Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 762 – 773

doi:10.3906/elk-1308-154

Design and implementation of a man-overboard emergency discovery system based on wireless sensor networks

Abdullah SEVİN[1,*], **Cüneyt BAYILMIŞ**[1], **İsmail ERTÜRK**[2], **Hüseyin EKİZ**[3], **Ahmet KARACA**[4]

[1]Department of Computer Engineering, Faculty of Computer and Information Sciences, Sakarya University, Sakarya, Turkey

[2]Department of Computer Engineering, Faculty of Engineering, Turgut Özal University, Ankara, Turkey

[3]Faculty of Engineering and Natural Sciences, Süleyman Şah University, İstanbul, Turkey

[4]Department of Electrical-Electronics Engineering, Faculty of Technology, Sakarya University, Sakarya, Turkey

Received: 26.08.2013 • **Accepted/Published Online:** 26.09.2013 • **Final Version:** 23.03.2016

Abstract: Recently, wireless sensor networks (WSNs) have been widely employed in many different fields such as military, surveillance, health, agricultural, automation, and environmental monitoring. This paper presents a designed and implemented WSN-based man-overboard emergency discovery system, abbreviated as W-MEDS, that discovers the location of a person in emergency circumstances and runs an alarm system on a ship. The developed W-MEDS carries out a fast man-overboard (MOB) discovery and initiates the vital rescue procedure. It mainly consists of a WSN and a control and discovery system. When a MOB accident occurs, this situation is easily detected through the WSN nodes capable of real-time sensing (i.e. temperature, humidity, and acceleration) and the system enables location estimation. The control and discovery system analyzes and displays the received data from the WSN nodes. The most noteworthy advantage of the proposed W-MEDS is that it enables both real-time alarm monitoring and fast recovery. In addition to the implementation of the W-MEDS, considering hardness in performance evaluation of the real system, it has also been simulated in the OPNET Modeler to confirm the accuracy for different sizes and numbers of nodes.

Key words: Wireless sensor networks, emergency discovery system, man-overboard, remote sensing, environmental monitoring

1. Introduction

Nowadays, there are numerous applications that utilize wireless sensor networks (WSNs) in many different areas including military, medical, detection of natural disasters, surveillance, environmental monitoring, intelligent buildings, and home and factory automation. A WSN is a type of network that consists of numerous tiny nodes. These nodes communicate with each other in the wireless medium. Wireless sensor nodes are able to sense physical quantities such as humidity, temperature, and pressure and to communicate each other within a short distance. These nodes are capable of limited data storage and processing power due to their physical size limitations [1]. A sensor node transmits data to a gateway (sink node) directly or over other nodes. After that, the gateway sends the data to a computer system for control or discovery.

A literature review shows many different WSN-based [2–4] or RFID-assisted [5] applications and some of them are as follows: ZebraNet [6] is a habitat tracking system employing many GPS-integrated wireless sensor nodes. ZebraNet locates the position of zebras via GPS signals aimed at understanding their interactions and

*Correspondence: asevin@sakarya.edu.tr

influences on each other. The CodeBlue [7] project is also one of the pilot projects for healthcare services employing a WSN. Various types of wearable sensor nodes are used in this project to collect a patient's physiological data, like electrocardiograph and electromyograph signals, and locate the position of the patient. In [8], a WSN was designed for monitoring a human being's motion and local position in an indoor environment, which can be expanded to applications designated for vehicles, animals, or any other object.

As seen in Table 1, many people have died as a result of man-overboard incidents. According to the formal statistics published by the Marine Accident Investigation Branch [9], the number of casualties is relatively high in the United Kingdom compared to other countries. Motivated by this report and its main suggestions, we focus on the man-overboard (MOB) issue and propose a WSN-based solution in this paper. A MOB situation is the event of someone falling from a ship into the sea. That is one of the most common emergency cases in the shipping sector. The duration of being in the water is not so important for inland seas but is definitely vital in cold waters such as an open sea because the temperature produced by the human body would be insufficient. In such circumstances, body temperature decreases rapidly. Remaining in water at 4.4 °C for 1 h causes a decrease of body temperature to 30 °C. For this reason, the survival rate of a person goes down to 50% [10].

Table 1. Casualties in MOB incidents [9].

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
Merchant vessels	5	10	10	9	5	13	11	7	11	10	7	117
Fishing vessels	11	11	6	7	6	11	14	8	7	13	9	119

Most people know of the *Titanic* wreck. In this tragedy, the primary manner of death among the passengers was hypothermia. This term means that body temperature is less than its normal range. The temperature of the North Atlantic Ocean water was –2 °C when the *Titanic* wreck happened. Therefore, when the rescue teams arrived to the wreck area after 110 min, nearly all the people in the water had already died. Any victim in this situation must be taken out of the water as soon as possible. To do this, some procedures need to be fulfilled immediately. First of all, the MOB situation must be noticed and announced. The second step is to determine the position of the person. Rescuing the person from the water is the last and most crucial step. Each procedure has its own subcategories as explained in the following sections of the paper highlighting the proposed system.

In order to decrease the casualties in MOB incidents, we have designed and implemented a WSN-based man-overboard emergency discovery system, abbreviated as W-MEDS. The realized system tracks the movement and position of each person onboard, and when an emergency occurs, it activates the alarm system. The alarm system architecture consists of a siren and a light source. We propose a cost-effective solution for MOB problems, consisting of discovering the location of victim, initializing a real-time response to the MOB case, noticing the MOB case automatically, and informing the crew about the situation. In addition, the use of WSN technology provides several advantages in the proposed W-MEDS, such as a cost-effective infrastructure, easy installation and usage, long lifetime, and being operation-effective.

The remainder of the paper is organized as follows. Section 2 deals with the overview of the MOB issue and some solution products for the MOB issue, and it fleshes out the WSN concept. Section 3 details the designed and implemented W-MEDS architecture. In Section 4 simulation results from W-MEDS are provided, followed by final remarks in the last section.

2. Preliminaries

2.1. Man-overboard (MOB)

There are many kinds of possible incidents in the sea environment for anyone (workers or passengers). Workers must particularly take some precautions and employers have to provide a safe workplace for people at sea. In this paper, we choose the fast recovery of the MOB issue and immediate rescue action for the application field.

Many people have died as a consequence of MOB circumstances over the years. It is an ongoing problem, especially for marine workers. Therefore, a risk management process needs to be carefully designed. When an accident happens, the steps of the process must be meticulously performed one by one [11]. Basically, the risk management process includes the following three vital steps:

- Noticing and announcing,
- Movement and operation,
- Rescue.

Today the noticing and announcing process is carried by means of communication systems. Formerly, this process was carried out by people, leading to the death of many people just because the MOB incident was missed. Therefore, some appliances were developed to overcome this problem, such as:

- Sea Marshall SARfinder 1003 MK3,
- Sea Marshall CG 121 MKII,
- Raymarine LifeTag,
- Kannad WaveFinder,
- Mobilarm V100.

The SARfinder 1003 MK3 MOB Locator Unit communicates at 121.65 MHz and is based on a range method. It is used by the North Sea Oil Companies and Canadian and Danish Coast Guards. Its base unit (receiver) checks whether the transceiver beacon is within safety limits. If it passes the limit, the distance and localization are shown on LEDs in the control unit and an alarm initiates after 2 to 5 s. The SARfinder triangle antenna must be in the highest possible position for ensuring maximum coverage. Personal locator beacons (PLBs) have transmission times of 24–36 h and are capable of transmitting a low-power signal to the receiver [12,13]. Shortcomings of this system are that it requires fine-tuning for the antenna and that it shows the localization and distance on LEDs.

The Sea Marshall CG (Crew Guard) 121 MKII is another product by the same company, which is a low-cost alternative to the SARfinder. There are some differences between the SARfinder 1003 MK3 and CG 121 MKII units. The latter shows the signal strength but not the direction of the person and its PLBs transmit signal at a default of 121.5 MHz. It uses a rubber duck style antenna that decreases the monitoring range with respect to the SARfinder locator's triangle antenna [12,13]. Low-range antenna and not showing the direction of a person are the shortcomings of the system.

The Raymarine Company's LifeTag system, which is based on wireless communication technology, notices whether a person goes out of a predefined range. If the signal is lost from any tag, the alarm condition occurs. Wireless pendants and a base station have radio transceivers that communicate each other. When an alarm condition occurs, an audible alarm will be initiated by the base station [14]. It is a simple system that does not show the location or distance of a person but it can be expanded with an additional antenna for monitoring capabilities. On the other hand, the cost becomes too high compared to similar products.

The Kannad WaveFinder is a search and rescue system that was designed for the open sea only. The WaveFinder shows the distance and direction with LEDs, too, but its cylindrical antenna design is one of its main advantages. The standby mode has a discrete time design (waiting for an event) for long lifetime. The system works in good order if the installation rules are observed carefully [15].

The Mobilarm Crewsafe V100 system is based on a GPS-enabled technology that sends the MOB's GPS coordinates via VHF band to the base station. If possible, the MOB's GPS coordinates are sent to the onshore VHF receiving station and other nearby vessels. The V100 is automatically activated when the water sensors detect the submergence. PLBs can have singular maritime mobile service identity to identify the person. The Crewsafe V100 battery life is 12 h in transmission [16]. This system does not represent the location of a node visually, which is its worst disadvantage.

2.2. Wireless sensor networks (WSNs)

The term of 'wireless sensor network' was suggested in the early 1980s. At first, WSNs were used in military fields. Afterwards, decreasing costs caused widespread usage of WSNs [1]. Additionally, communicating wirelessly and pintsized nodes extend the usage.

WSNs integrate three main functions: sense, process, and transmission [17]. Sensor nodes sense physical quantities such as temperature, humidity, light, pressure, object movements, soil composition, noise level, existence of an object, and the weight, size, movement speed, direction, and location of an object [1]. In order to process the analog data, an analog/digital converter is embedded in a sensing unit [18]. New developments in the field of sensor technology will cause new possibilities for sensor technology.

The process function computes the data that are collected from the environment. It mainly aims at processing the signal and controlling the transmission and reception procedures. It has some basic tasks such as security, aggregation, and reduction of data, depending on the application [19]. The computing unit requires memory (RAM/ROM) for data and program storage. In general, the sensor node storage capacity is about 128 KB due to storing small amounts of data. There are several types of memory such as flash, SRAM, and EEPROM, which are preferred due to their low energy consumption, small physical size, and programmability [17].

Transmission functions are provided by a radio apparatus. The radio part consumes most of the energy with both data transmission and reception procedures. Due to the fact that WSN nodes have a very limited energy supply [20], the primary goal of the network is to live as long as possible. Radio power consumption is the most significant lifetime factor in WSNs [17]. There are three WSN layers (i.e. physical, MAC, and network), which influence the working of the radio function. In order to reduce the consumption of energy, all of the functions realized in these three layers must be well designed, and unnecessary usage must be minimized [21]. The system architecture of a standard sensor node is shown in Figure 1.

3. Design and implementation of the proposed W-MEDS

This section presents design stages and components of the implemented W-MEDS. The aims of the realized W-MEDS are to carry out a fast MOB discovery and initiate a vital rescue procedure when an emergency circumstance occurs.

The realized system consists of two main components: a WSN and a software-based control and discovery system. The WSN provides real-time sensing (i.e. temperature, humidity, and acceleration) and enables location estimation by means of an accelerometer sensor in the nodes in order to discover a MOB situation. The software system processes and displays the data and controls the emergency state.

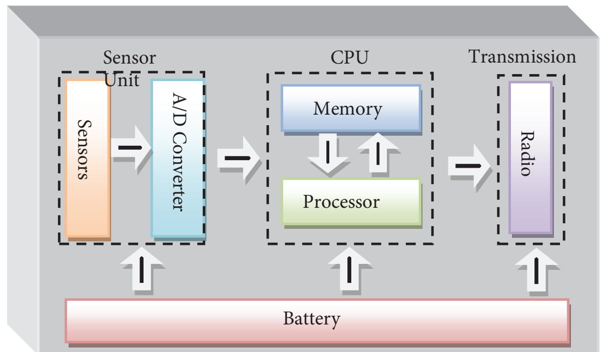

Figure 1. Sensor node architecture.

There are many kinds of techniques for location estimation, including absolute techniques such as GPS and relative techniques [22]. We use an inertial-based positioning technique, as shown in Figure 2, with accelerometer sensors that obtain the location of a person, as in other applications in the literature [23–26]. In relative techniques, the position can be estimated by the previous location of a person and so we have to know the initial position of person. For the application scenario, we assume that the initial position is fixed because of the life jacket's fixed place. The acceleration data show the rate of change of the velocity and that is displacement with respect to time; consequently, the position of a person is estimated as in Eq. (1).

Step 1- Start initial position at lifejackets place
Step 2-Get accelerometer data with X,Y direction
Step 3-Calculate displacement
Step 4-Estimate current position
Step 5-Go to step 2

Figure 2. Position estimation algorithm.

$$\vec{a} = \frac{d\vec{v}}{dt} \text{ and } \vec{v} = \frac{d\vec{s}}{dt} \therefore \vec{a} = \frac{d\,(d\vec{s})}{dt^2} \tag{1}$$

There are two kinds of nodes in a WSN, i.e. fixed nodes and mobile nodes. Fixed nodes are deployed at various positions of the ship to increase the coverage area. Mobile nodes, which are clipped onto the life jacket of the person, send the sensed data to the central system directly or over the fixed nodes, and then the control and discovery software checks the location of mobile nodes for an emergency. If any mobile node is not aboard the ship, the MOB alarm system is activated. The control and discovery software analyzes the data received from wireless sensor nodes in real time.

For the application scenario, fixed sensor nodes are deployed at optimal points on the vessel. Mobile nodes are clipped onto life jackets to communicate with the gateway directly or over fixed nodes. Positions of people are shown on the computer screen that is placed in the control center of the ship. Furthermore, temperature, humidity, and acceleration data, which show the real-time status of a person, are displayed in the other tabs of the designed software. When an emergency circumstance occurs, the system is activated automatically. After that, the system sounds an alert and turns on the light and rotates it to the MOB position of the victim. The working process of the implemented W-MEDS is outlined in Figure 3. A simplified process flow diagram of the W-MEDS system is provided in Figure 4.

Figure 3. The example scenario used for W-MEDS.

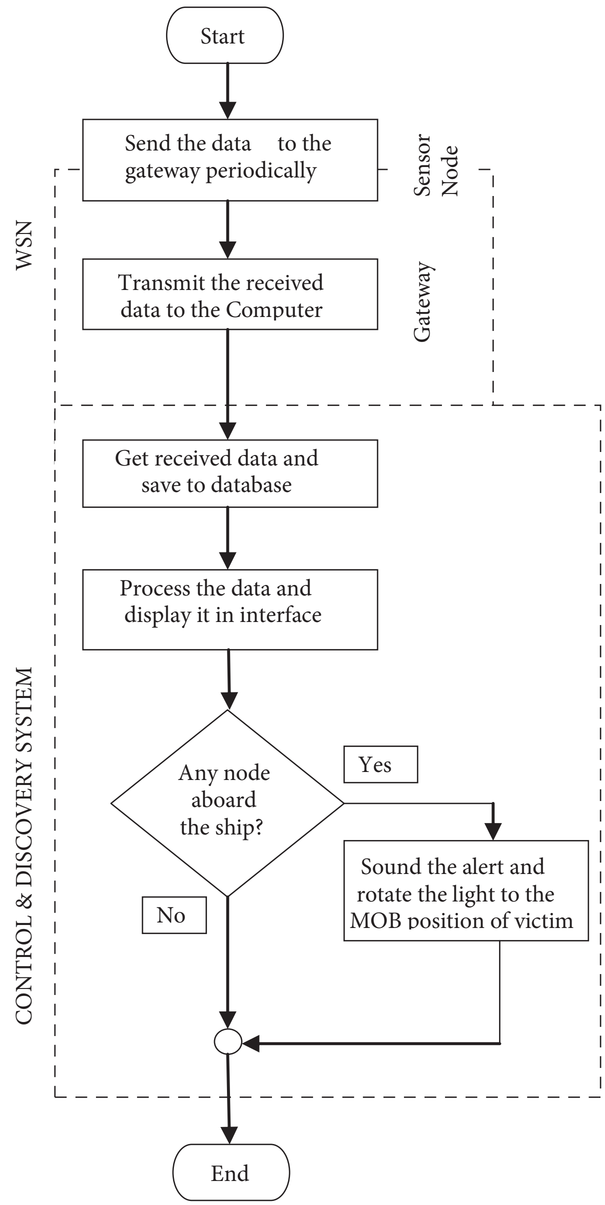

Figure 4. Simplified process flow diagram of the W-MEDS.

3.1. Implementation of the W-MEDS prototype

The WSN and control and discovery system are composed of a hardware platform in the proposed W-MEDS architecture. In the network part, Crossbow's MICAz motes are chosen as sensor nodes. The sensor node integrates a processor/radio board (MPR2400), an antenna, and a sensor board (MTS420CC), which are powered by two AA batteries. The integrated sensor board includes a dual-axis accelerometer and sensors for barometric pressure, ambient light, relative humidity, and temperature sensors [27]. A block diagram and a picture of the sensor board are shown in Figure 5.

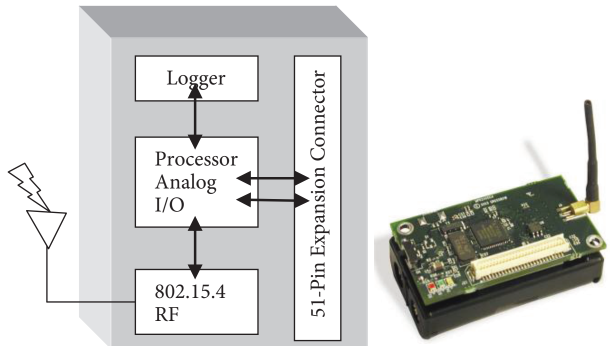

Figure 5. The block diagram and a picture of a MICAz mote.

The control and discovery system has three main parts: a central computer, a control circuit, and alarm devices. The central computer is the center of the control and discovery system as it processes the collected data. A PIC 16F877A microcontroller is used for the control circuit in order to control the pan-tilt motor. The light on the pan-tilt motor and the siren are the alarm devices.

3.2. Development of the W-MEDS software

The discovery system interface has been written in C# programming language. The control software accomplishes two basic processes. The first one is acquiring data from the nodes and processing and visualizing the events. The second is real-time control of the position of the nodes for MOB emergency action. In the first step, the received data are stored in the database by performing some transformations for data accreditation.

All of the measurements including voltage, humidity, temperature, two-axis acceleration, time, and node id data are shown on the data tab in the software interface so that the status of each node can be followed easily. The appearance of the data tab is presented in Figure 6.

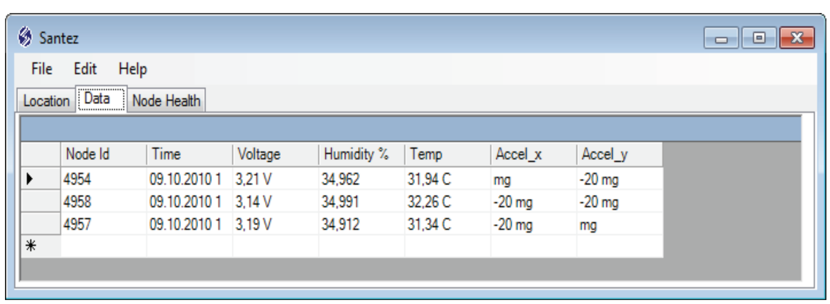

Figure 6. The W-MEDS interface "Data" tab.

The location of each node is shown on the location tab in real time. Thus, the position of each person can be monitored easily on the ship. The appearance of the location tab is also shown in Figure 7. The person's position is tracked in real time. If any node goes outside the defined border, the alarm system is activated. In the alarm state, a message gives a visual warning while the siren gives an aural warning. At the same time, the MOB victim's coordinates are sent to the microcontroller that rotates the light source to the MOB position, and the status of the person is shown in a panel by the developed interface. Figure 8 shows that the prototype system is in a MOB alarm situation.

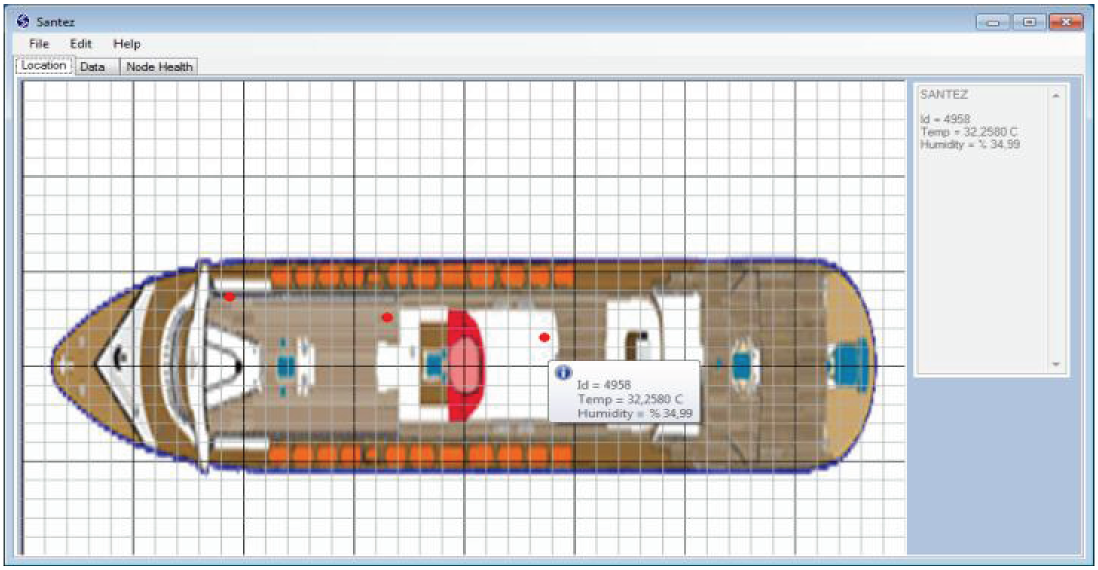

Figure 7. The W-MEDS interface “Location” tab.

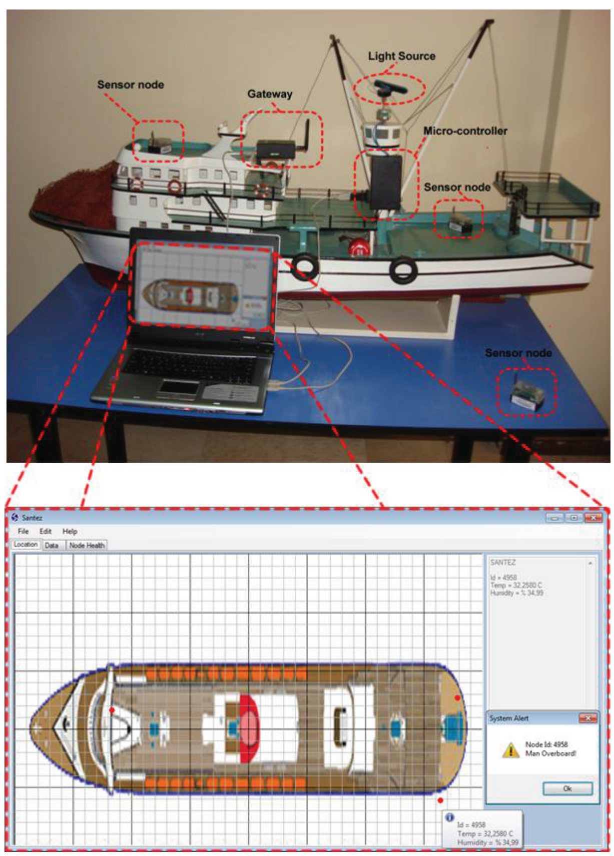

Figure 8. The W-MEDS “Alert” state (real system).

4. Performance evaluation of the W-MEDS in example scenarios

It is difficult and costly to understand the system behavior because of the numerous nodes and distances in a real system such as our system. Therefore, simulation software is used for performance evaluation and verification of systems. To this end, we use OPNET Modeler v14.0 [28], which allows us to evaluate the respective performance of the proposed W-MEDS design and prototype. In general, packet loss ratio, utilization, end-to-end delay, and throughput metrics are important to evaluate discovery systems. We thus consider these performance metrics in our design. The used parameters are given in Table 2.

Table 2. Simulation parameters.

Parameter	Value(s)
Area size (m^2)	10 × 10/10 × 20/10 × 30/10 × 40/10 × 50
Number of nodes	5/10/20/30/40/50
Node mobility	Random - 1 km/s (speed)
Buffer size	250 kb (packets)
Packet size	30 (byte)
Traffic	Exponential
Data rate	250 kbps
Frequency of nodes	2.4 GHz
PHY and MAC layer	IEEE 802.15.4

In the simulation environment, we explore the effects of increasing the numbers of nodes and sizes to confirm system validity. The OPNET standard Zigbee node model is used instead of our sensor node models in the simulation environment since it has approximately the same attributes as MicaZ motes. In the realized system, there are four fixed nodes and variable mobile nodes from 5 to 50 that have random trajectories in the simulation environment. The area size scales up from 10 × 10 to 10 × 50.

Figure 9 shows the average packet loss rate for various numbers of nodes and area sizes. Average packet loss rate changes between 0.002% and 0.016% but the average is roughly equivalent for varied area sizes, as seen in Figure 9. However, increasing the number of nodes from 5 to 50 also increases the average packet loss rate. We take an acceptable packet loss rate level (0.016%) with 50 mobile nodes and 10 × 10 area size.

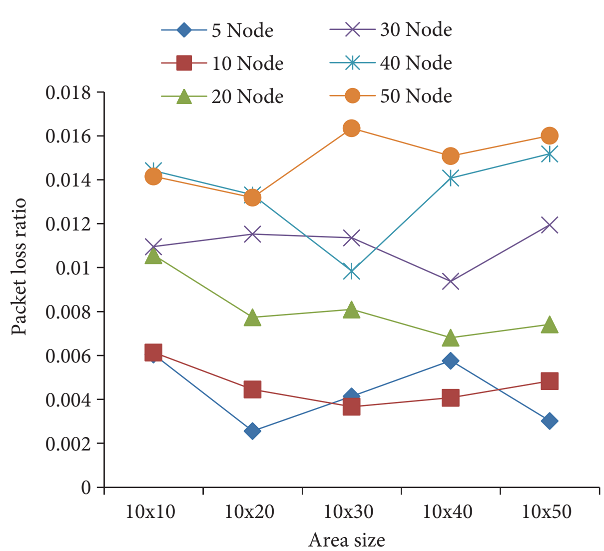

Figure 9. Packet loss ratio as a function of area size and number of node metrics.

In Figure 10, the measured delay average is less than 14 ms, which is reasonable for discovery systems. The delay results from the density of nodes and CSMA-CA-based protocol. End-to-end delay takes longer when the intensity of network increases in contention-based protocols.

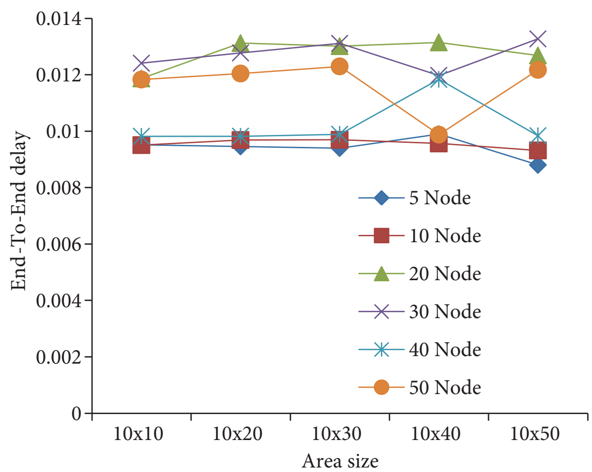

Figure 10. End-to-end delay as a function of area size and number of node metrics.

Radio receiver utilization is shown in Figure 11a. When the amounts of nodes increase, radio signals comparatively increase in the medium and nodes receive more radio signals from the environment. Hence, utilization results of the nodes' receiver increase relatively. Figure 11b illustrates the throughput of the network, which averages about 2500 bits/s. The data rate from each node is constant at 250 kbps in all scenarios. Therefore, there has not been a regular increase in spite of the changes in the number of nodes or area size.

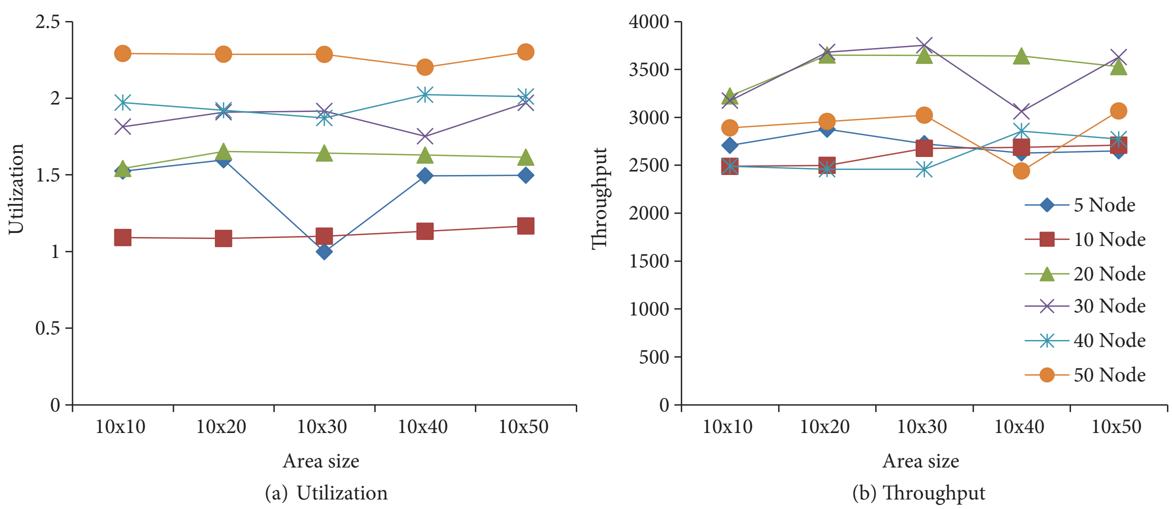

Figure 11. Utilization (a) and throughput (b).

5. Summary and final remarks

In the presented work, a new emergency discovery system based on a WSN for ships has been realized. The reasons for using a WSN in this application include its reliability, long lifetime, smaller-sized node design, developable platform, ability to use a wireless communication medium, and capability to sense numerous physical quantities. The proposed W-MEDS application consists of hardware and software components. The former include a WSN, central computer, microcontroller, and audible and visible alarm devices, while the latter are composed of processing the data received from the mobile WSN nodes and visualizing the events that occur in a MOB case. We have also evaluated the system behavior for varied numbers of nodes and area sizes in a simulation environment by using the OPNET Modeler. Simulation results together with experimental results are used to validate the functionality of the developed W-MEDS for several MOB circumstances.

There is also an important outcome of the developed and implemented W-MEDS application. It is the need for a worldwide standardization body for regulation to overcome the casualties in MOB incidents. The W-MEDS system will allow reduction of casualties, which cost the lives of people, as a result of immediate and effective intervention. In addition, a cost-effective WSN infrastructure, easy installation, long lifetime, highlighting of the MOB position, and visual presentation of the position features make a significant contribution to the works in this field.

Acknowledgment

This research work was supported by the Ministry of Science, Industry and Technology of Turkey under the contract SANTEZ 00246.stz.2008-1

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