# Low-Cost Alternatives for Urban Noise Nuisance Monitoring Using Wireless Sensor Networks

**Article** *in* IEEE Sensors Journal · September 2014

DOI: 10.1109/JSEN.2014.2356342

Jaume Segura Garcia
University of Valencia
**160** PUBLICATIONS **1,078** CITATIONS

Santiago Felici-Castell
University of Valencia
**93** PUBLICATIONS **854** CITATIONS

J.J. Perez-Solano
University of Valencia
**64** PUBLICATIONS **875** CITATIONS

Juan Miguel Navarro
Saint Anthony Catholic University
**53** PUBLICATIONS **682** CITATIONS

# Low-Cost Alternatives for Urban Noise Nuisance Monitoring using Wireless Sensor Networks

Jaume Segura-Garcia, Santiago Felici-Castell, Juan J. Perez-Solano, Maximo Cobos, *Senior, IEEE,*
Juan M. Navarro

***Abstract*—Noise pollution caused by vehicular traffic is a common problem in urban environments that has been shown to affect people's health and children's cognition. In the last decade, several studies have been conducted to assess this noise, by measuring the equivalent noise pressure level (called $L_{eq}$) to acquite an accurate sound map using wireless networks with acoustic sensors. However, even with similar values of $L_{eq}$, people can feel the noise differently according to its frequency characteristics. Thus, indexes which can express people's feelings by subjective measures are required. In this paper we analyze the suitability of using the psycho-acoustic metrics given by the Zwicker's model, instead of just only considering $L_{eq}$. The goal is to evaluate the hardware limitations of a low-cost wireless acoustic sensor network that is used to measure the annoyance, using two types of commercial and off-the shelf sensor nodes, Tmote-Invent nodes and Raspberry Pi platforms. Moreover, to calculate the parameters using these platforms, different simplifications to the Zwicker's model based on the specific features of road traffic noise are proposed. To validate the different alternatives, the aforementioned nodes are tested in a traffic congested area of Valencia City in a vertical and horizontal network deployment. Based on the results, it is observed that the Raspberry Pi platforms are a feasible low-cost alternative to increase the spatial-temporal resolution, while Tmote-Invent nodes do not confirm their suitablity due to their limited memory and calibration issues.**

***Index Terms*—Nuisance monitoring, wireless acoustic sensor network, psycho-acoustic, road traffic, low-cost, real deployment**

## I. INTRODUCTION

Noise pollution is a common problem in urban environments, affecting human behavior, health and even children's cognition. Recognizing this as a major issue, the European Commission adopted a directive [1], requiring main cities (with more than 250.000 inhabitants) to gather real world data on noise exposure in order to produce local action plans and to provide accurate mappings of noise pollution levels. Several cities around the world provide these kinds of noise maps such as New York [2], London [3], Munich [4], Beijing [5].

The traditional way of conducting noise measurements is by collecting noise samples manually, but this technique has many drawbacks. On the one hand, only local and sparse measurements are taken. On the other hand, it is expensive due to the measuring equipment and personnel costs. From these measurements and by using numerical tools and propagation models, noise maps are estimated [6]. However, the European Commission recommends for higher granularity of noise data both in space and time. In this scenario, Wireless Sensor Networks (WSN) represent an alternative that can overcome the drawbacks of the current noise data collection procedure.

WSNs are wireless networks of small autonomous nodes with sensing capabilities. Each node has its own power supply, processing unit and memory. The nodes communicate using multi-hop routing protocols and at least one node (called *sink*) acts as a gateway for external connection. Nevertheless, these networks and their applications are still far from being mature, due to the constraints on resources such as energy, memory, computational speed and communications bandwidth. In the last decade, several studies have been conducted using WSN for noise pollution monitoring as shown in Section II. All of these studies are based on the equivalent sound pressure level over time $T$ (denoted by $L_{eq,T}$ [7]). Although these measurements provide sufficient information about the noise level, they fail to provide enough information related to the subjective annoyance [8].

The goal of this paper is to analyze the suitability of different low-cost hardware alternatives for measuring the psycho-acoustic metrics according to the Zwicker's annoyance model [9] applied to road traffic, as a further step towards the smart cities. To this end, low cost WSNs using commercial and off-the-shelf sensor nodes are considered, in particular Tmote-Invent (TmI) motes and Raspberry Pi (RPi) platforms. This model measures the Nuisance (N) based on other parameters which are: Loudness (L), Sharpness (S), Roughness (R) and Fluctuation Strength (F). The computation of these parameters requires a costly signal processing stage for these nodes and therefore we propose different simplifications to approximate these parameters by taking into account the features of road traffic noise, such as the dynamic range in the acquisition step (bits per sample), the sampling frequency and the number of critical bands used within the model, as explained in Section III. The nodes sample the noise, estimate N (measuring L, S, R and F) and finally send the results in a data packet to the *sink* through the multihop network. To the best of our knowledge, WSNs have not been used before to perform dense and distributed spatial-temporal noise pollution measurements based on the mentioned psycho-acoustic metrics.

The rest of the paper is structured as follows. Section II discusses the related work. Section III expounds the Zwicker's annoyance model applied to the assessment of the nuisance from road traffic noise. Section IV describes the proposed

This work was supported by the Spanish Ministry of Economy and Competitiveness and FEDER under project TEC2012-37945-C02-02.

J.Segura-Garcia, S.Felici-Castell, J.J. Perez-Solano, M.Cobos are with School of Technical Engineering, University of Valencia, Burjassot, Spain (email: felici@uv.es).

J.M.Navarro is with Grupo de Telecomunicaciones Avanzadas, Universidad Catolica San Antonio de Murcia, Spain.

alternatives based on the TmI and RPi platforms. Section V exhibits the results obtained from the different experiments. Section VI concludes the paper.

## II. RELATED WORK

Road traffic noise and subjective annoyance has been studied in [10]. The authors provide a review of the annoyance from the road traffic noise and analyze its main features and frequency spectrum (between 20 Hz and 8 kHz). The authors measure the annoyance using two different methods, the first is by the means of manual surveys to the citizens, while the second is by using the day-night average sound level to estimate the percentage of highly annoyed from the psychological point of view. In [11], the Zwicker's annoyance model [9] is used for soundscape categorization to determine how an acoustic environment sounds like, using manually collected noise samples. Further details about the subjective annoyance can be found in Section III.

Several works have already considered the use of Wireless Acoustic Sensor Networks (WASN) for noise monitoring. In [12] and [13], the authors evaluate a WASN based on two different motes, Tmote-Sky [14] and TmI, to monitor road traffic noise measured by the $L_{eq,T}$ [7] with 8 kHz sampling frequency and for counting the number and type of vehicles. They conclude that the Tmote-Sky has excessive self-noise and the TmI (with on-board microphone) has apparently good audio features. In these references, the authors do not provide any calibration. In [15] and [16] show a WASN deployed in Ostrobothnia (Finland), reporting different tests to evaluate the noise impact. The authors measure the $L_{eq,T}$ with $T = 125ms$ using a sampling frequency of 33 kHz, with 14 calibrated motes (MicaZ from Crossbow/MEMSIC with an adhoc acquisition circuitry to allow a dynamic range of 60 dB), globally synchronized during 96 hours with good results.

Other references such as [17], [18] and [19] use the mobile phones for noise pollution monitoring. Although the results are interesting, in our opinion the lack of information about the recording conditions prevents getting accurate noise measurements. When assessing noise indicators, the location of the measuring devices must follow defined rules [1].

In the previous references [12] - [19], the measurements are based on the $L_{eq,T}$, even with the A-weighting filter (ITU-R 468) with $L_{eqA,T}$, that is a frequency-selective filter picking up the frequency range around 3-6 kHz, to which the human ear is most sensitive. These parameters are measured in dB and dBA respectively. Nevertheless, these parameters do not provide information about the subjective annoyance from the point of view of human perception [8][9][11].

## III. PSYCHOACOUSTIC METRICS AND URBAN NOISE ANALYSIS

Psycho-acoustic metrics are an alternative to express people's feelings by subjective measures rather than $L_{eq,T}$ [7]. In this section, we describe the Zwicker's annoyance model [9] applied to road traffic by measuring N, S, L, R and F. Also, we check this model with different sound sources for testing purpose and perform a statistical analysis using correlation techniques with the $L_{eq,T}$ measurements.

### A. *Zwicker's Psychoacoustic Model*

This model is based on the anatomy of the human hearing. When complex sounds are being considered the frequency spectrum of the psycho-acoustic metrics is made in terms of Critical Bands (CB) [20], that refers to the frequency bandwidth of the *auditory filter* created by the *cochlea*, the sense organ of hearing within the inner ear. The human hearing combines the sound stimuli which are situated in close proximity of each other in terms of frequency into particular CB. When serializing these CBs, a frequency scale is created, called the CB rate scale and measured in the unit *Bark*. In [9], this is defined as a mapping from the physical frequency scale to the CB rate scale (or *Bark* scale) from 1 to 24.

Table I summarizes the numerical expressions used to estimate the different parameters defined to measure N, L, S, R and F [9]. The signal processing that these parameters require is out of the scope of this paper. These parameters are measured using different temporal window sizes over the audio signal. The definitions of these parameters are as follows:

- Nuisance (N) is a perceptual attribute that allows an objective quantification from the physical characteristics of the signal, based on the mean values of L, S, R and F
- Loudness (L) is the value that deals with the sound volume (intensity sensations), measured in *Sones* with a linear scale. It is standardized in ISO 532B. The process used to calculate L is based on the Specific Loudness ($L'(z)$ or L contribution for each CB, where $z$ identifies the CB number), measured in *Sone/Bark*. The total $L$ is the result of the different contributions. $\Delta z$ is the bandwidth of each *Bark*
- Sharpness (S) is a value of sensory human perception of unpleasantness in sounds that is caused by high frequency components. It is measured in *Aures* in a linear scale
- R describes the perception of the sound fluctuation even when L or $L_{eq,T}$ remains unchanged. It analyzes the effects with different degrees of frequency modulations (around 70Hz) in each CB. The basic unit for R is *Asper*. For each *Bark*, $f_{mod}(z)$ is the modulation frequency (estimated analyzing the frequency response) and $\Delta L_E(z) = 20 \cdot log(\frac{L'_{max}(z)}{L'_{min}(z)})$, where $L'_{max}(z)$ and $L'_{min}(z)$ are the maximum and minimum values of $L'(z)$
- Fluctuation Strength (F) describes how strongly or weakly sounds fluctuate. It depends on the frequency and depth of the L fluctuations, around 4 Hz in each CB. It is measured in *Vacils*

### B. *Urban Noise Analysis*

In order to implement the Zwicker's model [9] in a low-cost platform, some simplifications are needed to reduce the computational requirements, such as the dynamic range in the acquisition step (bits per sample), the sampling frequency and the number of CBs used. Fig. 1 shows the frequency spectrum of the road traffic noise, measured in the facade of a 50 meters height tower in a traffic congested area in Valencia city, at the rush hours on the floors 0, 4 and 9, as described in Section V-C. The spectrum is band limited for low and medium frequencies, and above 8 kHz the power level decreases by more than 40 dB. Then taking into account this information,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2014.2356342, IEEE Sensors Journal

TABLE I
NUMERICAL EXPRESSIONS FOR N, L, S, R AND F

$$N = L\left(1+\sqrt{\left(\frac{3(S-1.75)log(L+10)}{4}\right)^2+\left(\frac{2.18(0.4F+0.6R)}{L^{0.4}}\right)^2}\right)$$

$$L = \sum_{z=0}^{24Bark} L'(z)\cdot\Delta z$$

$$S = 0.11\cdot\frac{\sum_{z=0}^{24Bark} L'(z)\cdot e^{0.171\cdot z}\cdot z\cdot\Delta z}{L}$$

$$R = 0.0003\cdot\sum_{z=0}^{24Bark} f_{mod}(z)\cdot\Delta L_E(z)\cdot\Delta z$$

$$F = 0.032\cdot\sum_{z=0}^{24Bark}\frac{\Delta L_E(z)\cdot\Delta z}{\frac{f_{mod}(z)}{4}+\frac{4}{f_{mod}(z)}}$$

TABLE II
NUMBER OF CBS ANALYZED FOR EACH SAMPLING FREQUENCY ($f_s$). DETAIL OF THE CENTRAL AND MAXIMUM FREQUENCY ($f_c$ AND $f_{max}$) OF THE LAST CB

| $f_s$ (kHz) | Last CB | $f_c$ (kHz) | $f_{max}$ (kHz) |
|---|---|---|---|
| 22.05 | 24 | 13.50 | 15.50 |
| 20 | 23 | 10.50 | 12.00 |
| 8 | 19 | 4.80 | 5.30 |

TABLE III
NUMBER OF VALUES FOR L, S, R AND F FOR EACH SAMPLING FREQUENCY ($f_s$) WITH 10S, 200 MS AND 500 MS OF AUDIO

| $f_s$ (kHz), duration | L | S | R | F |
|---|---|---|---|---|
| 44.1, 10s | 215 | 215 | 13728 | 574 |
| 22.05, 10s | 107 | 107 | 13728 | 574 |
| 20, 10s | 98 | 98 | 12500 | 574 |
| 8, 10s | 40 | 40 | 10000 | 574 |
| 20, 0.2s | 1 | 1 | 250 | 12 |
| 8, 0.5s | 1 | 1 | 500 | 29 |

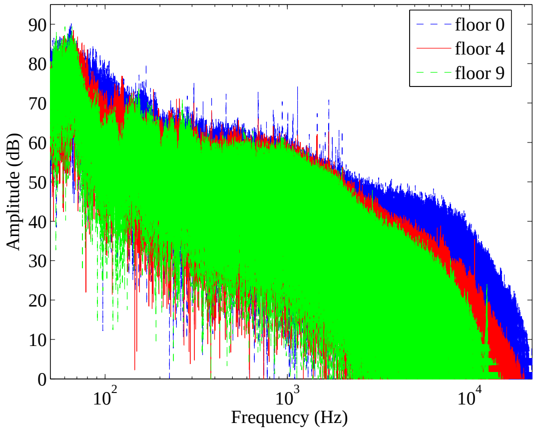

Fig. 1. Spectrum of the road traffic noise measured in the facade of a 50 meters height tower in a traffic congested area at the floors 0, 4 and 9.

we have selected appropriated sampling frequencies for each platform. The number of the analyzed CBs are related to the sampling frequency. Table II shows for each sampling frequency, the last CB included (or *Bark*), specifying both the central and maximum frequencies of this CB. Due to the different temporal window sizes required by each parameter, in Table III we show the number of values obtained for the different psycho-acoustics parameters with 10 s, 200 ms and 500 ms of audio recordings.

Finally, to calibrate the recording systems, we measured the $L_{eqA,10s}$ with a the Type I standard sound level meter (CESVA SC-310) with readings within the range of 65 to 75 dBA.

### *C. Correlation Analysis of Effective Sound Pressure and Psychoacoustic Parameters*

To evaluate the Zwicker's model we have tested different sound sources, using available audio files (at http://www.freesound.org/people/) such as: a) a circular saw (`kolczok_circ-saw-05.wav`), b) a violin (`jcveliz_violin.wav`), c) road traffic (`klankbeeld_traffic.wav`) and d) a pure tone calibrated to 92 dB (`pure_tone_to92dB.wav`). Table IV shows the mean values for the $L_{eqA,10s}$, N, L, S, R and F. From these results, it can be seen that the $L_{eqA,10s}$ is poorly related with N for the road traffic and the pure tone.

To extend this analysis, we have computed the normalized covariance without lag (correlation coefficient $\rho$) between the $L_{eqA,T}$ and N, L, S, R and F for the different audio files, testing the no correlation hypothesis with a 0.05 probability (significance level) using *p*-values. In Table V, we show the correlation coefficients ($\rho$) and the *p*-values. For the different sources, the correlation is significant for the psycho-acoustic parameters (*p*-value is lower than 0.05) except for the pure tone in N, R and F. In general S, R and F have very low correlation with $L_{eqA,T}$, except for the circular saw. For the road traffic and the violin, the $L_{eqA,T}$ is correlated slightly with N and L, but not with S, R and F.

This confirms that the Zwicker's model provides more information than the $L_{eqA,T}$ to assess the subjective annoyance from the point of view of human perception.

## IV. SENSOR NETWORK DESIGN AND CONSTRAINTS

WASNs allow distributed noise monitoring both in space and time through a multihop network. In Fig. 2, we show on the right, the off-the-shelf TmI with embedded microphone and on the left, the RPi over the protective housing and

TABLE IV
ANALYSIS OF MEAN VALUES FOR $L_{eqA,10s}$, $\overline{N}$, $\overline{L}$, $\overline{S}$, $\overline{R}$ AND $\overline{F}$ FOR DIFFERENT SOUND SOURCES

| Audio file | $L_{eqA,10s}$ | $\overline{N}$ | $\overline{L}$ | $\overline{S}$ | $\overline{R}$ | $\overline{F}$ |
|---|---|---|---|---|---|---|
| *Saw* | 73.06 | 82.78 | 21.79 | 4.64 | 1.94 | 0.03 |
| *Violin* | 76.79 | 89.62 | 35.89 | 3.65 | 0.88 | 0.13 |
| *Traffic* | 76.20 | 229.09 | 42.57 | 3.15 | 3.28 | 0.05 |
| *92 dB tone* | 93.50 | 70.29 | 49.97 | 2.34 | 0.25 | 0.01 |

TABLE V
ANALYSIS OF THE CORRELATION COEFFICIENT ($\rho$) / $p$-VALUES BETWEEN $L_{eqA,10s}$ AND THE PSYCHO-ACOUSTIC PARAMETERS ( N, L, S, R AND F) FOR DIFFERENT SOUND SOURCES

| *Audio file* | N | L | S | R | F |
|---|---|---|---|---|---|
| *Saw* | 0.99/0 | 0.99/0 | 0.99/0 | 0.87/0 | 0.79/0 |
| *Violin* | 0.73/0 | 0.86/0 | 0.63/0 | 0.19/0.05 | 0.30/0.01 |
| *Traffic* | 0.81/0 | 0.95/0 | 0.66/0 | -0.23/0 | -0.09/0.01 |
| *92 dB tone* | 0/1 | -1/0 | 1/0 | 0/1 | 0/1 |

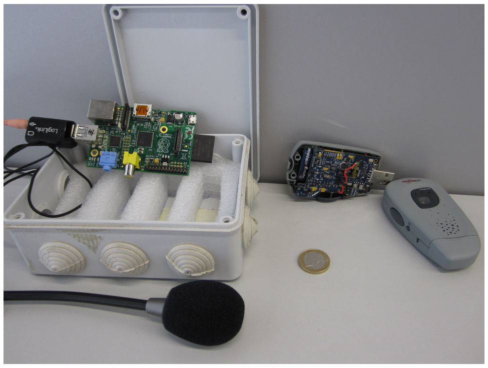

Fig. 2. View of the off-the-shelf Tmote-Invent mote (right) and the Raspberry Pi platform with an external microphone and a WiFi adapter (left).

the external microphone. The TmI nodes are based on IEEE 802.15.4, while the RPis are based on IEEE 802.11b (WiFi). For the purpose of noise pollution monitoring using the psycho-acoustics metrics, we consider the following features to assess these platforms: sampling frequency, memory size, sound quality acquisition (dynamic range or bits per sample) and CPU processing capabilities. All the nodes monitor the road traffic noise, acquiring and processing the noise periodically every 10 minutes, calculating L, R, S and F to estimate N, and finally send the results (with the psycho-acoustic parameters) in a data packet to the *sink*, through the multihop network.

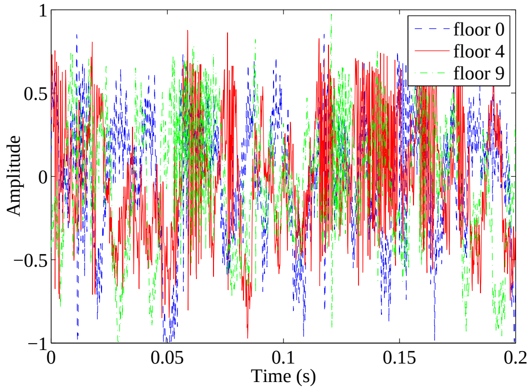

Fig. 3. Example of road traffic noise recording for 200 ms with the TmI at 20 kHz sampling frequency, 12 bits/sample, measured in the facade of a 50 meters height tower in a traffic congested area at the floors 0, 4 and 9.

## *A. TmI Platform*

*1) Hardware Issues:* Tmote-Invent (TmI) from Moteiv is an off-the shelf adaptation of the commercial TelosB motes [14], with support for audio recording (with an electret omnidirectional microphone) and an integrated suite of sensors, equipped with 750mAh (3v) rechargeable batteries and placed within a protective housing (Fig. 2, right). TmI is based on a 16 bit microcontroller (TI MSP430) with an external 32kHz clock, a TI CC2420 transceiver, 10 kB of RAM, 48 kB of Flash memory and an on-board inverted-F microstrip antenna with indoor and outdoor ranges of 50m/125 m respectively. From the TmI's Data Sheet, the output signal from the microphone is processed by an AD SSM2167 preamplifier, filtered through a Low Pass Filter (LPF) that has a cutoff frequency of 10 kHz, afterwards connects to the 12 bit Analog-to-Digital Converter (ADC) of the TI MSP430 microcontroller. The microphone has a sensitivity $-35 \pm 4$ dB (0 dB = 1V/Pascal at 1 kHz tone) with a flat frequency response of 20-20000 Hz.

The major constraint of these nodes is the 10 kB RAM memory (but only 8 kB are available for the user). This small amount of memory limits the recording time. To cover the dynamic range for the audio input, that is 65 to 75 dBA approximately as seen in Section III-B, a full 12-bit ADC conversion can compensate a dynamic range of $20 \cdot log_{10} 2^{12} = 72.24$ dB, with 2 bytes per sample. 8 kHz and 20 kHz sampling frequencies are used to record 500 ms and 200 ms respectively. The 8 kHz sampling frequency is selected for testing purposes, as it is too low to measure the psycho-acoustic metrics due to: a) the maximum frequency of the road traffic noise is around 8 kHz [10] (see Fig. 1), and b) the 10 kHz cutoff frequency of the LPF at the first stage of the ADC, that it can introduce aliasing. The 20 kHz sampling frequency is a tradeoff to avoid the aliasing and to maximize the recording time. Fig. 3 displays a 200 ms audio recording for the TmI at 20 kHz, 12 bits/sample. It should be noted that even with 12-bit ADC, some sound saturation problems still exist as can be seen at $t = 45ms$, due to the limitations of the TmI and some sound instantaneous peaks were outside this range.

*2) Software Issues:* Since the noise indicators require long-term audio processing, transmitting raw data back to the *sink* is not feasible due to the energy required to send and forward all these packets. Thus, we have customized a data gathering application available in TinyOS v1.0 [21] repository, called *Delta*, with a multihop routing protocol, called *MultihopLQI* [22]. This application includes a Synchronous Low Power Listening that coordinates the duty cycles of all the motes, switching them ON and OFF periodically by configuration. Note that this software has already been used in [23], although with a different purpose, for a long term environmental monitoring application. The application running in the TmI, has a measured mean consumption of 0.4 mAh with a 1% duty cycle (11 ms in working period in front of 1 second sleeping period). It should be noticed that our application does not perform a continuous audio recording, but only 200 or 500 ms (depending on the sampling frequency) every 10 minutes. In particular with the measured consumption and taking into account the normal charge of 750 mAh of the TmI's batteries, it allows a life time of 78.12 days approximately.

TABLE VI

ANALYSIS OF THE AVERAGE (AND STD. DEVIATION) FOR N AND $L_{eqA,10s}$ WITH A 10 S SEQUENCE OF ROAD TRAFFIC NOISE, USING THE SIMULATED CONSTRAINTS IMPOSED BY THE RPI AND TMI. THE DIGITAL RECORDER (DR) SHOWS EXACT VALUES. FOR EACH DEVICE WE SPECIFY THE RESOLUTION (BITS/SAMPLE) AND SAMPLING FREQUENCY $f_s(kHz)$. FOR TMI, WE INCLUDE THE RESULTS WITH 200 AND 500 MS OF AUDIO SEQUENCES

| Device (bits)/$f_s(kHz)$/size | $\overline{N}$(std. deviation) | $L_{eqA,10s}$ |
|---|---|---|
| *DR (24)/44.1/(10s)* | 17.12 (5.10) | 73.94 |
| *RPi (16)/22/(10s)* | 17.34 (5.33) | 73.93 |
| *TmI (12)/20/(0.2s)* | 11.20 (n/a) | n/a |
| *TmI (12)/8 /(0.5s)* | 10.93 (n/a) | n/a |
| *TmI (12)/20/(c10s)* | 158.08 (44.90) | 73.90 |
| *TmI (12)/8/(c10s)* | 118.08 (28.55) | 73.81 |

### B. RPi Platform

*1) Hardware Issues:* The Raspberry Pi (RPi) platform is based on Broadcom BCM2835 System on a Chip, including an ARM1176JZF-S 700 MHz processor, a Graphic Processing Unit (GPU) and 256 MB of RAM, with a SD slot card memory. We installed in the RPis a *Logilink UA0053* USB sound card, with an electret omnidirectional microphone (Fig. 2, left) and a WiFi adapter *TP-Link TL-WN725N* with IEEE 802.11 b/g/n standard. This configuration allows each node to acquire 10 s of audio with 16 bits per sample (allowing a dynamic range of $20 \cdot log_{10} 2^{16} = 96.33$ dB) at a sampling frequency of 22.05 kHz. The RPis have been placed in protective housings, each with 3 Kodak 1.5V KD LR20 batteries (19500 mAh). We measured a mean current consumption of 400 mAh (4.5 V), disabling all unnecessary services. It allows a life time of 39 hours, considering an 80% efficiency for the batteries.

*2) Software Issues:* We installed Raspbian Operating System, which is a GNU/Linux version optimized for the RPi hardware, based on a Debian distribution. To implement a Wireless Mesh Network, we used the Babel [24] routing protocol, which is a loop free, proactive and based on distance vector algorithm. Babel is implemented in the Quagga [24] routing software suite, with GPL license.

## V. EXPERIMENTAL RESULTS AND TEST BEDS

We evaluate the subjective annoyance following the Zwicker's annoyance model [9]. Initially we simulate the constraints imposed by the alternatives, and afterwards, we proceed to analyze the real platforms in the network comparing the noise measurements with the calibrated equipment.

The following devices are used in these experiments: a) RPi nodes with a 22050 Hz sampling frequency and 16 bits/sample, b) TmI motes with a 8 and 20 kHz sampling frequencies with 12 bits/sample (denoted as TmI8 and TmI20 respectively), c) a professional Handy Digital Recorder (DR) H6 Sound Lab ZOOM, with a 44.1 kHz sampling frequency and 24 bits/sample, and d) a Type I standard sound level meter (CESVA SC-310). The DR is used to record different audio tracks to calculate and measure off line the psycho-acoustic metrics. The CESVA SC-310 is used to calibrate and check the different measurements at the same time of the experiments.

TABLE VII

ANALYSIS OF THE AVERAGE (AND STD. DEVIATION) FOR L, S, R AND F WITH A 10S AUDIO SEQUENCE OF ROAD TRAFFIC NOISE, USING THE SIMULATED CONSTRAINTS IMPOSED BY THE RPI AND TMI. THE DIGITAL RECORDER (DR) SHOWS EXACT VALUES. FOR TMI, WE INCLUDE THE RESULTS WITH 200 AND 500 MS OF AUDIO SEQUENCES

| Device | $\overline{L}$ | $\overline{S}$ | $\overline{R}$ | $\overline{F}$ |
|---|---|---|---|---|
| *DR* | 7.41(3.27) | 1.20(0.27) | 0.96(0.27) | 0.04(0.02) |
| *RPi* | 7.54(3.08) | 1.18(0.26) | 0.95(0.26) | 0.04(0.01) |
| *TmI20(0.2s)* | 7.75(n/a) | 0.71(n/a) | 0.23(0.19) | 0(0) |
| *TmI8(0.5s)* | 6.24(n/a) | 0.83(n/a) | 0.53(0.27) | 0(0) |
| *TmI20* | 12.92(6.41) | 1.44(0.35) | 8.57(3.47) | 0(0) |
| *TmI8* | 12.46(4.60) | 0.92(0.16) | 6.46(2.42) | 0.01(0.01) |

### A. Simulation Results

Using the previously recorded audio files of road traffic noise with the DR, as described in Section III-B, we analyze the mean and standard deviation of the $L_{eqA,10s}$ and N, with the constraints imposed by the RPi and the TmI platforms, as shown in Table VI. We simulate these constraints (in terms of sampling frequency, bits/sample and duration of the audio recorded) in Matlab. We show in the DR(24) row the exact values (without constraints) and in the following rows, the results for each alternative: the RPi, TmI8 and TmI20. In particular for the TmI, because the available RAM for the audio recording is only 8 kB as described in Section IV-A, we analyze these parameters over 500 and 200 ms audio sequences, for the TmI8 and TmI20 respectively, as well as over 10s piecewise audio sequence, denoted by c10s (c: concatenated). We have created the piecewise audio sequence by concatenating several audio pieces from 500 and 200 ms audio chunks, assuming that we record the audio chunks in the 8 kB RAM and save them in the Flash memory. If we analyze the measurements and the relative errors compared with the DR(24), the $L_{eqA,10s}$ values are within $\pm 1$ dBA. However with the Nuisance, we have a relative error of 1.2% using the RPis and more than 30% using the TmIs. It should be noticed that using the concatenated audio sequences of 10s in the TmI, the $L_{eqA,10s}$ measurements are correct, but not N. The reason behind this is that the experiment is not conducted over a continuous audio sequence (only piecewise), that strongly affects the psycho-acoustic metrics. In addition, Table VII shows the mean values for $\overline{L}$, $\overline{S}$, $\overline{R}$ and $\overline{F}$, previously calculated to estimate N. We see the similarities between the DR(24) and RPi, but the differences with the TmI motes, in particular for the $\overline{L}$, $\overline{S}$ and $\overline{R}$. Note that using 200 and 500 ms of audio sequences, we cannot calculate the standard deviations (n/a) for N, L and S in Tables VI and VII, since we have only one value as shown in Table III.

### B. Sensor Nodes' Calibration

Before setting up the network test, we performed a standard calibration using piston phones, to avoid the misalignment in the measured parameters due to the mismatches in microphones' sensitivities and frequency responses. The measurements were compared with a Type I standard sound level

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2014.2356342, IEEE Sensors Journal

Fig. 4. Detail of the vertical and horizontal network deployment at the outskirts of Valencia city, exit to Barcelona (Highway A7). In vertical, over a 50 m height ”Torre Miramar” tower, in horizontal over a distance of 290 m.

TABLE VIII
$L_{eqA,10s}$ AND $\overline{N}$ AT THE FLOORS 0, 4 AND 9 WITH REAL DR, RPI, TMI8 AND TMI20

| Floor | $L_{eqA,10s}$ | *DR* | *RPi* | *TmI8* | *TmI20* |
|---|---|---|---|---|---|
| 0 | 71.0 | 126.48 | 142.6 | 98.58 | 52.94 |
| 4 | 68.3 | 98.28 | 110.47 | 145.45 | 139.13 |
| 9 | 67.2 | 88.73 | 99.80 | 101.32 | 42.13 |

meters (CESVA SC-310) and showed a less than ±2dB error in both short-term and long-term, except for the TmI that only kept the calibration for a few minutes. Several reasons may explain this issue with the TmI: a) a bad shielding between the analog and digital circuits and b) an unstable voltage reference due to fluctuations of the batteries.

### *C. Network Deployment and Road Traffic Noise Evaluation*

The network test was carried out in a vertical and horizontal deployment. In Fig. 4, the black line details the deployment and the white circles indicate the locations of the nodes. In vertical, we used the facade of a 50 meters height tower (called ”Torre Miramar”), as can be seen on the left part of Fig. 4, close to the A-7 highway in a traffic congested area of Valencia city. This tower has 10 floors, from 0 (ground floor) to 9, and it is placed in the middle of a roundabout. The roundabout has different water pools and waterfalls, and at the basement of the tower reside the water pumps. In horizontal, we measured every 20 meters over a distance of 290 meters from the bottom of this tower, with the aim to create a noise map.

TABLE IX
$\overline{L}$, $\overline{S}$, $\overline{R}$ AND $\overline{F}$ AT THE FLOORS 0, 4 AND 9 WITH REAL DR, RPI, TMI8 AND TMI20

| *Floor* | *DR* | *RPi* | *TmI8* | *TmI20* |
|---|---|---|---|---|
| Avg. Loudness [*Sone*] | | | | |
| 0 | 27.90 | 30.08 | 14.37 | 5.46 |
| 4 | 22.79 | 24.69 | 17.47 | 17.99 |
| 9 | 21.22 | 22.99 | 14.61 | 5.59 |
| Avg. Sharpness [*Aures*] | | | | |
| 0 | 2.60 | 2.69 | 2.65 | 2.09 |
| 4 | 2.33 | 2.40 | 2.98 | 2.66 |
| 9 | 2.10 | 2.18 | 2.37 | 1.57 |
| Avg. Roughness [*Asper*] | | | | |
| 0 | 2,68 | 2,84 | 4.47 | 6.65 |
| 4 | 2.52 | 2.64 | 5.59 | 5.14 |
| 9 | 2.42 | 2.54 | 4.53 | 5.00 |
| Avg. F. Strength [*Vacil*] $\cdot 10^{-3}$ | | | | |
| 0 | 6.2 | 6.18 | 8.2 | 6.4 |
| 4 | 5.10 | 5.02 | 7.2 | 6.3 |
| 9 | 5.36 | 5.39 | 4.8 | 8.2 |

TABLE X
STATISTICAL LEVELS (L10/L90) AT THE FLOORS 0, 4 AND 9 WITH REAL DR, RPI, TMI8 AND TMI20 FOR N

| *Floor* | *DR* | *RPi* | *TmI8* | *TmI20* |
|---|---|---|---|---|
| 0 | 153.03/107.02 | 174.97/120.45 | 131.92/26.64 | 77.45/6.04 |
| 4 | 116.02/81.77 | 130.31/91.54 | 180.83/52.22 | 219.56/24.09 |
| 9 | 102.55/75.86 | 114.62/86.23 | 132.14/40.47 | 54.62/8.64 |

Initially, once the calibration was done, to evaluate the performance of the real RPi and TmI, we measured the noise at the different floors, between 8:00-9:00 am (rush hour) in week 11 of the year 2014. Table VIII shows the average $\overline{N}$, along with the $L_{eqA,T}$ from the CESVA SC-310, at the floors 0, 4, and 9 for the RPi, DR, TmI8 and TmI20. If we analyze again the measurements and the relative errors compared with the DR(24), the RPi has a 12% of error approximately (due to the microphone, its orientation and the platform itself), but the TmI has an error greater than 22%. We consider reasonable values around 10-12%. Table IX shows also the $\overline{L}$, $\overline{S}$, $\overline{R}$ and $\overline{F}$. As expected, we see the similarities between the DR and RPi and the differences using the TmIs. Table X shows the L10 and L90 for N, which are respectively the levels exceeded for 10 and 90% of the time. The values from the TmIs are very different from those of the RPi and DR.

Finally, due to their poor and unreliable measurements, the TmI8 and TmI20 alternatives are not used for the following results. Fig. 5 and 6, show the mean values using the RPi and DR for $L_{eqA,10s}$ and N, both in the vertical and horizontal deployment, respectively. At each location we measured during 2 minutes with the RPi and DR. The standard deviation is introduced as error bars for the different values. Note that RPi and DR used different microphones with slightly different orientations, explaining the offset in the measurements. Based on the results, we can confirm that the RPi and DR have similar accuracy to measure the psycho-acoustic metrics, stating that the RPis are a feasible, low-cost and off-the shelf platforms to perform the noise pollution monitoring. In addition, we performed the same correlation analysis, as described in Section III-C, at each node location (Fig. 7). We observe similar correlation coefficients, as in Table V, between the $L_{eqA,10s}$ and the psycho-acoustic metrics for road traffic noise. In particular, N and L show high correlation with $L_{eqA,10s}$, while S, R and F show low correlation.

### *D. Network Deployment With Raspberry Pi Platforms*

For the testing purpose, we deployed 10 RPi nodes in each floor of the tower. The network was operational for two days during week 11 of the year 2014, measuring N, L, S, R and F. In Fig. 8, we see a screen shot from the web application used for management purpose of the network (http://moteserver.uv.es), with the link and path utilization. Note that although the noise maps are done horizontally, we

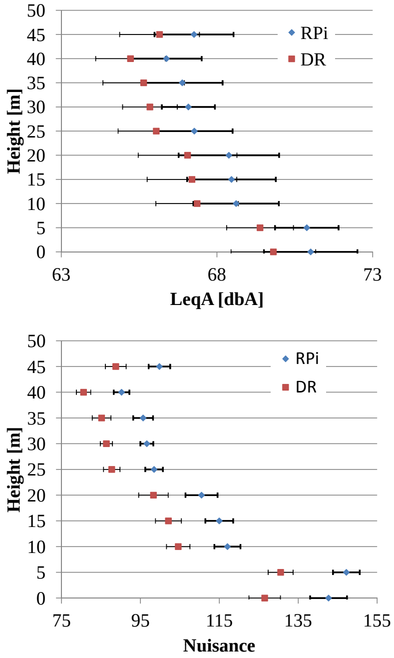

Fig. 5. $L_{eqA}$ and N measurements in the vertical network deployment with the RPi and DR.

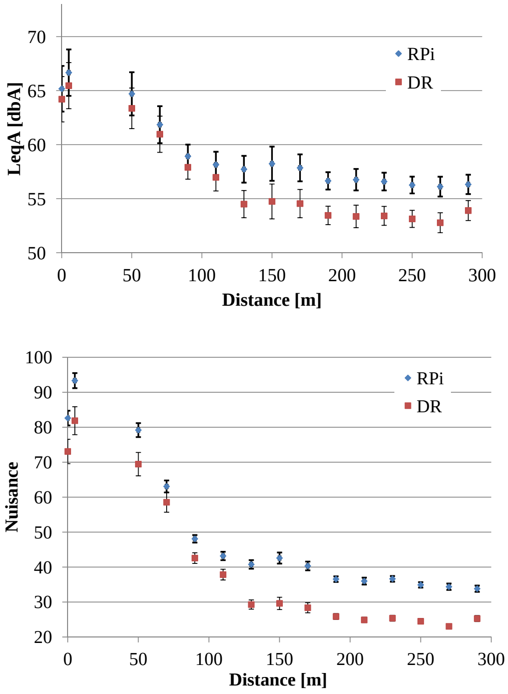

Fig. 6. $L_{eqA}$ and N measurements in the horizontal network deployment with the RPi and DR.

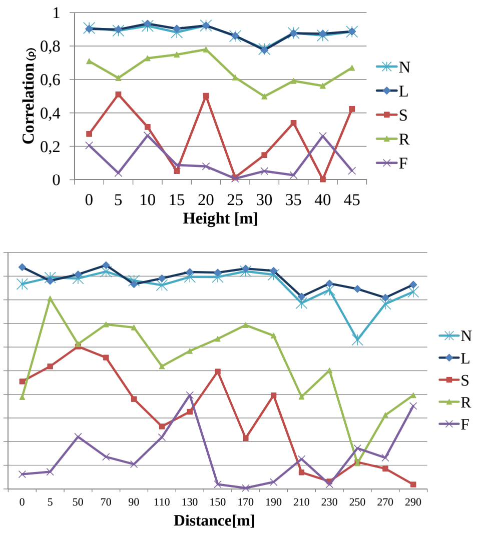

Fig. 7. Analysis of the correlation coefficient ($\rho$) between $L_{eqA}$ and the psycho-acoustic parameters (N, L, S, R, F) at each node location, both in the vertical (above) and horizontal (below) network deployment.

GLOBAL DATA
Total packets : 8007
Correct packets : 4721
Lost packets : 3286
Duration weighted average hop count: 2.38

Fig. 8. Link and path utilization for the WASN with 10 RPi nodes deployed in ”Torre Miramar” (Valencia). Screen shot from the interface of the management application.

consider a contribution to analyze these parameters vertically, analyzing the noise exposure to the people in their daily life within the cities.

## VI. CONCLUSIONS

In this paper, a set of experiences are reported in using the TmI and RPi platforms for collecting road traffic noise pollution data in outdoor environments and measuring the subjective annoyance, and pointed out the potentials and limitations of these two hardware alternatives. While the results showed the feasibility of WASN to be used as noise pollution sensors, in particular based on the RPi platforms, they also illustrated the practical limitations of today’s commercial and off-the shelf available platforms. The alternative based on the TmI platform does not lend itself well for accurate

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2014.2356342, IEEE Sensors Journal

measurements of the psycho-acoustic parameters due to its short RAM memory and its low-performance audio recording circuit. Also, we showed that concatenating audio sequences (to bypass the RAM memory problems), strongly affect these measurements.

We explored the interest for the psycho-acoustic parameters and their additional information related to the road traffic noise monitoring, by a correlation analysis with the $L_{eqA,10s}$. We found that for road traffic noise, the $L_{eqA,10s}$ is correlated slightly with N and L, but not with S, R and F. This confirms that the Zwicker's model provides more information than the measurements based on the equivalent noise pressure level, in particular $L_{eqA,10s}$, to assess the subjective annoyance.

## REFERENCES

[1] END, "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," July 2002.

[2] "New York City, Noise map," accessed: 02/01/2014. [Online]. Available: http://nycopendata.socrata.com/Social-Services/2012-NYC-Noise-Complaints-Heat-Map/sw33-t3vk

[3] "The London Road Traffic Noise Map," accessed: 02/01/2014. [Online]. Available: http://www.londonnoisemap.com

[4] "Department for Health and Environment of the City of Munich (Germany)," accessed: 02/01/2014. [Online]. Available: http://tinyurl.com/2gg7dl

[5] B. Li, S. Tao, and R. Dawson, "Evaluation and analysis of traffic noise from the main urban roads in Beijing ," *Applied Acoustics*, vol. 63, no. 10, pp. 1137 – 1142, 2002.

[6] M. Mircea, I. Kovacs, I. Stoian, A. Marichescu, and A. Tepes-Bobescu, "Strategic mapping of the ambient noise produced by road traffic, accordingly to European Regulations," in *Automation, Quality and Testing, Robotics, 2008. AQTR 2008. IEEE International Conference on*, vol. 3. IEEE, 2008, pp. 321–326.

[7] International Electrotechnical Commission, "61672: Sound level meters Standard."

[8] M. Raimbault, "Urban soundscapes: Experiences and knowledge," *Cities*, vol. 22, no. 5, 2005.

[9] H. Fastl and E. Zwicker, *Psychoacoustics: Facts and Models*, ser. Springer series in information sciences. Springer, 2007.

[10] D. Ouis, "Annoyance from road traffic noise: a review," *Journal of environmental psychology*, vol. 21, no. 1, pp. 101–120, 2001.

[11] M. Rychtáriková and G. Vermeir, "Soundscape categorization on the basis of objective acoustical parameters," *Applied Acoustics*, vol. 74, no. 2, pp. 240–247, Feb. 2013.

[12] S. Santini and A. Vitaletti, "Wireless Sensor Networks for Environmental Noise Monitoring," Aachen, Germany, pp. 98–101, Jul 2007.

[13] S. Santini, B. Ostermaier, and A. Vitaletti, "First Experiences Using Wireless Sensor Networks for Noise Pollution Monitoring," in *Proceedings of the 3rd ACM Workshop on Real-World Wireless Sensor Networks (REALWSN'08)*, Glasgow, United Kingdom, Apr 2008.

[14] J. Polastre, R. Szewczyk, and D. Culler, "Telos: enabling ultra-low power wireless research," in *Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on*, april 2005, pp. 364 – 369.

[15] I. Hakala, I. Kivela, J. Ihalainen, J. Luomala, and C. Gao, "Design of low-cost noise measurement sensor network: Sensor function design," in *Sensor Device Technologies and Applications (SensorDevices), 2010 First International Conference on*. IEEE, 2010, pp. 172–179.

[16] J. L. Ilkka Kivela, Chao Gao and I. Hakala, "Design of noise measurement sensor network: Networking and communication part," in *The Fifth International Conference on Sensor Technologies and Applications*, 2011, pp. 280–287.

[17] S. Santini, B. Ostermaier, and R. Adelmann, "On the Use of Sensor Nodes and Mobile Phones for the Assessment of Noise Pollution Levels in Urban Environments," in *Proceedings of the Sixth International Conference on Networked Sensing Systems (INSS 2009)*, Pittsburgh, PA, USA, Jun 2009.

[18] N. Maisonneuve, M. Stevens, M. Niessen, and L. Steels, "NoiseTube: Measuring and mapping noise pollution with mobile phones," in *Information Technologies in Environmental Engineering*, ser. Environmental Science and Engineering, I. Athanasiadis, A. Rizzoli, P. Mitkas, and J. Gmez, Eds. Springer Berlin Heidelberg, 2009, pp. 215–228.

[19] N. Maisonneuve, M. Stevens, M. E. Niessen, P. Hanappe, and L. Steels, "Citizen noise pollution monitoring," in *Proceedings of the 10th Annual International Conference on Digital Government Research: Social Networks: Making Connections between Citizens, Data and Government*. Digital Government Society of North America, 2009, pp. 96–103.

[20] S. Gelfand, *Hearing: An Introduction to Psychological and Physiological Acoustics, Fourth Edition*. Taylor & Francis, 2004.

[21] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, "System architecture directions for networked sensors," *SIGARCH Comput. Archit. News*, vol. 28, no. 5, pp. 93–104, Nov. 2000.

[22] "The MultiHopLQI protocol," 2009, accessed: 02/01/2014. [Online]. Available: http://www.tinyos.net/tinyos-1.x/tos/lib/MultiHopLQI/

[23] V. Gallart, S. Felici-Castell, M. Delamo, A. Foster, and J. J. Perez, "Evaluation of a real, low cost, urban wsn deployment for accurate environmental monitoring," in *Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on*. IEEE, 2011, pp. 634–639.

[24] J. Chroboczek, "The Babel Routing Protocol, RFC 6126," Quagga Routing Software Suite, GPL licensed, April. 2011, accessed: 02/03/2014. [Online]. Available: http://www.quagga.net

**Jaume Segura-Garcia** received the M.Sc. and Ph.D. in Physics from the University of Valencia in 1998 and 2003, respectively. Since 2008, he joined the Computer Science Department of the University of Valencia, where he is Associate Professor. He has coauthored more than 90 technical papers in international journals and conferences. He is a member of the Spanish Acoustics Society and the European Acoustics Association.

**Santiago Felici-Castell** received the M.Sc. and Ph.D. degree in Telecommunication Engineering from Polytechnical University of Valencia in 1993 and 1998, respectively. He is Associate Professor at the University of Valencia. His research has focused on networking, communication systems and multiresolution techniques for data transmission with quality of service. He is also a Cisco Systems certificated instructor and author of more than 25 technical papers in international journals and conferences.

**Juan J. Perez-Solano** received the M.Sc. in Physics and Ph.D. degree in Electrical Engineering from the University of Valencia in 1994 and 2002, respectively. In 1996 he joined the Computer Science Department of the University of Valencia, where he is Associate Professor. His research interests include multiresolution techniques, spread spectrum communications, wireless data transmission and wireless sensor networks.

**Maximo Cobos** received the M.Sc. and Ph.D. degree in Telecommunication Engineering from Polytechnical University of Valencia in 2007 and 2009, respectively. His Ph.D. dissertation was awarded with the Ericsson Best Thesis Award on Multimedia Environments from the Spanish National Telecommunications Engineering Association. In 2009 and 2011, he was a visiting researcher at Deutsche Telekom Labs., Berlin, Germany, working in audio and multimedia signal processing for telecommunications. He has published more than 70 technical papers. He is a full member of the Acoustical Society of America and a senior member of the IEEE.

**Juan M. Navarro** received the M.Sc. degree in Polytechnical University of Cartagena (Spain) in 2008 and the Ph.D. degree in Telecommunication Engineering from the Polytechnical University of Valencia in 2012. His Ph.D. dissertation was awarded with the Ericsson Best Thesis Award on Multimedia Environments from the Spanish National Telecommunications Engineering Association. Since 2006, he is an Assistant Professor at the Polytechnic Science Department, Universidad Catolica San Antonio de Murcia. His interests include acoustics simulation and array signal processing.