A case study for evaluating IEEE 802.15.4 wireless sensor network formation with mobile sinks

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Abstract—Wireless Sensor Networks are traditionally composed of a multiplicity of sensor nodes that sense given phenomena and deliver the sensed data to specific sink nodes. In the most of the application scenarios, sensor nodes have been considered motionless. On the contrary, interesting possibilities arise if some sensors are embedded in devices carried by mobile agents as people, cars, animals, etc. If sinks move within the considered sensor field, they are able to provide both sparse sensing and collecting of data measured by static sensors placed at fixed locations. The main goal of this work is to evaluate, through simulations, the impact of sinks’ mobility in a wireless sensor network created by using the topology formation mechanism provided by the IEEE 802.15.4 Standard. To this aim, as a practical case study, we consider a wireless sensor network deployed in a museum used to monitor the presence, the localization and other parameters of artworks exposed in it. In this context, we analyze how sinks’ mobility affects connectivity and energy consumption for network formation and re-configuration.

Index Terms—Wireless Sensor Network, IEEE 802.15.4, topology formation, sinks’ mobility.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are conceived as a plethora of small sensor devices able to sense physical or environmental phenomena and with the task of delivering, possibly through multi-hop paths, to a specific node (named sink) the collected information [1]. These scenarios can offer incredibly new possibilities if some sensors are embedded in devices carried by mobile nodes as vehicles, humans, animals and so on. In the emerging architecture for WSNs (see papers [2], [3] and [4]), the sinks move in the system and have the task of measuring the environment by themselves and/or of collecting data measured by other nodes (e.g., by a static branch of the WSN). Typically in these architectures sinks are cellular phones equipped with sensing devices and short range wireless interfaces like ZigBee [5].

The idea of exploiting the mobility of data collection points (sinks) for the purpose of increasing the lifetime of a WSN with energy-constrained nodes, has been explored in several papers ([6], [7]). In these scenarios sinks pick up data from fixed sensors, buffer it and drop off the data to given access points, when in proximity. The possibility to have mobile sinks offers several advantages:

• it is not required an optimized pre-deployment of WSNs;
• by controlling the sink movements it is possible to obtain remarkable lifetime improvements (as shown in [6]);
• mobile sensors can match the coverage of static nodes with considerably fewer nodes (as presented in [7]).

In this paper we focus on an application of a WSN with mobile sinks (museum monitoring) and we concentrate on a specific wireless technology: the IEEE 802.15.4 [8]. The focus on this standard is motivated by the fact that several museums preserve their works of art by controlling systems based on wireless sensor technology and these wireless monitoring solutions are based on ZigBee ([9]). Furthermore, apart the specific application scenario, we aim at evaluating in general some effects of the sinks’ mobility on network formation and re-configuration in an IEEE 802.15.4 network. While several works have analyzed the performance of the IEEE standard when transferring data in an already formed WSN (e.g. the paper in [10]), few works have looked at the control part of the network formation and in a context where sinks move. For this reason, we concentrate only on the network part related to sinks and to their exchange of control messages. During both network formation and re-configuration control messages are exchanged to allow sensors to associate one each other and to form a network able to retrieve sensed information. These control messages have a significant weight on the energy consumption of the WSN as shown in the work in [11]. We evaluate how this energy consumption is influenced by the mobility of the sinks. Also the effects of the mobility on network connectivity is considered.

The paper is organized as follows: Section II focuses on IEEE 802.15.4 topology formation and on network re-configuration in presence of mobile nodes. In Section III we describe the considered application scenario. In Section IV we present and discuss the results of the simulation analysis. Finally, the overall conclusions of the paper are provided in Section V.

II. IEEE 802.15.4 TOPOLOGY FORMATION AND RE-CONFIGURATION WITH MOBILE NODES

An IEEE 802.15.4 WSN is composed of one sink, named Personal Area Network (PAN) coordinator, and a set of nodes that can be Full Function Devices (FFDs), allowing the association of other nodes to the network, or Reduced Function Devices (RFDs), that do not permit the association of other nodes. The sink is always a FFD, intermediate nodes allowing data relay (router) are FFDs too, whereas the RFDs are the leaves of the tree.

The standard defines a set of procedures implemented by the PAN coordinator to initiate a new Wireless Personal Area Network (WPAN) and by other nodes to join an existing one. The PAN coordinator starts by selecting a channel among those
specified in the standard. The channel selection is performed by the Energy Detection (ED) scan by means of which the measure of the peak energy in each channel is returned; it gives indications on the interference present on that channel. The procedure adopted by sensor nodes to join a network is named association procedure and it establishes relationships between nodes within the network itself. The operations performed by a node to join a WPAN are: 1) the node searches for the available WPANs, 2) it selects a coordinator¹ belonging to the available WPANs and 3) it starts a message exchange with the selected coordinator to associate with it.

The discovery of available WPANs is performed by scanning the beacon frames broadcasted by the coordinators. Two beacon broadcasting modes are defined in the standard: beacon-enabled and nonbeacon-enabled. In beacon-enabled mode, coordinators transmit beacon frames periodically and the available WPANs can be discovered by eavesdropping the wireless channels (passive scan). In nonbeacon-enabled mode, instead, the beacon frames shall be explicitly requested by a node by means of a beacon request command frame (active scan).

In the beacon-enabled mode, the time is divided into a superframe structure. The superframe is bounded by beacon frames that are transmitted periodically and that allow nodes to synchronize. The superframe duration is called Beacon Interval \( I_B \): it is composed by an active part, named Superframe Duration \( S_D \), and an inactive period that can be activated for power saving purposes. \( I_B \) and \( S_D \) depend on the Beacon Order (BO) and Superframe Order (SO) values \([8]\).

After the beacon scan a node selects the coordinator it wants to associate to and sends an association request message to it. The coordinator grants or denies the access to the network of the new node by replying with an association response command frame. A BO = SO = 15 means that the network operates in nonbeacon-enabled mode. The values of BO and SO affects also the duration of the active/passive scan: in accordance with the standard, it is directly proportional to BO. As a consequence the message exchange with the selected coordinator is delayed of a time depending on the duration of BO too. The association procedure results in a parent-child relationship among nodes. These parent-child relationships among nodes define a tree rooted at the PAN coordinator.

In case of mobility, nodes can lose the synchronizion with their coordinators. In a beacon-enabled WPAN, if a node misses 4 consecutive beacon frames from its coordinator, it concludes that it has lost the synchronisation with its parent and it becomes orphan. If the orphan node is a FFD, it immediately stops transmitting its own beacons. Instead, in a nonbeacon-enabled WPAN, a node concludes that it is orphan if it receives repeated communication failures to its requests to transmit data. In both cases, when a node becomes orphan, it performs an orphan scan to attempt to find again its coordinator. If the orphan scan fails, the node has to perform again the association procedure to find a new coordinator to connect with.

¹Coordinators are sinks or those nodes that can act as relay nodes.

III. APPLICATION SCENARIO

We considered, as practical case study, the use of a WSN in a museum to monitor the presence, the localization and the integrity of the artworks exposed in it. Sensors measure also other parameters like temperature, humidity and luminous intensity within the rooms of the museum. The museum is composed by \( N \) rooms and several corridors. In the considered scenario there are three types of nodes:

- fixed RFDs (named FixRs) located in each room (\( R_R \) per room) positioned on the artworks that should be monitored (the total number of FixRs in the scenarios is \( R = N \cdot R_R \));

- \( F \) fixed FFDs (named FixFs) positioned on doors of some of the \( N \) rooms (e.g., considering a specific corridor of the museum, if \( F = N/2 \) one FFD covers two adjacent rooms, if \( F = N/4 \) one FFD covers four adjacent rooms and so on);

- \( S \) mobile FFDs (named MobFs): they move along the corridors, going from one point to another one and they stay in each point for a certain amount of time. These \( S \) nodes operate as sinks and are devices carried by people that act as surveillance moving along the corridors.

The \( R_R \) FixRs placed in the same room monitor the status of the artworks. Each room has a reference FixF which collects the information measured by FixRs. People dedicated to the surveillance move in the museum and collect, via the sink node located in their portable device (e.g., cellular phone or mobile WiFi device equipped with an IEEE 802.15.4 interface) the status of the artworks by interacting with the FixFs. The surveillance people are then MobFs.

When a sink (which is moving) enters the coverage range of a generic FixF, a connection between these two nodes is established (in accordance with the IEEE 802.15.4 network formation mechanism) and a new WPAN forms. However, it is important to notice that this parent-child relationship is not permanent in the time, due to the mobility of the sink: when it moves and goes out from the coverage range of the considered FixF, this node loses the association and has to try to connect to another sink which comes in its coverage range. Moreover, if the FixF loses the association with the sink, also its children can lose the connection with the WPAN.

For the sinks, we considered two different mobility models, that well match the movement of people (acting as surveillance) that carry them:

- Random Waypoint (RWP): the next waypoint is randomly chosen among waypoints uniformly distributed over a given convex area. At the start of each leg a random speed value, \( v_{m} \), is drawn from the velocity distribution and nodes can have so-called "thinking times", that is when they reach each waypoint they can stop for a pause time \( t_{p} \), where durations are independent and identically distributed random variables \([12]\);

- Deterministic (D): the next waypoint of a sink, its constant speed \( v \) and the pause times are a priori deterministically defined.
### IV. PERFORMANCE ANALYSIS

#### A. Simulation metrics

In this performance analysis we study the impact of sinks’ mobility on the following metrics:

- percentage of nodes connected to the network;
- energy consumption for network formation and reconfiguration.

The percentage of nodes connected to the network ($P_{\text{conn}}$) is the ratio between the number of F IXRs and F IXFs that result connected to a WPAN and the total number of F IXRs and F IXFs ($R+F$). In the considered scenario, in a given time instant, at maximum $S$ contemporary WPANs exist. A F IXF or a F IXR can be or not be connected to one of these WPANs. We analyze both the mean value of $P_{\text{conn}}$ measured during the simulation and the trend of $P_{\text{conn}}$ during the time, in order to evaluate how this percentage varies when sinks move.

The energy consumption for network formation and reconfiguration ($E_{\text{form&reconf}}$) is evaluated on average on total number of nodes (M OB F + F IX F + F IX R) deployed in the considered scenario. This metric represents the energy that a node consumes on average during the time to join a WPAN and to maintain this association.

#### B. Simulation models and results

In this Subsection we present results obtained considering two different scenarios, one with mobility model RWP (Scenario 1) and the other with mobility model D (Scenario 2).

We consider a multi-sink network with $S$ M OB Fs, $F$ F IX Fs and $R$ F IX Rs deployed in museum with a square area of side $L$. Each room of the museum has a square area too and side $L_R$. Figure 1 shows the map of the museum with a zoom on a single room, where $R_R$ motionless F IX Rs are randomly placed. The $F$ fixed F IX Fs are placed on the doors of some rooms; we consider three different values of $F$ in the simulations. Besides, within the corridors of the museum, there are $S$ M OB Fs that move in accordance with the considered mobility models. The transmission range of each node is $T_R$. We hypothesize that node failures cannot occur. On the contrary, at link level, MAC beacon frames can collide, since they are transmitted in accordance with the CSMA-CA protocol. We change the values of $BO$ and $SO$ of the coordinators (see Table I), with the exception of sinks, that always operate with $BO = SO = 6$. As for the propagation model, we take into account that during the transmission of a packet from a transmitter to a receiver, several paths different from the direct one can create, depending on obstacles present in the room (like people and objects). We suppose that all nodes have a value of initial energy $E$ big enough so that nodes do not die during the simulation.

We performed simulations using a modified version of the ns-2 module originally provided by Zheng and Lee in [14]. We extended its original version (that implements the association procedure provided by the IEEE 802.15.4 standard), to simulate IEEE 802.15.4 multi-sink networks. In Table I all the simulation parameters are summarized for both Scenarios. The parameters that differ in the 2 Scenarios are emphasized in bold.

1) Performance results in Scenario 1: In Figure 2 it is shown the mean value of $P_{\text{conn}}$ as function of $F$ for different values of $BO$. The height of a bar represents the mean value of $P_{\text{conn}}$, evaluated during the whole duration of the simulation (that is equal to 2000 seconds).

In the case of F IX Fs operating in beacon-enabled mode, $P_{\text{conn}}$ is always less than the value achieved in case of nonbeacon-enabled mode. The reason is that, in the first case, when a F IX F connected to a moving sink loses the association, it stops the transmission of beacons and, due to the mechanism described in Section II, this causes a loss of association in the whole branch rooted at this F IX F. This loss of association happens in a domino-like manner.

In case of beacon-enabled mode, the best value of the $P_{\text{conn}}$ is obtained for $BO = 6$ that allows to reach a good balance between two contrasting effects. In fact, when the value of $BO$ is low, the number of collisions between beacons and

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**Fig. 1.** Map of the museum with a zoom on a single room.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SIMULATION ASSUMPTIONS AND PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Scenario 1</td>
</tr>
<tr>
<td>Side of the museum, $L$</td>
<td>45 m</td>
</tr>
<tr>
<td>Number of rooms, $N$</td>
<td>168</td>
</tr>
<tr>
<td>Side of a room, $L_R$</td>
<td>3 m</td>
</tr>
<tr>
<td>Number of sinks (M OB F s), $S$</td>
<td>10</td>
</tr>
<tr>
<td>Number of F IX F s, $F$</td>
<td>21, 42, 84</td>
</tr>
<tr>
<td>Number of F IX Rs for room, $R_R$</td>
<td>2</td>
</tr>
<tr>
<td>Overall number of F IX Rs, $R$</td>
<td>336</td>
</tr>
<tr>
<td>Initial energy of sensor nodes, $E$</td>
<td>100 J</td>
</tr>
<tr>
<td>Transmission energy, $E_{TX}$ [13]</td>
<td>0.0756 µJ/bit</td>
</tr>
<tr>
<td>Reception energy, $E_{RX}$ [13]</td>
<td>0.0828 µJ/bit</td>
</tr>
<tr>
<td>Beacon Order, $BO$</td>
<td>3, 6, 9, 15</td>
</tr>
<tr>
<td>Superframe Order, $SO$</td>
<td>3, 6, 9, 15</td>
</tr>
<tr>
<td>$BO$ and $SO$ for M OB F s</td>
<td>6</td>
</tr>
<tr>
<td>Radio transmission range, $T_R$</td>
<td>15 m</td>
</tr>
<tr>
<td>Mobility model of sinks</td>
<td>RWP</td>
</tr>
<tr>
<td>Mean speed of sinks, $v_m$</td>
<td>0.4 m/sec</td>
</tr>
<tr>
<td>Mean pause time of sinks, $p_t$</td>
<td>500 sec</td>
</tr>
<tr>
<td>Constant speed of sinks, $v$</td>
<td>-</td>
</tr>
</tbody>
</table>
association requests increases: this produces an increment of loss of connectivity. But, when the value of BO is low, the scan duration decreases, reducing the time necessary to restore the connectivity.

A very high value of $P_{\text{conn}}$ is reached when FixFs operate in nonbeacon-enabled mode ($BO = SO = 15$). With respect to the previous cases the loss of connectivity of a FixF with its MoBF does not produce the domino-like effects in the loss of associations. In fact, when a generic MoBF moves, some FixFs directly connected to it (in the following named FixFs*) can lose the association (because they might miss 4 consecutive beacon frames). Since FixFs* do not transmit beacons, their children do not lose the association with them because this loss of association can happen only in case of data transmission (as described in Section II). We do not consider traffic, therefore we can only presuppose that in presence of data transmission there might be a decrease of $P_{\text{conn}}$ in case of $BO = SO = 15$: this decrease is low if traffic is transmitted at low rates.

In Figure 3 it is shown the mean value of $E_{\text{form&rec}} (J)$ as function of $F$ for different values of BO. The height of a bar represents the value of the energy consumed on average by a node. This metric is composed by the energy consumed:

- to perform the channels scan (active, passive or orphan);
- to transmit and/or receive messages for the association with a coordinator;
- to transmit and/or receive beacon frames (that synchronize the nodes and maintain the network).

The lowest energy consumption is achieved in nonbeacon-enabled mode ($BO = 15$). In general, in this case, there is a reduction of the energy consumption for the management of beacons, that involves only sinks and their children. Moreover, as already explained, just FixFs* lose the association and, for this reason, only they have to consume energy to recover the lost association.

If FixFs operate in beacon-enabled mode, the best value of BO is equal to 6, like in the case of Fig. 2. This happens because, when the value of BO is high (e.g., $BO = 9$), the contribution of consumed energy due to the transmission/reception of beacons is low, but the one due to the channels scan is high; the opposite situation verifies when the value of BO is low (e.g., $BO = 3$).

2) Performance results in Scenario 2: From the results of Scenario 1, in case of beacon-enabled mode a $BO = 6$ is the most convenient setting. Therefore in Scenario 2 we consider that all FixFs operate in beacon-enabled mode with $BO = 6$. To implement the deterministic mobility model we move each MoBF in specific time instants: each sink goes to a specific location (the next waypoint) and stays in this location until the next moving instant. As for the waypoint, we have 4 movements along a straight line and the last one is a return to the initial position (in Figure 1, the sequence of points A→B→C→D→A is an example of sinks’ trajectories followed by one person of surveillance). In the first simulation we move MoBFs contemporaneously in the following time instant: after 250 seconds of simulation, after 500 seconds, after 750 seconds and, finally, after 1000 seconds of simulation. In Figure 4 it is shown $P_{\text{conn}}$ as function of the time. From Figure 4 it is possible to notice that in correspondence to the time instants when sinks move, there are bottomlands of $P_{\text{conn}}$ due to the loss of some associations, in the domino-like effect as previously described. After the movement of MoBFs, nodes that lost the association try to reconnect to another WPAN and $P_{\text{conn}}$ increases again.
The depth of the bottomlands is proportional to the distance between two consecutive waypoints. A high distance between two waypoints is equivalent to the loss of a major number of associations. Moreover, the depth of a negative peak in a given time instant is also proportional to the number of sinks that contemporaneously move in correspondence to that instant. For this reason we perform another simulation where sinks move one by one. We analyze the trend of $P_{conn}$ in the Scenario 2, when just 5 MOBFs move one by one in accordance with Table II, where $i = 0, 1, ..., S - 1$ represents the generic MOBF identifier.

Figure 5 shows results that we obtained considering this new scenario. As in Figure 4, in correspondence to the time instants when one of the sinks moves, there are negative peaks of $P_{conn}$, for the same reasons explained above. However, in this case the loss of connectivity due to the movement of sinks is, in general, lower than the one obtained in the previous case (for instance, the minimum value of $P_{conn}$ is, in this case, about 78%, against the 25% obtained in Figure 4). Therefore, the fact that two or more sinks contemporaneously move heavily affects the connectivity in a WSN, compared with the case in which MOBFs move one by one. All these results suggest that to preserve the connectivity in scenarios like the ones that we studied, the movement of people that act as surveillance should be suitably scheduled.

### V. OVERALL RESULTS AND CONCLUSIONS

With our simulations we aimed at measuring, in a given case study of IEEE 802.15.4 wireless sensor networks, the effects of sinks’ mobility on connectivity and energy consumption for network formation and re-configuration. In an IEEE 802.15.4 WSN when a sink moves, sensors that are connected to it can lose the association. We measured the percentage of nodes connected to the network in correspondence to the sinks’ movements and we showed that network connectivity can be heavily affected. Also, the loss of association due to sinks’ mobility, has an impact on the network energy consumption, because nodes spend energy to continuously restore the associations. As a general result, we can state that it is important to suitably manage these variations of connectivity and energy consumption, to avoid performance worsening. For instance, if the application is data loss sensitive, it is recommended to provide nodes with buffers suitably dimensioned to prevent loss during lack of connectivity.

Furthermore, the IEEE 802.15.4 nonbeacon-enabled networks are not as sensitive to sinks’ mobility as beacon-enabled ones. However, performance of nonbeacon-enabled networks must be evaluated when data traffic is considered. In this case mobility affects loss of packets and data transfer delay. Moreover, with our simulations, we showed that when beacon-enabled networks are used, it is important to choose a suitable value of BeaconOrder, since network performance concerning formation and re-configuration is affected by the value of this parameter.

### ACKNOWLEDGMENT

This work has been partially supported by the IT-funded FIRB/PNR INSYEME (protocol number: RBIP063BPH).

A special thanks goes to Fabrizio Capaldi, for the support in the simulations.

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