Area-based environmental noise measurements with a wireless sensor network

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Summary
Environmental noise levels have created major environmental problems, and millions of people suffer from the effects of exposition to them on a daily basis. Traditionally, noise models are calculated by characterizing several points but in a way that characterizes one point in one time interval. Due to this, the measurement results could be affected by time-dependent parameters like source emissions and weather conditions, leading to a set of single values from different locations at different time periods. Wireless sensor networks can be used to perform environmental monitoring for variously shaped and sized areas in different surroundings. In this paper, we present a wireless noise sensor network for new area-based noise monitoring. The network enables synchronized measurements in several locations in real-time. In this area-based noise monitoring, the network calculates one equivalent noise value for the monitored area. The measurement method's feasibility and reliability is evaluated in a real measuring pilot that involves 12 noise sensor nodes. The experience gained from the utilization and deployment of the network is discussed together with network performance analysis.

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1. Introduction

Environmental noise has been regarded as one of the big issues of environmental pollution [3]. Several recent studies have shown that this unwanted and harmful outdoor sound has clear effects on working and living comfort. Millions of people are suffering from too noisy environments worldwide [14][2]. Noise has also a direct effect on productivity, and the European Commission has classified environmental noise as one of the main environmental problems in Europe [3].

Traditionally, environmental noise characterization is based on local measurements or provisional calculations. For local measurements, sound level meters are used, and, for provisional calculation, sources of noise and terrain topography are defined and/or identified and entered into the calculation software, which then calculates a computational noise map of the area with the estimated noise levels. Noise map quality depends on the availability and quality of the information: noise sources (e.g. type of noises, noise level emissions), topography to generate the terrain model, ground characteristics, obstacles to noise propagation and weather conditions, among others. The noise maps' values are typically yearly averages, so they cannot distinguish short-term events when the noise may have exceeded the limitations or occasional noise spikes that may occur. Even a small change in road traffic conditions or changes in the environment or weather conditions can cause major changes in environmental noise conditions. To be able to notice these short-term changes, real-time observation of the noise measurements have a great importance.

Authorities and measurement agencies typically use commercial sound-level meters to carry out short routine noise measurements from one point at a time. Since these sound-level meters are relatively expensive (depending on their characteristics: the individual instruments costing between 500 - 30.000 euros) it is not ideal to leave them unattended for longer periods of time at multiple measurement locations. Therefore, these measurements almost always require an operator to do and supervise the measurement. Traditionally, spatial noise measurements are made to characterize several points but in a way that characterizes one point in one time interval. Due to this, the measurement results could be affected by time-dependent parameters like source emissions and weather conditions, leading to a set of single values from different locations at different time periods. As a consequence of the high costs involved, a representative measurement network would be impractical as well as prohibitively expensive. There is, therefore, an urgent need to complement existing noise monitoring methodologies with flexible and affordable alternatives, to improve monitoring capabilities for both scientific and legislative purposes, to allow source attribution, to improve understanding of health impacts of noise quality and mainly to protect people. Several studies have discussed alternatives to traditional fixed-site monitoring stations using participatory sensing or low-cost sensors [9, 10, 8, 7, 11, 12].

Another problem with the commonly used methods is the separation of various noise sources from each other. Public authorities should be able to distinguish the noise sources from each other without hesitation, so that, when the noise levels are exceeded, the noise source can be allocated to the correct operator. One disadvantage of the noise maps is that they do not give the true picture of the varying noise values over shorter time periods. One solution to overcome the issues of traditional noise measurement is to use measurements that use a different network-like approach to widen, synchronize and integrate the measurements.

Although the usage of WSN (Wireless Sensor Network) technology has grown in many application fields, measurement of environmental noise with WSN is not common. Compared to traditional noise-level measurements, WSN technology offers some important benefits: wide areas can be covered with battery-powered devices, the energy-efficiency of these devices makes long-term monitoring possible, and typically there is also real-time access to data. By using WSNs, measurements can be done without any other disturbance except that caused by the deployment of the network. Thus, the results would also be free from any external disturbance. With affordable components, WSN can be a cost-effective noise measurement system.

Kokkola is a small town on the western coast of Finland, and there are noise maps of the city's center. Environmental authorities of Kokkola are looking for a way to verify the noise maps. Because noise maps represent yearly averages, the authorities need a flexible and inexpensive method to measure noise over long periods. The measurements should be carried continuously from several days to 2-3 months. This local need and disadvantages associated with the traditional method gave us the motivation for the design and implement CiNetNoise - a wireless noise-sensor network, developed by Kokkola University Consortium Chydenius. Promising results of the developed noise sensor and reliable network performance are presented in [6, 5]. Noise measuring process in sensor nodes is energy-hungry due to active sampling and calculation tasks. To facilitate future long-term measurement, the area-based measurement method is presented in this paper.

The paper is organized as follows. First we overview some related research articles in which WSN-based systems have been proposed or applied for noise monitoring. In the second Section, the CiNetNoise wireless noise measurement system is described. The area-based measurement method is introduced in Section 3. The measurement pilot setup is described in Section 4, and the results of the pilot are presented in Section 5. As a conclusion, the experiences of the pilot are discussed briefly in Section 6.

2. Related work

Multiple WSN-based noise monitoring demonstrations has already been published. In this chapter, some of the latest developments are discussed. Authors in [12] propose a use of consumer-level microphones in environmental noise monitoring. The study shows that it is possible to identify cheap microphones that highly correlate to the reference microphone. The evaluation was conducted in a continuous half-year outdoor experiment.

In [11], authors present an energy-harvesting noise-sensing WSN mote. Because of the energy-hungry nature of noise sensing, the authors presented a concept of noise peak detection while node is being powered by energy harvesting. The node performance was tested and methods of energy charging discussed.

Authors in [8] introduce a mathematic algorithm for wireless sensor node. They mention that the perception of the noise can be very different from the value measured. Thus, they propose an algorithm that calculates the sound pressure level and a Fuzzy Noise Indicator. The results show the indication of annoyance is improved when using the Fuzzy Noise Indicator.

In [10], authors analyze a psychoacoustic model used for measuring noise annoyance. Even with similar values of Leq, people can experience the noise differently according to its frequency characteristics. The low-cost wireless acoustics network was used measure the annoyance, and hardware limitations were examined using TmoteInvent motes and Raspberry Pi platforms.

Authors in [1] present an overview of the current WSNs developed for environmental noise monitoring. Development approaches are evaluated in terms of several aspects: i.e. costs and reliability. They also present the TNO system, which is based on two types of nodes: a basic sensor node and an advanced sensor node, in a scalable architecture. The authors discuss automatic classification and accurate synchronization of sensor nodes.

In [13], authors present an environmental IoT (Internet of Things) application, a real-time noise simulation system for road traffic. The system based on neural network was trained using real sound levels. The sound levels were measured by using WSN technology.

The studies discussed above use different aspects of noise monitoring based on WSN technology. This paper deals with an area-based measurement method for a wireless noise-sensor network.

3. CiNetNoise - wireless noise sensor network

CiNetNoise is a wireless environmental noise monitoring system. It was developed in University of Jyvaskyla, Kokkola University Consortium Chydenius. At the beginning of the development, the following requirements were specified: 1) Sensor measuring range should be from 30-90 dBA, 2) operating time of the sensors should be from hours to several months, 3) measurements should be synchronized, 4) data should be available real-time, 5) and the system should be affordable.

By adopting these requirements, the goal was to develop an easily installable noise measurement system. The CinetNoise system consists of battery-powered wireless noise sensors, a gateway, and a backend server for storing and displaying real-time measurements in the website. The monitoring network will provide much more information about noise levels than a traditional handheld sound-level meter. The system is capable of measuring environmental noise from several places at the same time. The measurement of the noise values is done in real time, and the data visualization can immediately indicate some variations in the values. The system enables time-synchronized measurements at different areas, which can help to locate and recognize the noise sources. Expanding the measurement area is relatively easy. The network is self-organized, so new sensors can be added to the network automatically. A typical application scenario of the system can be seen in Figure 3. The system was designed to be an autonomous measurement system to enable long-term measurements with a minimum amount of maintenance. The system has been used in several different noise measurement applications from live concerts events to industrial activity monitoring. A typical measurement cluster consists of 12 sensor nodes together with a gateway node. The gateway node has an internal GPS, which provides accurate time to the network. It also has a 3G/GPRS modem or WiFi connection to transmit data to the backend server. The system can handle several synchronized measurement clusters, which can be located for example at the surroundings of a windmill or other noise source (see Fig. 3). The CinetNoise sensor node consists of a cheap (1 euro) electret microphone, amplifier+filter electronics, and Zigbit 900 wireless microcontroller module (Figure 1). The sensor has been calibrated and field-tested with a Pulsar model 94 Sound Level Meter (Class 2) [4]. The test and calibration report are available in [6]. The sensor node is powered by a battery pack (2 x 3.6V/8500mAh). The description of the network operations is described in [5]. The sensor module's performance is very reasonable, even when using an affordable microphone.

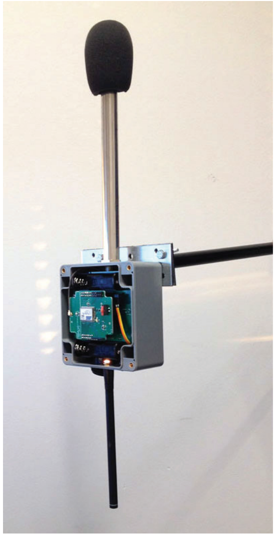

Figure 1. Noise node

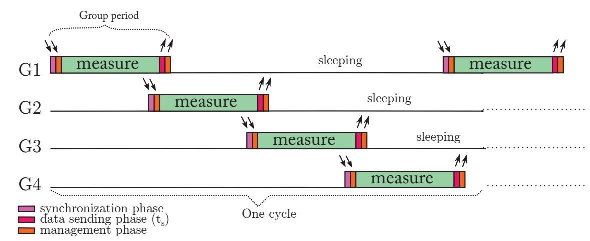

Figure 2. Scheduled group activity in area-based measurement.

4. Area-based measuring method

In this chapter, we introduce the area-based measuring method, which is based on the CinetNoise system. In this method, the measurement area is covered by several noise sensors. The measurements are combined to one area equivalent L_{Aeq} value. By default, the system measures noise continuously, which drains the batteries after one month. The area-based (scheduled) method can significantly increase the lifetime of the system.

When considering the use of the scheduled area-based method, one requirement has to be taken account. The measurement area distance from the main noise source has to be three times greater than the maximum distance between two sensor nodes in the

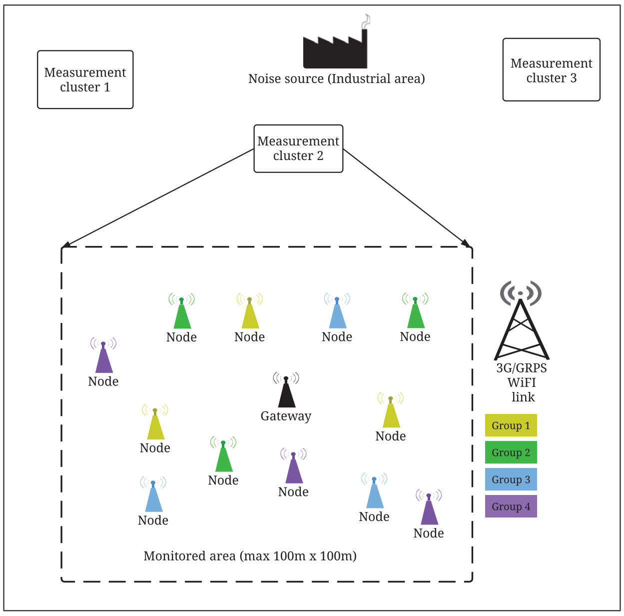

Figure 3. Typical application scenario in area-based measurement

measurement area. This prevents the readings of individual sensor nodes from affecting the calculation of the area L_{Aeq} value too much. The area-based method applies a scheduled measurement procedure. Instead of using individual noise sensors for continuous measurement, the network is divided into groups (see Fig. 3). The grouping is implemented by using a scheduling algorithm in the gateway, which is grouping the sensor nodes geometrically equal so that each group represents the measurement area as well as possible. Each group has its own color in the figure. A group typically contains 2-5 nodes which are measuring simultaneously when the group is active. Other groups are sleeping while one group is measuring (see Fig. 2). By using scheduled measurement in groups, longer measurement time can be achieved since battery life is extended. After the measuring period, each noise sensor will send the measurements to the gateway. The gateway will calculate the groups' equivalent noise level L_{Aeq}, maximum L_{Aeq_max} and minimum L_{Aeq_min}. The L_{Aeq} is calculated as a geometric group average and describes the average equivalent noise level of the measurement area. After the calculation, the gateway will transmit the values to the backend server. The server provides a website which shows current noise levels, graphs and other statistics.

The area-based measurement is applied in the measurement pilot, which is described in the next Section.

5. The measurement pilot

Environmental officials in Kokkola city have a need for a flexible and inexpensive method to monitor environmental noise over a period of a month. The city has a fresh noise map which was wanted to be verified using long-term measurements in a particular area of the city. The area-based measurement method was used to achieve a long enough measurement period. The accuracy of this method was also evaluated.

In this pilot, a school yard was chosen as the measurement place. The assumption was that its noise level is annoying, because it is next to the Port of Kokkola and nearby industrial area. Conducting measurements there was interesting both for the people and officials. The measurement cluster was installed to the school's playground. During the measurements, the school was closed, so the main noise source was the port and the industrial area.

The measurement cluster had 12 nodes, which were deployed to the area. The cluster was divided into four groups, each containing three nodes. Figure 5 shows the measurement sensor locations and the reference measurement l. The nodes were attached to trees with the help of bar and load straps. The measurement cluster was measuring two months (July - August) continuously without interruptions.

The reference measurements were conducted with one sensor node and two reference sound-level meters (Cirrus Optimus Red (CR:161C) and Pulsar Model 94). The node and the reference devices were installed next to each other (see Figure 4). Three independent reference measurements were carried out on 29th of June. The measurement positions can be seen in Figure 5. Each reference measurement was of 15 minutes duration, and the devices were measuring $L_{Aeq,1s}$ noise values.

During the reference measurements, the measurement cluster was measuring continuously $L_{Aeq,1min}$ values. It also reported maximum and minimum $L_{Aeq,1s}$ values together with $node_{id}$.

The goal of these measurements was not only to find out the accuracy of the area-based measuring method but also how well noise maps are corresponding to real measurement values.

6. Results

This chapter presents the reference measurement and the noise map verification results.

The calculated average errors compared to Cirrus are presented in Table I. The table contains average errors and standard deviation of errors from three measurements (meas. 1,2,3 indicated by the subscript added to the meter name). It can be seen that the average error is far below 1 dB in the sensor node in all time equivalents (L_{Aeq}). Pulsar (Class 2 meter) is about the same scale. The sensor node's maximum error is high in $L_{AEq,1min}$, but in the $L_{Aeq,15min}$ it is no more than 0.6dB. Moreover, it can be seen that devices' standard deviation of error are almost equivalent. Although the reference measurement had only one sensor node compared, it can be assumed that the

Figure 4. Node attachment and reference sound level meters

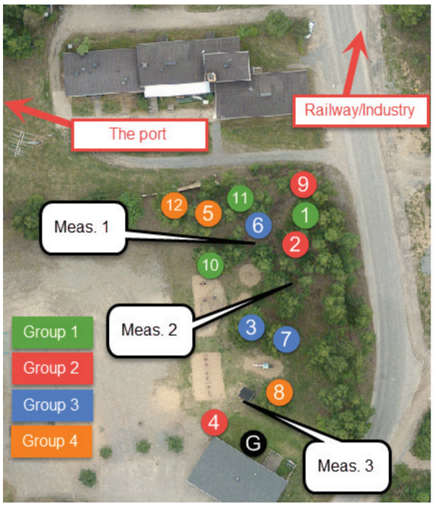

Figure 5. Network topology in pilot. Sensor nodes are numbered (G=Gateway).

accuracy is in the same scale in the calibrated sensor nodes of the measurement cluster. Figure 7 represents the $L_{Aeq,1min}$ levels of the reference measurement(meas. 2). It can be seen that the cluster level is lower than the other devices' level. The measurement cluster value is the aggregated value of multiple noise sensors, thus it can't be the same as that of the fixed point sound-level meter.

The measurement cluster values are compared to the noise model to find out how well the noise model is corresponding to real measurement data. Two months' equivalent day-night noise levels are shown together with the noise maps' day-night values in Figure 6. The noise map specifies the following levels for the area: $L_{Aeq,d}$>55dB, $L_{Aeq,n}$>50dB. It can be seen that there is only one minor crossing

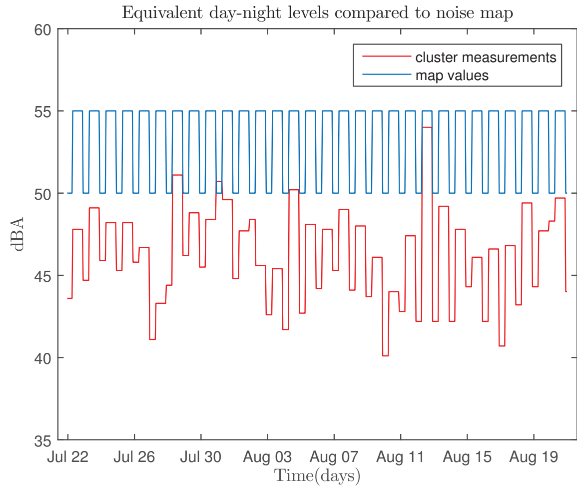

Figure 6. Day-night values compared to noise model

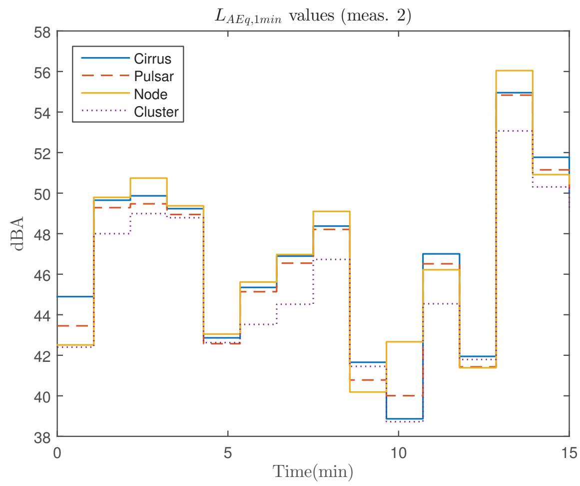

Figure 7. Example graph of the reference measurement (Meas. 2)

of night level (50dB). It appears that the actual measured noise level is much lower than the noise map defined for the area.

The measurement cluster provided also $L_{AEq,1s}$ values. The share of the peak values among the sensor nodes was distributed to the nodes (node/share) 5/24,1%, 6/24%, 9/25% and 11/25%. These values indicate that the main noise source is industry area/railway. Identification of the noise sources is one of the advantages of CinetNoise system. This information can't be retrieved when using hand-held sound level meter.

7. Conclusion

This paper presents the area-based measurement method for environmental noise monitoring. The accuracy of the CinetNoise system is evaluated by using

Table I. Calculated *average error*, *standard dev.*, *maximum error* (in dBA) and compared to Cirrus L_{Aeq} values. Subscript in device names indicates the measurement number.

	avg error	*std*	*max error*	*avg error*	*std*	*max error*	*error*
$Pulsar_1$	0.4	0.1	0.6	0.4	0.1	0.5	0.5
$Node_1$	0.7	1.1	4.3	0.5	0.5	1.2	-0.5
$Cluster_1$	0.6	0.6	1.9	0.6	0.3	1.0	-0.7
$Pulsar_2$	0.5	0.4	1.4	0.3	0.1	0.4	0.3
$Node_2$	0.9	1.0	3.8	0.5	0.3	0.8	-0.4
$Cluster_2$	1.2	0.9	2.5	1.4	0.2	1.7	1.4
$Pulsar_3$	0.3	0.2	0.7	0.2	0.1	0.3	0.2
$Node_3$	0.4	0.6	2.1	0.5	0.2	0.7	-0.6
$Cluster_3$	1.3	1.4	5.6	1.0	0.2	1.2	0.9

two commercial sound-level meters as reference. Both individual sensor-node and cluster readings are in satisfying accuracy, taking into account the low-cost microphone used in sensor nodes. Long-term measurements indicate that day/night values computed by noise model are different from the actual measurements. The area-based measurement method offers a flexible way to conduct noise monitoring. The measurement cluster operated successfully over two months without any interruptions and data was available real-time. In addition to the noise levels the measurement network provides, it can also tell the direction of the main noise source.

References

[1] T. Basten and P. Wessels. An overview of sensor networks for environmental noise monitoring. In *The 21st International Congress on Sound and Vibration on Sound and Vibration, Beijing/China*, July 2014.

[2] European Commission. Green paper on future noise policy. com (96) 540 final. Official Journal of the European Communities, November 1996.

[3] European Commission. Directive 2002/49/ec of the european parliament and of the council of 25 june 2002 relating to the assessment and management of environmental noise. Official Journal of the European Communities, 07 2002.

[4] Ismo Hakala, Ilkka Kivela, Jukka Ihalainen, Jari Luomala, and Chao Gao. Design of low-cost noise measurement sensor network: Sensor function design. In *Proc. of The First International Conference on Sensor Device Technologies and Applications (SENSORDEVICES 2010)*, July 2010.

[5] I. Kivelä, C. Gao, J. Luomala, and Hakala I. Design of noise measurement sensor network: Networking and communication part. In Laurent Gomez ja Yenumula Reddy Jens Martin Hovem, Joshua Ellul, editor, *Proceeding Of The Fifth International Conference On Sensor Technologies And Applications (SENSORCOMM2011)*, pages 280–287, Chatham, 2011. Xpert Publishing Services.

[6] I. Kivelä, C. Gao, J. Luomala, J. Ihalainen, and Hakala I. Design of networked low-cost wireless noise measurement sensor. *Sensors & Transducers Journal*, Vol. 10:171–190, 2010.

[7] Nicolas Maisonneuve, Matthias Stevens, and Bartek Ochab. Participatory noise pollution monitoring using mobile phones. *Info. Pol.*, 15(1,2):51–71, April 2010.

[8] J.A. Mariscal-Ramirez, J.A. Fernandez-Prieto, M.A. Gadeo-Martos, and J. Canada-Bago. Knowledge-based wireless sensors using sound pressure level for noise pollution monitoring. In *Intelligent Systems Design and Applications (ISDA), 2011 11th International Conference on*, pages 1032–1037, Nov 2011.

[9] Silvia Santini, Benedikt Ostermaier, and Andrea Vitaletti. First experiences using wireless sensor networks for noise pollution monitoring. In *REALWSN '08: Proceedings of the workshop on Real-world wireless sensor networks*, pages 61–65, New York, NY, USA, 2008. ACM.

[10] J. Segura-Garcia, S. Felici-Castell, J.J. Perez-Solano, M. Cobos, and J.M. Navarro. Low-cost alternatives for urban noise nuisance monitoring using wireless sensor networks. *Sensors Journal, IEEE*, 15(2):836–844, Feb 2015.

[11] Wilson Tan and Stephen Jarvis. On the design of an energy-harvesting noise-sensing wsn mote. *EURASIP Journal on Wireless Communications and Networking*, 2014(1):167, 2014.

[12] Timothy Van Renterghem, Pieter Thomas, Frederico Dominguez, Samuel Dauwe, Abdellah Touhafi, Bart Dhoedt, and Dick Botteldooren. On the ability of consumer electronics microphones for environmental noise monitoring. *J. Environ. Monit.*, 13:544–552, 2011.

[13] Cuiping Wang, Guoqiang Chen, Rencai Dong, and Haowei Wang. Traffic noise monitoring and simulation research in xiamen city based on the environmental internet of things. *International Journal of Sustainable Development & World Ecology*, 20(3):248–253, 2013.

[14] World Health Organization. Occupational and community noise. Fact sheets, 02 2001.