DETECTION OF WOOD LOGGING BASED ON SOUND RECOGNITION USING ZIGBEE SENSOR NETWORK

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ABSTRACT

Illegal logging and international trade in illegally logged timber is a major problem for many timber-producing countries in the world. There is currently no system for prevention of illegal logging that provides continual and real-time monitoring of endangered forests capable of instant detection of logging. This paper introduces our unique solution to this problem, based on real-time analysis of sounds from surroundings using sound recognition. We describe complete architecture of our system with main focus on its wireless sensor network that is responsible for sound collection and actual exposure of logging. In this paper we also introduce the experiments of ZigBee communication range in forest environment.

Index Terms— sensor network, forest monitoring, ZigBee, illegal logging, sound recognition

1. INTRODUCTION

Illegal logging and international trade in illegally logged timber is a major problem for many timber-producing countries in the developing world. The scale of illegal logging is difficult to be accurately figured, but according to the estimates from the year 2006, it costs world governments at least 15 billion USD annually in lost revenue [1]. More than half of all logging activity in the most vulnerable forest regions is believed to be conducted illegally.

Global forest cover is a key indicator of the health of the planet. Forests purify air, preserve watersheds, improve water quality, prevent erosion and provide us with natural resources. It is estimated that 1.6 billion people worldwide rely on forests for their livelihoods and 60 million indigenous people depend on forests for their subsistence [2]. Forests absorb a lot of carbon dioxide, a major greenhouse gas in global warming, and thus help to protect our planet from upcoming climate change. Illegal logging causes unmanaged and often irreparable deforestation which is a great threat to maintaining biodiversity, as nearly ninety percent of terrestrial biodiversity is found in the forests [3].

The forest is considered to be one of our most important and indispensable resources. We believe that the potential deployment of the forest environment monitoring systems could have great impact on many problematic areas of contemporary civilization.

As a result of an analysis of existing systems which monitor logging activities (e.g. system based on reconnaissance satellites [4]) we have determined several imperfections of currently used systems. In this paper we propose an approach to forest monitoring that implicitly denies the drawbacks of the existing approaches. The proposed system “Forest Guardian” recognizes and localizes the sound of logging activities in the wide forest areas. It utilizes wireless sensor networks (WSN) for communication in the covered critical forest areas. It collects information and makes it available to users through a web application. The proposed system is designed modularly and is thus ready for future extensions. The main improvements of the system we have proposed are fast reaction when logging occurs and permanent monitoring of critical forest areas.

The next subsection describes related work in all problem areas relevant to our project – illegal logging, sound recognition, wireless sensor networks and web map applications. In the next section, we describe the main idea of the proposed system “Forest Guardian”. Section three deals with the architecture of the proposed system. In section four we describe and discuss the performed experiments. The final section concludes the document and gives a look out to further work.

1.1. Related Work

One system which is currently used to monitor and detect illegal logging is based on reconnaissance satellites. It identifies logged areas through obtained satellite images and gives forestry departments choice to verify whether the logging process is legal and whether an action needs to be taken. The long time needed for detection of logging area is the system’s serious disadvantage as it often takes between one day and one month to work – time in most cases too long to actually stop illegal logging [4].

Although the proposed idea of monitoring the forest from illegal logging by sound recognition is unique, we have recently encountered a project called “Forest Watcher,” a monitoring system for preventing forest devastation [5] which is closely related to our work. This project utilizes a sensor network based on Bluetooth technology. Its sensors, along with sound, measure also temperature and humidity. The network of up to 200 wireless sensors covers a forest area up to 200 hectares. We didn't find any employment of this system in commercial use yet.

Automatic Sound Recognition for the Hearing Impaired [6] is one of many projects on scene using sound recognition as means for processing audio inputs. The authors design a system which helps hearing impaired persons by recognition of simple mechanical sounds such as doorbells, phones, teapots etc. All of these sounds have clear distinct spectral peaks. The authors develop a new method of recognition – normalized peak domination ratio (NPDR). This system can be integrated into as small device as a watch.

Another project – Non-speech sound recognition with microphone array [7] from Mitsubishi Research Institute – can identify seven types of sounds such as a bell ringing and hand clapping with an accuracy of 80% or higher. System uses a microphone array and conventional PC to process audio input, perform sound recognition and even compute relative position of its source.

Wireless sensor networks are nowadays widely used in various areas. K. Romer and F. Mattern in [6] describe different custom made sensor network applications which are being used for research purposes in natural sciences like biology, meteorology, geology, medicine and monitoring purposes in everyday life, especially when time is an essential factor.

Research paper *Springbrook: Challenges in Developing a Long-Term, Rainforest Wireless Sensor Network* [8], describes design and development of wireless ecological sensor network intended for deployment in rainforest environment. The main focus of the paper is on analysis of energy and communication issues in the specific environment of a rainforest.

The wireless sensor network presented in Ref. [16] uses acoustic localization to passively observe vocal animal species. This system is able to localize free-ranging wild ant bird songs with mean error of 0.199 *m*. Localization accuracy was minimally affected in cases, when only a short segment of each song was used or when a subset of sensor nodes was utilized.

We have encountered several web applications using maps with visualization. One of these works represents the project "Eye on Earth" [9] which monitors air and water stations in Europe. It uses Bing maps control with the ability to navigate between the stations and see their information.

The recent accident in Fukushima I Nuclear Power Plant led to the creation of a national real-time map of radiation data, accessible to everyone. Volunteers in Japan used the Pachube platform to interlink Geiger counters across the country to monitor nuclear fallout [10].

2. FOREST GUARDIAN IDEA

The basic idea of Forest Guardian is to build a system that would provide users with real-time information about logging activities in the monitored forest areas. We intended to build a wide system which would be capable of monitoring the forest and instead of visual information (as satellite systems do), would be able to use real-time analysis of the sounds from surroundings to reveal the illegal logging activities. The "real-time" requirement means a permanent monitoring of critical areas in a forest with a particularly fast reaction when logging occurs.

Logging activity has its own characteristic sound. Forest Guardian permanently monitors the forest via sensors recording the sounds of surrounding environment. It compares acquired sound samples to the general samples of the logging tools (e.g. logging machinery or chainsaws) in order to detect any logging activity. In the case of detection of logging in monitored area Forest Guardian immediately notifies responsible personnel (via email, SMS etc.), so they can take direct actions to stop illegal logging. This is one of the main advantages of our proposed solution when compared to currently employed satellite-based systems.

The proposed extension above the basic idea is to provide this information not only to responsible personnel but also to the public users through an interactive web application. The main aim is to increase the public knowledge of this global problem. The proposed web application is capable of visual representation of logging activities on an interactive world map.

Typical use of Forest Guardian consists of placing wireless modules in the forest area and connecting the central point of the network to the Internet. When the sensor network detects sound from surroundings which is similar to the sound of logging tools, the central point sends e-mail messages to preconfigured recipients. The web application provides the public with data about the logging activity in the covered areas. As making the exact location of the logging activity publicly available would reveal the location (and coverage) of the sensor network, the web application provides only estimate location data to anonymous users. In this way, the Forest Guardian is "guarding" the forest and can be used for prevention of illegal logging. The basic idea of the system along with sensing coverage of sensors using microphones in one forest area is illustrated on Fig. 1.

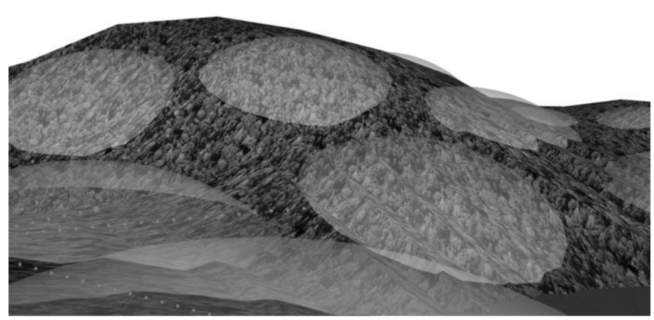

Fig. 1, Sensing coverage of sensors deployed in a forest

3. SYSTEM ARCHITECTURE

Forest Guardian is divided into three logical layers (see Fig. 2): sensor network, local aggregating points (LAP) and central information system (CIS). Each sensor network is composed of sensors and routers – battery-powered embedded devices designed with regard to low cost, durability, energy preservation and weather resistance. These devices are appropriately distributed throughout a forest, each of them fastened to strategically positioned tree. Each sensor periodically acquires sound sample, processes it and transmits the processed data to its router. Router performs sound recognition and transmits the results along with the location information to LAP.

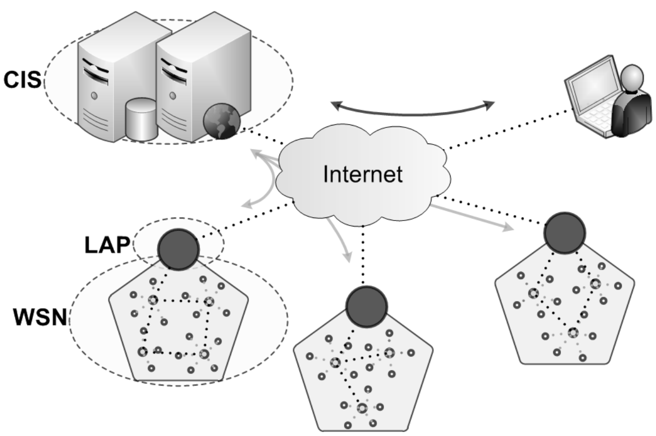

Fig. 2, Forest Guardian architecture

Local Aggregating Point acts as a collector of data received from the sensor network. It computes the logging location, stores the pertinent data and if necessary (e.g. detection of logging activity) notifies the responsible personnel. Information about logging activities in monitored forest area is periodically propagated to central information system.

CIS manages the system of local aggregating points, archives information received from LAPs, provides user interface to users with the ability for privileged users to send configuration parameters to LAPs.

3.1. Wireless sensor network

Proper design of WSN for use in large space monitoring can be a very challenging process, though. When designing any wireless network, one of the basic questions that must be answered is the maximum distance between two nodes that still ensures a reliable wireless connection. The answer depends on many parameters such as transmitter output power, receiver sensitivity, signal propagation environment, signal frequency and parameters of an antenna [11].

Our system is to be employed in the forest area, which is a heterogeneous environment with many factors influencing wireless communication propagation. The foliage medium especially can attenuate the propagating radio wave significantly. According to the communication characteristics and energy consumption limitations of the system, WSN is designed to form a cluster-tree topology network (as shown in Fig. 3) and to use a ZigBee communication protocol [12]. ZigBee with its focus on energy preservation, operating frequency bands of 868/915 *MHz* and 2.4 *GHz* and relative popularity on the market that ensures a variety in available ZigBee-compliant devices is a suitable option for the use in our project. The experiments verifying the suitability of the use of ZigBee transceivers operating in 868 *MHz* band are documented in section 4.1 of this article.

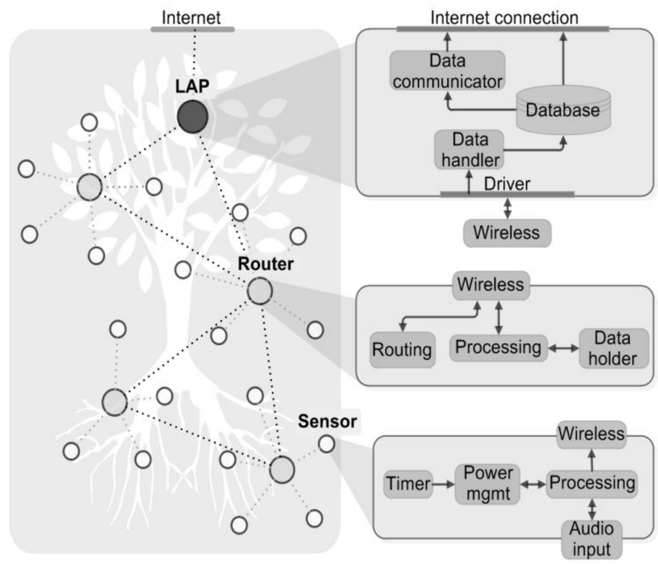

Fig. 3, Wireless sensor network architecture with components' structure

Sensors are devices that generate actual data of interest – they acquire and process the sound sample, create messages containing the processed sound sample along with power status information. Sensors are grouped into star-topology clusters that form a star topology sub-network with a router acting as a cluster head. In this sub-network the transmit distance can be intentionally limited by configuring a low value of output power on the sensors in order to preserve the energy of sensor devices

A *router* is a device that processes and aggregates collected data from its sensors or other routers and transmits messages towards the base station that is LAP.

Clustering reduces the data to be transmitted to the LAP by processing all data locally (on a router). Data aggregation is used to combine relevant data into a small set of data that contains only relevant information.

Fourier transform is undertaken on a recorded sample in order to enable actual sound recognition and to minimize amount of data needed for transport to the routers. Routers process the received frequency domain representation of recorded sound and compare it with the known frequency domain representation of logging devices sounds (e.g.

chainsaws or logging machinery). The router's task is also to prepare informational messages for the LAP and propagate them through the network.

A sensor periodically samples audio input of given length (approx. 1 *sec*). The Fourier Transform that is consecutively applied on this sample produces a frequency based representation of acquired data (instead of an original time based representation). Using this processed sample the carrier frequencies can be easily identified. The carrier frequencies (also spectral peaks) have the highest energy in comparison with other spectral components and are least affected by background noise.

To preserve energy, the sensor devices carry out their function only once in two minutes (this time slot is configurable) – their task is to record sound, process it (Fourier Transform) and to form and send a message to the associated router. When all these tasks are done, the device set its timer to wake it up after two minutes and switches to sleep mode. As one of the objectives of the WSN is to merge with the surroundings, we have designed the sensor devices as small and unobtrusive as possible, regarding the size of the battery that provides sufficiently reasonable lifetime for the device.

Opposing to the sensor devices, the router devices stay active for substantially longer time, as their task is to receive messages from the associated sensors and to propagate the messages from other routers. Because of this, we have designed the routers more robust and equipped with larger battery as sensor devices.

The technology used for the WSN prototype is: 868 *MHz* RF ZigBee compliant transceivers (XBee Digi's 868 XBee-PRO modules)[1], ARM7 architecture (ATMEL AT91SAM7S256 BOARD), 9 *V* PP3 batteries, 3.3 *V* very low dropout voltage regulators and microphone with preamplifier. The reason of employment of 868 *MHz* transceivers is that 868/915 *MHz* frequency band has better physical attributes (lower attenuation and larger communication range) than 2.4 *GHz* frequency band although it is capable of lower bit rates. Raw bit rate on 868 *MHz* with the binary phase shift keying (BPSK) modulation is 20 *kbps* which results in longer transmission time than would be required if the 2.4 *GHz* frequency with its 250 *kbps* raw bit rate were used. However, the physical attributes of this frequency band are, according to our experiments with Microchip's MRF24J40MA modules (we haven't published the results), insufficient.

For the actual sound recognition in the matching process the method called NPDR [6] is used, that shows high successfulness in sound recognition in noisy environment. NPDR computes with not only spectral peaks but also with spectral valleys. This approach ensures elimination of strong noise components that can potentially be present in the sample. The characteristics of NPDR result in the independence of attenuation. The sound recognition is not affected with growing distance as far as the received signal is not attenuated so much that it is significantly drowned by the present background noise.

3.2. Local Aggregating Point

LAP serves as a personal area network coordinator for the ZigBee sensor network. It sets up and manages the network of routers. It receives and evaluates data messages, stores relevant information and periodically, or as an answer to a query from central information system, propagates the information about logging activity. Old data stored in memory are periodically purged. Local aggregating point computes the logging location and in case of detection of logging activity, it immediately notifies responsible personnel.

LAP's hardware contains, among others, ZigBee compliant module with high-energy antenna and Internet connection module (e.g. Ethernet or GPRS).

On the developed LAP device, Windows Embedded Compact post version 6.0 release 3 (also commonly known as Windows CE 6) is used as operating system. Several designated applications are written in order to ensure all requested functionality. Applications are developed in Microsoft Visual Studio 2008 using .NET Compact Framework 3.5. Mutual relations among these applications can be clearly seen in Fig. 3, section "LAP".

Driver provides standard interface for communication with wireless device through ZigBee protocol and thereby ensures communication with sensors and routers.

Data handler is responsible for receiving and evaluating data from the sensor network. The data will be processed and then saved in local database. When some critical facts (e.g. detection of logging or small battery level on some device) are found during processing of data, this component can directly contact responsible persons via notification message. The data handler can also start system routine for sending data to central database on the higher layer – central information system (CIS).

Data communicator is responsible for inserting data from the local database to the central database on CIS. Stored data will be accessed in periodic intervals and can also be sent asynchronously when the component is notified by the Data handler. If no Internet connection is available in the moment, Data communicator delays dispatch of data until Internet connection is re-established.

Authorized personnel can configure some aspects of LAP's functionality through configuration table in the local database. Critical facts, such as when responsible persons are to be contacted and how often the data should be sent to the central database, can be adjusted. The authorized personnel can also actualize routers firmware through this table.

[1] Manufacturer's web site: http://www.digi.com/products/wireless-wired-embedded-solutions/zigbee-rf-modules/point-multipoint-rfmodules/xbee-pro-868.jsp#overview

3.3. Central Information System

Applications, running on general purpose computers (data and web servers), constitute central information system. CIS is composed of two main parts – Web application running on a web server and Central database server.

The web application retrieves information about logging activities and other data from Central database and displays them appropriately on an interactive map. It provides the user with interfaces by graphically representing information about monitored areas: networks total coverage (map), location of LAPs (map) and logging history of selected area (caption). It also presents essential information on the list of LAPs: its location, the responsible personnel and time of the last update. Lastly, it provides detailed information about selected LAP's sensor network components: list of connected devices with their location, battery status, logging activity and time of last update (list). Privileged users are capable to connect to the selected LAP in order to send configuration parameters to LAPs.

Web application could conveniently be implemented using Bing Maps, Microsoft Silverlight 3 and .NET Framework 4.0.

The most important data in the Central database are logging's GPS coordinates varying with time, start date and time and intensity which depends on how many sensors detect logging activity.

Given the danger of potential misuse of detailed information available to the central information system it is desirable to restrict the access to the system. Public users are allowed to see only general information about logging activity displayed on the map. Detailed information is available only to privileged (and authenticated) users in order to enable subsystem maintenance and law enforcement supervision.

4. EXPERIMENTS AND EVALUATION

The prototype device of the proposed system has been implemented. We have performed several experiments with the particular subsystems of the Forest Guardian. In order to determine the suitable ZigBee modules for our application, we have measured the communication range of various ZigBee devices in the forest environment. To determine the needed accuracy and computing demands of the sound recognition, we have tested the prototype devices with various configurations. Some measurements have been performed also to determine the devices' power consumption and thus specify the needed batteries and estimate the devices' battery life.

We have also prototyped web application on Windows Server 2008 and successfully tested data presentation from central database on Bing map. Communication between prototype of local aggregating point and central database was also successfully tested.

4.1. Communication range

For the verification of the suitability of the chosen communication technology, we have performed measurements studying ZigBee communication characteristics in a forest environment. We have measured in the deciduous forest composed of oak and acacia trees. The forest is about 80 to 100 year old, with the average thickness of tree trunks is about 15.5 *cm* and the average tree trunk separation about 2.25 *m*, ranging from absolute nearness to as much as 6 meters. During measurements the temperature was within a range of 13 *°C* to 17 *°C*, atmospheric pressure was 1026 to 1027 *hPa*, relative air humidity was 49% to 52%, wind speed was 11 to 22 *kph* and it was a cloudy day. For the measurement we have used two 868 *MHz* transceivers (Digi's 868 XBee-PRO modules) with output power set to 0 *dBm*. The receiver was equipped with an omnidirectional RPSMA antenna and the transmitter had simple wired antenna. The accuracy of measured signal power has been restricted by the information provided by the PHY layer of transceiver with its maximal reported value of -64 *dBm* and minimal reported value of -104 *dBm*. This experiment is described extensively in [11].

While measuring in the almost same distance from transceiver, with moving the device only in tens of centimeters in vicinity of measured location, we usually received signals within a range of notably different power values as shown in Fig. 4. Signals with different values will most likely be received even when the transmitter and the receiver are immobile but the minimum to maximum difference will be smaller. According to multipath-null phenomenon it is important to place the transmitter and the receiver carefully in suitable relative positions.

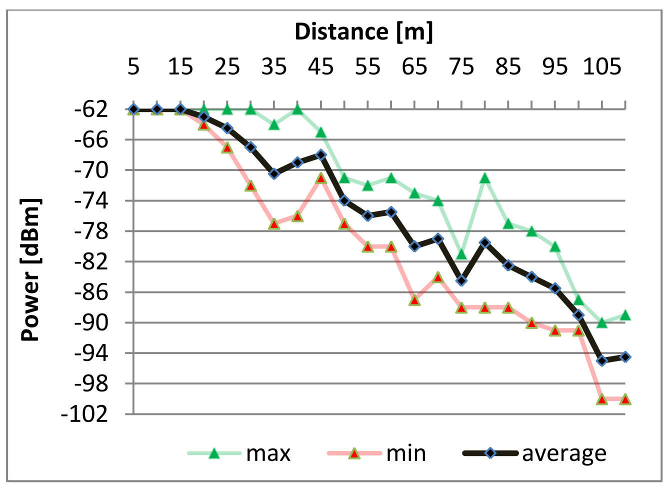

Fig. 4, The communication characteristics with output power 0 *dBm* and 868 *MHz*

Forests are distinguished by different parameters such as trunk and foliage density, ratio of deciduous and coniferous trees, relief, humidity and others. Moreover, these parameters vary over time. Although the path-loss exponent of any given environment cannot be exactly defined, the path-loss exponent accurate for a current state of a given environment can be experimentally determined and its tendency in variation can be monitored over time. According to [14] it is found that the through-vegetation path loss in general can be well represented by:

$$L_{foliage}(dB) = A \cdot f^{B} \cdot d^{C} \qquad (1)$$

Where f is the frequency, d is the distance and A, B and C are parameters that can by empirically optimized through regression techniques based on specific measured data.

Using equation (1), the experimental data acquired for measurements in 0 *dBm* and NLREG program [13] we have performed a nonlinear regression and determined a through-vegetation path-loss for the experimental environment. This measurement shows that the results of nonlinear regression are approximately equal to the used theoretical characteristics. The empirical model based on our measurements is:

$$Func_{NLREG}(dB) = 5{,}052.10^{-5} \cdot f^{0{,}95} \cdot d^{1{,}388} \qquad (2)$$

This relation together with free space loss (FSL) [11] is shown in Fig. 5. Other empirical models are shown for comparison as well – Weissenberger's modified exponential decay model (Lw), ITU Recommendation model (Litu-r) and Fitted ITU-R model (Lfitu-r). For detailed information regarding these models see [14].

As seen in Fig. 5, the measured loss in signal strength is noticeably lower than other empirical models suggest. This is most likely caused by the structure of the forest that is possibly sparser that forests that are described by these models. It is also expected that the attenuation will be higher when the forest is fully in leaf.

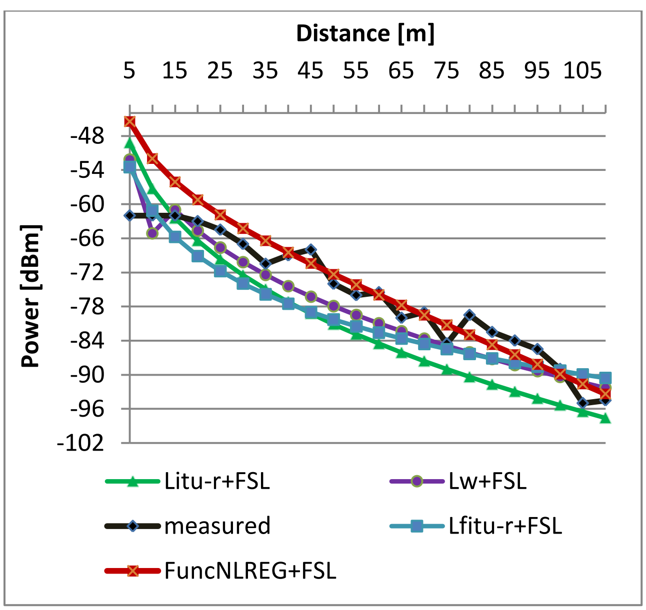

Fig. 5, The Comparison of measured data and mentioned empirical models at 868 *MHz* carrier frequency

Using the relation (2) based on performed measurements and the maximum reported sensitivity of Digi's XBee PRO 868 devices (that is -104 *dBm*) we can estimate the maximum reliable communication range in given experimental environment to approximately **140 *m***. This is the average maximum distance between two communicating nodes using given transceivers with 0 *dBm* output power.

4.2. Sound attenuation and recognition

The signal received by the microphone is influenced mainly by the distance from the source and by the impact of surrounding forest, atmosphere, humidity, temperature and frequency components [15]. Sound pressure level in relation with octave band values of the acquired sound sample can be described as [15]:

$$[L_{ft}] = [L_w] + [A] \qquad (3)$$

Where L_w is the octave band power level relative to reference power 1 *pW*, D_C is directivity correction, and A is an octave band attenuation. Attenuation can be described by equation (4) [15]:

$$[A] = [A_{div}] + [A_{atm}] + [A_{gr}] + [A_{bar}] + [A_{misc}] \qquad (4)$$

Where A_{div} is geometrical divergence, A_{atm} is an attenuation of atmosphere, A_{gr} is ground attenuation, A_{bar} is an attenuation of barrier and A_{misc} is a miscellaneous attenuation such as forest attenuation. Equation 5 shows that distance from source do not depend on frequency [15]:

$$[A_{div}] = [20\log(d/d_0) + 11] \ \ dB \qquad (5)$$

As shown in Fig. 6, lower frequencies are more immune to attenuation caused by the environment than higher frequencies. This fact indicates that the sound recognition accuracy can be significantly reduced for high frequencies in growing distances.

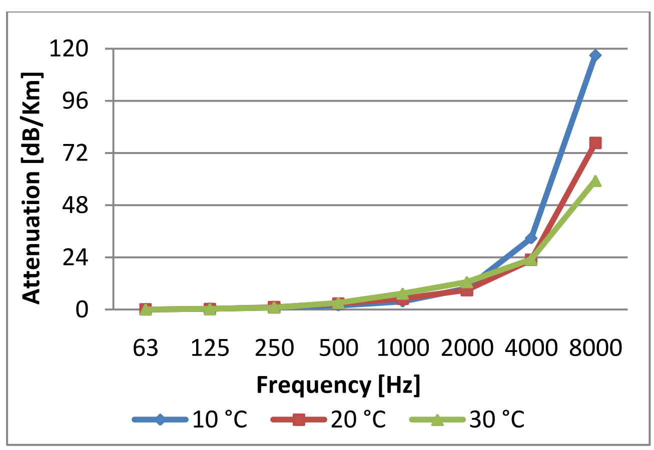

Fig. 6, Atmosphere attenuation at relative humidity 70% [15]

We predict maximum recognition distance less than one hundred meters. As a next step in our work, we plan to carry out the experiments to provide us with information about maximum operating distances for carrier frequencies of sound spreading in mildly noisy environment.

As means of verification of the NPDR [6] method we have used a simple testing apparatus that consists of a microphone, two speakers and a laptop. Testing have been divided into phase 1 – the acquisition of a sound sample conducted in as noiseless environment as possible (workroom/indoors) and phase 2 where the acquired samples were replayed in a noiseless environment and mildly noisy forest environment and consecutively have been sampled and the NPDR have been performed. Simple peak extraction algorithm based on average energy was used to select spectral peaks. The measuring distance between the speakers and microphone was 0.5 *m*. Each sound sample has been processed with 22.05 *kHz* sample rate taken with 16 *b* quantization. The sound samples have 186 *ms*. The results of the experiments shows that in noiseless environment the average sound recognition successfulness was 80% for sound of chainsaw. However, the results determine the need for a better extraction algorithm of peak frequencies to enlarge effectiveness. Miss recognition of sound in both environments was 0%. This fact indicates that sounds of forest do not affects sound recognition algorithm.

4.3. Energy consumption

Effective energy management is an important aspect of designing WSN. There are many factors influencing total energy consumption of the system. Apart from total energy consumption, the way and homogeneity of energy consumption is also essential. The techniques for optimization of energy management include estimation of energy consumption and proper selection of batteries, energy scavenging, software optimization, employing of low-power modes, communication protocol optimization and energy-efficient routing.

ZigBee communication protocol itself is focused on using as little energy as possible. While designing the sensor nodes and routers hardware and software we have focused on software optimization (e.g. employing of low-power modes, beacon-enabled communication network with relatively long inactive periods, low complexity Fourier transform and sound recognition algorithm), hardware optimization (e.g. the optimized design, the use of components with very low energy consumption).

The most energy demanding of the mentioned tasks is the Fourier Transform and NPDR algorithm, as it requires relatively difficult computations and needs to access the memory excessively. Fourier Transform of 32 *KiB* of data at 2 MHz frequency lasts about 5 *s*. Capture of sound sample adds another 1 *s* to computation length. The transmission of data as large as 4 KiB using ZigBee protocol can be done within several seconds (considering 20kbps raw bit rate). Other source of high energy drain is possible need of retransmissions. This is countered by the use of beacon-enabled network, where each sensor has its own assigned time-slot when the communication from sensor to router occurs and by this mechanism the occurrence of collisions is markedly decreased.

M. N. Halgamuge, M. Zukerman, and K. Ramamohanarao, “AN ESTIMATION OF SENSOR ENERGY CONSUMP- TION” Progress In Electromagnetics Research B, Vol. 12, 259–295, 2009

The maximum battery size depends on the needs of the system’s camouflaging and .

5. CONCLUSIONS

This paper has proposed an original approach to online forest monitoring in order to detect logging activities. We have designed a system consisting of a heterogeneous sensor network and a web application capable of presenting the gathered data to the user in a convenient way. A prototype of the proposed system has been implemented and several experiments have been performed.

The experiments show that the proposed wireless sensor network is capable of communication in reasonable distances that correspond with the need of sensor placement in order to obtain sound samples. We have further assured that the proposed method of sound recognition (NDPR) is suitable for our application both in means of accuracy and needed computational power. The performed measurements of the devices power consumption indicate that the proposed devices are capable of continuous operation for the period measured in order of months or years where the choice of a battery to be used is a constraining factor.

The proposed system has a great potential especially for monitoring the particularly important and critical forest areas, with the requirement of fast action. In such a way, it could be used for monitoring nature reservations and protected areas. The system can also find its utilization in protecting the private forested acres. The system can be also deployed in large forest areas particularly liable to illegal logging activities but according to its initial and maintenance cost, it is considerable to lay out the sensors only in strategically important areas (forest peripheries, access paths, attractive locations etc.).

The main advantages of the proposed system are its accuracy, reaction time, modularity and reliable communication up to hundred meters. Furthermore, providing information about the scale of logging activities to the public would certainly improve the public knowledge of the illegal logging problem.

The system has been designed in modular way so it offers rich possibilities of upgrade and modification. The stored samples can be changed or updated – by this we can adjust the system to recognize also other sounds from the environment (e.g. motor vehicles, certain agreed emergency signals, animal sounds etc.). The firmware of the routers can be upgraded remotely, e.g. to update the reference sound sample database or modify the sound recognition algorithm. This way, the existing and deployed system can be fully modified and used for other purposes when needed.

The network has been designed in a way which enables adding also other sensor devices to the system – for example a sensor device that measures wind speed, sun intensity or other environment characteristics. In such way, the existing system could be modified to serve several purposes at once, by adding new hardware devices to the system.

The prototyping process showed that the proposed system concept is suitable for the considered application. In our further work, we plan to focus on improving the sound recognition successfulness, adjusting the system to the outdoor environment and deploying it for long term experimental operation.

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