A Two-Layered Deployment Scheme for Wireless Sensor Network based Location Tracking

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Abstract

The tracking of objects and humans has recently received a lot of attention as a tool to improve business processes, occupational and public safety. In wireless sensor networks location information is needed to put sensor readings into geographical context. In industrial environments wireless sensor networks can facilitate deployment of tracking applications as they can establish a standalone communication infrastructure (so called mesh networks).

Nevertheless the communication infrastructure and thus the tracking applications rely on radio transmission. Therefore problems like ambiguous locations and the neighboring-room problem known from other radio-based tracking solutions may occur. We propose a two layered deployment scheme for wireless sensor networks to overcome these limitations. It consists of a robust communication layer and a flexible location layer, which enable per-room accuracy. Such accuracy is sufficient for many types of tracking applications.

1. Introduction

Localization has always been a major research area in wireless sensor networks because many sensor readings need to be put into geographical context. Various interesting approaches have already been described to solve this problem, but it was only recently that continuous tracking of mobile sensor network nodes has emerged. Such location tracking systems help to greatly improve occupational safety, especially in industrial settings.

The construction and maintenance of industrial plants typically involves many tasks that require testing plant parts for proper functionality. Ensuring that the plant is clear of personnel is crucial to safely conduct these tests. Likewise, many areas in industrial plants demand special technical qualification, safety training, and professional experience. Persons that do not have appropriate training should be warned automatically by a system when they accidentally enter such a critical area.

In case of an emergency a location tracking system provides essential information to systematically alert the fire department and other rescue teams, and to efficiently coordinate these teams. By that rescue teams do not need to search the plant for potential casualties, but instead the location tracking system can guide them directly to injured persons. And even the position of rescue team members could be monitored throughout their mission and, thus, increase their safety as well.

Of course the location tracking system cannot be used to guarantee the absence of people within a critical section but offers a redundant source of information for human controllers. So if a part of an industrial plant is put back into operation after maintenance the location tracking system can alert if it senses a person within a critical section. A human controller manually has to assure the safety of the plant and to give the start command.

Most important for the described use-cases is the number of persons per room, but these figures need to be given with high confidence (i.e., persons have to be matched unambiguously to rooms). Of minor importance–though still

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desirable–are the exact positions within the rooms; private information (e.g., a person's identity) does not increase safety further and can thus be easily discarded to increase privacy.

Sensor networks (e.g., based on Berkeley motes running TinyOS/Zigbee) are particularly interesting in large-scale industrial environments for the following reasons:

- Sensor network nodes (motes) automatically form a reliable, redundant, fail-safe, and cost effective communication infrastructure in the form of a mesh network, only some of the nodes need access to the company network
- The operating system gives extensive access to the underlying hardware (e.g., to influence the radio transmission range)
- The hardware is far less expensive than other RF based systems (e.g., active RFID readers, mobile WLAN devices)
- Optional sensor boards can extend the tracking system with additional contextual information (e.g., the current temperature, or the presence of toxic gases)
- Motes are packaged in small form factors and can easily be integrated into every-day items

Stojmenovic in [10] describes the localization problem in terms of two hardware sub-problems: first, the problem of defining a coordinate system, and second, the problem of calculating the distance between nodes in the localization system. Both problems are not unique to sensor network localization and thus many proposals to solve them already exist. But isses such as scalability, ease of deployment, maintenance, and fail-safety still need to be addressed to make sensor network location tracking applicable in industrial applications.

2. Related Work

Bachrach and Taylor in [10] discuss RF localization concepts applicable in wireless sensor networks: beacon nodes, received signal-strength indication, radio hop count, time difference of arrival, and angle of arrival. They also compare centralized and decentralized algorithms, and identify issues in localization algorithm design (node density, environmental obstacles, and resource constraints).

Chraibi in [2] uses a priori information (known bounding boxes in the motes' transmission ranges) to localize motes by trilateration. However, the bounding boxes are hard, if not impossible, to obtain, since known effects, like multi-path radio signal propagation, continuously influence a mote's range (a fact that Chraibi also notes in his extensive discussion of RSSI experiments).

An example for the use of time difference of arrival and angle of arrival is given in [6]. Additionally, the proposed algorithm reduces the localization in 3-dimensional space to the 2D problem by aligning all sensors in the network with the earth's gravity direction. Time difference of arrival and angle of arrival typically rely on microphone arrays since the computations based on the propagation speed of sound result in a much better distance estimate as those based on the propagation speed of light (and RF signals), but noisy industrial environments are hostile to this form of distance estimate.

Terwilliger et al. in [11] use evolution strategies to simultaneously compute the position of all nodes in the network. The main advantage over trilateration/triangulation is that each node in the network does only need one other node in its wireless range. The algorithm is, due to its runtime, only applicable in stationary networks during deployment (in a network of 200 nodes the algorithm converges in 11 minutes).

In [1] the presence of mobile nodes in the network is included in the algorithm design. The approach seems to be promising, although the authors cannot yet give feedback from real-world deployments.

[5], [8], and [4] describe sensor network systems explicitly built for tracking mobile motes. They deploy static motes with known positions in a dense mesh network. The received signal-strength indication (RSSI) of static motes within reach of a mobile mote is then used to compute the mobile mote's position by trilateration/triangulation or by matching the values with a RSSI signature database.

Though the described systems compute quite accurate positions under laboratory conditions, there are nevertheless situations where position disambiguation is needed: e.g., these systems do often have problems to unambiguously match a person near a wall to the correct room. This problem is often called neighboring-room problem (cf. [4]). For emergency rescue teams and for plant managers on duty it is very important to know in which room a person is located in. To build a successful localization system in such application domains it is necessary to solve the neighboring-room problem. We developed and tested a two-layered deployment scheme that allows us to create exact boundaries between rooms or within rooms when needed. The deployment scheme is designed to be easily deployable, scalable to different area extents, and robust to failing nodes.

3. A Redundant Two-Layered Deployment Scheme

Our deployment scheme consists of a *communication mesh network* to transmit location data, and a *location layer* that generates location information.

3.1. Communication Layer

The communication layer consists of *hubs*, *bridges*, and *gateways* that all operate their radio chips with high power to cover a large area and to build redundant paths in the network (see figure 1).

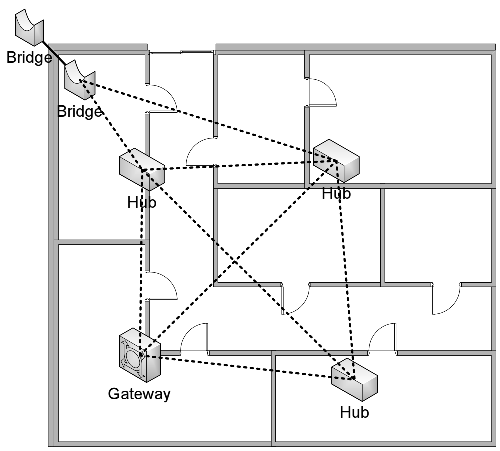

Figure 1. Communication layer

In industrial environments suitable wired or wireless network communication is often expensive to install or incurs running expenses (public networks like GPRS or UMTS). A mesh network based on Zigbee motes establishes a cheap and reliable network infrastructure solving the problem of transmitting data to a remote localization system.

A hub simply forwards location information to neighboring hubs, bridges, and gateways. A bridge consists of two hubs linked by cable; it is used to connect two adjacent areas that cannot be connected wirelessly (e.g., due to thick walls). A gateway connects the wireless network to another enterprise network, like WLAN or cabled Ethernet networks. In the deployment of the communication network special attention must be paid to the placement of bridges and gateways: if not carefully placed they can easily become a single point of failure in the network. The communication network is typically highly redundant and makes use of Zigbee's flexible routing capabilities to ensure the reliability needed in industrial settings .

3.2. Location Layer

The location layer comprises *location beacons* and *mobile tags*, as shown in figure 2.

Location beacons are placed at known positions whereas mobile tags identify a person/asset and, hence, their position is unknown. The location beacons' radio range and antenna

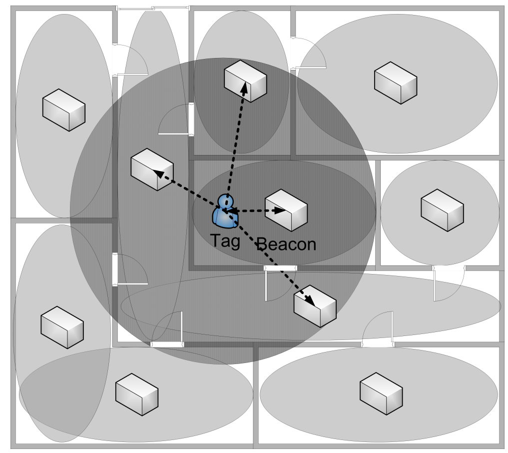

Figure 2. Location layer

are adjusted so that they never intersect with the radio range of location beacons in adjacent areas (intersection with beacons deployed to the same area is allowed and can be used to compute a more precise location within the area). By that the neighboring room problem can be effectively eliminated, because already thin walls can separate radio cells. An area may span several physical rooms or cover just parts of a room.

The mobile tag periodically sends location query messages that are replied by location beacons. After receiving the reply, the tag computes and broadcasts its position and the communication mesh network forwards this position message to the central location tracking system. Subsequent location queries are then addressed to the beacons in the same room to lessen energy consumption in the network; only if these beacons do not answer, another location query broadcast is issued.

Mobile tags operate with high radio power to reach as many hubs as possible when broadcasting location information through the communication network. Therefore, many beacons may receive the tag's location query message and reply to it, but the tag only receives the reply messages from the beacons in the corresponding room as the communication range of beacons might be smaller than that of the tag (see Figure 3 for a possible way of communication in the mesh network).

This semi-active approach ensures that the statically deployed infrastructure remains inactive most of the time and, thus, increases battery runtime. The mobile tags can typically be recharged at the end of each working shift.

To increase the mote density of the described components, a mote in the sensor network may host one or more of the described components. Static motes that do not border on neighboring areas can host a location beacon and a hub. Mobile motes can host a mobile tag and a hub. In case

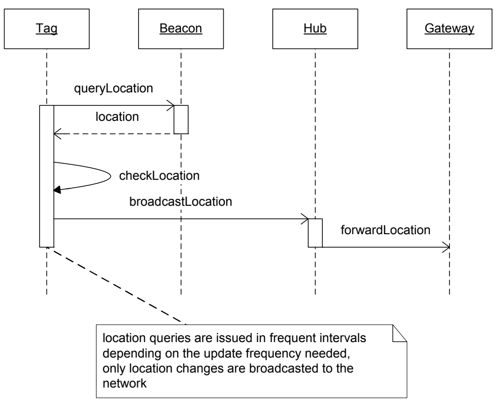

Figure 3. Communication sequence

of an emergency, mobile tags carried by the members of the rescue teams can substitute possibly damaged hubs of the communication infrastructure and, thus, repair the location tracking system.

4. Performance Evaluation and Discussion

We implemented the described deployment scheme with Crossbow MICAz motes (see figure 4 and [3] for a technical specification). The motes have a combined processor/radio current draw of about 30mA. They are equipped with two Panasonic AM-3PI batteries (see [9]), which means that they can fully operate for nearly 100hrs. In sleep mode, a mote consumes around 35μA.

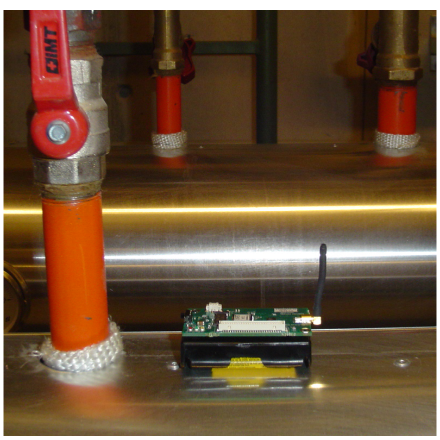

Figure 4. MICAz mote

Battery Runtime

The statically installed motes (i.e., beacons, hubs, bridges and gateways) are passive components in the described system and only draw battery power when they are activated by tags. By that the battery runtime of static motes (on which battery power is a scarce resource) can be extended. Additional batteries can also be installed to enhance battery runtime (form-factor is not a big issue for statically deployed hardware in industrial environments). By contrast, the tags are required to issue frequent location queries, which shortens battery runtime depending on the update interval needed, and additional batteries are infeasible because a small form-factor is important. But mobile tags can be easily carried to charging points and recharged periodically.

Tags that frequently change their position stress the communication layer's battery power because they often report location changes, but they balance the battery load among beacons. Non-moving tags drain a single beacon's battery with frequent location queries (and the subsequent replies), but they do not communicate location changes.

Temporal Resolution

The interval at which tags broadcast location queries defines the temporal tracking resolution reachable within the network. A tag that travels at a pace of 1m/s in a tracking environment with a spatial resolution of 10m requires a temporal resolution of 10s or better to enable continuous tracking. A very pessimistic estimation of a work load of 10% for such a tag means that it needs to be recharged every 1000hrs. In some application domains a much longer update interval might still be sufficiently accurate.

Spatial Resolution

The spatial resolution is determined by the radio range of the sensor network hardware in use. The radio transmission power of the MICAz motes in our installation can be adjusted from -24dBm to 0dBm that roughly translate into radio ranges from 1m to 20m indoors or to 75m outdoors (see [3]). Adjusting the transmission range saves energy (a mote's current draw is 17mA at 0dBm and 11mA at -10dBm) and the beacon's battery runtime can be optimized with respect to the area it is operated in.

Figure 5 shows the tradeoff that has to be found between the three main tracking quality properties. An implementer of a tracking solution can pick any two; the third property is then dictated by technology.

- If high spatial resolution and long battery runtime are needed, the temporal resolution will suffer, because battery runtime will then be maximized by lengthening the location query broadcast interval.
- If high temporal resolution and long battery runtime are needed, the spatial resolution will suffer (less beacons can be placed, because frequent location changes drain the communication layer's batteries).

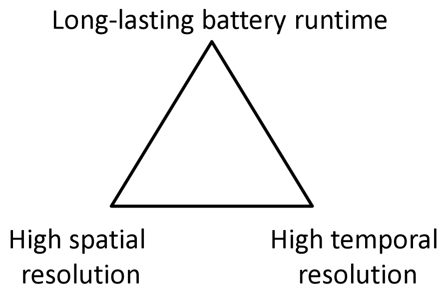

Figure 5. Tracking quality triangle

- If high temporal and high spatial resolutions are needed, battery runtime is decreased.

Costs and Reliability

The costs of a sensor network based tracking solution are determined by the number of motes deployed in the static network, and the number of tracked tags. Infrastructure costs, e.g., for providing network access and power supply, are not incurred in such a tracking solution. Reliability in a sensor network is, as usual, reached by redundancy. An executive triangle can be defined to describe the relationship between costs, reliability, and quality (spatial, temporal, battery) as shown in Figure 6.

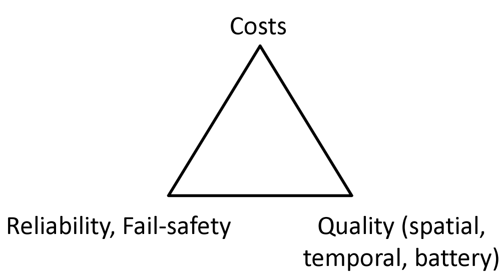

Figure 6. Executive triangle

5. Conclusion and Further Work

Previous research laid the foundation for building large-area location tracking systems but ignored issues that arise in real-world (industrial) application. The described deployment scheme proved to be sufficiently accurate, easy to install and maintain, and feasible in industrial settings for improving occupational safety.

Using Zigbee motes as mobile tags brings along several advantages: motes are of a small form-factor and can easily be integrated into everyday objects (e.g., into mobile phones, see [7]). The combination of motes and mobiles phones promises ground-breaking applications. We plan to improve the tracking system with breadcrumb navigation that calculates the best escape route for rescue team members (based on the various tracks–recorded as breadcrumb trails–that were taken when entering the building). To further increase reliability and fail-safety we plan to evaluate a form of paper chase navigation that could still guide rescue team members to injured persons even when most of the location infrastructure failed. In such situations a comprehensive view on injured persons' whereabouts might not be possible. However, we could still support rescue team members by alerting them when they approach a mobile tag during their search for persons (which could be extremely helpful, e.g., in areas with heavy smoke).

Additional context information–available from environmental sensors attached to the motes–is not yet integrated into our platform. It could provide valuable insight into the conditions in the disaster area for rescue teams.

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