A decentralised low-power ZigBee-based localisation approach

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Abstract—Wireless sensor networks have been deployed widely. Sensor networks involve sensor nodes which are very small in size, low in cost, and have a short battery-life. One of the critical wireless sensor network applications is localisation and tracking mobile sensor nodes. ZigBee is a new, emerging technology for low rate, low power, and low range communication networks, which aims to provide long battery-life for network devices. In this paper, we propose a decentralised ZigBee-based tracking system to detect and track the location of mobile nodes indoors. End-devices have limited connection capabilities which cause a problem in localisation. End-devices are collaborated in the tracking process in order to reduce the power-consumption for ZigBee networks. The proposed tracking system can be deployed in an area where the density of router nodes is very low. The tracking system is implemented by ZigBee sensor devices, and experiments have been done to evaluate the proposed tracking system based on battery life and communication cost.

Keywords—Tracking, Localisation, ZigBee networks.

I. INTRODUCTION

A wireless sensor network is a distributed collection of nodes that are resource constrained and competent of operating with minimal user attendance. Sensor networks can be created using unattended sensor nodes to promise to provide an effective, low cost solution for several applications. The potential applications of wireless sensor networks involve environmental monitoring, military surveillance, search and rescue, and tracking people and equipment.

Sensor networks are considered to be systems of many small and simple devices deployed over an area of interest, in order to sense and monitor events or track objects or people as they move within the area of interest. Sensor nodes are tiny electronic devices equipped with a battery for an energy source, a sensing part for sensing physical characteristics, a processor for performing computations, a wireless transceiver for two way communications with other sensors and memory for storing information and for local computation. A sensor node has the following characteristics: (1) small physical size, (2) low power consumption, (3) limited processing power, (4) short-range communications and (5) a small amount of storage [1].

Wireless sensor systems can be deployed in several applications; one of the critical applications for wireless sensor networks is tracking applications. Tracking is the estimation of the state of a moving target based on remote measurements.

Target tracking has become one of the critical problems in wireless sensor networks. Tracking mobile targets based on wireless sensor networks was initially investigated in 2002. Target tracking systems are usually composed of two main components as seen in Figure 1: the localisation method, and network standard method. The localisation technique includes the method which calculates the distance for target devices with unknown positions. Network standard enables collaborative information to be processed among multiple sensor nodes.

In this paper, we concentrate on the second component which is a network standard. Tracking targets based on ZigBee network standard is an emerging field. Tracking based on ZigBee networks is a challenging task due to the limited communication capabilities of ZigBee components.

Figure 1: Tracking System Components

This paper is organized as follows: Section 2 reviews the existing localisation and tracking techniques. Section 3 presents our proposed tracking system based on ZigBee network standard. Section 4 involves implementing our work on real ZigBee-based sensor devices. Section 5 includes evaluating the presented approach based on battery life and communication cost. Section 6 gives a discussion about the proposed system. And finally, Section 7 presents a conclusion and future work.

II. TRACKING SYSTEMS

Tracking is the ability to find out the coordinates of a mobile target in real time. Generally, each tracking system includes one or more localisation technique. The localisation technique works by determining the location of the sensor node based on other sensor nodes with known locations. Several localisation techniques are described in [2].

Localisation techniques can be categorized based on the communications between nodes into centralised and
decentralised. Centralised techniques involve transmitting data to a central node to compute the location for each single node. The proposed works in [3] & [4] offer reliable localisation systems to work within hundreds of sensor nodes. Both systems require the transmission of each single packet to a central node in order to calculate the position for the target nodes.

Decentralised localisation systems do not require centralised computation, and rely on each node to calculate its location. Decentralised systems are systems in which each sensor node is responsible for determining its location with only limited communications with nearby limited nodes. The proposed work in [5] presents a decentralised localisation system, which allows sensors to locate their locations with no need for centralised computation.

Distributed or decentralised localisation techniques have much better scaling properties than centralised techniques, because the distributed techniques have lower communication cost, since each sensor node has to communicate with its neighbours instead of communicating with a central node. Centralised techniques are more expensive than decentralised techniques, in which each sensor node has to send localisation information to a central computer in order to make all the calculations there, and that reduces the life of each sensor node. Consequently, the distributed solutions are more attractive for large sensor networks including thousands of nodes.

In this paper, we concentrate on designing a tracking system based on a decentralised ZigBee network standard.

A. Related work

Tracking based on ZigBee network is an emerging technology. Many localisation systems have been developed based on ZigBee network standard, such as the proposed work in [6], which presents a tracking system including a GeoZigBee sensor with a GPS wristwatch tracking device. The produced device includes a low power GPS sensor, flash memory, and a ZigBee wireless data link, and it offers ultra low cost and low-power design enabling operation for 30 days. The system can only be deployed in outdoors as it’s based on GPS signals which can not penetrate obstacles and walls.

The proposed work in [7] involves estimating the distance between target nodes and stationary sensor nodes based on measuring the received signal strength values. The density of nodes was set to 0.27 nodes/m². In [8] a new localisation system based on the ZigBee network standard was presented. The proposed system involves finding out the location of the target node based on four stationary sensor nodes with known positions. The mobile target was considered as a coordinator, while the stationary sensor nodes were routers. The final distance can be calculated based on received signal strength values from stationary sensor nodes (routers).

The presented work in [9] presents a tracking system to find out the location of construction materials in a large scale outdoor environment, based on the ZigBee network standard. Several routers and one coordinator device were deployed to evaluate the presented work.

III. ZIGBEE-BASED TRACKING APPROACH

As aforementioned, routers and coordinator are mains-powered as they can not go to “sleep mode”, and, consequently, installing a high number of routers is not a power-efficient solution for tracking applications as it leads to an increase the power-consumption in sensor networks.

Our tracking system is different from the previous proposed systems, as it is developed based on the ZigBee network standard and uses the RSS system. In this paper, we focus on the network standard as the localisation method was described in a [10].

A. ZigBee Network Standard

ZigBee is a low-power, low data rate, low cost wireless communication standard, which aims to be used in home automation and remote control applications. ZigBee has been designed to offer minimum cost and power connectivity for devices which require battery life for as long as several months to several years. ZigBee devices are expected to cover 10-75 meters based on the RF environment and output consumption required for a given application.

It’s important to distinguish ZigBee from IEEE 802.15.4 network standard, since IEEE standard 802.15.4 describes the specification for radio PHY and MAC (Medium Access Control) layers at 2.4 GHZ, 868 MHZ and 915 MHZ. IEEE standard 802.15.4 aims to offer the fundamental lower network layer of Wireless Personal Area Network (WPAN) which focuses on low cost, low power consumption.

![ZigBee Network Standard](image)

Figure 2: ZigBee Network Standard

Each ZigBee network involves three ZigBee device models as shown in Figure 2: coordinator, routers, and end-devices. A single coordinator is required for each ZigBee network, and it initiates the network formation. A router is an optional network component; it may associate with the coordinator, and participates in the multi-hop routing of messages. And finally, the end-device, which is optimised for low power operation, and only connects to one router or coordinator. The main distinguishing characteristic between a router and an end-device is that routers can connect to more than one device, in order to route messages between them, but each end-device can...
connect to only one router or coordinator. ZigBee supports both star and mesh networks [11].

B. The Proposed ZigBee-based Tracking System

Several tracking systems have been proposed recently. In our research, we concentrate on tracking mobile targets through distributed low density ZigBee-based sensor nodes. The proposed tracking system has been developed to work with the ZigBee network standard.

Most of the previous proposed ZigBee-based tracking systems are based on router and coordinator devices to locate the position of mobile targets. End-devices were not involved in the tracking process due to the limited connection capabilities, and that increases the power-consumption for a huge ZigBee network. End-devices can only connect to one router or coordinator in a ZigBee network, which causes a problem in the localisation process. The mobile target needs to be connected to at least 3 beacon nodes in order to find out its current location. In this paper we address this issue by involving end-devices in the tracking process.

For instance, if the mobile target is covered by one router and 2 end-devices as shown in Figure 3, that will not be enough to find out its current location, because the mobile target can only connect to the router device, and can not connect to the end-devices because they are already connected to another router. We have suggested a solution for this problem by disconnecting the end-devices from their parent, and connect them to the mobile target node. The mobile target can find out its position if it's connected to 3 beacon nodes.

There is another challenge that has been overcome while tracking targets through the ZigBee network standard. The problem was what type of device the mobile target should be considered to be in the ZigBee network standard. The mobile target can not be considered as an end-device, because each end-device can connect only to one router or coordinator, and the mobile target needs to connect to a minimum of 3 devices, in order to be able to locate itself. The mobile target can not be considered as a coordinator; because there is only one coordinator in the network, in addition to that the coordinator should be mains-powered.

The only possible solution for this problem is to consider the mobile target as a router. In this case, the mobile target can connect to other routers and the coordinator in the ZigBee network. The router device can not connect to any end-device which is already connected to another router or coordinator, as the end-device can only connect to one device.

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Figure 4: ZigBee-based Tracking Phases

Our ZigBee-based tracking system involves 3 main phases as shown in Figure 4. \( n \) represents the total number of beacon nodes, \( m \) refers to the total number of routers nodes, and \( resp \) refers to the total number of respond messages. Each phase is described below. The tracking system algorithm is implemented in Figure 5.

\[
\text{Begin} \begin{align*}
1 & \quad \text{Initialisation Phase} \\
& \quad \text{For} (i = 0; i < r; i++) \\
& \quad \quad \text{Send("Hello";)}; \\
& \quad \quad \text{if}(resp < 3) \text{then} \\
& \quad \quad \quad \text{2 \quad Connection Phase} \\
& \quad \quad \quad \quad \text{For} (j = 0; j < n-m-1; j++) \\
& \quad \quad \quad \quad \quad \text{Disconnect(Node(i));} \\
& \quad \quad \quad \quad \text{3 \quad Reconnection Phase} \\
& \quad \quad \quad \quad \quad \text{For} (i = 0; i < n-m-1; i++) \\
& \quad \quad \quad \quad \quad \quad \text{Reconnect(Node(i));} \\
& \quad \quad \quad \text{End}
\end{align*}
\]

Figure 5: ZigBee-based Tracking Algorithm

1) Initialisation Phase: The mobile target enters the tracking area and sends "Hello" messages to all beacon nodes (routers) in its range, and waits for responses from them. All sensor routers with known positions in the mobile target range will send acknowledgements to that mobile target. If the mobile target receives at least 3 beacon messages from 3 different routers, then it will find out its position based on these routers. But if the mobile target receives less than 3 beacon messages, then it will turn to the connection phase. Figure 6 (a) shows a mobile target connected to one router in its range.

2) Connection Phase: The mobile target asks the closest router if it is connected to any end-devices. So, if the mobile target asks the router to disconnect the end-device nodes as shown in Figure 6 (b). The disconnected end-devices will search for a new parent to connect to; usually the end-devices connect to the mobile target if it’s close to them as seen in Figure 6 (c). If the closest router is not connected to any end-devices, then the mobile target will ask the 2nd closest router node if it’s connected to
any end-devices. This phase will be repeated till the mobile target is connected to at least 3 beacon nodes.

3) Re-connection Phase: As soon as the mobile target moves away from the end-devices, then the end-devices will search for a new parent to connect to. In most cases, the end-devices will connect back to the previous parent.

![Figure 6: Tracking Phases: (a) Initialisation Phase, (b) Connection Phase, (c) Re-connection Phase](image)

### IV. EXPERIMENTS

To evaluate our approach we implemented our proposed ZigBee-based system on Jennic ZigBee-based devices. In this section we explain the main features of the sensor devices which have been used in our experiments. The experimental testbed is described, and the main experiments are illustrated.

#### A. Hardware Platform

In our experiments, we use a JN5139-EK010 sensor node platform. This module offers low power-consumption and low processor overhead, and is a low cost platform for wireless sensor networks. It supports complex tree and mesh network topologies providing reliable coverage over large areas. Jennic’s ZigBee stack API offers rapid application development by offering simple programming to the standard ZigBee network layer.

#### B. Experimental Testbed

Our experimental testbed consists of 7 Jennic ZigBee-based sensor nodes where they are distributed in known locations. Our network involves one coordinator, 2 router devices, 6 end-devices, and one mobile target which was considered as a router.

We have done our experiments at Loughborough University, in FK & FG research areas. We assume that the sensors must be capable of estimating the distance of the target to be tracked from the sensor readings.

#### C. Main Experiments

The main goal of this work is to incorporate end-devices in the tracking process, as routers and coordinator are mains powered. We deployed our sensor nodes in a huge area, in order to test the efficiency of our tracking system. One mobile target was moving around the area of interest. The mobile target needs to be covered by at least 3 stationary sensor nodes in order to find out its location. Two main experiments have been tested in order to evaluate the power-consumption. Figure 7 shows an experiment in which all the beacon nodes were considered as router devices, and Figure 8 involves an experiment where several end-devices were deployed in order to test the tracking efficiency.

### V. EVALUATION

Tracking based on ZigBee has some limitations, such as end-devices can only connect to one node (coordinator or router). In this section, the proposed tracking system is evaluated based on battery life, and communication cost.

#### A. Battery Life

One of the critical issues in developing a tracking system for sensor nodes is a battery life issue. Sensor devices are designed to work from a few months to many years. As mentioned above, ZigBee network standard offer three types of devices (Coordinator, Router(s), and End-device(s)). Coordinator and router devices are required to be “wakening up” all the time, as the coordinator needs to initialise the network, and routers are responsible for routing the messages between network devices. End-devices can go to “sleep mode” as soon as they complete their duties.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Charge (µC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wake from Sleep</td>
<td>143.46</td>
</tr>
<tr>
<td>Transmit Data</td>
<td>111.232</td>
</tr>
<tr>
<td>Sleep</td>
<td>0.0034</td>
</tr>
</tbody>
</table>

Two main experiments have been implemented to evaluate the power-consumption in two different cases. The final time for both experiments was 9 minutes. The
first experiment (A) involved 6 router devices and one mobile target moves in that area as shown in Figure 7. The second experiment (B) included 2 routers and 4 end-devices, in order to reduce the power-consumption for the whole ZigBee network as seen in Figure 8. Table 1 shows the power charge (µC) required for each phase.

Therefore, 360391.68 µC of charge is consumed over a total cycle time of 540 s (9 minutes) for the first experiment. And 241785 µC is consumed over the same time for the second experiment.

Involving end-devices in the tracking process can help to reduce the total power-consumption of ZigBee networks. Figure 9 shows the difference in power consumption between two experiments. The power-consumption in experiment B is a more power-efficient solution for tracking applications than the power consumption in experiment A.

![Figure 7: A tracking Experiment based on Routers](image)

![Figure 8: A tracking Experiment based on End-devices](image)

**B. Communication Cost**

ZigBee network standard aims to provide low wireless network cost. A low cost system allows ZigBee technology to be widely used in wireless control and monitoring applications. The proposed tracking system does not require any additional hardware. It only depends on the sensor device capabilities with no need for any extra hardware.

Our system does not require a high number of messages to be exchanged between mobile target node and beacon nodes. The calculations are processed in the mobile target node, with no need for centralised computation.

Distributed tracking solutions are more attractive for large sensor networks including thousands of nodes. Centralised systems are more expensive than decentralised in that each sensor node has to send localisation information to a central node, and that reduces the battery life for each sensor device. We evaluated the communication cost in both systems.

In a centralised system, all the messages have to be sent to a central node. For instance, if the mobile target receives 3 beacon messages, then it needs to send the received messages to a central node. The total number of messages which are required to be exchanged between sensor nodes in a centralised system is notated as \( l \), where its presented in equation 1.

\[
l = n^2 \times f
\]

where \( n \) refers to the total number of beacon nodes, \( f \) is the final time in seconds. \( l \) is measured based on the number of beacon nodes \( n \) which sends two messages every two seconds to the mobile target.

There is no need to send the received messages to a central node in a decentralised system, as all the calculations are processed in the mobile target device. The total number of messages which are required to be exchanged in the decentralised system is presented in equation 2.

\[
l = n \times f
\]

Figure 10 involves a comparison between both systems (centralised and decentralised) based on the total number of messages which need to be exchanged per second. The decentralised system requires a low number of messages to be exchanged between nodes and therefore reduces the power-consumption for the whole network.

**VI. DISCUSSION**

In this paper we investigated the ability of end-devices to reconnect to other sensor nodes in their range in order to be incorporated in the tracking process and therefore give better tracking efficiency and accuracy, and reduce the power-consumption. The main advantage behind deploying our tracking system in the ZigBee network standard is that it’s a power-efficient network when high numbers of end-devices are deployed, because end-
devices can reduce the total power-consumption in a ZigBee network.

As mentioned above, many tracking systems have been proposed based on the ZigBee network standard. Most of the previous systems did not deploy end-devices in the tracking process as they suffered from limited connection capabilities. The presented system in [6] is power-consuming and the device can work only for 30 days, so this is not an acceptable solution for tiny sensor devices, as they are expected to stay for 18-24 months.

The proposed system in [7] involves sending the sensor ID, target ID, packet number, and sensor-to-target distance to the sink node, and this is a power-consuming issue, since deploying this technique in a huge network requiring the exchange of a high number of messages between sensor nodes.

End-device nodes are a power-efficient solution for wireless sensor networks. In [7], [8], & [9], they deployed their systems based on router and coordinator devices to track a mobile target. End-devices didn’t take place in their experiments, and that increases the power-consumption and cost for cheap wireless sensor networks.

Our tracking system can be deployed in many tracking applications, such as tracking patients and doctors in hospital, and tracking fire-fighters in emergency situations. There are many tracking systems which have been deployed widely, however our system is different from the previous systems as we have overcome the problem in the previous works. The end-devices are collaborated in the tracking process in order to increase the efficiency and accuracy of the tracking system, in addition to reducing the total power-consumption for tiny sensor nodes.

The decentralised systems are more efficient than centralised as they don’t need to send the received messages to a central node.

![Figure 10: A comparison between Centralised and Decentralised Tracking Systems](image)

VII. CONCLUSION AND FUTURE WORK

Tracking mobile target applications through wireless sensor networks is a critical and emerging field. ZigBee networks benefits from having the ability to quickly attach information, detach, and go to “sleep mode”, which offers low power-consumption and extended battery life.

The implemented system presented a tracking system through the ZigBee network standard. End-devices offer efficient and reliable components for ZigBee networks. In our system we have collaborated end-devices in the tracking process in order to increase the tracking accuracy where the density of router nodes is low. Our proposed system is decentralised in order to reduce the total number of exchanged messages.

Our proposed system involves tracking one mobile target. One of our future works is to overcome the challenges in tracking multi-mobile targets through the ZigBee network standard. We intend to focus on the second important part for developing tracking systems which is localisation technique, as this part is considered to be a critical part for cheap wireless sensor nodes.

REFERENCES