications for Smart Communities, along with the latest advances in technology and device consumption, have driven WSN deployment strategies to devise more and more adapted solutions. Such particular features have turned WSNs into one of the most versatile options for the definition of ad-hoc communication networks. The core of WSNs is formed by a variety of small and simple communication nodes with power autonomy, reduced processing capabilities and most likely with sensing ability. The nature and features of the WSN scenarios, typically with a significant number of sensor nodes connected to a central node (high energy communication node (HECN)), joined to the huge amount of possible applications, have presented many challenges in WSN design and management.

Considering the autonomous and low-consumption nature of WSNs, one of the crucial challenges lies in the physical link and network layers, which are of paramount importance in the effective development of WSNs with a guaranteed lifetime and performance. Many efforts have been applied to research on these issues [2], related to efficiency for the radio frequency (RF) interface, network power awareness and low duty cycle or node processing capacity, among others. All those efforts drive to a hard necessity of reducing the entire power consumption of the different nodes, mainly the critical ones, and the network as a whole. The nodes considered as critical are the ones that play a more active role in the network's performance, either because they generate a higher flux of data toward the HECN, or because they act as node relays of large chunks of data coming from other nodes. Strategies to address this issue at both the network and physical layers are usually adopted.

On the one hand, at the network layer, the

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main target is to find energy-efficient transmission routes that also pursue the lifetime preservation of such critical nodes that may determine the entire network lifetime. In such a situation, the complete network energy consumption and its distribution within the network nodes depend directly on the routing strategy defined. This strategy must also guarantee the reliable transmission of data from the sensor nodes to the destination. Depending on the distribution of the network nodes and the traffic flow through the network, there are many routing strategies [3] that may be combined to form an intelligent wireless network that accounts for maximizing the network lifetime.

On the other hand, at the physical layer, an effective way to expand the network lifetime is to reduce the energy consumption of the nodes, particularly that of the critical ones (bottlenecks), by optimizing the wireless communication that takes place through them. In such a situation, the losses at the wireless channel that the radio signals suffer may provide useful information to save energy. This information is about how the radiation pattern and its main beam are configured to reach the desired destination with minimal energy consumption without disrupting the communication. The possibility of reconfiguring the radiation pattern, commonly known as beamforming [4], enables the efficient usage of energy by maximizing the transmission and reception gain of the channel power balance. Beamforming is based on the coordinated and combined functioning of several antennas radiating to generate a directive beam in some particular direction, and therefore requires some sort of clustering or grouping of the WSN nodes. Indeed, it has been shown that beamforming is able to extend the lifetime of WSNs [5]. This can be done through a smart use of the radiation pattern, reducing the energy radiated toward the unwanted directions and maximizing the energy in the desired directions. The minimization of the radiated energy in undesired directions has additional benefits besides saving energy, for example, for avoiding interferences in order to maximize the throughput, improving security by blinding enemy nodes, and so on.

This article presents a novel approach to provide WSNs with intelligence capabilities for Smart Communities, based on node grouping and beamforming. This approach lets us reduce the effect of critical nodes in the network by distributing node contribution to the network in terms of functioning time. The article is organized as follows: the following section refers to related works. Then we present the configuration and architecture of the proposed approach. The following section is devoted to the experimental frame, the results of a real example of a WSN in Smart Communities, and their discussion, including security issues related to the isolation of vulnerable nodes through alternative routes. Finally, conclusions are drawn.

RELATED WORKS

Several approaches exist regarding efficient WSN deployments in order to try to maximize the network lifetime while maintaining the level of performance. A recent survey [6] distinguishes up to nine different techniques in order to maximize the WSN lifetime and includes up to 179 works especially aimed at this goal. The baseline point to understand the latest proposals to improve the WSN operation is to know the main constraints that such networks present. As mentioned, WSNs have some problems regarding hardware constraints and energy limitations due to the node electronic operation and protocol performance. The possibility of scaling the number of nodes in a WSN and the kind of topologies to be implemented under this technology are also several issues to be considered [7]. While years ago WSNs were mainly deployed forming star networks with a very limited number of nodes, nowadays we can find WSN solutions with hundreds of nodes forming a mesh network. This section revises several proposals that elaborate, separately, on saving energy with beamforming, clustering and adding intelligence in the context of WSNs.

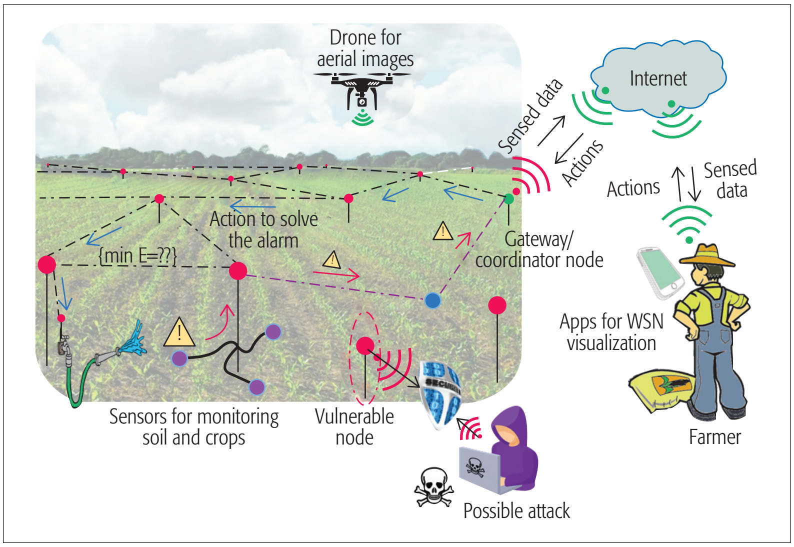


Figure 1. Example of Smart Community applied to precision agriculture.

At first glance, it is easy to find several proposals where beamforming is used to improve the network lifetime [6]. This is the case, for example, in the work presented by J. Feng *et al*. [8], where the authors use collaborative beamforming to save energy in the process of data transmission, as this technique improves the directivity of the electromagnetic waves. This induces that the received signal strength at the receiver is stronger, allowing the usage of longer distances to reach a destination node and, in most of the cases, also a reduction in the number of nodes.

Another quite interesting technique for organizing WSN nodes and saving energy is the use of cooperative group-based configurations [9]. In this case, Garcia *et al*. propose this technique to reduce the global energy consumption of the WSN. In addition, this way of grouping nodes reduces the number of the messages transmitted between nodes. Consequently, it has registered an increase of the network lifetime.

Beamforming and clustering can also be used jointly [5] to prolong the WSN lifetime, where the waste of energy linked to the increase in the communication distance is compensated by beamforming. Other problems are the overhead of the nodes or cluster-head nodes that are near the HECN, which have to transmit data from the nodes out of the range of the HECN. The work also discusses the potential incurred delay

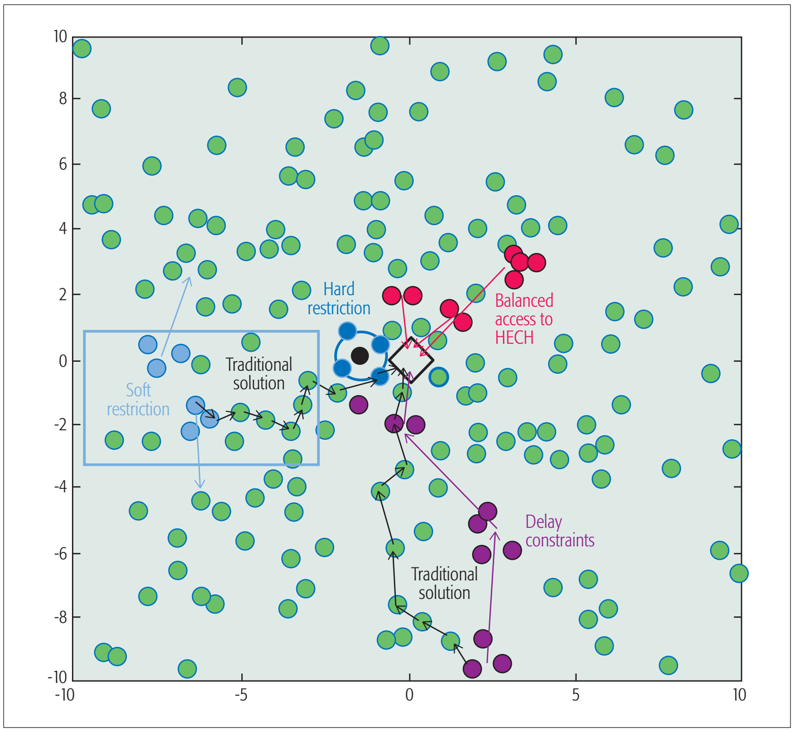


Figure 2. Schematic example of sensor deployment based on a global parametric optimization. The traditional solutions are in dark green, the soft restrictions (adverse propagation conditions avoidance) are in cyan, the hard restriction (enemy node avoidance) are in deep blue (enemy node in black) and delay-related constraints are in pink colour. The HECN is considered to be in the center of the figure.

when multi-hop strategies are implemented, and even more if nodes might be in sleep or standby modes.

The current tendency related to WSNs is to include new features that provide certain intelligence to this type of network. It is also a requirement and an enabling technology for Smart Cities and Smart Communities, as stated in [10]. However, despite the variety of solutions that can be found in the literature in order to improve the performance of WSNs, such as the selection of works previously mentioned, the concept of *intelligent WSN deployment* introduced in our work has not been contemplated before. There are some works that mention the concept of intelligence, such as [11], but they mainly present efficient management approaches based on existing solutions, and they do not propose new tools or algorithms to afford them. In our approach, the idea is to deploy WSNs that are able to react and adapt their features as a function of environmental conditions, that is, if the WSN is deployed in a very variable environment, the network should be able to reconfigure and decide to select the best setting to transmit, while maintaining the quality of service (QoS) and enlarging the network lifetime. This is the main goal of our proposal.

INTELLIGENT WSN CONFIGURATION AND ARCHITECTURE OF THE PROPOSED APPROACH

As previously described, there are many solutions in the literature in order to improve lifetime, throughput, security and delay constraints for WSNs. However, for Smart Communities a global approach that solves adequately all these necessities simultaneously is required. Our solution is a Smart WSN that permits the adjustment of different parameters, being adapted dynamically to the WSN conditions. This solution goes through the combined implementation of beamforming and sensor deployment based on a metaheuristic algorithm.

Considering the addition of intelligence to the WSN, the advantages of beamforming are introduced in the network not only in the operation stage, but also in the initial deployment stage, deciding the optimal node placement. As a consequence, with smart beamforming and sensor deployment, we can select and configure the best architecture and topology to reduce to the minimum any of the following parameters in the WSN. First, we can reduce the energy consumption of the nodes that are near to the HECN in order to maximize the lifetime of the entire WSN. With such approach, we can improve the hop distance for maximizing the number of nodes or groups of nodes that can reach the HECN and, in this way, distribute the information that they must forward from other nodes to the HECN, behaving as a relay. Second, the nodes can implement smart routing because the protocols have a huge amount of new options for routing with different grouping possibilities and different hop distances, depending on the beamforming configuration. Thus, the routing protocol must consider the following possibilities: avoidance of adverse propagation channel conditions (soft restriction), avoidance of enemy nodes (hard restriction), and the minimization of the number of hops in order to reduce the delay and network latency. Finally, with beamforming it is easier to add reconfigurability to the networks to react against changes in the network performance, by finding routing alternatives when a node fails, or by balancing some heavy traffic routes in order to distribute the energy consumption of the critical nodes (the more active ones) surrounding the HECN, thus maximizing the WSN lifetime. This innovative intelligent solution is shown in Fig. 2. In this figure, we can see the different "intelligent solutions" that the algorithm can reach by using beamforming, versus the "traditional solutions." Moreover, Fig. 2 illustrates the different problems that can be solved with an intelligent WSN that implements beamforming. In that way, this figure includes, marked as dark green arrows, what a quite standard solution is usually deployed: information gathered in the most outer nodes of the WSN is routed using a shortest path strategy. The smart solutions that the algorithm can reach by using beamforming are indicated as follows. Red nodes: do not have direct connection to the HECN when operating individually; can be grouped to use beamforming and then act as a relay, reducing the overload of the critical nodes that are adjacent to the HECN. Cyan nodes: if a region of the working area does have adverse propagation conditions, grouping nodes to perform beamforming can reach alternative paths to the HECN (soft constraint). Deep blue nodes: if an enemy node is detected, beamforming can null signals toward this direction to increase security (hard constraint). Pink nodes: information from nodes at the outer regions of the working

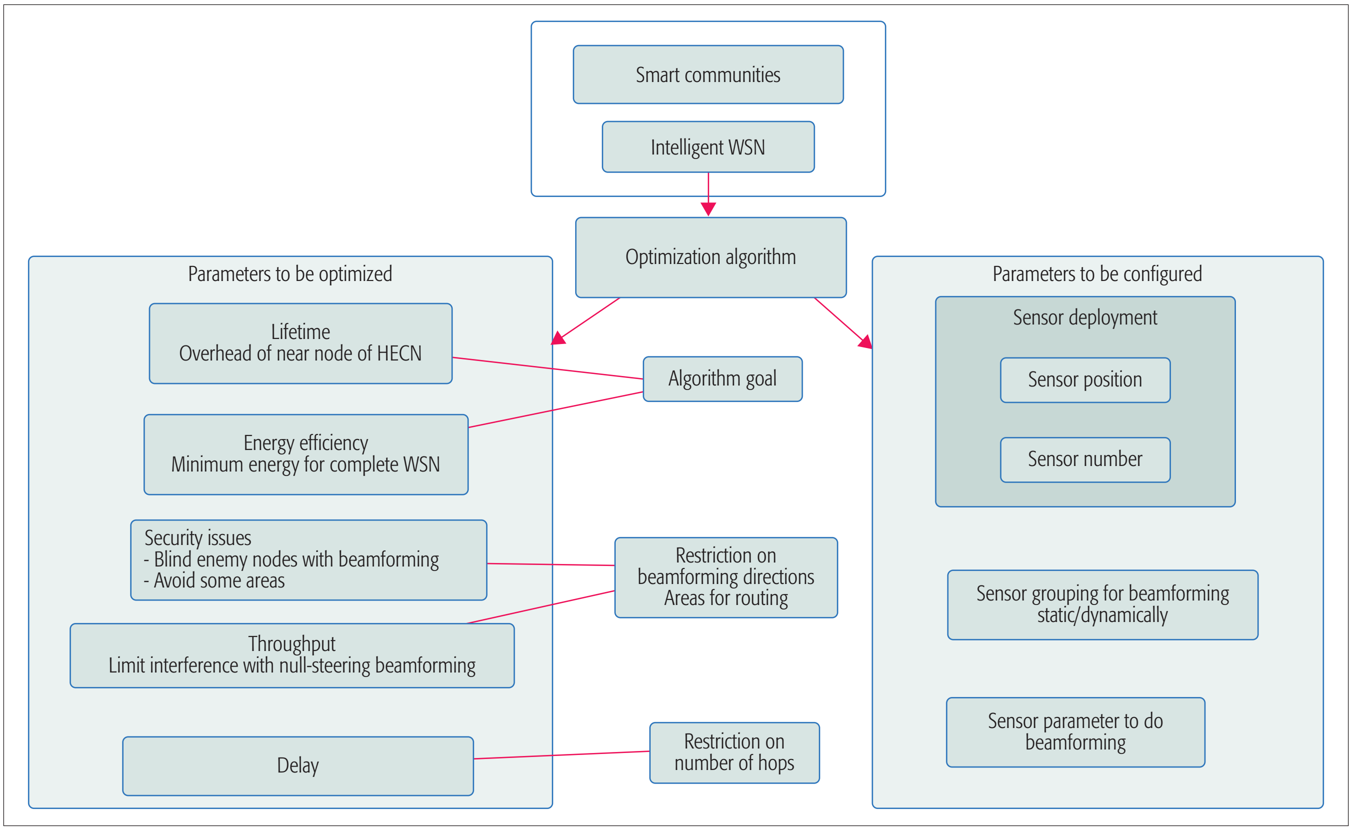


Figure 3. Proposed intelligent functions for Optimization Algorithm.

area can be forwarded to the HECN in a smaller number of hops.

In order to add intelligence to WSNs, it is necessary to propose a smart algorithm that can manage all the restrictions and requirements together and make decisions to optimize the performance of the WSN. As *"restrictions and requirements,"* it is understood: the data from the WSNs (battery state, data to send, and so on), the delay, channel or security restrictions (delay constraint, enemy node positions, adverse propagation conditions), and the desired goal performance of the WSN (minimum global energy consumption, and lifetime and coverage maximization), and routing. The algorithm can act on the following parameters dynamically: first, the position of the sensors, which allows the algorithm to place sensors strategically; second, the algorithm also determines whether sensors transmit signals jointly with other sensors (using beamforming) or individually (without beamforming). That is, for example, one node can transmit individually, jointly with another node or jointly with two nodes. This architecture of intelligent algorithm is displayed in Fig. 3. Different options can be chosen to implement the intelligent algorithm. Our approach is based on a two-layer optimization problem, as shown in Fig. 4. The first optimization layer is a multi-objective optimization problem in which, given a set of nodes, they have to be placed in the working area (Step 1 in Fig. 4). In this deployment phase, nodes can be activated (green background) or deactivated (grey background). A deactivated node is as if it does not exist anymore in the WSN, and hence it is not taken into account for any subsequent computation of the problem objectives by the multi-objective optimization algorithm. This activation flag is used to enable the algorithm that manages solutions with a variable number of deployed nodes. The number of deployed nodes is the first problem objective, which has to be minimized (i.e., reduce the cost of the WSN). Then, in Step 2, the beamforming phase takes place. It requires two basic parameters: the number of nodes that are allowed to conform the beam together, and the minimum communication range within which beamforming can be performed. With these two parameters, an extended set of nodes now appear in the working area (Fig. 4): the actual nodes (green nodes), and the beamforming (BF) nodes (red nodes), that are placed in the centroid of the set of original nodes. For simplicity, a BF node cannot be used to conform the beam of other BF nodes. Then, the second optimization layer comes into play: from the set of all nodes (either actual or BF), a subset of them has to be chosen so that they all are connected to the HECN, and the consumed energy is minimal (or, equivalently, the WSN lifetime is maximum). The former criterion (connectivity) is a constraint, whereas the latter (energy consumption) is the objective function to be minimized in this step. This energy efficiency is actually measured in terms of the node that depletes the fastest its available energy, thus being the first one that runs out of battery life. In this second optimization step, a single-objective optimization problem is therefore defined. This resulting WSN lifetime of the second optimization layer is the second objective function for the first optimization layer. There are several constraints that any feasible solution has to satisfy:

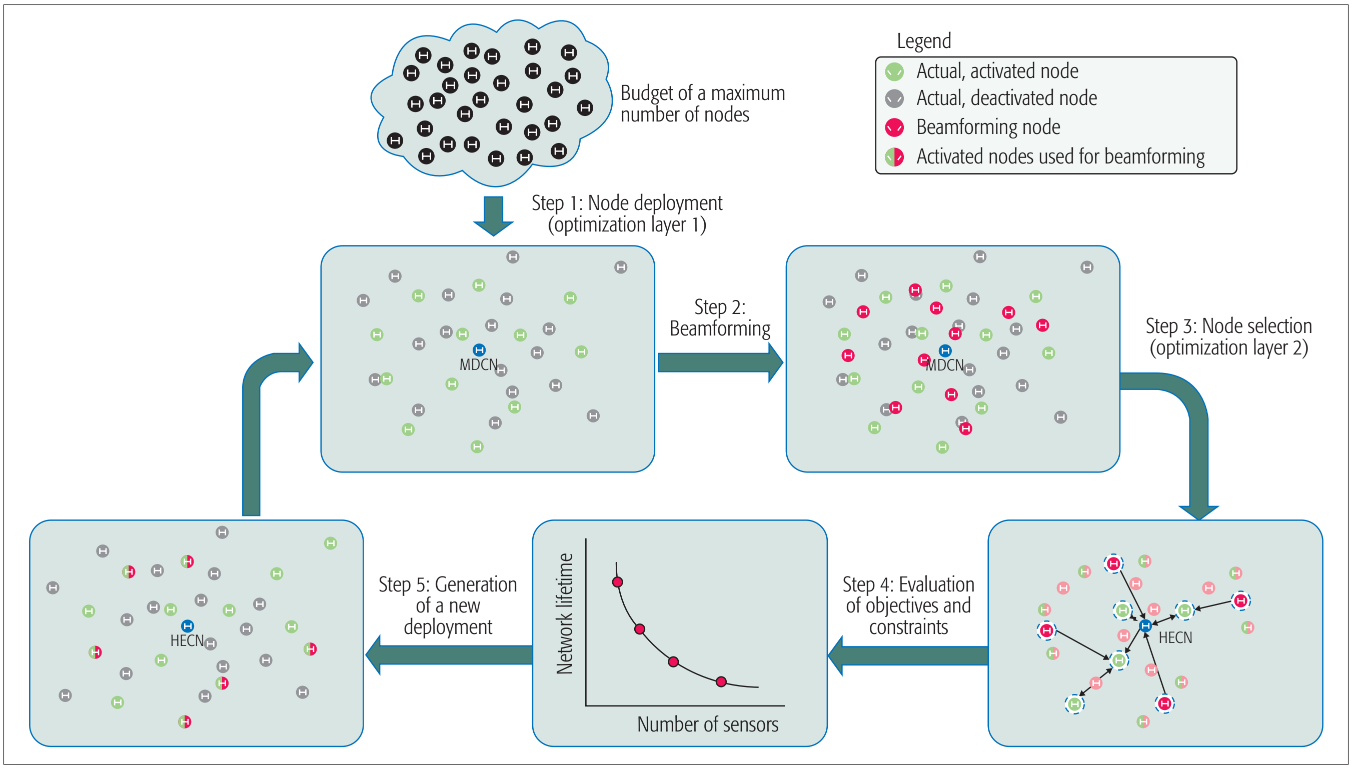


Figure 4. Proposed approach based on a two-layer optimization problem: layer 1 is a multi-objective optimization problem for node placing and layer 2 is the subsequent optimization step for node selection. Black nodes are the maximum number of nodes, Grey nodes are the possible placement node, green nodes are the simple nodes, red nodes are the beamforming nodes.

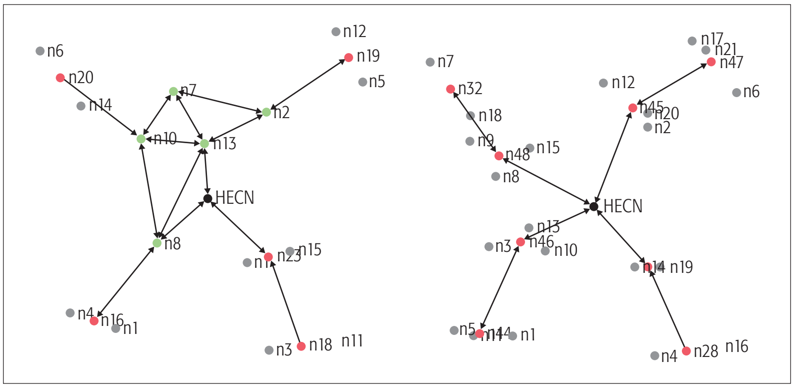


Figure 5. Two trade-off solutions of 100x100 m2 instance with a) 15 deployed nodes and an energy consumption of 247.80 J, and b) 22 deployed nodes and a consumed energy of 22.19 J.

- At least 90 percent of the area must be monitored by the deployed nodes.
- There must exist a path between any deployed node and the HECN.
- BF nodes cannot share their component nodes, that is, an actual node that is used to conform the beam of a BF node, cannot be used to conform the beam of any other BF node.
- Also, if enemy nodes exist, none of them can receive any signal by directing the beam toward a different direction.

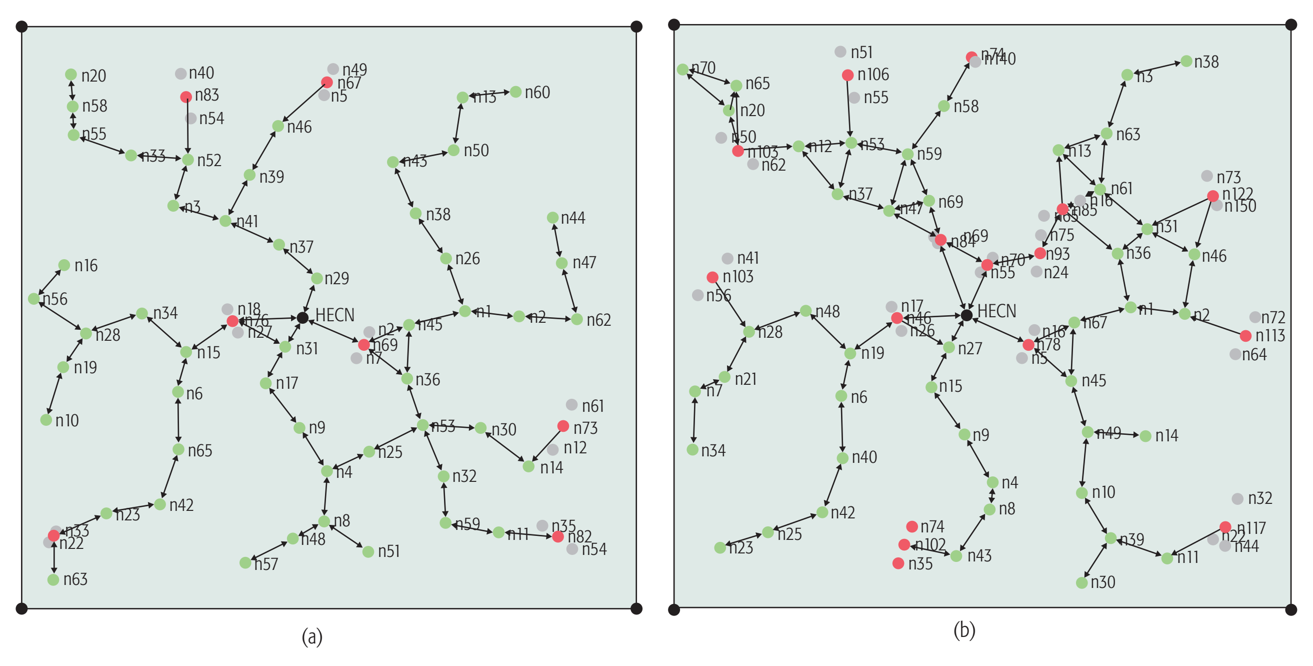
Let us briefly provide the reader with a bit more on the details of the approach. The two optimization problems defined are addressed with metaheuristic algorithms as they are that complex and potentially that large that exact algorithms cannot be used. NSGA-II [12] (multi-objective) and a steady-state genetic algorithm [13] (single-objective) are the metaheuristics used, respectively, in optimization layer 1 and the optimization layer 2. An enhanced algorithmic feature has also been required to face the large computationally demanding tasks that involve this two-level approach: parallelism. Indeed, the NSGA-II algorithm has been parallelized in a master/worker approach [14] so that Steps 1 and 5 in Fig. 4 are performed in the master node, and Steps 2, 3, and 4 are remotely done in parallel in the worker nodes. The algorithm is able to profit from a computing platform composed of 550 cores. The Java source code of both the problem and the algorithmic framework is available for free downloading at http://metanet5g.lcc.uma.es/files/bf.zip.

It is important to remark that our intelligent deployment algorithm can be easily modified in order to adapt to the particular necessities of Smart Communities. For example, the algorithm is able to assign priority to some goals, as the maximization of the lifetime versus the global energy consumed. Also, the algorithm is able to satisfy very hard constraints.

EXPERIMENTAL FRAME AND RESULTS

EXPERIMENTAL RESULTS

Two different results provided by the metaheuristic algorithm are respectively shown in Figs. 5 and 6, where the deployment of the nodes (their position) and the route from each one to the HECN are included. Nodes are labeled with a unique id number, and their color indicates whether the nodes are using beamforming or not. Indeed, green nodes are actual nodes



(a)

(b)

Figure 6. Two trade-off solutions of 500x500 m2 instance with a) 66 deployed nodes and an energy consumption of 1291.92 J, and b) 77 deployed nodes and an energy consumption of 1291.92 J.

working individually (without using beamforming), while red nodes are the equivalent nodes (fictitious) of the actual nodes that are actually grouped to perform beamforming, being these real nodes colored with gray background. As has been already stated, the intelligent algorithm can be modified in order to optimize several objectives. Two different scenarios are chosen as an example of the algorithm performance regarding the size and the amount of data to be sensed. Figure 5 shows two compromise solutions reached by the algorithm for a small scenario (100x100 m2) that is fully covered, that is, the entire working area is monitored by a sensor, and all the sensors have a path that connects to the HECN. In Fig. 5a, a tentative solution with 15 deployed nodes and an energy consumption of 247.80 J is displayed. It can be seen that node n13 is a potential bottleneck as it has to act as a relay for all the data gathered by, from left to right, n6, n14, n10, n7, n2, n5 and n12, requiring three hops in the worst case to reach the HECN (i.e., nodes n6, n14, n5 and n12), which increase the energy consumed at n13. On the other hand, Fig. 5b shows a non-dominated solution with respect to that of Fig. 5a, using 22 sensors deployed, and a consumed energy of 22.19 J. This solution also meets the constraints above, but using a different deployment in which all nodes are grouped to use beamforming. With this new configuration devised by the multiobjective metaheuristic, any node of the network can reach the HECN in two hops at most, decreasing the energy consumed as fewer hops are required. Analogously, Fig. 6 includes two compromise solutions for a larger scenario (500x500 m2). In Fig. 6a, the solution displayed has 66 nodes deployed and an energy consumption of 1291.92 J, whereas Fig. 6b plots a solution with 77 nodes and an energy consumption of 999.76 J (note that they are non-dominated as one objective cannot be improved without worsening the other). Indeed, in the former, beamforming is scarcely used and, as a consequence, nodes that are adjacent to the HECN have to forward data from many nodes located in the outer zones of the working area. In the latter figure, more nodes are grouped to perform beamforming, which allows an increase in the communication distance, reducing the total number of hops to transfer data to the HECN, and thus reducing the energy consumed, but at the cost of increasing the number of nodes deployed.

DISCUSSION

After analyzing the results of the use of the optimization in network deployment and the subsequent performance that beamforming offers, we can conclude that there are several scenarios considered as Smart Communities where the use of our proposal would greatly improve the performance, stability, efficiency and safety level of these intelligent WSNs [15].

Some examples of these could be underwater WSNs for aquatic environment monitoring or autonomous networks for efficient control of precision agriculture, among others. As we can see in the example of Fig. 1, these types of networks are composed of a set of wireless nodes that take data from sensors located on the soil. Because these WSNs work under wireless technologies, some of these nodes may be susceptible to attack. Thanks to our approach, the nodes used to transmit data can be reorganized and, after calculating the beamforming, these vulnerable nodes can be left out of those necessary for the transmission of the events generated in the network. Furthermore, the minimum energy for data transmission can easily be calculated at runtime in order to enhance the network lifetime and stability. The network itself, through the coordinator nodes, can establish a series of actions, such as the activation of water sprinklers, to solve problems detected. Finally, this type of network allows us to remotely view and control agricultural exploitation through mobile devices, if necessary.

Our approach introduces the concept of intelligent WSN deployment for global network adjustment that adequately solves all the possible constraints simultaneously. Our solution permits the adjustment of different parameters, being adapted dynamically to the WSN conditions, to maximize different performance metric as the network lifetime and global energy consumption.

CONCLUSION

This article presents a novel idea in order to introduce intelligence in the deployment of WSNs. Our approach introduces the concept of intelligent WSN deployment for global network adjustment that adequately solves all possible constraints simultaneously. Our solution permits the adjustment of different parameters, being adapted dynamically to WSN conditions, to maximize different performance metrics such as the network lifetime and global energy consumption. Several experimental results were shown for different scenarios. This solution goes through the combined implementation of beamforming and sensor deployment based on a parallel multi-objective metaheuristic algorithm. This proposal makes WSNs able to react and adapt their features depending on the environment conditions, maintaining the quality of service (QoS) and enlarging the network lifetime. The results show different solutions regarding the algorithm configuration. Future work may be focused on the implementation of intelligent sensor harvesting in order to add more reconfigurability and performance improvements to the algorithm.

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BIOGRAPHIES

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