Wireless Sensor Networks for Environmental Noise Monitoring

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ABSTRACT

While environmental issues keep gaining increasing attention from the public opinion and policy makers, several experiments demonstrated the feasibility of wireless sensor networks to be used in a large variety of environmental monitoring applications. Focusing on the assessment of environmental noise pollution in urban areas, we provide qualitative considerations and preliminary experimental results that motivate and encourage the use of wireless sensor networks in this context.

Keywords

Wireless sensor networks, environmental noise, noise indicators

1. INTRODUCTION

In 1996, the European Community estimated in about 80 millions the number of its citizens that were exposed to unacceptable levels of environmental noise, while another 170 millions suffered serious annoyances from high noise pollution during daytime [2]. Directive 2002/49/EC of the European Parliament has since made the avoidance, prevention, and reduction of environmental noise a prime issue in European policy, requiring member states to firstly determine the exposure of its citizens to environmental noise, and secondly, to ensure that information on environmental noise and its effects is made available to the public [1].

According to the directive, Member States are required to provide an accurate mapping of environmental noise exposure in urban areas like public parks, schools, hospitals, and other noise-sensitive zones, starting from June 2007. While current noise maps are mostly based on sparse data and ad-hoc noise propagation models, a recent position paper by the Commission [6] has stressed that *“every effort should be made to obtain accurate real data on noise sources,”* since *“detailed noise modelling/mapping and noise exposure assessment may have to be undertaken in order to produce detailed local action plans.”* The demand for accurate data about noise exposure levels will likely increase dramatically, as this statement makes its way into mandatory regulation. We believe that wireless sensor networks will be able to satisfy this demand by providing noise measurements with an accuracy and cost-efficiency that current noise assessment procedures cannot afford.

Wireless sensor networks have already been used in a large variety of environmental monitoring applications, e.g., to monitor bird habitats and habits [8, 11], to investigate the growth model of redwood trees [5], or to study the influence of environmental parameters on the quality of agricultural products [9]. Wireless sensor networks also allow monitoring pollution parameters in urban areas at an accuracy and scale that were previously unreachable, e.g., within the CitySense[1] testbed, which plans to use a fixed network of 100 line-powered wireless sensors to collect fine-grained air pollution data and deliver it in real-time to the users. To the best of our knowledge, however, wireless sensor networks have so far not been used to perform fine-grained measurements of noise pollution levels.

This article presents a preliminary assessment for using wireless sensor nodes to measure noise exposure levels in urban settings. After briefly summarizing today’s environmental noise assessment procedures, we give an overview of the various quantities involved in measuring environmental noise. We close with initial experimental results of using a sensor node to compute these quantities.

2. NOISE POLLUTION ASSESSMENT TODAY

Today’s noise measurements in urban areas are mainly carried out by designated officers that collect data in a location of interest for successive analysis and storage, using a sound level meter or similar device. This manual collection method using expensive equipment does not scale as the demand for higher granularity of noise measurements in both time and space increases. Instead, a network of cheap wireless sensor nodes deployed over the area of interest could collect noise pollution data over long periods of time, and autonomously report it to a central server though the sensor’s on-board radio, requiring human intervention only to install and subsequently remove the sensing devices. Moreover, since sensor nodes are typically equipped with several different sensors, they can label the collected noise data with additional information like, e.g., the temperature and humidity values registered as the noise measurements were collected. This information must indeed be provided for any properly collected set of noise exposure data, along with other meteorological parameters like wind speed and direction.

Collected noise data is typically stored in a land register and used, together with additional information about exist-

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[1] http://www.citysense.net/

ing noise sources, to feed computational models that provide extrapolated noise exposure levels for those areas for which real data is unavailable. Even if this assessment procedure is still compliant with European regulations, today's computational models often fail to provide accurate estimations of the real noise pollution levels[2]. Indeed, while the free propagation properties of noise generated from typical noise sources[3] are well understood, shadowing and reflection effects hinder accurate estimation of noise levels in complex urban settings. For instance, estimated noise levels on internal buildings façades (e.g., facing a courtyard) are typically unreliable, and this inaccuracy may become critical if noise exposure data is used to drive decisions about construction planning or to elaborate local noise abatement policies. The accuracy of estimated noise levels could be easily verified and improved by installing a wireless sensor network at those locations for which computational models are likely to provide inaccurate estimations. In these settings, noise assessment points must be closely spaced (about every 2 to 3 meters), and measurements should be taken simultaneously at all assessment points in the presence of sound from a noise source. While this distributed sensing setup is extremely hard to realize with current measurement procedures, it is a "natural" setup for wireless sensor networks.

Wireless sensor networks may bring significant improvements also in the assessment of noise pollution due to vehicular traffic on urban roads. The current procedure requires estimating, for several different vehicle classes, the average number of units passing-by at daytime, evening and night and the average noise level for each vehicle pass-by [4]. This estimation is either performed through computation, with the drawbacks and problems outlined above, or it is performed manually, i.e., by a designated officer standing nearby the road and annotating the type and number of vehicles passing-by. Wireless sensor networks have already proved their ability to detect and classify vehicles [3] and could therefore be used in this context to automate the vehicle counting procedure and, at the same time, record the corresponding noise levels.

3. MEASURING NOISE

Acoustic waves are pressure fluctuations, usually caused by a solid vibrating surface, that propagate through an appropriate medium like air or water. Sound is the sensation induced at the human ear by incident acoustic waves that are captured and converted into neurological stimuli by the hearing system. Similarly, a microphone converts pressure fluctuations into an equivalent electrical signal, that can be post-processed to compute the loudness of the noise source that generated the acoustic wave. Average loudness levels over long periods of time are commonly used as *noise indicators*. For instance, the European directive 2002/49/EC requires Member States to apply the L_{den} and L_{night} indicators for the preparation and revision of strategic noise mapping [1]. Before getting to the formal definition of these indicators, we need to explain how the equivalent sound pressure level of a noise source can be computed from the output signal of a microphone [4].

The instantaneous sound pressure level (SPL) of a sound is usually expressed in logarithmic units with respect to a given reference pressure level and is computed according to the following equation:

$$L_p(t) = 10\log_{10}\frac{p(t)^2}{p_{ref}^2} = 10\log_{10}p(t)^2 - 10\log_{10}p_{ref}^2 \quad \text{(dB)} \tag{1}$$

in which $p(t)$ represents the instantaneous pressure of an acoustic wave impinging the membrane of the microphone. The standard reference pressure p_{ref} is $20\mu Pa$ and conventionally represents the minimum audible sound. Substituting this value into equation 1, one obtains:

$$L_p(t) = 10\log_{10}p(t)^2 + 94 \quad \text{(dB)}. \tag{2}$$

If $E(t)$ is the microphone output voltage induced by an incident acoustic wave $p(t)$, equation 2 may be rewritten as:

$$L_p(t) = 10\log_{10}E(t)^2 + 94 - S \quad \text{(dB)} \tag{3}$$

The sensitivity S of the microphone that appears in equation 3 defines how the microphone responds to a certain pressure input and is typically expressed in decibel with respect to a reference level. The following equation holds for the sensitivity S of a microphone:

$$S = 20\log_{10}\frac{Ep_0}{E_{ref}p} \quad \text{(dB)} \tag{4}$$

It is common practice to set $E_{ref} = 1V$ and $p_0 = 1Pa$ and thus to express the sensitivity as a (negative) value with respect to the reference value: 0 dB = 1V/Pa.

Since noise typically fluctuates significantly even over short periods of time, the instantaneous sound pressure level as defined in 3 is of little practical relevance. The loudness of a given noise source is therefore better represented by the average of the time-varying sound pressure level $L_p(t)$ over a given period of time T:

$$L_{eq} = \frac{1}{T}\int_0^T 10^{\frac{L_p(t)}{10}}dt \quad \text{(dB)} \tag{5}$$

The equivalent sound level pressure L_{eq} defined above is the quantity that is typically measured by a sound level meter and that drives the computation of most commonly used noise indicators. For instance, the L_{day}, $L_{evening}$ and L_{night} noise indicators are the equivalent sound levels averaged over day, evening and night periods[4]. The L_{den} (day-evening-

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[2] The authors are indebted to Hans Huber and Fridolin Keller of the department for environmental noise protection of the city of Zurich, who pointed this out in a personal in-depth interview.

[3] Typical noise sources are, e.g., human activities, motor vehicles, railways, aircrafts or industrial machinery.

[4] Accurate definition of these indicators is provided in ISO

night) level is accordingly defined as:

$$L_{den} = 10\log_{10}\left[\frac{1}{24}\left(12\cdot 10^{\frac{L_d}{10}} + 4\cdot 10^{\frac{L_e+5}{10}} + 8\cdot 10^{\frac{L_n+10}{10}}\right)\right] \tag{6}$$

where we abbreviated L_{day}, $L_{evening}$ and L_{night} to L_d, L_e and L_n, respectively[5]. For the purpose of noise mapping, Member States of the European Community must provide noise pollution data in terms of the L_{den} and L_{night} indicators [1].

Even if there are several different standard procedures for the computation of the above defined noise indicators, a few important issues like, e.g., the spatial distribution of the measurement points or the necessary acoustic data processing, must always be carefully considered when measuring sound pressure levels. Indeed, since the human ear does not respond equally to all the frequencies in the audible range, measured sound levels must be adequately weighted (in the frequency domain) to take into account this selective behavior of the human hearing system. Among the available standard weighting methods the European regulation requires the use of the A-weighting function, originally defined in [7] and then adopted in numerous international standards. Even if A-weighting should better be performed using an analog filter before sampling, digital post-sampling filtering is also tolerated, even if typically less accurate. The A-weighted sound level pressures and noise indicators are indicated in A-weighted decibels or dB(A).

When assessing noise indicators, the location of the measuring devices must follow clearly defined rules [1, 6]. In particular, for the purpose of noise mapping near to buildings, the assessment points must be 4.0 ± 0.2 m above the ground and at the most exposed façade. If necessary, other heights may be used but they shall never be less than $1,5$ m above the ground, and results should be corrected in accordance with an equivalent height of 4 m. This requirement assumes particular importance since it disqualifies portable hand-held devices like mobile phones to be used for noise pollution measurements.

4. PRELIMINARY RESULTS

To be used as noise pollution sensing devices, wireless sensor nodes must be able to compute the noise indicators defined in the previous section. We therefore performed a preliminary study to understand the feasibility of currently available sensor networks platforms to compute such indicators. We used the Tmote Sky prototyping platform[6], equipped with the SBT80 multi-modality sensor board available from EasySen[7]. This sensor board features, among other sensors, the EM6050P-423 omni directional condenser microphone, which we used to capture audio signals from the environment. The output voltage of the microphone is quantized using the Tmote Sky's 12 bits analog to digital converter (ADC). The voltage levels recorded by the microphone may be reconstructed from the ADC samples using the simple formula: $E = \frac{E_{ADC}}{4096} \cdot V_{ref}$, where V_{ref} is set to 2.5V for the Easysen sensor board and E_{ADC} are the ADC samples. Figure 1 reports the (A-weighted) voltage response of the microphone to a synthetically generated 250Hz sine wave stimulus, whose amplitude has been progressively increased to bring the microphone to saturation. The raw signal samples, read from the ADC at a a 2kHz rate, has been sent from the node to the pc through the serial port. We post-processed the data in Matlab to compute the A-weighted equivalent SPL, which is 90 dB(A).

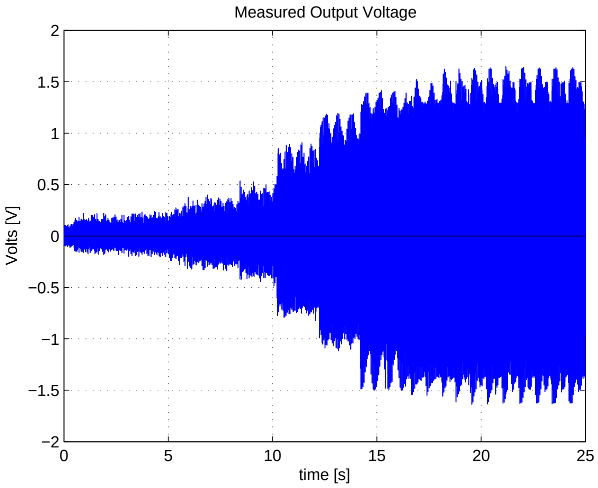

Figure 1: Microphone response to a 250Hz sine wave stimulus of increasing amplitude.

The first consideration we can derive by observing the sample data in figure 1 is the high level of background noise. The EM6050P-423 has indeed a self-noise level of 54 dB(A) SPL[8], which makes sounds corresponding to SPL levels below 54 dB(A) to be indistinguishable from electrical background noise[9]. Since this high level of background noise seriously limits the applicability of the EM6050P-423 for our purposes, we are considering using alternative acoustic sensors like e.g., the Tmote Invent[10] on-board microphone or a custom made sound level meter. The EM6050P-423 has indeed further suboptimal characteristics. First, its frequency response start deviating from linearity already at 5kHz and distorts significantly harmonic components above 10 kHz. Second, the EM6050P-423 datasheet does not report the maximum SPL the microphone can measure without significant total harmonic distortion (THD). This parameter is nevertheless necessary to define the upper bound of the dynamic range of the microphone and without a specification it is unclear up to which SPL level the microphone may

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1996-1:2003 (that very recently replaced the currently withdrawn ISO 1996-2:1987 standard).

[5] L_{den}, L_d, L_e and L_n are all expressed in dB.

[6] www.moteiv.com

[7] www.easysen.com

[8] The self-noise (or equivalent noise) level may be computed subtracting the nominal signal to noise ratio (S/N) from the reference sound pressure level of 94dB. For the EM6050P-423 the S/N is 40 dB.

[9] 54 dB(A) is the SPL level that corresponds to the noise produced during a normal conversation taking place at about 1 m distance from the microphone.

[10] www.moteiv.com

provide a reliable response.

Besides the electrical and acoustic characteristics of the microphone there are other issues influencing the quality of the performed noise measurements like the rate at which voltage samples are read from the ADC. Since the human ear can only perceive acoustic waves whose frequencies range from 20 Hz to 20 kHz, sampling the output signal of a microphone must occur at at least 40 kHz [4,10]. In the context of noise pollution measurements this sampling frequency may be reduced 32 kHz since the hearing system of adult humans cannot perceive frequencies above 16 kHz [4, 8]. Nevertheless, this sampling rate seems prohibitively high for sensor network platforms, which typically rely only on limited computational resources. However, as long as no radio communication is involved, the Tmote Sky is able to support the required sampling rate. Since noise indicators are are long-term SPL averages, transmitting raw data back to a central sensor is not necessary as the aggregated noise indicators are of interest and not the time-varying pressure levels. Furthermore, sensor nodes must not necessarily continuously sample the acoustic levels, but they can apply intelligent data collection techniques to estimate noise indicators in accordance to pre-specified accuracy requirements. Limiting radio communication and data acquisition, the power consumption of the sensor nodes can be adequately controlled to allow long-term, unattended network operation.

In order to rapidly get first quantitative data we neglected calibration issues, that should otherwise be considered carefully. Sensor nodes needs indeed to be opportunely calibrated in order to be used as noise pollution sensors. The calibration procedure may be carried out using a pistonphone, i.e., a device that generates (in anechoic conditions), well-defined sound pressure levels. Measuring discrepancies between the effective microphone response and the expected (ideal) response would allow to adequately tune individual sensor nodes gains to make them provide reliable SPL measurements. Furthermore, in-network calibration methods could be investigated to ensure long-term correct network operation.

Even if the way to the first "wireless noise sensing network“ must still pass through several important milestones, the considerations and the preliminary results reported in this paper show that using wireless sensor networks for environmental noise monitoring is not only technically possible, but would also bring significant advantages with respect to the current assessment procedures. We will therefore concentrate our future work in building a reliable hardware/software prototype, and in testing it extensively in the real, noisy world.

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