On-the-Fly Deployment of Wireless Sensor Networks for Indoor Assisted Guidance

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***Abstract*—The goal of an indoor assisted guidance (AG) system is to aid people reach points of interest within a building, regardless of their current location. Assisted guidance systems can be efficiently implemented using wireless sensor networks, but the deployment of such systems faces serious challenges. Most deployment schemes in the literature require tedious planning based on floor plan information. Often, such plans are unavailable or they lack significant information. We introduce a new deployment scheme for indoor AG which we call On-the-Fly Deployment (OFD). The proposed scheme does not require floor plan information. Motes can be placed by an operator in a building with arbitrary layout, in an ad-hoc fashion. They become aware of the building layout and get configured for the target application already during their placement. The scheme also provides visual feedback in order to ensure correct installation of the system. As a proof-of-concept, we apply this new deployment scheme to a dynamic building evacuation system.**

I. INTRODUCTION

One of the most compelling applications of Wireless Sensor Network (WSN) are Assisted Guidance (AG) systems. Motes scattered throughout a building are able to inform occupants about the best route to a given location. While topics such as data gathering, power management, radio packet routing, coverage and scalability are often addressed in WSN literature, the deployment aspect is often taken as granted, or completely disregarded. Deployment is defined as the actual placement of the motes inside the building and the configuration of the network. For AG systems to work properly, it is necessary to transfer the physical topology of the building into the motes. Most of the existing deployment strategies assumes that a floor plan can be used to plan the location of the motes and their configuration.

In this paper, we propose a new deployment scheme for indoor WSN-based AG systems, which we name On-the-Fly Deployment (OFD), with the following characteristics:

1) Requires no floor plan of the building, and can be applied to any building layout;
2) It is self-contained, i.e, deployment requires no other hardware besides the motes and navigation signs;
3) Node locations are decided on-the-fly, during placement, according to a simple set of rules;
4) Real-time visual feedback aids mote configuration and informs about the radio connectivity between link nodes.

This paper is organized as follows. In Section II, a survey of the existing deployment methods is given. Section III defines our model of the building. The new deployment protocol OFD is explained in Section IV. In Section V, an application of our deployment technique to a concrete system is shown. Conclusions are given in Section VI.

II. RELATED WORK

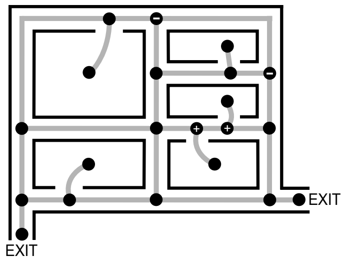
The deployment task is crucial to obtain a fully-operational system, and is recognized as labor-intensive and cumbersome. The details on practical deployment are scarce [1]. Several authors disregard or do not explain deployment rules [2], [3]. Others simplify the problem by disposing sensors in a uniform two-dimensional grid [4]–[6]. Some provide partial information but assume that floor plans are available [3], [7]–[10]. The corresponding configurations require floor plans in order to plan the locations of the motes in the building, and disseminate *a posteriori* the information necessary for the application in mind. Such approaches possess two main advantages: (i) the placement task can be predicted, including needed number of sensors, their locations and estimated radio connectivity; (ii) the length of the walkable paths can be easily determined, which is a key metric for the application that we target, assisted guidance. Nevertheless, this presents some major drawbacks: (i) floor plans are not always available, and rarely in digital formats; (ii) predicting the real radio connectivity is challenging - even detailed plans cannot account for all factors that might affect radio connectivity; (iii) the deployment of the motes in their previously planned positions, according to floor plans, is tedious and prone to errors.

III. MODELING ASSUMPTIONS

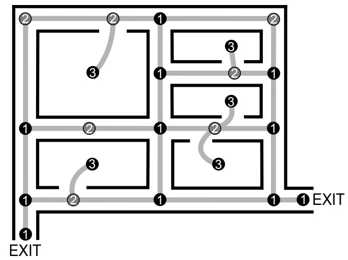
The main task of the navigation algorithm of an AG system is to obtain a directed graph from any point of the building to any other point. This directed graph is usually built upon a representation the building, also in graph form. OFD is a way of transferring the building graph to the WSN.

A. Building-graph $B(V, E)$

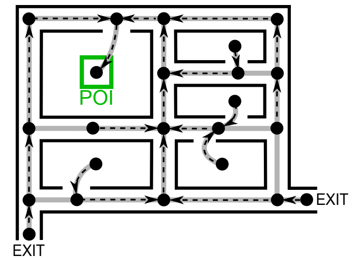
In indoor AG systems, the topology of a building is commonly modeled by a graph (e.g., [5], [11], [12]), which we will refer to as the Building-graph $B(V, E)$. The nodes V correspond to building locations that can be viewed as different spaces, such as rooms, corridor intersections, doorways, or hallways. The set E refers to walkable links between two nodes V, i.e., physical routes that can be followed by people between nodes [6]. The weight associated to a link is usually a function of the walkable distance between the two corresponding locations. Some authors (e.g., [5]) define it as the longest time for a person to travel between these locations. Figure 1a provides an example of a Building-graph.



(a) Example of a Building-graph $B(V, E)$. Links represent walkable paths in the floor. Nodes are placed inside rooms, at exit doors and intersections. Marked nodes are explained in the text of section III-B.



(b) Building-graph B(V, E) from Figure 1a has now evolved to Mote-graph $M(V, E)$, according to the three rules enunciated. Numbers indicate which rule forced the deployment of each mote.



(c) Direction-graph $D(M, E)$ derived from the Mote-graph $M(V, E)$ of Figure 1b. At each node, there is a directed link that corresponds to the shortest way to arrive to the POI.

B. Mote-graph $M(V, E)$

The Mote-graph $M(V, E)$ is an enhanced version of the Building-graph $B(V, E)$, as it takes into account technical constraints such as wireless connectivity, and being conservative with number of motes in use. In some building layouts, some nodes of B may be too close to justify the deployment of two motes; (cf. nodes with symbol "+" in Figure 1a). Deployment according to the Building-graph B provides no guarantees about radio connectivity (cf. nodes with symbol "-" in Figure 1a). Taking into account all these practical considerations, WSN deployment is done as follows:

1) A mote is deployed at each intersection of corridors.
2) Starting at one of the extremities of each corridor, motes are successively deployed ensuring that they are within radio range (and visible) from previously deployed mote.
3) A mote is deployed at each room, making sure that they have radio connectivity with nodes in the corridor.

The motes placed by this process, together with the walking paths between them, constitute the Mote-graph $M(V, E)$ (cf. Figure 1b). The numbers associated with the nodes indicate which rule lead the deployment of that mote.

C. Direction-graph $D(M, E)$

In order to operate an AG system, it is necessary to set at least one of the nodes of M as a point-of-interest (POI), and every link must have an associated weight h which represents the cost of using that link. We consider the link weight to be a function of several metrics, i.e., $h = f(m_1, m_2, ...)$, where $f(\cdot)$ and the respective metrics are defined according to the requirements of the AG system. The length d of a link is a common metric. In a building evacuation scenario, the hazard intensity along a link would be a crucial parameter.

The Mote-graph $M(V, E)$ defines the placement of motes and their roles (POI or not), and the walkable links between adjacent motes as well as their costs. The operation of AG systems relies on the computation of the shortest path from any node to a POI node based on the information of the Mote-graph $M(V, E)$. This problem is known as the "multiple-destination shortest path problem", and a solution to this problem is presented as a directed tree/forest, in which each mote is assigned at most an outgoing link. We call this Direction-graph $D(V, E)$, and an example is shown in Figure 1c. A suitable algorithm for solving this problem is a variation of the Dijkstra's shortest path algorithm [13] for the case of multiple destinations.

IV. On-the-Fly Deployment Scheme

A. System and Deployment Overview

The OFD scheme allows the *operator* to configure the AG system during the deployment of the motes. Each mote is able to activate a set of guidance (e.g. visual) signs. We denote their set by $Y = \{y_1, ..., y_n, y_{\text{req}}, y_{\text{del}}\}$. The subset $\{y_1, ..., y_n\}$ corresponds to signs used to guide occupants inside the building. The number n depends on the technology chosen for this purpose and the variety of intersections that exist in the target building. The signs y_{req} and y_{del} help the *operator* during the deployment stage by providing feedback about the system configuration. The first indicates that a mote is "receiving a request for establishing a new link"; the second that it is "receiving a link-deletion request".

OFD also requires each mote to be equipped with a set of $n+5$ inputs, denoted by X, all for configuration purposes. The first n inputs $\{x_1, ..., x_n\}$ enable the *operator* to select one of signs $\{y_1, ..., y_n\}$. The remaining five are used by *operator* to: (i) request the creation of a new link (x_{req}); (ii) delete a link (x_{del}); (iii) check the existence of a link (x_{chk}); (iv) set a mote as POI (x_{poi}); and (v) confirm actions (x_{ok}). Set X may be implemented with push-buttons, a key-pad, or any other user interface.

From the point of view of the *operator*, deploying the AG-WSN is done as follows. The *operator* places a mote at every exit and intersection of corridors, as described in the first rule of the Mote-graph model (cf. Section III-B). Complying with the second rule (Section III-B), *operator* deploys motes along corridors. *Operator* identifies a pair of already deployed motes at the end of a common corridor (e.g., motes A and Z of Figure 2). Using input x_{req} of mote A, *operator* initiates the configuration of a new link. *Operator* selects the guiding sign y_i that A will use to point in the direction of the other end of the corridor by activating input x_i of mote A. Mote A shows a guiding sign pointing to Mote Z (step 1 of Figure 2). Then, *operator* selects a new mote B to be deployed along the corridor. While mote B is in radio range of mote A, it will show the sign y_{req} to the *operator*. The *operator* moves towards mote Z (step 2 of Figure 2), carrying mote B. During his movement it may happen that mote B exits the radio range of A, or that the visibility of the guiding signs of A decreases. In that case, the *operator* steps back and deploys mote B within radio and guiding signs range of A, by actuating input x_{ok} of mote B (step 3 and 4 of Figure 2). As the quality of a link may vary in time, the RSSI threshold of mote B may be defined with a safety margin, to underestimate the radio range.

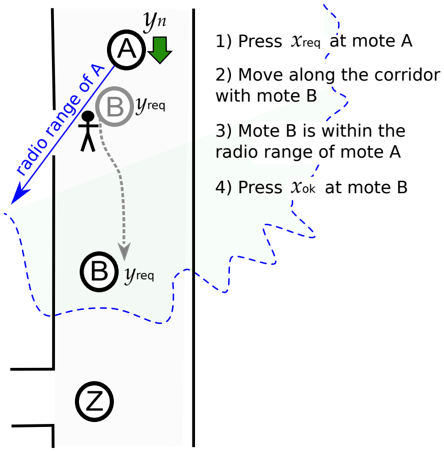


Fig. 2: Example of steps for placement and configuration of two motes, in the point of view of the *operator*

Operator uses x_{ok} input of mote B to finalize the creation of link $\{A, B\}$. The procedure is completed when *operator* chooses the guiding signs on B that points to A (cf. step 4 of Figure 2). The time the *operator* takes to walk from A to B is used to estimate the link length d (defined in Section III-C). The *operator* must repeat the procedure described above, until all walkable paths in the building are defined. Finally, according to the third rule of Mote-graph deployment (Section III-B), the *operator* deploys one mote at the center of each room. These motes must be connected to the motes in the corridor using the same procedure.

B. OFD Radio Protocol

During a typical deployment, the most common use case is Link Creation. This was described in the previous section from the perspective of an *operator*; the internal operations at each mote and required messages exchange between motes are now presented. The system behavior is specified by the Finite State Machine (FSM) depicted in Figure 3. This FSM has two main sets of states: on the right side, the behavior of a mote when requesting a link creation; on the left side, the behavior of a mote when receiving a request for link creation. We assume bidirectional radio links. To initiate the creation of a link $\{A, B\}$, an *operator* starts by choosing the guiding signs using a input x_i on mote A. This causes the state of the FSM to change from "INIT" to "Wait Sign Config A". When the sign is chosen, the *operator* uses the "request new link" input x_{req} to initiate a link. Mote A initiates a periodic broadcast (with a period $\tau = 200$ms) of a `LinkRequest(A)` message to inform other motes about its intention to establish a new link. When *operator* moves along the corridor, he carries Mote B which shows the sign y_{req} (state "Wait Path Length Estimation") while it is in radio range of Mote A. This provides feedback to *operator* regarding the guiding sign range as well as radio range. Internally, Mote B starts a `DistTimer` timer that estimates the walk time of the link that is being created. `ConnTimer` is used to turn off y_{req} and pause `DistTimer` if motes are no longer communicating, *Operator* installs mote B according to the second rule of Mote-graph model (Section III-B), and uses the confirmation input x_{ok} on Mote B to finalize the creation of new link $\{A, B\}$ and to stop `DistTimer` (transition to state "Wait Sign Config B"). t_{walk} is the elapsed time of `DistTimer`

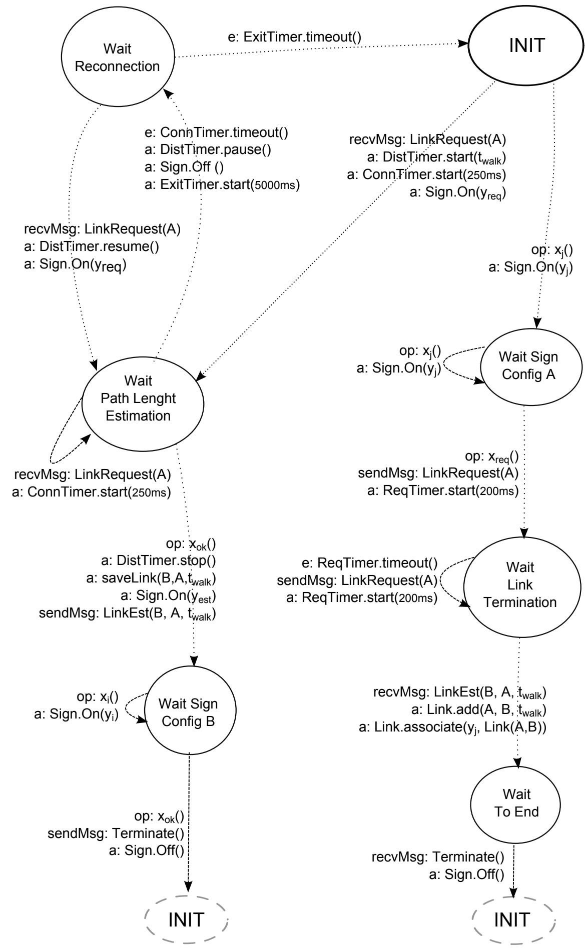


Fig. 3: This FSM describes the OFD operation for the Create Link use case. Circles represent states and arrows transitions. Each arrow has a block of instructions; the first is the transition condition, and the remaining the associated actions.

between triggering x_{req} and x_{ok}. This will ultimately be the metric $d_{\{A,B\}}$, as it is roughly the human travel time from A to B. x_{ok} also triggers mote B to send a radio message to A to announce a new established link. The sent message is named `LinkEst(B,A,twalk)`. Mote A can already associate the chosen guiding signs y_i to link $\{A, B\}$. At this stage, *operator* uses x_j on mote B to choose the sign that points to A, in order to associate sign y_j to link $\{B, A\}$ (state "Wait Sign B"). Finally, *operator* calls x_{ok} again to terminate the procedure. This triggers mote B to send a radio message to A named `Terminate()` to inform it about the completion of the procedure. All "guiding signs" are now off.

We consider the time metric to be more relevant than the physical distance between two points. Even if the *operator* backtracks his movement, or walks faster, when creating some links, we assume that those errors have a negligible impact in the route computation. The value of τ may also be different than the one used here, which will affect usability.

Other use cases, such as defining a mote as POI, checking the existence of a link, or deleting a link, may be described in a similar way.

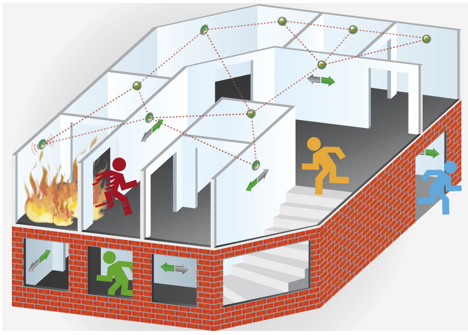


Fig. 4: The goal of the Building Evacuation System is to guide people out of the building in the event of an hazard.

V. Proof of Concept

We have applied our deployment scheme to a Building Evacuation System (BES). The goal of this system is to guide people along the safest and shortest paths to the exits, in case of a hazard. Figure 4 illustrates a typical fire scenario. In our implementation, we enclose TelosB motes together with LED displays in acrylic boxes. Four guiding signs are provided to the occupants: y_1="forbidden", y_2="go ahead", y_3="go left" and y_4="go right" (see Figure 5). Outputs y_{del} and y_{req} are indicated by displaying all red, or all green LEDs, respectively. The signalization boxes include a push-button for the four inputs x_{i} in order to choose the visual signs y_i. Apart from this button, five more push-buttons are used for configuration, namely: $x_{\text{req}}, x_{\text{del}}, x_{\text{chk}}, x_{\text{poi}}, x_{\text{ok}}$.

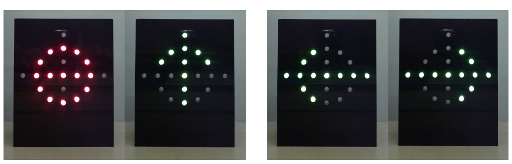


Fig. 5: The guiding signs displayed.

The operation of a BES is based on two modules: exit route calculation, and link-state dissemination. The first concerns the computation of the shortest and safest route from any point in the building to an exit. We have used an adapted version of the Dijkstra algorithm. The weight of a link e is given by the time d_e a person takes to cross a link and the current hazard status of that link h_e. Based on the temperature readings, h_e is chosen from a scale of four hazard levels. The weight of a route α defined by a set of links (e.g.: $\alpha = e_{\text{A,B}} + e_{\text{B,C}}$) is computed using the time it takes to cross that walkable route $d_\alpha = d_{\{\text{A,B}\}} + d_{\{\text{B,C}\}}$, and its status $h_\alpha = \max\{h_{\{\text{A,B}\}}, h_{\{\text{B,C}\}}\}$. The second building block, link-state dissemination, is in charge of efficiently disseminate information throughout all the network. It is made necessary by Dijkstra's algorithm, that requires each mote to learn the state of all walkable links in the network at all times. The link-state dissemination is based on a flooding mechanism. The link advertisements are radio messages generated by every mote, conveying the information d_e and h_e for all adjacent links e.

OFD successfully helped to fulfill the following requirements for the correct system operation: (i) enable sufficient wireless connectivity for quick and consistent dissemination of the information; (ii) provide a way to input the spatial topology information; (iii) guarantee that at any location in the building, a visual sign is visible to the user; (iv) ensure sensing coverage taking into account the range of the sensors.

VI. Conclusions

In this paper, we introduced On-the-Fly Deployment (OFD), a new deployment scheme for Wireless Sensor Networks whose application is Assisted Guidance. It renders unnecessary any prior knowledge about the building topology, and may be applicable to any building layout. The location of each node is decided on-the-fly during deployment, by observing a set of simple rules. Simple deployment procedures ensure that the system becomes aware of the building layout during this stage. As a proof-of-concept, OFD was applied in a dynamic building evacuation system.

Acknowledgments

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