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Mobile Tracking Architecture in Zigbee RFID Sensor Networks

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Abstract—Zigbee is one of the most exciting wireless sensor network (WSN) technologies for monitoring and control. In our previous research, an integrated Zigbee RFID sensor network was designed as an ‘all-in-one’ system as well as a connectionless inventory tracking solution for Humanitarian Logistics Center (HLC) resource management. Various field trials, which have justified the feasibility and features of such a system, have also revealed the requirement for simple yet reliable mobile tracking architecture for mobile target in Zigbee networks. In this paper a connectionless stochastic reference beacon architecture based on Zigbee RFID sensor network is proposed, for tracking both inventory and mobile targets. Such an architecture not only inherits the previous connectionless inventory tracking system’s features, but also has longer hardware battery life, lower network traffic level and extends the system’s capability to enable mobile target tracking. The implementation of such an architecture and model is also discussed with a demonstration system presented at the end of the paper.

Keywords: Zigbee, Real-time tracking, RFID sensor network

I. INTRODUCTION

In the general field of logistics management research, much work has been done to prove that improving the whole supply chain performance relies on improving the external service quality at each distribution point on the chain, which initially requires the internal service performance at each distribution point to be improved [1]. This is particularly important in humanitarian logistics. In fact, Thomas [2] suggests that the speed of response for major humanitarian programs depends on the ability of logisticians to procure, transport and receive supplies at the site of an humanitarian action, such as the humanitarian logistics centers (HLCs) which are the most important sites where both freight and information flows are congregated, relayed or distributed. Systems such as typical RFID systems and information networks have been implemented in some logistics centers in the general supply chain, but the rapid emergency response features of humanitarian logistics prevent them from being adopted directly in humanitarian logistics centers. As a result, in our previous research [3][4], an integrated Zigbee enabled RFID sensor network architecture has been proposed, aimed at helping increase the efficiency of each humanitarian distribution point/centre by providing higher freight and resource visibility and state monitoring ability for internal process management. Such a architecture integrates sensors and passive and active RFID systems into a unified Wireless Sensor Network backbone. We have demonstrated in our previous work, that it can provide the distribution centers in the humanitarian supply chain with a simple, robust, rapidly implementable and multifunctional information system infrastructure. But in our previous demonstration system [4] problems were raised regarding the architecture of current Zigbee based tracking solutions, which have dense device implementation, mobile routers in the network and low battery life for mobile nodes. In an attempt to overcome these issues, we have proposed, in our previous research [5] a connectionless inventory tracking architecture for indoor Zigbee RFID sensor network that supports warehouse inventory tracking with the least additional hardware requirement, reasonable mobile node battery life while at the same time providing a server localization algorithms with accurate data input by avoiding any accumulated localization error. But the issue for tracking mobile targets was raised in the previous proposed connectionless tracking architecture, which was mainly designed to track the pallets and trays used in warehouses for standard goods transfer and storage. In this paper we introduce an improved structure, which is called ‘the connectionless stochastic reference beacon’, and is proposed for use in tracking both freight inventory and mobile targets such as staff and working vehicles.

The remainder of this paper is organized as follows: first we briefly introduce the current prototypes for Zigbee based mobile tracking; after that, our connectionless stochastic reference beacon architecture is presented; An explanation of an network architecture implementation in a warehouse is followed by a demonstration system shows the feasibility of our design; The final section of the paper contains a discussion and conclusion on our current design and its hardware realization.

II. CURRENT ZIGBEE TRACKING ARCHITECTURES

One of the main tasks performed by Zigbee RFID sensor networks is inventory tracking. Various solutions have been proposed for Zigbee based mobile tracking. [6,7,8] The authors in [6] proposed a Zigbee indoor tracking system in which all the reference nodes, as well as the mobile target nodes, are Zigbee router devices. This ensured a fully connected network in which mobile node can communicate with all the reference points nearby in order to satisfy the centroid localization algorithm adopted. The prototype proposed in [7] used a similar, but improved architecture, by modifying the localization algorithm with a triangle algorithm and weighted LQI model. Such systems require dense router deployment and the whole network is a full router network. However in most cases, this is not very practical. Typical Zigbee network have only a small number of router devices
while most of the task nodes are end devices so that they can be kept in sleeping mode most of the time to save battery life.

The authors in [8] proposed an improved system in which the fixed reference points can either be router or end device. Mobile nodes are still Zigbee routers and, using a proposed re-connection phase, the mobile router can get access to all the nearby fixed nodes. The mechanism in the re-connection phase is actually to force the network to re-organize and hope that the nearby fixed end devices can change their parent node to the mobile router. The problem with such a system is that the network is constantly under reorganization and this is a very high battery consuming procedure. Furthermore, the system performance decreases rapidly when the number of mobile nodes in the same area increases, because when one mobile node is measuring the RF strength by communicating with the reference nodes within the area, it will fully occupy all the end device reference nodes, making them unable to talk to any other mobile nodes in the same area. Another important issue is that as all the mobile nodes in such system are Zigbee routers, the system’s network topology becomes inconsistent. This effect will be discussed in the next section.

A further improved model based on the system in [8] is an attempt to overcome the reference nodes occupying problem. The method proposed is when the first mobile node is being tracked and occupies some of the end device reference nodes within the area; the other mobile nodes will consider the tracked mobile node as a reference node when looking for reference triangulation. As soon as it finds its own reference triangulation and is tracked, the other mobile nodes will also consider it as a reference point. While this method seems to allow multiple mobile nodes in the same area to be tracked simultaneously, its network structure is still inconsistent and it brings a new problem of accumulated localization error. Using a mobile node as a reference point will result in its localization error being partly accumulated into the error of the second mobile node’s location calculation.

As an attempt to improve the current systems, we have proposed in our previous work [5] a connectionless tracking architecture. This allows the using of Zigbee end devices (ZEDs) as mobile target node, and introduced the concept of “RF listener” for mobile node without any established network link with the reference nodes. The environmental monitoring nodes also acted as reference nodes, the information messages sent back to the server by those nodes were also heard by the mobile nodes and were used as reference message to measure the receiving signal strength (RSS) between the mobile and reference nodes. This design provided a solution for warehouse inventory tracking with the least hardware requirement, reasonable mobile node battery life and at the same time provided the server localization algorithms with accurate data by avoiding the accumulated localization error. But we had to let the fixed nodes generate enough network traffic in order to ensure a mobile node can monitor enough fixed reference nodes in each active period. Thus such architecture requires that the sensor nodes periodically report to a central server. The interval of two adjacent reports is fixed and is not only a compromise between the application requirements and hardware battery life, but also is a compromise between the battery life of the fixed and mobile nodes, which have been proved to be in an inverse relationship. We concluded that the information report interval of the fixed nodes should be much shorter than the mobile node location-updating interval. This is designed for the inventory tracking applications in which stock information is updated infrequently about every 10-20 minutes or even longer, and both the tagging and fixed nodes’ battery life are to be maximized. For mobile target tracking, which requires that localization has to be updated more frequently, about every 2-3 seconds, the previous designed model results in fixed nodes, which sends messages with a much shorter interval, sending report tens or even hundreds times per second. This is not desirable, as the fixed nodes will quickly exhaust their batteries. It will also cause a high traffic load within the network that would result in traffic congestion. To overcome these issues we propose an improved architecture called “the connectionless stochastic reference beacon”, which enables the tracking of mobile target in our Zigbee RFID Sensor Network, while at the same time maintaining normal network traffic loads and long device battery life.

III. CONNECTIONLESS STOCHASTIC REFERENCE BEACON ARCHITECTURE

A. Concept of Design

Battery life: Our interviews with engineers from relevant companies, suggest that in the real applications of mobile tracking, battery life of fixed nodes are of greater concerned to the users than the battery life of mobile nodes. In the inventory tracking architecture, our discussions are based on the principle that both the mobile nodes and the fixed nodes work with on board batteries that cannot be replaced or recharged frequently. But in mobile target tracking, the mobile nodes are either carried by vehicles/machines, where they can easily get access to the on-board batteries that are usually more than sufficient for any Zigbee hardware, or carried by the human staff, where they can be recharged on a daily basis. The battery life of the fixed reporting/reference nodes is what the engineers and users are actually interested in, because these batteries cannot be recharged on a daily basis and are not expected to be replaced frequently. This is the biggest difference between the applications of inventory tracking and mobile target tracking. Thus our design for the mobile target tracking architecture need only try to prolong the battery life of the fixed reference nodes. Without the need for compromising between the battery lives of fixed nodes and mobile nodes, we let the mobile nodes stay on and listen to the RF channel all the time, in this case the fixed nodes can send their report/reference messages only at the rate that is equal or very close to the localization updating rate required.

Network traffic: The previous connectionless architecture design is not applicable for mobile target tracking also because in such applications it will cause high traffic load within the network that leads to congestion. Environment monitoring nodes, which report to central server nodes too frequently, can also cause serious congestion within the network backbone, as Zigbee is a low data rate standard. Enabling all the fixed nodes to report to central servers at a
high updating rate is not practical. This will prevent the more important information from arriving at the server in time, or even totally bring down the network service. High network traffic loads will also reduce the node battery life in the network backbone when, in certain circumstances, they lost mains power support. Thus our design for the mobile target tracking architecture must also try to reduce the network traffic. By having the mobile nodes listen to the channel all the time, the sending rate of environment information is reduced. But in applications, the required update rate for environment monitoring report is usually much smaller than the rate required for mobile target tracking, so using monitoring report messages for such types of localization means that most of the network traffic caused by environment reporting is wasted, because the central server is not interested in such frequent environment information updating. For example, monitoring information may need to be reported every 10 minutes, but at the same time, localization process may need an updating interval of 2 seconds. To satisfy the localization process each fixed node has to report to central server every 2 seconds, though most of these messages are of no interest to the application itself. Network loads and hardware battery life are largely wasted in such a frequent reporting mechanism. To solve such problem, in our design for mobile target tracking, we will prevent the messages sent for localization purpose from propagating within the network. This is achieved by letting the fixed nodes send short beacon type messages rather than monitoring reports for the mobile nodes to analyze. The short beacon messages are enough for mobile nodes to determine the RSSI of the sender nodes, but will be marked as not eligible for propagating within the network. To avoid interference between data transmission and beacon broadcast, the main network and the short beacon message mechanism will need to work on different IEEE 802.15.4 channels.

Connectionless Beacon: For a beacon network, the common network standards usually require a central coordinator device to broadcast timing frame periodically to start a beacon interval, and all beacon nodes to receive and follow such frames for accurate synchronization so that they could then be lined up for transmission in a beacon interval without confliction [9,10]. In the IEEE 802.15.4 network standard, the only way of achieving this is the guaranteed time slot (GTS) mechanism in beacon enabled mode. In this method of network organization each beacon node needs to listen to the channel constantly for a timing frame and to synchronize with each other. There has to be a central coordinator device that covers the whole operation area and broadcast the beacon timing frames, and those synchronizing activities consume a considerable amount of energy on the beacon nodes, which is even higher than the power consumption of actual beacon sending. According to the hardware datasheet for the Jennic JN series Zigbee wireless sensor node, the RF receiver is an independent circuit with greater power consumption than the RF transmitter module. What’s more, the RF receiver has to be powered on during the whole operation cycle because the node itself cannot anticipate when the next frame will arrive, whereas the RF transmitter needs only to be turned on during actual frame transmissions, which are very short periods. According to the datasheet of the sensor nodes we used, not only does the RF receiver work for a much longer time than the transmitters during operations, but they also have larger power consumption per unit time than the transmitters [11]. Thus, reducing receiving time is more efficient than reducing transmitting time in prolonging the nodes’ battery life. For beacon nodes the RF receiver exists only because they need to be synchronized in order to avoid collisions with adjacent beacon nodes. But actually, it is not a disaster to have collisions so long as the collision occurrence probability is below an acceptable threshold, which should be given by real application regulation, and performance of the localization process is not noticeably affected. In this case, we consider the synchronizing function of the beacon nodes to be unnecessary. Consequently, in our case, the role of a receiver is redundant. So in our design we only need the beacon nodes to transmit reference messages without any responsibility for listening. According to the power consumption calculation of the Jennic JN5139 application notes, this should be able to prolong the nodes battery life by 3-5 times depending on the application. The beacon messages are sent randomly through the time line and the collision probability can be controlled by adjusted the average beacon transmitting rate.

B. Connectionless Stochastic Reference Beacon architecture

Taking into consideration all of the discussions in the previous section, we propose our connectionless beacon architecture for mobile target tracking in Zigbee RFID Sensor Network. The network architecture is illustrated in Figure 1. The central server, network routers and environmental monitoring nodes remain the same as for the connectionless tracking architecture. We add battery powered beacon nodes at reference points to assist the system localization process. The mobile target nodes listen to the messages sent periodically by the reference beacons and generate their RSSI information for localization purposes. The reference beacons operate in a different Zigbee/IEEE802.15.4 channel to that used by the main data network to avoid unexpected collisions.

**Network level 1**: A Zigbee coordinator together with the local server at the top level of the network is responsible for establishing and initialization the indoor Zigbee network. The coordinator also acts as the sink node for the Zigbee network.
It is connected directly to the central server via a cable link, such as RS-232 or USB serial interfaces. Using this direct link, the central server should be able to retrieve all the information gathered from the network nodes.

**Network level 2:** At the mid-level Zigbee router devices are responsible for data relaying and ensuring the full RF coverage of the network within the building. Zigbee is a multi-hop network in which the path is constructed from a chain of several routers who pass the information packages along from the previous node to the next one. In the Zigbee specification, the routers are required to have access to a main power resource so that they can always be active; these router devices can provide a full network coverage as long as each one has at least one router reachable, or in other words within its RF range, anywhere in the building.

**Network level 3:** At the lowest level there are ZEDs for data collection. These ZEDs are divided in two categories. The first category (CAT1) includes those fixed data nodes responsible for gathering information at specific location. ZEDs carrying temperature, humidity or chemical sensors deployed at various environmental control points in the warehouse fall into this category. The other category (CAT2) includes the mobile ZEDs located on pallets or trays and the mobile targets such as staff or forklift trucks. We have discussed in our previous work the advantage of using ZEDs as mobile nodes, which means cheaper and more power efficient hardware, more stable network topology and less network routing overhead. [5,12,13] The CAT1 ZEDs can also carry connectionless stochastic beacon function to act as reference nodes; while the other ZEDs in CAT2 also make use of them as the dedicated beacon nodes at reference points for their localization. Dedicated reference beacon devices are used in cases where a CAT2 mobile node cannot get within RF range of at least 3 reference beacons.

**Data communication:** The data communication of the resource management system network is handled completely by the Zigbee standard. Primary data communications occurring in the network of our system are regular information reports from all the level 3 nodes to the coordinator/server. In addition, the data stream from the Zigbee-enabled passive RFID readers at various access points are sent to the server as well as responses to data inquiries started by the server addressed to one node or a number of network nodes. These data communications are typical point-to-point network data transmissions that can be managed by the standard network protocols used by Zigbee.

**Tracking mobile nodes:** The connectionless tracking mechanism of our Zigbee RFID Sensor network can be described as follows: the CAT2 mobile nodes are typical Zigbee end devices equipped with a RF listener module whose function is to analyze the beacon packets it can hear on the beacon channel used. From each packet it hears, the RF listener module retrieves and provides the CAT2 node processor with the ID of the reference beacon node that sent the packet, the RF power strength and the error check result. Failure of the check code indicates that there were collisions or significant interference during the packet transmission, this will invalidate the reading of the source ID, which may have been incorrectly transmitted, and its RF power strength reading, which may be incorrect due to collision or interference. If the check is passed, then the source ID and RF strength reading is accepted as a reference pair. The mobile nodes analysis the beacon channel for a predefined period R, then summarize the reference pairs it received in the last receiving period and send them via the main Zigbee data network to the server to update the database. Proper localization algorithm on the server will locate the CAT2 nodes based on the reference information pairs in the database.

Most of the current localization algorithms require at least three reference points for a mobile node to be located with satisfied accuracy, so the minimum deployment requirement of the connectionless tracking architecture is to ensure that at any place in the building/site, a CAT2 mobile nodes should be within RF range of at least three reference beacon nodes only one of which nodes is required to be a router providing network access. Dedicated reference beacon nodes can be deployed where necessary to help meet this requirement. And normally the more reference beacons reachable by a mobile node, the higher the accuracy that can be achieved.

IV. IMPLEMENTATION OF SYSTEM NETWORK ARCHITECTURE

A diagram of the network implementation of a Zigbee enabled RFID sensor network with connectionless stochastic beacon architecture is shown in Figure 2. The central server together with the Zigbee network coordinator at network level 1 would be installed in the warehouse office. The coordinator is responsible for the establishment of the Zigbee network, and acts as the network sink node from which the server will retrieve all the information collected by the network devices. The central server is expected to run the database service and exchange information with user applications on demand, thus it should be at least a dedicated PC level device with a main power resource. As the Zigbee coordinator is physically connected with the server via a serial interface, it can easily obtain a main power supply and thus always be kept active.

![Figure 2: network implementation of Zigbee enabled RFID sensor network with connectionless stochastic beacon architecture](image)

The Zigbee routers at network level 2 will then be deployed in the environment. We will configure the Zigbee network as a mesh network to provide better support for mobility [8], thus the deployment criteria for the router devices are:

1. The Zigbee coordinator must connect to at least one router;
Each router must be able to connect to at least one other router that is reachable by the Zigbee coordinator device through a multi-hop path.

To achieve a proper router deployment the procedure is similar to drawing a topological graph, in which the nodes are Zigbee routers and two nodes are considered to be linked if the routers they represent are within each other’s RF range. The deployment procedure can be simply described as:

i. Deploy the router devices from near the coordinator, and then extend the network coverage by deploying more routers until the whole building/site is fully covered;

ii. For each new router deployed, make sure it can either connect directly to the coordinator device, or it can connect to at least one router that is already deployed.

Zigbee routers are supposed to be supported by mains power and always be kept active to guarantee the network connectivity. They can be deployed at locations where it is convenient for a main power connection as long as the deployment procedure above can be satisfied. In addition, they can carry on board battery for working in the situation when the HLC encounters, possible temporarily, power lost. According to our experience Zigbee routers can work for several days powered only by AAA batteries.

With a full Zigbee network coverage deployed, the end devices at level 3 can then be deployed. CAT1 nodes are fixed data nodes responsible for gathering information at specific locations. Their deployment will be based on the warehouse management regulations, which have no effect on the network architecture. CAT1 nodes carrying temperature sensors which are deployed at various in-warehouse temperature control points provide one possible example. Since the CAT1 nodes have fixed position after deployment, they can also be used as reference points for tracking CAT2 nodes. Thus CAT1 nodes can carry out beacon sending function as well as data monitoring tasks. Dedicated beacon nodes are then deployed to provide the area with full beacon coverage. To ensure the operation of the system’s tracking mechanism, full beacon coverage usually means that a mobile node should be able to receive the beacon signal from at least three reference nodes at any position in the operation area. This number can be larger and normally the more reference nodes reachable, the higher the accuracy and reliability that can be achieved.

The tracked targets carry CAT2 nodes. They are divided in two operation modes: mobile mode and inventory mode. Nodes that are defined to be in mobile mode are carried by mobile targets, such as staff, equipment and forklift. They listen to the beacon channel constantly in order to determine the received signal strength from each beacon node it can hear. The beacon information is summarized at the end of each receiving slot and sent periodically to the server via the Zigbee data network channel. The beacon information-updating interval is chosen according to the requirements of each particular application. Nodes, which are in inventory mode, are carried by tracked freights, such as on standard pallets or trays, and require a much longer tracking update interval.

These nodes monitor the beacon channel until they have gathered enough beacon information to be sent back to server via data network channel. They then go into sleep mode to save their battery power until the next information update time point. The information-updating interval is chosen according to the requirements of each particular application. These nodes also carry passive RFID tag so that they can be easily and accurately associated or dissociated with the inventory they are carrying by the Zigbee enabled passive RFID readers.

V. Demonstration System

The demonstration system was developed using the Jennic JN5139 development kit. Our system structure is shown in Figure 3. One module is set as the coordinator, which is used to receive messages from the remote nodes. Three more modules integrated with temperature and humidity sensors are deployed at fixed positions in an open environment within our laboratory. Among these three fixed nodes there is one router and two end devices. They are used as illustrations of the environmental control points in warehouse.

Five modules were programmed as connectionless beacon devices. Instead of using the standard Zigbee stack, we programmed them based on the production test API provided by Jennic, which allows full and accurate control of the device’s sleep/wake up and frame sending activities that are performed at lower network layers. The devices send reference messages at a predefined average beacon interval T.

The last end device was designed and programmed to be able to listen to the beacon channel and act as an end device in the Zigbee data network. This node will be considered as one of the mobile nodes carried by mobile targets.

![Figure 3: Structure of Demonstration System](image-url)

Figure 3 shows the system deployment for this experiment. The coordinator establishes the network on IEEE802.15.4 channel 14, followed by the connection of router and end devices making it a typical Zigbee monitoring system. The fixed nodes exchange environment info with the coordinator.
where the information is displayed on the screen. The beacon nodes send out reference messages, which occupy the beacon channel for approximately 1 to 2 ms, at an average rate of 0.5 sending/second on IEEE802.15.4 channel 18. The mobile end device successfully retrieved from these messages the ID of the fixed beacon nodes and their RSSI at its current position; this information is then sent to the server via the Zigbee network and could then be used by proper localization algorithms such as centroid, triangulation or RF finger prints. The network topology is maintained with only one normal end device joined per mobile target. By adjusting the average rate of beacon sending we can achieve on the receiver an acceptable beacon-receiving rate, which assures that the tracking performance is not noticeably affected by collisions.

According to the Jennic hardware power consumption document [14], the battery life of a JN51xx working as dedicated beacon, as in our demonstration system, is estimated as follows: Procedure for the device to wake up from RAM held mode needs 13.43ms at 9mA working current; sending a short beacon message should then take less than 1ms with 44mA working current; assuming another 5ms operation which is a comfortable length for the device to calculate the next beacon interval and go back to sleep, the current drawn is again 5mA. The current drawn during the sleep period is 0.025mA with RAM held, and the sleep period in our demo was an average of 2 seconds. Thus the average current drawn of the device, denoted by I, is given as:

\[
I = (9 \times 13.43 + 44 \times 1 + 9 \times 5 + 0.025 \times 2000) \equiv (13.43 + 1 + 5 + 2000) = 259.87 / 2019.43 \approx 129 \mu A
\]

With two 1250mAh battery, battery life B is estimated as:

\[
B = 1250 \times 2 / 0.129 = 19427 _{\text{hours}} \approx 809 \text{ days}
\]

This is already a very reasonable battery life considering that the national regulation requires that those electronic devices must be checked and serviced once a year. And as we are using a Zigbee sensor network development board, which is a more complicated and power hungry device than needed, the battery life can be further extended by having specially designed hardware for the dedicated beacon devices with simplified and streamlined components. Thus the performance of this demonstration system demonstrated the feasibility of our architecture and its hardware realization.

VI. CONCLUSION

In this paper we proposed a connectionless Stochastic Reference Beacon Architecture for mobile target tracking in Zigbee RFID sensor networks. Comparing to the traditional Zigbee based tracking system, the features of our design include: i). It allows mobile devices to use Zigbee end devices that can be supported by simpler, cheaper and power efficient hardware compared to the router devices used in current Zigbee tracking systems, and does not have performance decrease when multiple mobile targets are present in the same area; ii). Current Zigbee based tracking systems either requires a dense router implementation that leads to higher cost, less flexibility and a more complicated network structure, or suffer accumulated localization error due to using mobile nodes as reference points. The connectionless stochastic reference beacon architecture does not require dense router deployment. Instead, it is mainly based on the existing Zigbee RFID sensor network hardware and does not affect the network structure, implementation and performance. The data collection network could thus support warehouse inventory tracking with minimal additional hardware and cost while at the same time avoiding the accumulated localization error; iii). comparing to our previously designed connectionless inventory tracking system, the connectionless stochastic reference beacon architecture not only inherits the previous connectionless inventory tracking system’s features such as consistent network structure and no accumulated error, but also has longer hardware battery life, lower network traffic level and enables the tracking of targets with higher mobility while at the same time maintains support for normal inventory tracking with the least additional devices, which are the dedicated beacons that are very simple and low cost devices with reasonable battery life and simple deployment.

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