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Ear-Phone: A context-aware noise mapping using smart phones

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ABSTRACT

A noise map facilitates the monitoring of environmental noise pollution in urban areas. It can raise citizen awareness of noise pollution levels, and aid in the development of mitigation strategies to cope with the adverse effects. However, state-of-the-art techniques for rendering noise maps in urban areas are expensive and rarely updated (for months or even years), as they rely on population and traffic models rather than on real data. Smart phone based urban sensing can be leveraged to create an open and inexpensive platform for rendering up-to-date noise maps. In this paper, we present the design, implementation and performance evaluation of an *end-to-end, context-aware,* noise mapping system called Ear-Phone.

Ear-Phone investigates the use of different interpolation and regularization methods to address the fundamental problem of recovering the noise map from incomplete and random samples obtained by crowdsourcing data collection. Ear-Phone, implemented on Nokia N95, N97 and HP iPAQ, HTC One mobile devices, also addresses the challenge of collecting accurate noise pollution readings at a mobile device. A major challenge of using smart phones as sensors is that even at the same location, the sensor reading may vary depending on the phone orientation and user context (for example, whether the user is carrying the phone in a bag or holding it in her hand). To address this problem, Ear-Phone leverages context-aware sensing. We develop classifiers to accurately determine the phone sensing context. Upon context discovery, Ear-Phone automatically decides whether to sense or not. Ear-Phone also implements in-situ calibration which performs simple calibration that can be carried out by general public. Extensive simulations and outdoor experiments demonstrate that Ear-Phone is a feasible platform to assess noise pollution, incurring reasonable system resource consumption at mobile devices and providing high reconstruction accuracy of the noise map.

1. Introduction

At present, a large number of people around the world are exposed to high levels of noise pollution, which can cause serious problems ranging from hearing impairment to negatively influencing productivity and social behavior [1]. As an

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abatement strategy, a number of countries, such as the United Kingdom [2] and Germany [3], have started monitoring noise pollution. These countries typically use a *noise map* to assess noise pollution levels. A noise map is like a weather map for noise but it shows areas which are relatively louder or quieter [2]. It is computed using simulations based on inputs such as traffic flow data, road or rail type, and vehicle type. Since the collection of such input data is very expensive, these maps can be updated only after a long period of time (e.g. 5 years for UK [2]). To alleviate this problem, a recent study [4] proposes the deployment of wireless sensor networks to monitor noise pollution. Wireless sensor networks can certainly eliminate the requirement of sending acoustic engineers to collect real noise measurements, but the deployment cost of a dedicated sensor network in a large urban space will also be prohibitively expensive.

In this paper, we instead propose an opportunistic sensing approach, where noise level data contributed by *pedestrians*' mobile phones are used for monitoring environmental noise, especially roadside ambient noise.[1] The key idea in opportunistic sensing [5] is to "crowdsource" the collection of environmental data in urban spaces to people, who carry smart phones equipped with sensors and Global Positioning System (GPS) receivers. Due to the ubiquity of mobile phones, the proposed approach can offer a large spatial–temporal sensing coverage at a small cost. Therefore, a noise map based on participatory data collection can be updated within hours or days compared to months or years, making information provided by such a noise map significantly more current than that provided by traditional approaches.

It is non-trivial to build a noise pollution monitoring system based on mobile phones. Mobile phones are intended for communication, rather than for acoustic signal processing.[2] To be credible, noise pollution data collected on mobile phones should be comparable in accuracy to commercial sound level meters used to measure noise pollution. For practical deployability, an *in-situ calibration* technique is inevitably required, which can be easily carried out by non-technical users whenever needed.

Since a people-centric noise monitoring system relies on volunteers contributing noise pollution measurements, these measurements can only come from the place and time where the volunteers are present. Note that volunteers may prioritize the use of the microphone on their mobile phones for conversation. Furthermore, they may choose to collect data only when the phone has sufficient energy. Consequently, samples collected from mobile phones are typically randomly distributed in space and time, and are *incomplete*. To develop a useful noise pollution monitoring application, the noise map need to be recovered from *random* and *incomplete* samples obtained via crowdsourcing.

It is also unrealistic to expect that volunteers will always carry the phones in their hand, with the microphones correctly positioned for sampling ambient noise. Research conducted by Nokia [6] suggests that people tend to carry the mobile phone in their trouser pockets, bags, belt pouch and in their hand. In this paper we use the term "sensing context" to refer to the phone carrying locations. Because volunteers may contribute samples when the phone is in different sensing contexts, it is necessary to investigate if the sensing context has a significant impact on the noise level recorded by the phone and address it if so. In this paper, we address these challenges. Our key contributions are summarized as follows:

1. We present the design and implementation of an *end-to-end* noise mapping system, which we name *Ear-Phone*, to generate the noise map of an area using people-centric urban sensing. The data collection method of this new noise mapping system is expected to cost less than the traditional noise monitoring systems.
2. We study the impact of sensing context on the measured noise level. We find that when the phone is held in palm, the deviation from ground truth in the noise level is insignificant, but the deviation is quite significant when the phone is placed in trousers' pocket or in a bag. To enable data collection only in appropriate sensing contexts, we develop an energy-efficient classification algorithm, which detects the sensing context with 84% accuracy.
3. We evaluate Ear-Phone with extensive simulations and real-world outdoor experiments. The results based on our datasets show that (depending on the compressibility of the noise profiles) Ear-Phone can offer an accuracy of up to 3 dB[3] while incurring affordable resource consumption.

The rest of the paper is organized as follows. In the next section (Section 2), we contrast our work with the existing literature. We then describe the Ear-Phone architecture in Section 3, followed by the system design in Section 4. Then, we evaluate Ear-Phone with both outdoor experiments (Section 5) and extensive simulations (Section 6). Finally, we conclude in Section 8 after a discussion in Section 7.

2. Related work

We contrast Ear-Phone with the existing literature with respect to the contributions claimed in the paper. To facilitate the comparison, we discuss the literature in four different areas: mobile phones for noise mapping in general, noise reconstruction algorithms, context classification algorithms, and finally, microphone calibration.

Work conducted by Santini et al. [8], is one of the very first works, where mobile phones were used for assessing environmental noise. The authors survey technical issues influencing the design and implementation of systems that use

[1] We focus on roads because typically noise pollution is most severe on busy roads.

[2] For example, devices such as the Nokia N95, N97 or HP iPAQ do not support floating-point arithmetic, which must be emulated with fixed point operations.

[3] A difference of 3 dB is barely perceptible by human ear [7].