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# A wireless sensor network for urban environmental health monitoring: *UrbanSense*

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**Abstract**. Urban areas are generators of environmental emissions such as carbon dioxide ($CO_2$), harmful air pollutants and noise, all with the potential to negatively impact the health and wellbeing of its human and non-human inhabitants. There is an urgent need to understand the characteristics of urban areas associated with variability in emissions and the potential for exposure to potential harmful environmental conditions. *UrbanSense* is a wireless sensor network (WSN) infrastructure designed to monitor environmental conditions at different temporal and spatial scales. The scalable infrastructure includes an extended range outdoor wireless sensing and data aggregation system, a web-based data management and visualization platform, and real-time event-based data stream integration. Sensors monitor changes in carbon dioxide ($CO_2$), carbon monoxide (CO), noise ($LA_{eq}$), as well as several meteorological conditions including wind speed and direction, temperature, relative humidity and precipitation. The implementation will provide opportunities for real-time data integration and an analysis system for environmental quality assessment, and may be realized on top of products arising from spatio-temporal (statistical) analyses and remotely-acquired data products such as satellite data. Sensor swapping and co-location with sensors from projects with different aims (traffic volume modelling and human tracking research) will add value for research in transportation planning, environmental regulation and policy and epidemiological studies focused on associations between environmental exposures and health outcomes.

## 1. Environmental health implications of urbanization

In Canada, eighty-one percent of the population live in urban areas [1]. The change from nonurban to urban living has occurred over too few generations to provide much opportunity for evolutionary adaptation to urban environments. Many of the physical and social demands of rural, land-based life are absent from the urban environment, and new challenges are present including altered caloric energy budgets (the obesity epidemic), steeper socioeconomic gradients, greater social contact (disease transmission), and increased exposure to pollutants [2]. The study of exposure to environmental pollution is a key focus in Canada's Sustainable Development Strategy and is of great importance to Canadians because 1) the burden of illness and mortality from environmental exposures is significant and costly; 2) there is a general lack of environmental data to identify associations between environmental risk factors and health effects and to provide model inputs for more complex models (climate change); 3) characteristics of built environments, in addition to human activity patterns, are integral determinants of the dose and distribution of harmful pollutants.

Urban land use and transportation development policies have significant effects on health and the environment. Development in urban areas is often characterized by a significant increase in road traffic and the prevalence of industrial emission sites. Chronic exposures to road traffic noise and road traffic air pollution are associated with adverse health effects including cardiovascular (hypertension, myocardial infarction, stroke, atherosclerosis, heart disease), respiratory and oncologic mortality [3,4,5]. Cardiovascular disease (CVD) and cancer are the leading causes of death and hospitalization in Canada costing taxpayers over $45 billion annually for treatment and loss of productivity due to premature mortality [6]. Because air pollution and noise are strongly associated with road traffic and weather conditions, and have similar health endpoints, there is likelihood that the two pollutants act jointly, or that traffic noise may be a confounding factor in traffic-related air pollution studies and vice versa [7].

Robust, epidemiologically appropriate measures of the pollution in the urban environment are needed to overcome several important problems faced by environmental scientists and epidemiologists, including (a) lack of fine grained, neighbourhood-level measurements of environmental pollutants and related conditions; (b) a scarcity of environmental exposure assessment tools; and (c) an inadequate understanding of the linkages between the burden of exposure to pollution and social position. A number of research centers have explored how human health and well-being is shaped by urban development characteristics, but these generally have focused on inter-urban assessments and rarely consider the variation of environmental exposures at the intra-urban scale.

An important advance in environmental exposure assessment is the application of geographic theory and methods to estimate spatial variation of pollution. This is usually achieved with the addition of environmental sensors to existing monitoring stations on a short-term basis. Recent advances in wireless sensor network technologies allow for real-time monitoring of several key environmental pollutants and conditions [8] at the intra-urban scale. This is particularly useful since there is good evidence that variation in air pollution concentrations is greater at the intra-urban scale than between urban areas [9], and largely related to urban development and land use characteristics. Spatial analysis can help to illuminate health research by suggesting possible causal determinants of disease pathogenesis, and can create knowledge as to how people adapt or modify their environment, perceive health risks, or take actions to reduce exposure to environmental pollution. The strength of spatial analysis is the ability to align the multivariate characteristics of people and their environments to a specific location.

This paper describes the pre-deployment development and design of a novel, urban-scale environmental wireless sensor network (WSN) and testbed called *UrbanSense*. Data from the WSN will be analyzed using spatial analytic approaches to assess the influence of urban form and atmospheric characteristics on the distribution of key environmental measurements, and the translation of this information towards the development of knowledge about the linkages between exposure to pollution, social position, health outcomes and whether or not these exposures are distributed equally in the population.

## 2. Issues in urban environmental monitoring

Research progress in wireless and sensor networking in the last decade has been astounding. Developments include community-wide wireless mesh networks [10], and real-world sensor network deployments in environments as diverse as forests [11], and active volcanoes [12]. More recently, several experiments have demonstrated the feasibility of wireless sensor networks to be used in environmental monitoring applications, including the monitoring of weather conditions to predict the quality of agricultural products [13], and the monitoring of environmental conditions in urban areas. Depending on the density of sensor nodes across a study area, sensor networks allow for the collection of fine-grained sensor data, and can deliver this data (either in its raw or processed format) in real-time to project collaborators, research colleagues or the public. High resolution data collection is essential to foster scientific research and improve our understanding about the mechanisms underlying the spatial distribution of pollution, as well as their influence on the health of exposed population subgroups. Moreover, interventions aiming to reduce exposure to environmental pollutants may fail or be ineffective if there is a lack of adequate data available for planning and successive validation.

An important impetus for *UrbanSense* arises from previous work in environmental exposure assessment. Over the past few decades researchers wishing to investigate pollutant concentrations in urban areas were reliant on government monitoring campaigns consisting of few monitors for large geographic areas. Data from these monitors have been used to demonstrate significant short-term associations between urban air pollution and asthma [14]. Given the increasing prevalence of asthma and other respiratory diseases, as well as evidence confirming the role of urban air and noise pollution in explaining the rising prevalence of cardiovascular and cancer outcomes, focus has since turned to the contribution of chronic exposures within communities. For example, a disproportionate number of socio-economically disadvantaged persons live in environmentally unsafe areas [15], and they may be more affected by air pollution than others. To measure intra-urban pollutant variations, researchers have initiated large sampling campaigns (n > 50 sites) for a few weeks at a time (figure 1). While this approach can provide accurate, high resolution exposure data, the sampling campaigns are limited temporally, the data are generally inaccessible to other researchers (and the public), the sampling sites are static spatially, and there is no opportunity to move sampling equipment should excessive spatial autocorrelation be present. Collecting fine-grained pollutant measurement through the manual collection procedure described above is clearly inefficient and expensive. Wireless sensor networks represents a realistic approach that can overcome the drawbacks of current pollutant data collection procedures, and open new research opportunities and applications. Sensor networks, when adequately equipped, can be deployed and redeployed over a variety of terrains, collect pollutant measurements over long period of time, and operate unattended requiring human intervention only for network installation and removal [16].

### *1.1. Changing urban conditions from climate change*.

There is broad consensus among scientists and governments that global climate change is occurring, and that human activities are most likely the main cause [17]. Potential urban climate change impacts with implications for human health include increased weather variability (e.g. freeze and thaw cycles, heat waves, precipitation events) and increased frequency of air and water pollution episodes. Dynamical and statistical downscaling models show that many cities, including those in coastal areas, will experience marked warming, increased downward solar radiation, less frequent rainfall, and more frequent stagnation of air masses – all of which favour an increase in ambient thermal conditions and declining air quality [18]. In addition, the built form and land cover characteristics of urban environments can exacerbate `natural` hazards. Hence, urban environments can be considered as both a driver and receptor of climate change impacts.

The meteorological capabilities of the *UrbanSense* infrastructure will be used to examine two processes associated with climate change with known health implications – health effects arising from thermal stress and the frequency of freeze/thaw events. Urban centres can be up to several degrees warmer than the surrounding areas, and compared with vegetated surfaces, building materials retain more solar radiation during the day, and have lower rates of radiant cooling at night. Urban areas also typically have lower wind speeds, less convective heat losses, and less evapotranspiration, yielding more energy for surface warming [19]. Human physiology is sensitive to thermal stress in a relative fashion – the magnitude of temperature variation is just as important as absolute temperature. In Canada, thermal stress has been associated with cardiovascular-related morbidity and mortality, especially for susceptible population subgroups such as the elderly and those with pre-existing medical conditions [20]. In addition to thermal stress, winter freeze/thaw events, especially in cities with more moderate winter conditions (e.g. coastal cities) are associated with increased risk of falls, bone fracture rates and associated conditions [21], and can severely impact transportation network infrastructure via premature deterioration of pavement structures. Temperature and humidity measurements from *UrbanSense* will be analysed statistically to investigate the temporal and spatial distributions of anomalous events (e.g. times and locations where values exceed parameters of the normal distribution).

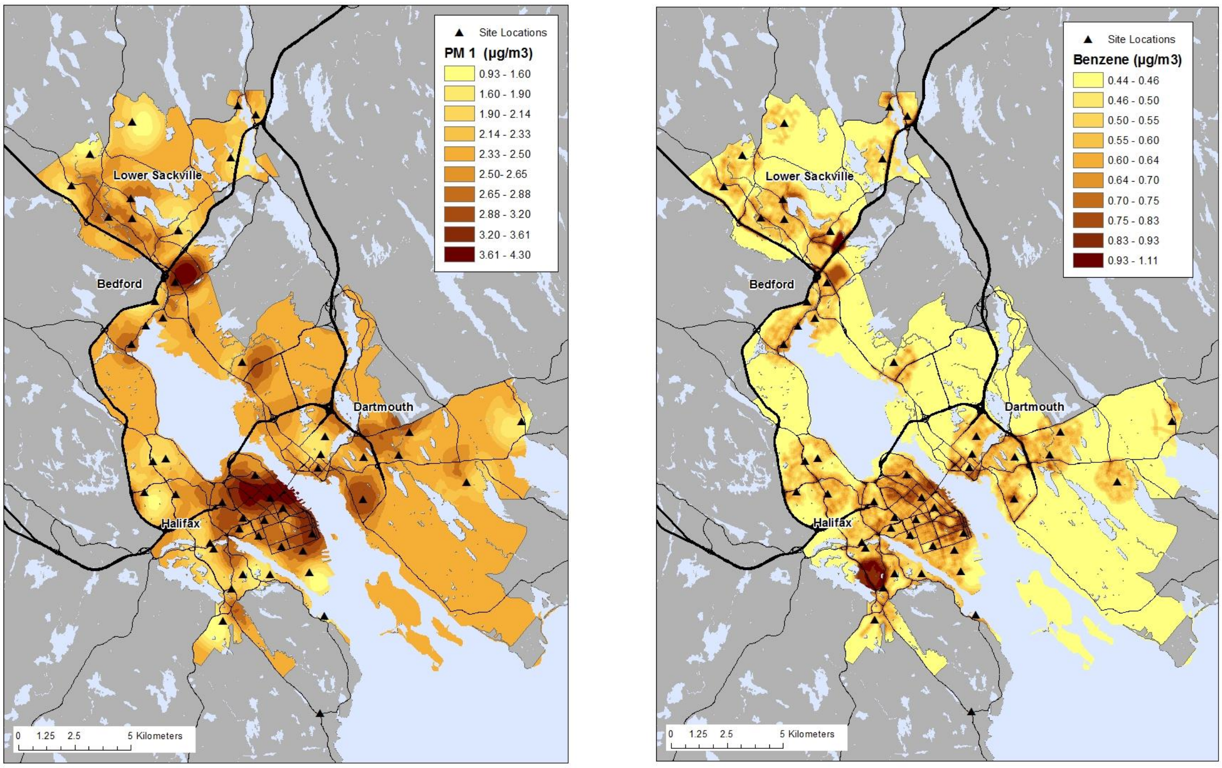


**Figure 1.** Intra-urban distribution of fine particles (<1µm, left) and volatile organic (e.g., $C_6H_6$, right) air pollutants in Halifax, Nova Scotia

*2.2 Urban noise and air quality monitoring*

Studies have reported significant associations between cardiovascular disease (and mortality) and both road traffic noise and road traffic pollution [20,22]. As both exposures are strongly related to human activities and land use, and because they share similar health endpoints, there is a possibility that the two pollutants act in concert, or that exposures interact thus modifying estimations of health risk. The largest source of air pollution and noise levels in urban areas can be attributed to road traffic. Land use is the primary mechanism by which values of air pollution and noise levels vary spatially in urban areas [9]. Local meteorology, topography, urban form, and population density also contribute to these spatial variations. To date, there has been limited effort to investigate health impacts arising from combined exposure to noise and air pollution.

Advances in wearable sensor technologies for measuring personal exposures have resulted in the detection of significantly greater variations in exposure when measurement occurs among personal microenvironments [23]. Similar investigations have also found a strong influence of urban land use on spatial variation of air pollution, but have yet to study this variation for extended periods of time in concert with associated covariates. This gap in our knowledge of longer-term noise and air quality patterns be resolved using the noise and air quality sensors that form part of the *UrbanSense* infrastructure. Noise data can be integrated across a variety of time periods, can be weighted to simulate the frequency response of the human ear, and form the basis for the calculation of equivalent sound level pressure required for the preparation of noise mapping products or similar data delivery mechanisms. Carbon monoxide (CO), a poisonous air pollutant produced from the incomplete oxidation of carbon during combustion processes, has been associated with cardiopulmonary mortality in most large Canadian cities, and if associated with traffic volumes will be helpful in determining the influence of urban designs on exposures to environmental pollutants. Published empirical studies of

CO monitoring using wireless sensor networks are few. The *UrbanSense* wireless sensor network will provide continuous, real-time data of ambient air and acoustical data in a spatially-representative fashion over extended periods of time [24].

*2.3 Social gradients of environmental exposures*

A key hypothesis about the origins of the social gradient in health status is that structural position in society predispose individuals to be exposed continuously to unhealthy social and physical environments [25]. The quality of both social and physical environments is also graded by social position. There is good evidence of the benefits of quality social environments for health from a study that found people who reported ties to the community experienced lower rates of disease and death than those without such links, even after taking into account differences in socio-economic status, health behaviours, and the use of health care services [26]. There has, however, been comparatively little research on the interaction between the burden of physical environment-induced morbidity or mortality and social position. Social position may lead individuals to live in poorer quality neighbourhoods that have higher levels of pollution. Thus, individuals lower down in the social hierarchy may have compromised resiliency to withstand additional environmental exposures. The advantage of monitoring environmental conditions using a wireless sensor network, like *UrbanSense*, is that the resulting data is fine-grained enough spatially to examine between neighbourhood characteristics of social position with exposure to pollutants. A second advantage is that the network structure can be reconfigured to focus on specific locations within the urban environment to focus on vulnerable populations, or alternatively, locations within the city perceived to be more polluted.

## 3. The development of *UrbanSense*

A scalable-wireless environmental monitoring system was developed in cooperation with sensor experts from Hoskin Scientific Ltd. and Lord Microstrain Sensing Systems, a leading developer and supplier of small, durable, smart sensor technologies. The main objective of *UrbanSense* is to remotely acquire continuous sensor data in an urban, outdoor setting. The system wirelessly has the capability to measure, log and transmit data for several environmental characteristics, including weather, atmospheric gases and noise (table 1).

**Table 1.** *UrbanSense* capability overview

| Requirement | Capability |
|---|---|
| Scalable sensor network | • 8 sensor channels per node<br>• Up to 10 nodes per wireless aggregator/base-station |
| Reliable wireless communication | • 100% data throughput (under typical operating conditions)<br>• Extended range radio link, up to 2 km line of site communication<br>• Time synchronizes to ± 32 milliseconds |
| Harsh conditions | • IP 67 packaging for continuous outdoor use<br>• Temperature range from -40°C to +60°C |
| Ease of use | • User configurable settings (local and remote options) |
| Low maintenance | • Very low power consumption, long battery life |
| Cost-effective | • Low cost per channel<br>• Low cost data transmission and cloud storage |

*3.1 Wireless monitoring node*.
The Microstrain ENVI-Link Mini (figure 2) was modified to support eight unique channels. Each node is deployed remotely and communicates wirelessly to a host base station, or data aggregator, up to 2 km away under ideal conditions. Based on preliminary radio surveys in urban settings this distance is reduced to between 100 to 500 m. Data from one node (or up to 10 nodes per base station) is aggregated and either stored locally or is forwarded to a web server.

The server provides global secure access to sensor data, as well as analysis tools and programmable alarms. Each node is fitted with a relative humidity/temperature sensor (RHT) and an outdoor air temperature sensor. For the *UrbanSense* WSN each node will also be connected to sensors to detect wind speed and direction, carbon monoxide (CO), carbon dioxide ($CO_2$) and noise. Sensor outputs are digitized by a 24-bit sigma-delta analogue to digital (A/D) converter thus providing high resolution data. Sensor data sampling rates can be programmed to vary between 2 samples/sec to 1 sample every 17 minutes.

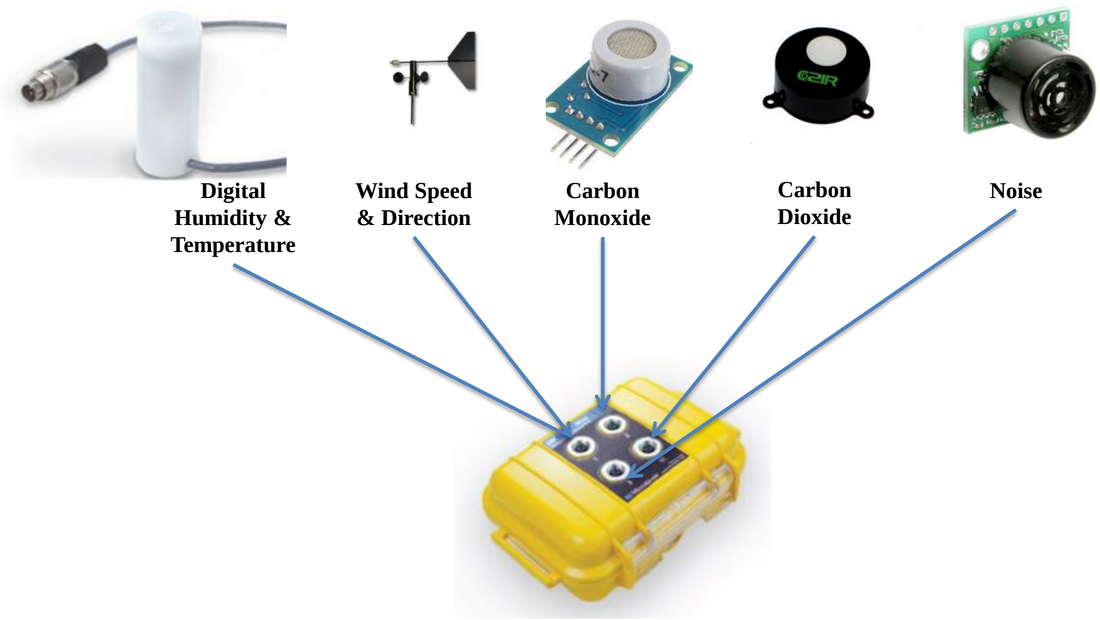


**Figure 2.** The Microstrain ENVI-Link – Mini wireless sensor node and associated sensors

*3.2 Proposed data fusion, analysis and distribution system*.
Simulations of sensor measurements clearly reveal challenges associated with the receiving/sending of continuous real-time data. The current *UrbanSense* WSN consists of ten base station aggregators and thirty individual nodes taking environmental measurements every 300 seconds resulting in 2,304 unique observations over a 24-hour period. While sensor data will be retrieved and formatted for efficient storage, an ideal system would support real-time processing and analysis, as well as possibilities for data sharing, mapping and "push" notifications or alerts when data thresholds or measurement levels are achieved. To accommodate these needs ESRI's ArcGIS Server software and GeoEvent Processor extension will be installed on a local server to capture real-time streaming data from the system data aggregators. The system employs a series of input connectors, for example receiving data from a web socket (cloud server), RSS feeds or data originating from social media and sharing sites. Processing occurs through a series of python scripts in the ArcGIS for server environment and then pushes data products (or raw data if desired) through a series of output connectors. In addition to event processing a web address will be created for the WSN allowing users to search, filter and download sensor data, view current sensor data output through a graphic

dashboard-type environment (e.g. trend plots and maps), and select options for notifications when events of interest occur.

## 4. Future work

Advances in sensor and communication technology provide opportunities for the creation of wireless sensor networks. These networks are emerging as ideal platforms from which to study consequences of increasing urbanization, including the impacts of urban environments and environmental change on human health and wellbeing. Several WSN projects have emerged in the past decade, although many have employed customized system architectures and network protocols making it difficult to extend or recreate projects elsewhere. The aim of this paper was to identify and discuss the linkages between urban land use, human activities and health outcomes, and to describe the development of a wireless environmental monitoring system. Much of the work to date has focused on selecting suitable sensors, integrating the sensors with existing, field-hardened hardware, and ensuring that the range and sensitivity of sensor measurement is useful for the assessment of human health impact.

Future work will include testing and validation of sensors to assess sensitivity to varying conditions and accuracy when compared to standard instrumentation used for regulatory or enforcement purposes. Experiments will also focus on sensor network maintenance (e.g. battery reliability), as well as the consistency and reliability of sensor data transmitted through the web. In the short term a portion of the WSN will be deployed to enable the development of the data capture, processing, analysis and sharing system.

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