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Complete System Design Based on Wireless Sensor Network for Disaster Prevention

***Abstract**. This paper presents various results of research on disaster prevention system using Wireless Sensor Network (WSN). Although we use the snow load sensing as a case study, the proposed system can be further easily adopted to detect other emergencies. Ongoing research on snow measurement is also briefly explained. We introduce architecture of the entire system along with our new modular WSN platform. Test results and evaluation of our WSN solution are presented as well. We verified that network performance is suitable for the purpose of Disaster Prevention system. Finally, a new data visualization framework which fulfills application specific requirements is demonstrated.*

***Streszczenie.** W artykule opisano system ostrzegania przed katastrofami wykorzystujący bezprzewodową sieć czujników. System testowano na przykładzie obciążenia śniegiem. Wykorzystano modularną platformę sieci bezprzewodowej. (**Projekt systemu ostrzegania przed zagrożeniami bazujący na bezprzewodowej sieci czujników**)*

Keywords: crisis management, data visualization, snow measurement, wireless sensor network.
Słowa kluczowe: sieć bezprzewodowa czujników, system ostrzegania

1. Introduction

It has been found out that spending on public safety already makes up 18% of a usual city budget and 62% of surveyed cities indicated that public safety gives rise to adopting new technologies such as Wireless Sensor Networks (WSN) [1]. Civil security is clearly still the main concerns of our society. We have designed a data collection system based on adaptive WSN aimed for a disaster prevention management application. Particular nodes communicate among themselves in a robust mesh network providing distributed sensing. WSN are composed of inexpensive devices with low power consumption. The low power requirements allow utilizing wide range of alternative energy sources. Nodes can be easily placed almost everywhere thanks to their small size. Our system operates in 2.4 GHz and sub-gigahertz ISM bands and can be equipped with various sensors. The number of nodes within a network can typically reach up to a hundred. Acquired data from WSN nodes are forwarded to one or more gateways for further processing, visualization and storing in the relational database. This system is also designed for tight cooperation with the national Early Warning System.

The main goal of our project is to develop an adaptive wireless sensor network for a broad usage. We focused on monitoring of:

- snow load,
- river and sea level,
- rainfall amounts and dryness,
- gas leaking,
- weather changes (speed of wind, temperature, air pressure).

It is crucial to know the amount of a snow load to precede a disaster caused by overloaded roofs. This information is especially important in case of large flat roofs with a low slope less than 30°. Moreover, it also increases personal and building safety, reduces fire brigade actions and thus municipal expenses. We use the snow load sensing as a case study in this paper and it is further described in more detail in section Snow Measurement .

The measurement of a river and sea level is a significant indicator of weather changes tightly related to rainfall amounts. Both measurements can predict floods in case of heavy raining or a probability of catching a fire in terms of long-term dryness.

The gas leakage is one of the most important parameters to measure. According to the statistics, 15% cases of gas leakage lead to deaths and injuries. Surprisingly, most of the accidents have happened inside a building instead of during transport. Ammonia, pesticides, organic mercurial compounds, acids and petroleum products cause the biggest number of catastrophes. Possible risky areas in the city are swimming pools, ice rinks, cooling chambers, etc. The EEB (European Environmental Bureau) also strongly suggests monitoring of releasing highly toxic mercury into the air around chemical industries.

Sensing of elementary phenomenon like temperature, speed and direction of wind or air pressure can help to increase the accuracy of other measurements and possibly determine the evolution of a particular disaster.

The system can be further easily adopted to detect other emergencies through numbers of digital and analog inputs.

The remainder of the paper is organized as follows. Section 2 informs about other related research in the field of crisis management. Section 3 introduces the whole system architecture with a technical solution, description of developed platform and results from our evolution tests. In Section 4, we present data visualization framework and finally in Section 5 we briefly explain the research on snow measurement.

2. Related Work

Most of WSN projects in the field of crisis management are generally aimed at Fire rescue applications. Particularly at emergency evacuation systems which help direct evacuees to the nearest “safe” exits through complex building layouts in disaster situations such as [2], [3] or FireNet [4]. A complex study of this application can be found in [6].

Other WSN projects solely focus on localization mechanisms for rescue application such as [4] where only radio signal strength (RSS) measurements is used or [6] where new algorithm called Monte Carlo Patient Localization is proposed. FireBug project utilize wireless sensors with the Global Positioning System (GPS) to monitor wildfires.

A popular commercial solution in the marketplace Inspiron Logistics Wireless Emergency Notification System (WENS) focuses on emergency notification via SMS and voice messaging. Nevertheless, it is stated [7] that it will take four minutes to inform administrators and it then takes another two minutes to inform all subscribers about the emergency.

There are two main differences that might be seen at the first sight. Firstly, as our data collection and warning system is adaptive, it can monitor much more parameters so it can be deployed in many different situations. Secondly, the main advantage of the proposed system is avoiding any hazardous states as there are not high requirements (e.g. real-time operation or mobile localization) during non-emergency cases.

3. WSN Architectural Overview

The whole system is divided into three main parts: WSN, Gateway section and Crisis Management (see Fig. 1). The first part consists of arbitrary number of: Wireless Sensors Unit (SU), Gateway (GW) and Sensor Alarm (SA).

The stationary SU collects data about particular phenomena through attached sensors and transmits them towards GW.

The SA is a special kind of node which is basically a SU but it is additionally equipped with audio-visual devices such as LED display, siren and light beacon to inform people about possible hazardous events. In terms of displays people might be directed to the nearest safe exit or to be informed about precaution action.

The GW acts as a bridge between WSN and Crisis Management server. The communication with Crisis Management is provided by the Internet or private infrastructure (802.11, 802.16, etc.). Since the data delivery in WSN is inherently asynchronous from the Crisis management requests we adopted XMPP (Extensible Messaging and Presence Protocol) [8] for the data transfer from WSN. The XMPP is an open, standardized and well established technology for real-time communication. Especially its Extension Protocols XEP-0060: Publish-Subscribe [9] is useful for building distributed event-driven applications. Thus, the Crisis management personnel can be easily subscribed to a particular data stream from WSN; regardless of which gateway the data stream is being generated by.

The Crisis Management office consists of a database and an application server (see section 4.) and all measured data can be visualized in the form of an interactive web application with map sources. As the main goal of the proposed system is to avoid hazardous situations, strict real-time applications are out of concern and thus the GIS (Geographic Information System) can be also used. GIS allows user to view and analyze information graphically and store that information in a database. Nevertheless, we developed multiplatform visualization framework consisting of two parts (WSNmonitor and WSNview) to fulfill our special needs. The WSNmonitor can serve the same data to the mobile clients through WSNview as well as to Crisis Management personnel in the same manner.

Besides, our system supports strong security over the entire data-path from WSN section where AES-128 is employed to the SSL for the path from the gateway to the Crisis Management.

3.1 Technical Background

We choose the radio standard IEEE 802.15.4 because of its proven performance and market availability. There are three radio bands defined according to the standard IEEE 802.15.4 [10] in the Industrial Science Medical (ISM) band and two of them are available for use in the Czech Republic. Particularly, the band of 2,4GHz and 868MHz are suitable. Although the band of 868MHz offers better penetrations and better resistance against noise and interferences, there is only one defined channel whilst there are 16 channels for the band of 2.4 GHz. Multiple channels are helpful in case of disruption of particular channel so that user can use the other one. We have already published the results of the measurement of the wireless technology coexistence, see [11]. In such a fail-prone RF environment mesh topology is highly advantageous. The basic idea of the mesh topology is to provide ability to a one node to communicate with any other node in the network.

Although the IEEE 802.15.4 is not purely a mesh technology, it can logically extend a one hop to multi-hop mesh communication. While there are many operating systems designated for WSN like Contiki and TinyOS, we chose an advanced solution based on ZigBee technology, particularly the BitClound stack [12] from Atmel Company. The biggest advantage of ZigBee is its interoperability through application profiles, availability of software stacks and security at different levels.

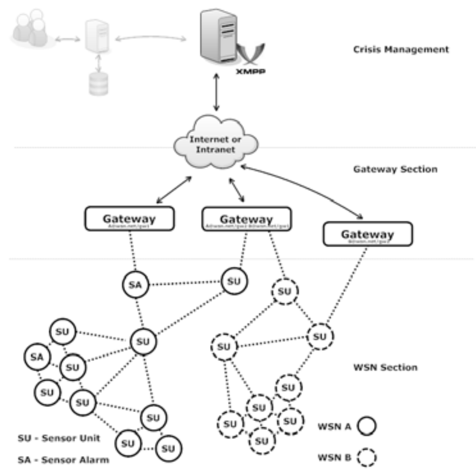

Fig. 1. System Architecture

According to our intended applications and needs we defined the following suggestions (see Table 1).

Table 1 Sensor Network Parameters

Parameter	Value
Number of Sensor Units	Up to 100
Number of Gateways	> 1
Sensor network topology	Mesh
Mobility of Sensor units	No
Transmission method	Wireless
Radio range	< 1000m
Radio band	868MHz/ 2,4GHz
Maximum transfer rate	10kbps
Maximum transfer delay	1s
Security	Not required
Power supply	Accumulator + powerline/ Accumulator + solar panel

3.2 WSN Performance Measurement

In order to get a real view of our WSN several measurements in 2.4GHz band were conducted. For this task the certified BitCloud ZigBee PRO v1.11.0 stack was adopted. We wrote a dedicated firmware for the measurement. It allowed us to configure appropriate parameters such as transmit power, data destination and payload size over the air. For the evaluation two important scenarios were defined.

The data are presented through a robust statistics based on median and box and whisker plot format. The box is represented by the lower quartile (25th percentile), median (50th percentile) and upper quartile (75th percentile). The whiskers describe the smallest and the largest observation in a particular dataset. Moreover, the median values are displayed at each column.

a) Routing Latency

We analyzed a multi-hop routing latency among routers with respect to the security and payload size (minimum 1B, maximum 77B). This is a time delay required for forwarding payload from one node to another. We tested different topologies with various number of nodes. Data travelled randomly through one to five routers. The routing latency illustrated in Fig. 2 shows median values of the time delay per hop. Fifteen repetitions were done and more than thousand samples were collected for each combination. Based on the results it can be concluded that in an arrangement where security was switched off, the payload size prolonged the latency just slightly. However, when the encryption was in use, the latency rose dramatically due to its computation expenses. The AES encryption with predefined 128bit key and 32bit MAC was implemented in software. In this case, the latency was very tied also to the payload size.

The latency was further recalculated to the throughput (see Fig. 3). The results show that throughput can vary from as low as 0.1 kbps to 83 kbps.

Typical topology usually does not exceed five hops and thus based on our measurements we might claim latency and throughput sufficient for our unsecured application. For the case of secure transmission higher latency needs to be considered.

b) Network Startup

The aim of this scenario was to verify, whether Zigbee network can be built and to measure the time delay for multiple devices trying to form a network simultaneously. This scenario is relevant for instance after the power outage, where more than one device is powered directly from power grid. We gradually increased a number of nodes in the network from 2 to 15. The impact of encryption with respect to the network startup time and physical network topology was further evaluated. We tested two types of physical topology. In case of the first one, so-called all-in-range, all nodes were in the radio range of each other in the network. The second topology, called multi-hop, consisted of nodes which were in the radio range only to the closest neighbors.

Finally, we conducted 30 repetitions for each arrangement, totally 480 measurements in this scenario.

The results are illustrated in Fig. 4. During the measurements we did not notice any single unsuccessful attempt to build a network, no matter how many devices were included. The interesting observation is that the security had only minimal impact on the network startup time, even though the encryption was implemented without any hardware support. On the other hand, physical topology had considerable impact on the startup time. In case of the multi-hop arrangement, the startup time was significantly prolonged in comparison to the all-in-range topology.

The simultaneous network startup scenario pointed out that 15 devices in the all-in-range arrangement are able to join within 5 seconds regardless of security mode. The same number of devices in the multi-hop arrangement needed 17 s and 24 s for unencrypted and encrypted mode, respectively. As a rule of thumb, it takes up to 0.5 second for one node to join to a network in all-in range topology and 1.6 seconds in multi-hop topology.
A comprehensive evaluation of the measurements will be published in a forthcoming paper.

3.3 Message Exchange

We defined four message types such as Report, Alarm, Statistics and Commands represented by the Zigbee APS endpoints.

After the SU is deployed and started, it joins the sensor network, the Report message is generated to the address of the GW with fixed address of 0x0000. This GW also acts as a coordinator of the whole network. The GW collects all overheard addresses and passes them out of the network to the Crisis Management server. When another GW is added to the network, it just requests a list of all nodes' addresses and sends them its own address. The sensor nodes communicate with both GWs and Crisis Management server takes care about the message redundancy.

All data acquired from attached sensors on SU are periodically reported to the GW in the form of a Report message, stored in local RAM and compared with previous measurement. Only when the currently measured value is greater than configured a difference from the previous sample, the Report message is generated immediately.

In the case of emergency, when the measured value is out of the configured thresholds, the Alarm message is generated with the sign of the highest priority.

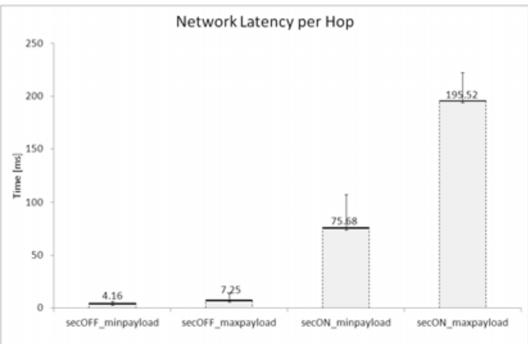

Fig. 2 Network Latency per Hop Measurement

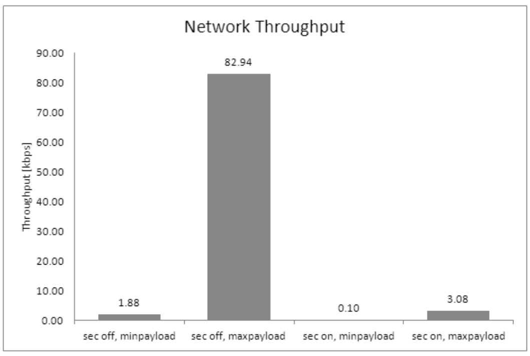

Fig. 3 Network Throughput

The dataset is divided into four groups with respect to the security and payload size as follows: 1st security is OFF and minimum payload (1B); 2nd security is OFF and maximum payload (77B); 3rd security is ON and minimum payload arrangement; 4th security is ON and maximum payload arrangement.

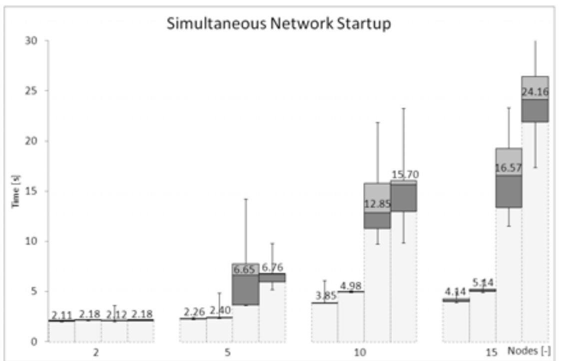

Fig. 4 Zigbee Simultaneous Network Startup Measurement

The dataset is divided into four groups according to the number of involved nodes. Each group is further divided into four columns as follows: 1st security is OFF and all-in-one arrangement; 2nd security is ON and all-in-one arrangement as well; 3rd security is OFF and multi-hop arrangement; 4th security is ON and multi-hop arrangement.

Apart from that a daily report is produced once a day. Daily report (Statistics) consists of statistical information about SU such as the number of received and transmitted bytes, running time, battery status, etc.

Command messages sent from the Crisis Management server allow over-the-air configuration of SU in terms of adjusting report intervals, thresholds and measuring tolerances.

3.4 Sensor Unit

We have developed SU driven by the Zigbit module [13]. The Zigbit provides 128 kB of Flash memory for firmware, 8 kB of RAM for data and 4 kB of EEPROM for nonvolatile parameters storing. The nonvolatile memory is further expanded by an external FRAM. There are five types of Zigbit modules and all of them are pin-to-pin compatible. The difference among the modules is mainly frequency bands to be used. Thus, the Zigbit module can be easily re-plugged thanks to our modular design allowing communication in any frequency band suitable for a particular application.

SU offers three digital inputs, two digital outputs and four analog inputs. The number of employed sensors and actuators can be further extended by utilizing I^2C bus or UART interfaces.

4. Visualization Framework

Data visualization is an important feature for crisis management. The key aspect of the application is to usably display data for humans in real-time fashion. Nowadays, there are dozens of visualization applications dedicated to WSN. A great review of most of them can be found in literature [14], [15]. One of the most famous WSN platforms comes from Crossbow Company. Their system is equipped with MoteView [16] visualization framework. However, MoteView is tightly tied to the Crossbow's products. Another promising modular technology called SpyGlass [17], originates from Institute of Telematics of the University of Lübeck. Unfortunately, none of the available visualization applications fits to our complex requirements. Therefore, we proposed our own multiplatform visualization application.

4.1 Communication Architecture

A data path from WSN to an end-user can be divided into three stages (see Fig. 6):

Data Source stage – Data from one or more WSNs are delivered through gateway via XMPP protocol to the XMPP server.

Data Processing stage – Data from an XMPP server are subscribed by a WSNmonitor. From the XMPP perspective the WSNmonitor is equivalent to any other XMPP client. This application performs the necessary processing of the received data. The data are further encapsulated to Objects which are passed to a Data Presentation stage via serialization mechanism. This information exchange is done by HTTP protocol. Thereupon, seamless integration to the current internet infrastructure is guaranteed. The Objects are also stored in a SQL database in parallel. This database was thoroughly designed for a wide range of WSN applications.

Data Presentation stage – The only purpose of this stage is to graphically display information in the most usable way. Thus, we designed a rich internet application called WSNview.

4.2 Implementation

As mentioned above, we designed the visualization framework which consists of two particular parts – WSNmonitor and WSNview. The WSNmonitor is written in Java and involves tree Java based frameworks. A Hibernate framework [18] is used for an object relation mapping. In other words, it transfers the data between WSNmonitor and SQL server. For the data transfer from WSNmonitor to WSNview we used BlazeDS framework [19]. The serialized data are encapsulated into Action Message Format (AMF) [20] which is much more effective than traditional chatty XML or JSON serialization techniques used in other visualization applications. Finally, we chose Spring framework [21] for reducing complexity of the application and for great security support.

The WSNview application is written in Adobe Flex [22] open source technology. Adobe Flex can be run almost on any system from Android and IOS mobile operating systems to the traditional Windows/Linux operating systems. Therefore, mobile personnel may use this service as well as Crisis management office.

5. Snow Measurement

In case of emergency caused by overloaded roofs with the snow, it is crucial to know the amount of the snow load. This information is especially important in case of large roofs. The snow height is not as important factor as the mass of water contained in the snow on a particular area. As there are at least four types of snow concentration, a direct measurement of snow weight is desirable. More information regarding the snow types can be found in an Equivalent Snow Load Table in the paper [23]. Another problem is uneven weight distribution, which can vary even on a small area. We found two off-the-shelf systems for measuring snow load directly. One of them, the Snow Scale device is based on load cells. The system consists of seven 2.8m x 2.4m and perforated plates [24]. The second device, so-called Snow Pillow, is based on measuring of a hydrostatic pressure caused by a layer of snow [25]. Both devices achieve high accuracy and they are suitable for meteorologists. Nevertheless, they are rather expensive and quite heavy for our application on roofs mounting. The price of the Snow Pillow is more than EUR 6,000. In

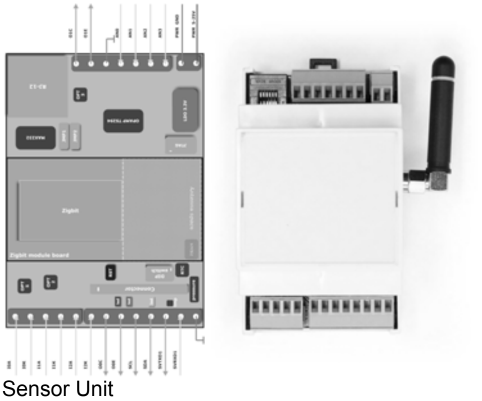

Fig. 5 Sensor Unit

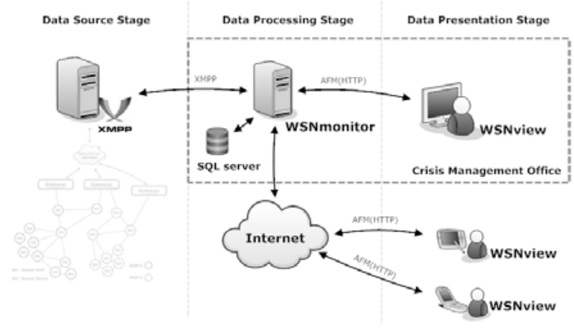

Fig. 6 Visualization Framework Architecture

addition, mounting the devices in other than horizontal direction can be problematic. There are several known methods for indirect snow weight measurement. Typically, the height is measured optically or ultrasonically and a density of the snow is estimated from atmospheric pressure, temperature, rainfall amount complemented with a historical data at a given geographical area. It should be noted that this process is complicated, strongly dependent on selected empirical model and often requires a human intervention. Thus, without knowing the snow density, any indirect method might be highly inaccurate. In our application we do not necessarily need to receive information at the highest precision which can be provided by the devices described above. For the purposes of our application it is sufficient to measure the snow load in several levels (e.g. normal to critical snow weight). Furthermore, considering unequal snow distribution we need more snow weight sensors on a roof. Hence, the low price per snow sensor is demanded.

5.1 Development of Snow Weight Sensor

It has been noted that direct weight measurement is very financially expensive. So far, there is no such sensor based on indirect method suitable for our application. Therefore, we have designed our own snow load sensor. A real snow cover is composed of several layers with significantly different density. The introduced sensor can measure the height of the snow and also distinguish the type of snow in each layer. With respect to this, we are able to derive a total weight of a snow cover. Besides this, the proposed sensor is rather small and can be easily mounted on roofs. The main idea is based on the parasitic electrical capacity. More information cannot be currently provided; the patent registration has been requested.

6. Conclusion

This paper presents results and a current state of the running project AWSN (Adaptive Wireless Sensor Network for Disaster Prevention with Data Visualization) designed for a wide usage in the emergency management. We have presented, along with evaluation tests, technical solution based on wireless sensors network driven by BitCloud. We have also introduced our sensor unit allowing communication in any frequency band suitable for a particular application. Finally, we have proposed our own multiplatform visualization framework and briefly explained research on snow weight sensor.

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