# Self-Organizing ZigBee Network and Bayesian Filter Based Patient Localization Approaches for Disaster Management

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***Abstract*— A self-organizing, scalable, heterogeneous and location aware WSN architecture called Disaster Aid Network (DAN) for assisting the responders to provide efficient emergency response was proposed in our previous work. The two main aspects of DAN are the communication and localization aspect. As part of the DAN communication aspect, in this paper we have undergone empirical investigations to identify the suitability of ZigBee's 2.4 GHz operation for DAN. A new self-configuring mechanism for patient data access by the doctor at the disaster site is also proposed. As part of the DAN localization aspect, in this paper we have implemented two new Bayesian filter based algorithms called Improved Range-Based Monte Carlo Patient Localization and Range-Based Unscented Kalman Filter Patient Localization for real time localization of large number of patients at the disaster site. The close-to-reality simulations of both these algorithms is done using a disaster management mobility model to identify their suitability for patient tracking. The new localization solution in tandem with the emergency response system shall facilitate efficient logistic support at the disaster site.**

***Keywords- Emergency response; ZigBee; self-configuration; patient localization; Bayesian filter based algorithms; close to reality simulation***

## I. INTRODUCTION

Wireless Sensor Networks (WSN) offer great opportunities and numerous applications are imaginable. But they also impose some new challenges that have to be dealt with. The main WSN challenges that researchers and developers are currently dealing with include heterogeneous network, scalability, self-organisation, self-sufficient operation, multi-hop communication, ad-hoc networks and localization. Self-Organising sensor network are WSN built from sensor nodes that may spontaneously create impromptu network, assemble the network themselves, dynamically adapt to device failure and degradation, manage movement of sensor nodes, and react to changes in task and network requirements. Self-organization can be classified into four aspects as follows.

- Self-configuration: The ability of WSN to automatically and seamlessly configure sensor nodes.
- Self-healing: The ability of WSN to automatically detect, diagnose, and repair localized software and hardware problems.
- Self-optimization: The ability of WSN to continually seek opportunities to improve their own performance and efficiency.
- Self-protection: The ability of WSN to automatically defend themselves against malicious attacks or cascading failures. A WSN should use early warning to anticipate and prevent system wide failures.

Some of the short range wireless communication standard based technologies that can be considered for WSN are Bluetooth, ZigBee, RFID, etc. ZigBee is a standard developed by the ZigBee Alliance that defines a set of communication protocols for low-data-rate short-range wireless networking based on the Open System Interconnect (OSI) basic reference model [20]. Its goal is to provide the means for low-cost implementation of low-data-rate wireless networks with ultra-low power consumption. The ZigBee standard distinguishes between three different device roles for the nodes of the network namely the coordinator, router and end device. It supports star, mesh and tree topology. *RFID* (Radio Frequency Identification) is a technology for contactless and automated identification. It joins other methods for identification like the bar code. However, the advantage of RFID is that it doesn't require a visual contact. The most familiar form of RFID is the RFID tag and a reader.

The potential problems faced in the aftermaths of a disaster are: response capabilities of the local jurisdiction may be insufficient, large-scale evacuations from the disaster site, complications in implementing evacuation management strategy, disruption of critical infrastructure (energy, transportation, telecommunications, etc.), tens of thousands of casualties, response activities must begin without a detailed situation and critical assessment as its time consuming to obtain an initial common operating picture [21].

A new emergency response system based on a Disaster Aid Network (DAN) was proposed by us to improve emergency response [3]. The two main aspects of DAN are the communication and localization aspect.

In the DAN communication aspect the goal is to develop a scalable and robust communication system that supports low power and self-organizing mechanisms. In this paper the focus is on the self-organizing mechanisms for the DAN communication aspect.

In the DAN localization aspect the goal is to track the patients at the disaster site. The task of tracking a patient [18] can be split into range estimation and position estimation. In this paper we focus on the position estimation part. We have developed two new Bayesian filter based position estimation algorithms and compared their performance to find their suitability for optimal patient tracking. The position estimation algorithm in tandem with the emergency response system shall facilitate efficient logistics at the disaster site by providing real time information about the patients' locations to the On-site Organizational Chief (OOC).

The paper is organized as follows: Section II explains the the Disaster Aid Network system. Section III details the empirical investigations for ZigBee 2.4 GHz operation. Section IV describes the self organization techniques for DAN. Section V mentions the state of the art of localization in WSN. Section VI explains our patient localization method and the two algorithms. Section VII shows the simulation results of these algorithms and Section VIII concludes the paper.

## II. DISASTER AID NETWORK

We focus on the disaster management strategy followed in Germany [2] called "Mass Casualty events" (MANV) but our system can also be adapted to other disaster management strategies. At the beginning of MANV, the disaster site organization chief designates the disaster site into four care zones as follows: The danger zone where the disaster itself happens, injured deposition zone where the patients are prioritized (triaging), treatment zone and transport zone. The patients are shifted from one zone to another before being evacuated [4].

DAN is a self-organizing, scalable, heterogeneous sensor network (see figure 1) [3] of 30-200 nodes comprising of:

- Patient nodes with electronic triage tag and optional continuous vital sign monitoring. They are also called blind nodes because their positions are unknown and have to be estimated.
- Pseudo anchor nodes are patient nodes whose positions are already estimated.
- Doctor nodes (mobile anchor nodes) are mobile nodes (Tablet PC) whose locations are known.
- The monitor station is a collector node which collects the patients' locations and visualizes them for the onsite organization chief (OOC).
- Static anchor nodes are nodes placed at fixed positions whose locations are already known.
- Server: A server running a database for data collection and aggregation is placed at the management centre (or data acquisition centre).

The specifications that the DAN communication aspect should satisfy are: robustness, scalability and self organizing communication system, support heterogeneous network, low power, the use of standard based technology and support distributed communication. Several standard wireless technologies (ZigBee, WLAN, etc.) were considered and due to the low-power, low data rate properties and the possibility to mesh network hundreds of nodes, the ZigBee standard is chosen for investigation to identify its suitability for DAN.

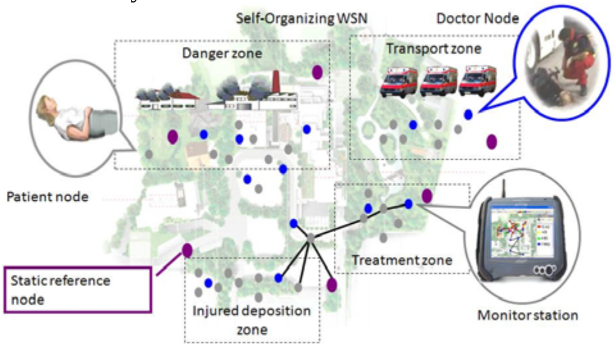


Figure 1. DAN system

The results of our investigations in [22] to find ZigBee's suitability for DAN in terms of power consumption, scalability, mobility and number of routers are summarized as follows

- Power consumption of ZigBee ready sensor nodes imply a battery lifetime of at least a day.
- Scalability: In a static scenario the network scales well up to 150 nodes in a 300m x 300m area. In a mobile scenario, the network does not scale as well as in the static scenario due to the high PLR (packet loss ratio).
- Influence of routers in the network: In a static scenario using more routers doesn't improve the network performance.
- Mobility: The performance of ZigBee network is affected when the nodes are mobile, especially when the mobile node density is high. However, the performance could be improved if the number of routing-capable devices is increased.

These results show that ZigBee is basically suitable for DAN even though detailed investigations will have to be done. In this paper the suitability of ZigBee's 2.4 GHz operation is analyzed and a self-configuring mechanism for DAN is proposed.

## III. ZIGBEE 2.4 GHZ OPERATION

The 2.4 GHz operation of ZigBee is analyzed by considering three main factors which are the node transmission range, RF attenuation and coexistence.

### A. Transmission Range Testing

The maximum transmission range of the ZigBee nodes are measured in different situations using CC2430DB demonstration boards (See figure 2(a)) from Texas Instruments (TI) [24]. The technical data of the CC2430DB is as follows: CC2430 System on Chip with an 8051 core and 2.4 GHz transceiver, a PCB antenna, a data rate of 250 kbps, transmission output power of 0 dbm, and receiver sensitivity of -92dbm. During the measurements the CC2430DB nodes are mounted in a quadrate form of plastic boxes. This simulates the housing case that will be used for

DAN nodes to protect them during the emergency response process.


a) CC2430DB board[1] b) Reference node and triage tag setup

Figure 2. Transmission range testing setup

When both the nodes are placed at the ground level with grass, the maximum transmission range measured is 12 m. This shows that a grass height of even 5 to 10 cm heavily attenuates the signals. When two nodes are elevated at a height of 1.5m using statives' in a line of sight field, the maximum transmission range between them is measured as 205m.

An experiment is undergone to test the transmission range between two nodes with one node acting as a reference node and the other acting as a triage-tag (patient node). In this experiment a CC2430DB node elevated at a height of 1.5 m acts as a reference node and a test person wearing a triage-tag (CC2430DB) are setup in a line of sight environment as shown in figure 2(b). The maximum transmission distance measured between the reference node and the test person (such that a communication is ensured) when the triage-tag is placed at different positions are mentioned in the table 1.

| Setup | Maximum Transmission Distance |
|---|---|
| Test person stands facing the reference node and wears the triage-tag on his chest | 205m |
| Test person stands facing the reference node and wears the triage-tag on his back | 95m |
| Test person lies in the ground and wears the triage-tag on his chest | 105m |
| Test person lies in the ground and wears the triage-tag on his back | 8m |

TABLE I. REFERENCE NODE – TRIAGE TAG MAXIMUM TRANSMISSION DISTANCE MEASUREMENT

### B. *Coexistence and RF Attenuation*

Since ZigBee operates in the 2.4 GHz ISM band which is also the operating frequency for several other technologies like WLAN and Bluetooth, it's often questionable if ZigBee can coexist. ZigBee network can access up to 16 separate 5MHz channels in the 2.4GHz band, several of which do not overlap all the time with US and European versions of IEEE 802.11 or Wi-Fi. A state of the art analysis related to coexistence indicates that that IEEE 802.15.4 suffers heavy packet loss when interfered by an IEEE 802.11 network specifically if both the technologies are running at overlapping channels. A new feature called 'channel agility' has been introduced in the 2007 version of ZigBee specification. This provides a method for the network to change channels in the event of interference. The network coordinator detects potential interference on a channel and directs the devices on the network to change to a better channel. Kupri's [25] experimental results show that a WLAN (IEEE 802.11 g and n) will not frequently block ZigBee / IEEE 802.15.4 traffic and the 802.15.4 system can co-exist with a WLAN network. Their test results show that even under the most severe 802.11 interference (IEEE 802.11n at 40 MHz bandwidth) by incorporating channel agility, IEEE 802.15.4/ ZigBee is a viable and stable solution for home control applications. They conclude that the implementation of channel agility improves the overall situation and increases the robustness of ZigBee networks.

In practice, a radio signal operating in a disaster site may encounter many objects (fixed, mobile, and transient objects) in its transmission path and undergoes additional attenuation depending on the absorption characteristics of the objects. In [26] they have measured the ZigBee 2.4GHz signal attenuation through the following objects: metal door-6dBm, human body-3dBm, glass wall with metalframe-6dBm, metal door in brick wall- 12dBm.

### C. *Summary*

The ZigBee 2.4 GHz ranging experiments indicate that during the deployment of nodes in DAN the reference nodes should be elevated at a height of 1.5m for a better transmission range and the maximum distance achievable between two reference nodes in LOS is 205m. The reference nodes can also be provided with range-extenders to increase their range and thereby reduce the number of infrastructure nodes. The maximum transmission distance measurements between a reference node and triage-tag shows that 2.4 GHz ZigBee is suitable for DAN except for the condition when the injured person lies in the ground and wears the triage-tag on his back, wherein the signal strength is strongly attenuated due to the influence of the human body.

However, the empirical investigations of the following topics will be part of future work: coexistence of ZigBee with other ISM band technologies, the effect of RF signal attenuation by obstacles at the 2.4 GHz operation, effect of antenna propoerties and verification of maximum data rate to identify the extent of application data that can be sent.

## IV. SELF ORGANIZATION OF DAN

Self-organization procedures associated with the communication network are necessary for reliable system operation. In DAN during the initial setup, the nodes (coordinator, static anchor nodes, and doctor nodes) should automatically form a network. Also during the emergency response process new patient nodes appear and leave the site (after evacuation). So DAN should automatically reconfigure nodes in the order of 200. The self-configuration characteristics [19] of ZigBee supports automatic

[1] Source: graphic from [24]

establishment of network and association of new nodes joining the network.

In DAN when a mesh network is established, a routing path has to be formed such that the patient nodes can send their data via routers to the server at the management centre of the disaster site. If any node in this route becomes faulty or if the patient nodes move, the routing paths have to be adapted dynamically such that the patient data is relayed in an optimal way to the server. The self-healing characteristics of ZigBee mesh networking [19] can optimally route, as the nodes move and can select alternative route if any node in the routing path stops functioning.

Even though the self-configuring and self-healing mechanisms of ZigBee are useful for DAN, they are not sufficient and new self-organization mechanisms to satisfy DAN communication aspect functionalities have to be developed. In the next subsection one such new self-configuring mechanism for seamless patient data access by the doctor node at the disaster site is explained.

### A. *Self-Configuration for Patient Data access by Doctor*

A doctor provides each patient with a patient node either at the danger zone or at the triage zone. The patient node is worn around the neck of the patients and switched on by the doctor. A doctor node can communicate with a patient node at the disaster site to fulfil any of the following functionalities

- In the triage zone the doctor uses his tablet PC to configure the patient node with triage and personal information.
- During the emergency response at the triage and treatment zone the doctor's tablet PC might have to often read the patient status (vital signs, triage information) from the patient node.

The following problems might occur during the doctor-patient node interactions

- Considering the large number of patients and fewer doctors present at the disaster site, it can be complicated and time consuming for the doctor to manually configure his tablet PC for accessing or configuring the data of a patient node.
- Thus, automatic configuration of patient-doctor nodes is required. But during automatic configuration there can be large numbers of patients at close proximity and the doctor node must be sure that it talks to the right node i.e. patient identification can be an issue.

In order to solve the above mentioned problems, a self-configuring mechanism using RFID and ZigBee is demonstrated in the next subsection to provide a simple, automatic and safe data access between the patient node and the doctor node.

#### 1) *ZigBee-RFID based Self-configuring Mechanism*

A doctor who needs to configure or access a patient data at the disaster site brings his Tablet PC in close proximity (in the order of cm or a meter) to that particular patient node and with a single click in his Tablet PC he can access the right patient's data safely, easily and automatically. This self-configuring mechanism is described below.

The patient node consists of a ZigBee transceiver and RFID passive tag. The RFID passive tag is used for patient identification and stores a unique id which in our case is the 64 bit IEEE address of the corresponding ZigBee-ready patient node. The RFID passive tag has a very short range. The doctor node is a Tablet PC enabled with a ZigBee module and an RFID reader and runs an application for patient data access.

When the doctor needs to access the patient's data he brings his Tablet PC in close proximity to that particular node and clicks a button on the Java application. Considering that the proximity of the tag is in the order of cm, the RFID reader of the doctor node can only read the tag of that particular node. Of course it is assumed that no two patients are present in proximity of cm range in the disaster site. The communication flow between the patient node and the doctor node is depicted in figure 3.

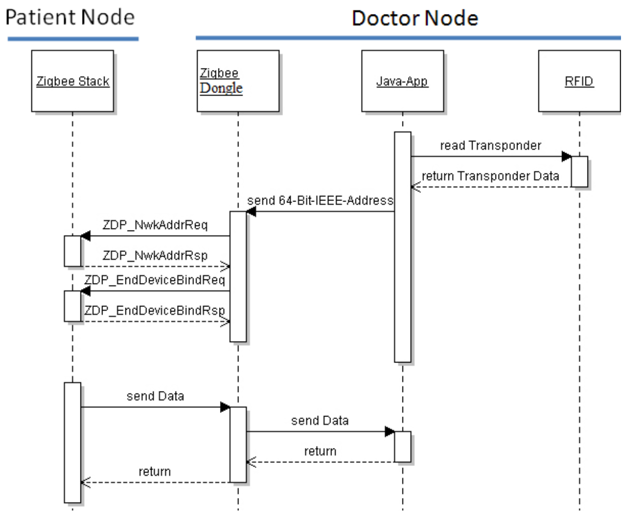


Figure 3. Communication flow diagram of ZigBee-RFID based self-configuring mechanism

The RFID reader reads the unique id of the patient node which is the 64 bit IEEEE address of that node and provides it to the application. The application then connects to the ZigBee stack of the dongle and sends this 64 bit IEEEE address via ZigBee communication and requests the network address of that node. Once the network address is received by the dongle it performs a ZigBee application layer binding between the doctor node and that patient node. After this a mobile ad-hoc network is formed and the doctor can safely access the patient data.

#### 2) *Demonstrator*

In order to verify the self-configuring mechanism for seamless data access between patient node and doctor node explained above, a demonstrator is constructed.

The ZigBee-ready temperature sensor node [22] attached with a RFID passive tag is used as the patient node. During the time of development of this demonstrator there was no Tablet PC available with a ZigBee module and RFID reader integrated. So the doctor node is represented in this demonstrator by a laptop connected to a ZigBee dongle and a

RFID reader. A ZigBee dongle which offers ZigBee 2003 compatible interface for the Plug & Play connection to a PC is used. The RFID reader is S4100 MFR from TI which has an ISO 15693 conformal RFID reader and connects via RS232 interface to a PC.

RFIDZigBee is a Java application with a simple GUI for patient data access and runs in the laptop. The ZigBee dongle is connected to the RFIDZigBee via a Python based intermediate layer developed by us that interfaces ZigBee stack of the dongle to RFIDZigBee. The demonstrator setup is depicted in figure 4. It consists of two patient nodes and a doctor node.

The doctor node is brought in close proximity to patient node1 and the "connect button" is clicked in the RFIDZigBee software. The RFID reader of the doctor node is able to read only the 64 bit IEEE address of patient node 1 followed by which the ZigBee dongle binds the doctor node to the patient node1 to form a mobile ad-hoc network. Now the doctor node safely received the test data from the patient node 1.

Thus the demonstration verifies that it is possible for the doctor node to automatically record the patient data from the patient node with a single button press. Besides the patient identification using RFID passive tag makes sure that the doctor receives data from the right patient and increase security.

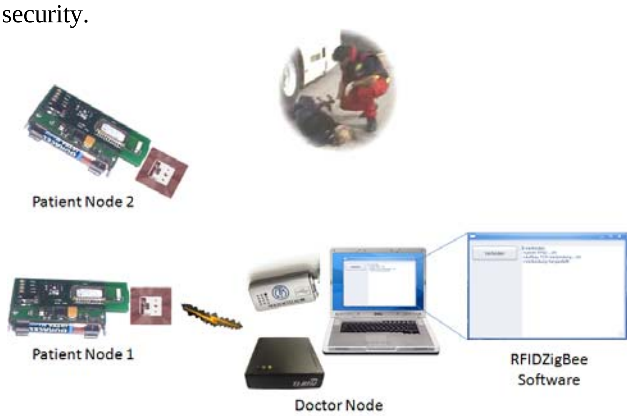


Figure 4. Self-Configuration for Patient Data access by Doctor-Demonstrator

### B. *Self-Protection*

In DAN the patient data should be securely sent to the server of the management centre and should be automatically protected against any malicious attack.

There can be two main types of security concerns in WSN: data confidentiality and data authentication [19]. Any message transmitted can be received by an intruder and cause confidentiality problems. Encrypting the message sent with a security key can solve confidentiality problems. The second security concern is the data authentication wherein an intruding node can modify and resend even an encrypted message. Including message integrity code (MIC) for each outgoing message can allow the recipient to check whether the message is corrupted.

Even intrusion of any device can be prohibited through device authentication technique. If the nodes are not tamper-resistant then an intruder can access the security key from the memory of the device. So tamper-resistant mechanisms for DAN nodes will have to be formulated such that once tampering is detected the node should automatically erase sensitive information.

ZigBee supports the AES standard for data encryption and also supports measures for device and data authentication. However testing the AES encryption, device and data authentication of ZigBee for DAN and devising tamper-resistant techniques are open questions and are not addressed within the scope of this paper. Also during an emergency response process different work groups (emergency doctors, etc) need to access the patient data and each group is hierarchical. So the data access has to be restricted based on the type of workgroup and the hierarchy of its members.

### C. *Fault Tolerance Mechanism*

Since DAN should operate in a hostile environment it should be fault tolerant to provide reliable service which is an open question. For example when the DAN is in operation the entrance of fire engine at the site can down one part of the network due to severe RF attenuation by the metal objects of the fire engine. This can be handled if a link degradation mechanism which can detect faulty links on the fly and inform the coordinator which can make alarm signals.

A simple fault tolerant approach is to resort to redundant deployment of sensor nodes and replication of information between sensor nodes can be adopted to overcome some of the related problems. Another approach is to provide the whole system self-healing capability in a cooperative way. The self-healing feature of sensor networks provides the ability to adapt to unforeseeable situations, diverse environments, and dynamic changes.

### D. *Summary*

In the self-organization of DAN section the need for self-organization with respect to the DAN communication aspect is mentioned. The self-configuring and the self-healing feature of ZigBee can be useful for the DAN network formation and for the healing of routing paths respectively. A self-configuring mechanism for safe and easy access of the patient data by the emergency doctors is proposed and evaluated using a demonstrator.

As part of the future work, new self-organization ideas to satisfy the DAN communication aspect functionalities will have to be developed. For instance, self-organizing techniques for the new patient nodes joining the DAN to automatically know their destination address (collector node) can be developed. Fault tolerance techniques leading to robust communication in DAN will have to be developed. Secure mechanisms for communicating patient data to the management centre and self protection techniques against malicious attacks will have to be developed.

## V. Related Work for Localization in WSN

Current localization systems like Active Badge [17], Cricket [16], RADAR [12], SpotON [11] and other RFID based systems like LANDMARC [18] require a lot of infrastructure while GPS [6] is not suitable for indoor scenarios.

Due to the non-linear, non-Gaussian properties of our scenario and the unpredictable movement of the patients, Monte Carlo Localization (MCL) based methods are investigated to solve our problem. Hu and Evans [10] proposed a range-free localization algorithm called MCL that only works in mobile sensor networks. Dil et al. proposed a range-based version of the MCL algorithm [13]. In [14] Baggio et al. introduced MCB as a variant of MCL.

In [15], Rudafshani et al. proposed MSL (Mobile Static Localization) as a range-free algorithm based on MCL, that improves localization accuracy by using the location estimates of all the anchor nodes and pseudo anchors present in first and second hops. Each node is assigned with a closeness value which indicates the accuracy of that node's location estimate. During initialization, samples are drawn from the entire area. A weight is then assigned to every sample depending on the closeness value of its neighboring nodes. MSL then computes a new location estimate (the weighted mean of samples) and a new closeness value. After initialization, the new samples are drawn during prediction within a circle centered at the current sample location and a radius of the maximum node speed.

## VI. RSSI based Patient Localization Method

The goal is to track the patient nodes at the disaster site and provide their real time locations to the monitor station. The requirements [7] for patient tracking, that the new algorithm and DAN must comply with, are: handle the different environments (both outdoor and indoor) since disasters can happen at different locations; use minimum or no special infrastructure (static anchor nodes) due to the lack of deployment time; track 30-200 patient nodes moving with varying speed (0 to 3m/s); attain an accuracy of around 10m; be scalable and robust; have low computation and communication overhead. The main challenge here is to handle the varying mobility and different environments with adverse RF conditions and also use minimum or no infrastructure. Based on these requirements a Received Signal Strength Indicator (RSSI) based [23] patient localization methodology is proposed for DAN.

At the beginning of the emergency response, a portable monitor station (typically a notebook) gets online; the static anchor nodes are deployed manually covering the disaster area; the emergency doctor nodes (can be a PDA with GPS [6]) act as mobile anchors; once a patient is found the doctor provides him with a wearable patient node. Each patient node runs a decentralized localization algorithm to estimate its real time location and sends it to the monitor station.

In DAN the only information about the patient node is its maximum speed $v_{\max}$, so our system equation is modeled as shown in equation (1).

$$\underline{x}_k = \underline{x}_{k-1} + \underline{w} \tag{1}$$

where $\underline{x}_k = \left(x_k, y_k\right)^T$ is the position of the patient node at time unit $k$ and $\underline{w}$ is a random variable which is uniformly distributed within a circle centered around the zero vector with radius of the maximum speed value of the node $v_{\max}$.

After each time unit, a patient node requests for the position, the RSS and the closeness value (a measure of the accuracy of the neighboring node's position estimate) of its entire one-hop neighbors. The patient node collects these values and estimates the ranges (distances) to these neighbors based on the RSS. Each range measurement is modeled according to the measurement equation (2)

$$z_k = \left\| \underline{x}_k - \underline{\tilde{x}}_k \right\| + v \tag{2}$$

where $\underline{x}_k = \left(x_k, y_k\right)^T$ and $\underline{\tilde{x}}_k = \left(\tilde{x}_k, \tilde{y}_k\right)^T$ are the positions of the patient node and the one-hop neighbor after time unit $k$, respectively, $z_k$ is the range measurement and $v$ is a Gaussian random variable with mean $\mu_v$ and standard deviation $\sigma_v$. The values for $\mu_v$ and $\sigma_v$ are given by the systematic and random error of the measurement model that is used for simulating the distance estimations of the patient node in our simulator. However, in a real scenario these values are deduced from the environmental factors i.e. all anchor nodes within the transmission range of each other compute the error between their actual distance and their estimated distance. All these values are collected in a single node and the mean $\mu_v$ and the standard deviation $\sigma_v$ are calculated.

Once the patient node estimates the distances to its one-hop neighbors it runs a new decentralized position estimation algorithm. None of the algorithms mentioned in Section V exactly meets the specific requirements for patient position estimation, in their current form. In terms of accuracy error, computation cost and communication cost, MSL from Rudafshani et al. acts as a good base for our scenario because it works well with any number of static and mobile nodes in an irregular shaped sensor network. But since MSL is a range-free algorithm it is unable to reach the required accuracy of our scenario. So we used MSL as base and developed the Range-Based Monte Carlo Patient Localization algorithm (MPL) [27]. MPL gave encouraging results with a Gaussian measurement model but we want to test our patient tracking solution with a realistic non-Gaussian measurement model and improve its performance. So in this paper we have developed the 'Improved Range-Based Monte Carlo Patient Localization' (IMPL). Also, to compare IMPL's performance with other non-linear filter approaches and to find its suitability for patient tracking we have developed a new unscented Kalman filter based algorithm called 'Range-Based Unscented Kalman Filter Patient Localization' (UPL). Either IMPL or UPL runs in each patient node to estimate its location and communicates it to the monitor station.

### A. *Improved Range-Based Monte Carlo Patient Localization (IMPL)*

IMPL [1] maintains a weighted sample set in order to estimate the patient node's position. Our new additions in IMPL are:

- Transmission range-based anchor boxing during initialization.
- Removing the usage of two-hop neighbors and conditional selection of one-hop pseudo anchors to gain higher accuracy and reduce computational costs
- A new method for sample weighting.

IMPL mainly consists of three steps: prediction, weighting and resampling.

*1) Prediction:* The prediction step depends on whether there's already an established sample set (after initialization) or not (during initialization).

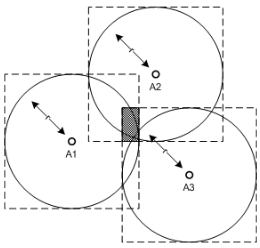


Figure 5. Forming the anchor box

In prediction during initialization, first the area to be sampled from is constrained to an anchor box. The region covered by the transmission range $r$ of each one-hop anchor is approximated to a box as shown in figure 5. The overlapping area of all the boxes (shaded area in figure 5) forms the anchor box. Then 50 uniformly distributed samples are drawn from the anchor box. In prediction after initialization, we take each sample from the previous time step and form a circle of radius $v_{\max} + addition$ centered at that sample's position. From every circle one new sample is drawn.

*2) Weighting:* A weight is calculated for each sample (based on the range measurements) to know if the sample is good or bad. In order to weight the sample $i$ all range measurements to one-hop anchors and to one-hop pseudo anchors with a closeness value less than the current blind node's closeness value are selected. If the range measurement $rm_j$ to one-hop neighbor $j$ is selected, a partial weight $wp_i^j$ will be computed for it. Therefore the range measurement is projected onto a Gaussian distribution (see figure 6), which has $\mu = d + \mu_v$ as mean, where $d$ is the distance between the sample and the one-hop neighbor, and $\sigma_v$ as standard deviation (see (2)).

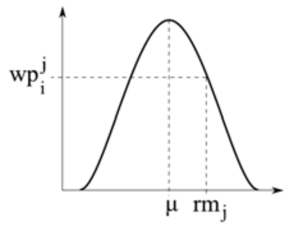


Figure 6. Calculating the partial weight

So the partial weight $wp_i^j$ for sample $i$ and range measurement $rm_j$ is calculated as

$$wp_i^j = \left(1/\sigma_v\sqrt{2\pi}\right)\cdot e^{-0.5\cdot(rm_j-\mu)^2/\sigma_v^2}. \quad (3)$$

The total weight $w_i$ for sample $i$ is the product of all the partial weights.

*3) Resampling:* After normalizing the weights of the sample set, samples are redrawn from the normalized sample set with a probability proportional to their weights. The size of the sample set remains the same and the same weight is assigned to all new samples such that the weights are normalized.

The position estimate $(x, y)$ of the blind node is calculated as the weighted mean of the sample set. The closeness value for blind node $p$ with $N$ samples is computed as

$$closeness_p = \sum_{i=1}^{N} w_i \sqrt{(x_i - x)^2 + (y_i - y)^2} / N \quad (4)$$

where $(x_i, y_i)$ denotes the position of sample $i$, $w_i$ denotes the weight of the sample $i$ and $(x, y)$ is the current location estimate of node $p$. The anchor nodes always have a closeness value of 0.

### B. *Range-based Unscented Kalman Filter Patient Localization (UPL)*

UPL [1] is based on an unscented Kalman filter [8] which only approximates the mean $\underline{\hat{x}}_k^+$ and the covariance $P_k^+$ of the posterior after time unit $k$. The trace of the covariance matrix provides the closeness value and indicates the position estimate's accuracy. In UPL distance measurements (measurement vector $\underline{z}_k$ ) to all one-hop anchors and to all one-hop pseudo anchors whose closeness value is below a threshold value (100) are used.

The mean $\underline{\hat{x}}_0^+$ and the covariance $P_0^+$ at time unit 0 are initialized with the mean and the covariance of a uniform distribution on a rectangle representing the area of the network, because there is no information about the patient node's position at the beginning. Since the system equation is linear the prediction step of the Kalman filter is used to calculate the mean $\hat{\underline{x}}_k^-$ and the covariance $P_k^-$ of the prior distribution after time unit $k$ as shown in (5).

$$\hat{\underline{x}}_k^- = \hat{\underline{x}}_{k-1}^+ \,,\; P_k^- = P_{k-1}^+ + Q_k \tag{5}$$

where $Q_k$ is the covariance of a uniform distribution on a circle with radius $v_{\max}$.

In the filtering step a set of four so-called sigma points $\underline{s}_k^i$ is deterministically chosen (see (6) and (7)) whose ensemble mean and covariance are equal to $\hat{\underline{x}}_k^-$ and $P_k^-$, respectively [8].

$$\underline{s}_k^i = \hat{\underline{x}}_k^- + \left(\sqrt{2 \cdot P_k^-}\right)_i^T, \quad i = 1,2 \tag{6}$$

$$\underline{s}_k^i = \hat{\underline{x}}_k^- - \left(\sqrt{2 \cdot P_k^-}\right)_{i-2}^T, \quad i = 3,4 \tag{7}$$

For every selected one-hop neighbor all sigma points are transformed according to the corresponding measurement equation. If $\tilde{\underline{x}}_k^j = \left(\tilde{x}_k^j, \tilde{y}_k^j\right)^T$ is the position of one-hop neighbor $j$, then one obtains (8).

$$t_k^{ij} = \left\| \underline{s}_k^i - \tilde{\underline{x}}_k^j \right\| + \mu_v \,, \tag{8}$$

where $t_k^{ij}$ is the transformation of sigma point $\underline{s}_k^i$. All transformed sigma points, which correspond to the same sigma point, form a transformed sigma point vector $\underline{t}_k^i$.

The predicted measurement vector $\hat{\underline{z}}_k$ is computed as

$$\hat{\underline{z}}_k = (1/4) \cdot \sum_{i=1}^4 \underline{t}_k^i \tag{9}$$

The covariance of the predicted measurement vector and the cross covariance between $\hat{\underline{x}}_k^-$ and $\hat{\underline{z}}_k$ are obtained as shown in (10) and (11).

$$P_k^y = (1/4) \cdot \sum_{i=1}^4 \left(\underline{t}_k^i - \hat{\underline{z}}_k\right)\left(\underline{t}_k^i - \hat{\underline{z}}_k\right)^T + R_k \,, \tag{10}$$

$$P_k^{xy} = (1/4) \cdot \sum_{i=1}^4 \left(\underline{s}_k^i - \hat{\underline{x}}_k^-\right)\left(\underline{t}_k^i - \hat{\underline{z}}_k\right)^T \tag{11}$$

where $R_k$ is a diagonal matrix with all its main diagonal entries equal to $\sigma_v^2$.

Now the filtering step of the Kalman filter can be applied to calculate the mean and the covariance of the posterior.

$$K_k = P_k^{xy}\left(P_k^y\right)^{-1} \tag{12}$$

$$\hat{\underline{x}}_k^+ = \hat{\underline{x}}_k^- + K_k\left(\underline{z}_k - \hat{\underline{z}}_k\right),\; P_k^+ = P_k^- - K_k P_k^y K_k^T \tag{13}$$

## VII. PERFORMANCE EVALUATION

We used the simulator used by Rudafshani et al. [15] to develop and test our algorithms. In order to do simulations close to reality we added the following new features: disaster management mobility model, range measurement model, anchor position error.

Disaster management mobility model: In order to create a mobility model that replicates the MANV scenario (see Section II) and test our algorithm a new trajectory based mobility model is developed. Since the nodes move in a random fashion in the random waypoint mobility model it cannot be used for modeling our scenario. This new mobility model is used to setup a MANV-disaster management scenario (see figure 7) within an area of 500m x 500m with 100 nodes that include 15 static and 35 mobile anchor nodes. The maximum speed of all nodes is set to 3m/s. At the beginning of the simulation the doctor nodes appear dynamically at the site followed by the patient nodes. Most of the patients are moved from one zone to another accompanied by at least one doctor. When a patient node arrives at the transport zone it leaves the site after predefined time units. Similarly the doctor nodes leave the site, too.

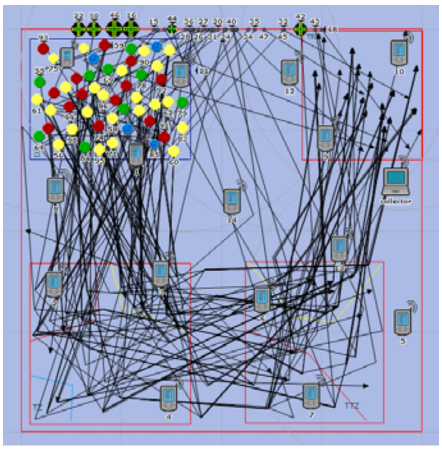

Figure 7. Disaster management mobility model

The simulations are also done for the random waypoint mobility model [5] in order to find the influence of certain parameters (transmission range, etc.) on the algorithms' performance.

Anchor position error: We incorporate erroneous anchor positions into the simulation. An additive zero-mean Gaussian error is used with a 3 sigma bound of 2m for static anchors and 10m for mobile anchors.

Range measurement model: We create a close to realistic measurement model. An outdoor area with adverse RF conditions, is setup with a sensor network and real RSS data is collected to obtain the distance estimations. A frequency distribution of the distance estimation error is plotted. The frequency distribution of error is analyzed along with the evolution of error over time and two factors are noticed: First, most of the time the actual distance is underestimated and second, the error is time-correlated. In order to account for the time-correlation the simulator keeps a state variable between all pairs of nodes which need to perform a distance measurement. Every state corresponds to one certain base error value in the range between -70m and 30m. Accessorily, a zero-mean Gaussian random error with a standard deviation of 5m is added to the base error. After a range measurement the state of the correspondent pair is updated according to a Markov chain. It may remain the same or a transition into the state with the next base error value below or rather above may occur. The transition probabilities are empirically determined to fit the error distribution of the outdoor experimental data. The mean and the standard deviation of the outdoor error distribution are used as systematic and random error of the measurement model, respectively. Since MSL is a range-free position estimation algorithm it is not affected by the range measurement model.

In all simulations we used an ideal transmission range of 200m for all nodes.

### A. *Simulation results for random waypoint mobility model*

The simulation setup is made considering an area of 400m x 400m with a total of 100 nodes that include 10 static and 20 mobile anchor nodes. All nodes move according to the random waypoint mobility model with their maximum speed set to 3m/time step.

1) *Accuracy using a static model:* To simulate a static model the maximum velocity of all nodes is set to 0m/time step. IMPL has an average error of 5.22m while UPL has an average error of 9.10m (see figure. 8). IMPL can therefore handle a static scenario better than UPL. The average error of MSL is 14.41m.

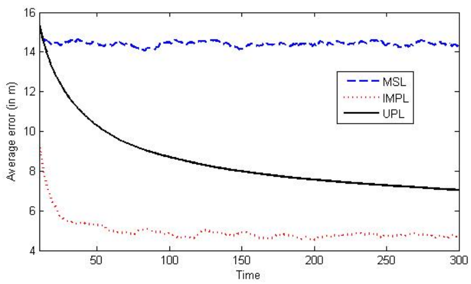


Figure 8. Accuracy using a static model

2) *Accuracy over time:* The average error of IMPL is similar to the average error of UPL but IMPL needs less time to converge during simulation start (see figure 9). The average error of MSL is constantly high.

3) *Accuracy over varying transmission range:* figure 10 shows that as the transmission range increases, the average error of both IMPL and UPL reduces. This is because with increasing transmission range the number of neighboring nodes (anchors or pseudo anchors) also increases. The accuracy error of MSL worsens with high transmission ranges which can be due to its weighting step.

4) *Accuracy over varying number of blind nodes:* As the number of blind nodes increases, both IMPL and UPL improve their accuracy slightly, showing that the usage of pseudo anchors has a positive effect. Compared to IMPL the accuracy error of MSL is very high (see figure 11).

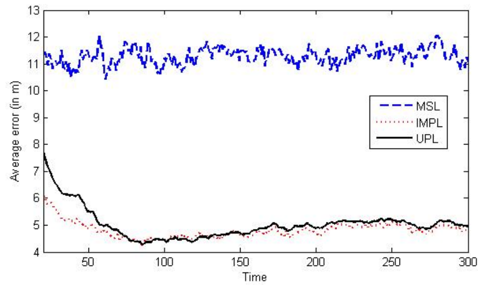


Figure 9. Accuracy over time in the random waypoint mobility model

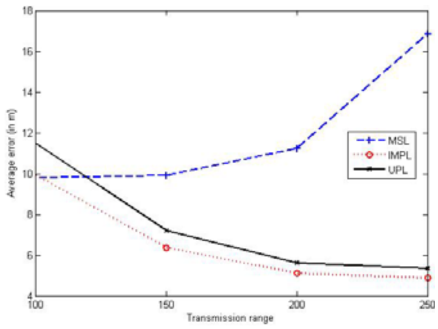


Figure 10. Accuracy over varying transmission range

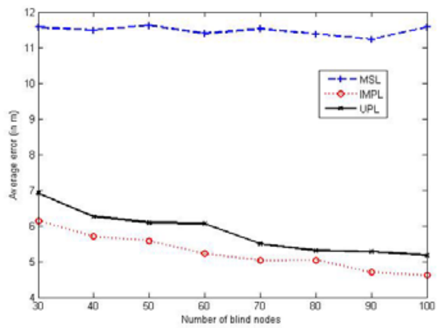


Figure 11. Accuracy over varying blind nodes

*5) Accuracy over varying number of anchor nodes:* The error of MSL stabilizes only when there are 20 anchor nodes. When the number of anchor nodes are less IMPL performs better than UPL. As the number of anchors increase both IMPL and UPL have similar accuracy error (see figure 12).

In Fig. 11 and 12 as the number of nodes increases (blind nodes and mobile reference nodes), both IMPL and UPL attain an accuracy of 5m to 10m implying that the algorithms scale with network node size in terms of accuracy.

*6) Accuracy over varying sample set size:* IMPL needs at least 20 samples to attain an average error of around 5m. MSL also converges at around 20 samples but its average error is significantly higher. After around 50 samples the average error of IMPL does not improve much so we chose a maximal sample set size of 50 (figure 13).

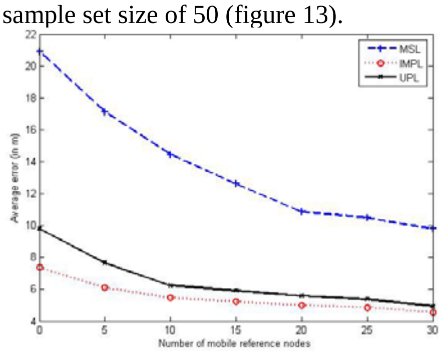


Figure 12. Accuracy over varying anchor nodes

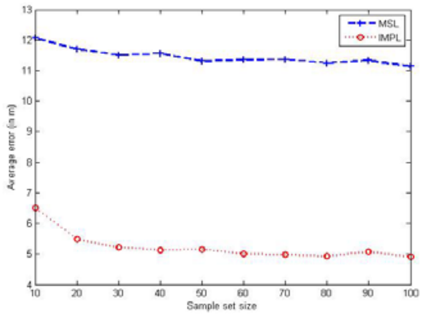


Figure 13. Accuracy over varying sample set size

## *B. Simulation results for disaster management mobility model*

Here IMPL and UPL are simulated for the disaster management mobility model described in Section VII.

*1) Accuracy over time:* IMPL achieves an average accuracy of 6.78m whereas UPL has an average accuracy of 7.87m (see figure 14). In between 600s and 1600s the accuracy of IMPL is stabilized. Before 600s and after 1600s the average error is less stable. This is due to the dynamic addition and removal of doctor and patient nodes which act as anchors and pseudo anchors, respectively.

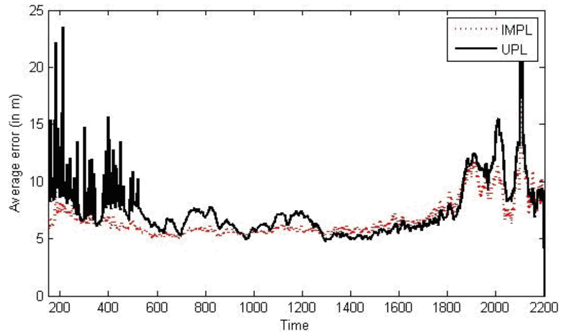


Figure 14. Accuracy over time in the disaster management mobility model

*2) Number of bad localized nodes for IMPL over time:* figure 15 shows that between 400s and 1200s almost all doctor and patient nodes are present. Around 20 patient nodes are localized with an error less than 5m and another 20 nodes with an error between 5m and 10m. The achieved accuracy is within the requirements defined in Section VI. The number of bad localized nodes for UPL was similar to that of IMPL.

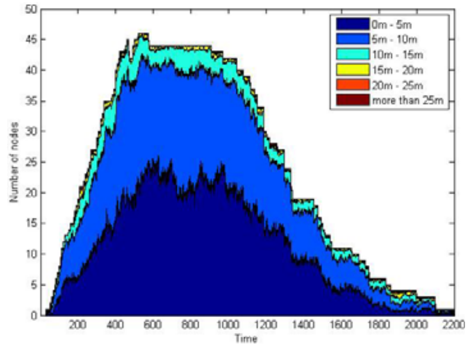


Figure 15. Bad localized nodes for IMPL in the disaster management mobility model

*3) Computation Cost:* The average arithmetic operations required to run IMPL or UPL once, at a particular time step are counted to form the computation cost as shown in figure 16. Although theoretically the computational costs of a particle filter based solution are higher than that of an unscented Kalman filter based approach [8], Fig. 13 shows the opposite for IMPL and UPL. This is because we have a smaller sample set size for IMPL in comparison to general particle filters used in Robotics [9]. UPL's high computation cost is due to its handling of high dimensional measurement vectors (because of large number of neighbouring nodes) which involves complex matrix operations.

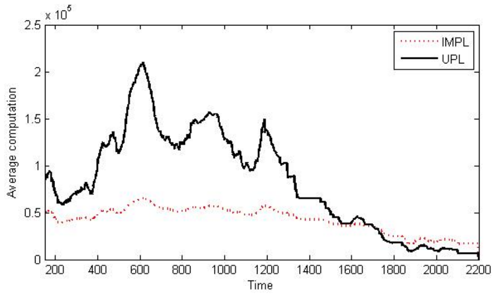


Figure 16. Computational cost in the disaster management mobility model

## VIII. CONCLUSION AND FUTURE WORK

In this paper ZigBee's 2.4 Ghz operation is tested using ranging experiments and the results show that ZigBee is basically suitable for DAN even though further empirical investigations for co-existence and RF signal attenuation will be future work. The self organizing features of ZigBee are are useful for DAN even though not enough. A new self-configuration mechanism for seamless patient data access by the doctor at the disaster site is proposed and verified by us using a demonstrator.

We have also proposed two Bayesian filter based position estimation algorithms - IMPL and UPL for tracking patients during emergency response. We have simulated IMPL and UPL using two mobility models - disaster management mobility model and random waypoint mobility model under realistic simulation setups (an outdoor experiment based range measurement model and anchor error inclusions). The simulation results for the random waypoint mobility model show that the average accuracy error over time is almost same (around 5.6m) for both IMPL and UPL while MSL has a high accuracy error (11.3m). With less number of anchor nodes and low transmission range, the accuracy error of IMPL is better, but as these values increase both IMPL and UPL have a similar performance. The simulation results for the disaster management mobility model show that both IMPL and UPL satisfy the requirements for patient tracking in terms of accuracy. Half the number of patient nodes has a localization error less than 5m and the other half (almost) is between 5m-10m. In terms of computation cost IMPL is better than UPL, but this is an indication obtained from a simple computation model. The results show that IMPL is better than UPL for patient tracking and in tandem with the emergency response system facilitates efficient logistics management at the disaster site. A demonstrator with IMPL running in each node will be implemented and tested as part of future work.

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