A Metropolitan-Scale Testbed for Heterogeneous Wireless Sensor Networks to Support CO_2 Reduction

Pablo E. Guerrero[1], Alejandro Buchmann[1], Kristof Van Laerhoven[1], Immanuel Schweizer[1], Max Mühlhäuser[1], Thorsten Strufe[1], Stefan Schneckenburger[2], Manfred Hegger[3], and Birgitt Kretzschmar[4]

[1] Dept. of Computer Science,
[2] Botanical Garden, Dept. of Biology,
[3] Energy Efficient Construction, Dept. of Architecture,
Technische Universität Darmstadt, Germany.
[4] Environmental Agency, City of Darmstadt.

Abstract. There exist two major contributions of network technology to reduce CO_2 levels: reducing the energy consumption of the network itself, and supporting areas of application to reduce CO_2 levels. The impact of the latter is potentially higher. Therefore, we present TUDμNet, a testbed for a metropolitan-scale heterogeneous sensor network with hundreds of nodes that help monitor and control CO_2 levels in urban areas. Our testbed has four major application domains where it is being applied: TU Darmstadt's award winning solar house, where temperature and CO_2 levels are monitored; an 80 year old building in which a WSN is deployed to measure ambient parameters that contribute to future energy-saving remodeling; mobile sensors mounted on the streetcars of the public tramway system to measure location-specific CO_2 levels that are collected in a publicly accessible database to obtain CO_2 profiles; and a hybrid sensor network in TUD's botanical garden to measure humidity, CO_2 levels and soil properties to improve the management of urban parks. In this paper we present the concepts behind the design of our testbed, its design challenges and our solutions, and potential applications of such metropolitan-scale sensor networks.

1 Introduction

The contributions of ICT to energy conservation, and given today's energy generation profile, to the lowering of greenhouse gas (GHG) emissions, and in particular CO_2 levels, has been widely debated and documented (e.g., in [8, 5]). The two main approaches are concisely characterized by the buzzwords *green ICT* and *ICT for green*. The former refers to the reduction of power consumption of ICT systems, while the latter refers to the use of ICT systems to reduce power consumption in other application domains. Network technology, as one of the basic building blocks of ICT systems, can be characterized in the same manner.

In this paper we address the problems of heterogeneous wireless sensor networks (WSNs) and their application in a variety of green application domains.

Research on sensor networks has largely concentrated on homogeneous setups under laboratory conditions, or single application deployments. Most deployments have been relatively small-scale and only recently large testbeds with few hundred nodes have been deployed (a comprehensive survey can be found in [2]). The testbed we discuss in this paper, TUDμNet [3], has several distinctive features. It is a metropolitan-scale hybrid sensor network that includes a variety of sensors on heterogeneous nodes, combines wireless and wired as well as stationary and mobile sensor nodes, permits running different applications on the same testbed, can be segmented through the use of scopes, and allows easy software deployment without manual restarting of the widely distributed sensor nodes. TUDμNet is being deployed in four domains, each addressing different *green* concerns and at the same time presenting their own realistic challenges.

The four green application domains addressed here are:

- The instrumentation of new, energy conscious buildings, realized in the testbed by instrumenting the award-winning solar house developed by the architecture department of the Technische Universität Darmstadt (TUD). Sensor nodes placed inside the house and attached at the house's façade measure environmental conditions to characterize how the house responds to these.
- The instrumentation of old buildings in which no infrastructure for sensor deployment exists and where WSNs are a cheap and effective way to collect data that can be used for energy-conservation measures and future energy-conscious renovation. This has been realized by deploying a sensor network in the large, 80 year old building of the CS Dept.
- The deployment of mobile, wireless sensor nodes on the streetcars of Darmstadt's public tramway transportation system to collect location-specific temperature data and CO_2 levels to build micro climate maps and the use of existing sensor infrastructure in Darmstadt for traffic management.
- The deployment of sensor nodes in open spaces that monitor humidity, solar radiation, temperature, soil properties, and CO_2 levels in TUD's botanical garden. Observations gained in this kind of deployment can enable an early and targeted response to environmental stress or dangers caused by the lack of water or fertilizers, and more generally to optimize the management of parks, the green lungs of urban areas.

Finally, the integration of the various domains allows us to study another set of interesting problems derived from the interplay of heterogeneous stationary/mobile and wireless/wired sensor nodes, and the integration and management of streams of sensor data.

The remainder of this paper addresses the challenges that are encountered in setting up a testbed in the four environments described above (Section 2). It then presents some details on how we addressed those challenges, and shows solutions that are implemented in TUDμNet to permit multiple applications and flexible and efficient software deployment in a metropolitan area sensor network, along with details of actual deployments and a sample of the data that can be obtained and the information that can be derived (Section 3). We conclude in Section 4 with an outlook.

2 Challenges

2.1 Testbed Services

Sensor network testbeds have been proposed as an intermediate solution between simulators and final deployments because these enable a rapid experimental evaluation of networked applications without having to physically re-deploy sensor nodes with every iteration. Essentially, testbeds offer two services: a) quick and robust software reprogramming of the underlying sensor platform under test, and b) reliable experiment data logging for its posterior evaluation. The heterogeneity of the underlying sensor platforms in terms of processing capabilities, physical and virtual communication possibilities, mobility patterns, among others, makes the realization of these two simple services a non-trivial endeavor. Moreover, exploratory experimentation, typical of embedded systems' software evaluation, means that the results of an initial version of an experiment's application can lead to a series of adjustments, which in turn must be executed on-demand on the testbed. This places additional non-functional requirements on the quality of service of the testbed, namely the need to assist testbed users with the experiment definition (e.g., site selection, node type selection, job scheduling, experiment parameter validation), provide adequate access control mechanisms to each deployment/site, support for concurrent experiment execution, and tools for an automated evaluation and visualization of the parameters of interest.

Testbeds resort to an extra hardware and/or software support layer between the underlying sensor platform and the testbed coordination server to fulfill their tasks. Although in certain setups the design of this support layer is constrained (e.g. in heritage buildings, network cabling through a façade might be not allowed, thus a wireless backend will be preferred, while a hospital deployment might forbid yet another wireless system), identifying its correct footprint has a big impact on the initial investment as well as the maintenance costs of the organizations running the testbed.

2.2 Application-Domain Level

Metropolitan areas typically span a number of different environments which offer varying potential for eliminating or reducing energy inefficiencies: urban areas with legacy buildings, green parks, commercial/industrial districts, and even new neighborhoods following modern construction techniques. A testbed must therefore match these areas with corresponding experimentation playgrounds that remain of a manageable scale, yet offer enough scientific fidelity to yield results applicable to other, similar environments. We next describe the challenges of a number of application domains which we are currently pursuing for the improvement of the energy efficiency.

Energy Efficient House Construction. The emergence of decentralized, micro-scale renewable energy sources (especially photovoltaic and geothermal heating/cooling) has led the sustainable construction of energy efficient residential homes into an interdisciplinary area of investigation beyond architecture and civil engineering, prompting ICT systems to come into play. The explosion of construction techniques and modern materials mobilized researchers and practitioners to establish a biennial competition, the Solar Decathlon [9], where participants measure their innovations applied to residential properties at a number of contests. These houses represent the state-of-the-art in low ecological footprint.

While many construction aspects are designed and validated through models and simulation, critical aspects of the construction remain unclear until a prototype is built: do the HVAC systems work as expected throughout the inner space of the house? are the (costly) materials of the ceiling and exterior walls correctly designed to tolerate the weather conditions to which they are effectively exposed (varying temperature and humidity levels)? are solar panels acting optimally and delivering the maximum amount of energy as originally planned? does the geothermal heat pump tunneling deliver the expected water temperature? These questions represent only some of the engineering challenges where WSNs offer an unprecedented monitoring resolution and can help to improve their energy consumption.

Old Buildings. In Europe, around 40% of energy consumption is due to building usage [7]. Buildings also are the largest source of CO_2 emissions [4]. Since energy usage is mostly caused during the operational stage (i.e. during user occupation), sensor networks become a key element for monitoring building usage and enabling intelligent (e.g. HVAC) control.

Public Transportation Systems. Transportation is responsible for approximately one third of the carbon dioxide emissions in the US. While policy makers are looking for more energy-efficient cars and alternative energy sources, a large amount of savings can come from smarter traffic management reducing traffic congestions [1]. As population density increases, it becomes a necessity to cope with increasing traffic.

To enable real-time traffic management for smart cities, data from different sources must be considered; counting cars is a first step, but not enough. To regulate traffic in real-time, knowledge about the amount and speed of cars is needed, together with projected traffic densities, wind speed and direction, microclimate in a given region, emission levels and a mechanism to reroute traffic. All of this data can only be collected on a metropolitan scale and might not be available from one provider.

Urban Park Management. Parks, squares and other open spaces are ever more important in metropolitan areas due to their effect in reducing environmental pollution, besides encouraging citizens to an active lifestyle and reducing stress through the interaction with nature. Urban park monitoring operations (open spaces, water streams, visitor counts), park irrigation and other maintenance tasks like lawn-mowing, pruning of trees, bushes and plants, and emptying garbage bins, all offer room for optimization.

2.3 Data Management

Cities often have a sensor infrastructure in place, and are becoming smarter by equipping themselves with a rising number of data sources from sensor nodes and mobile applications. Today, this data is application- and consumer-specific, and most importantly, closed (to government partners). The potential economic and societal value of these large data sets is slowly being uncovered through novel applications from businesses and other organizations (e.g. [10]) that reveal new exploitation schemes. This requires a new infrastructure that can cope with the volume of these data sources and is based on open data, standards and APIs.

3 Solutions

In this section we describe the general approach to experimentation through the federated testbed and two representative testbed deployments.

3.1 Architecture for Testbed Services

Figure 1 presents the high level architecture used in TUDμNet. Users define and schedule test jobs through a server, which offers a web interface and a set of scripts. The server interacts with a set of gateways, which control and assist the low-power sensor node layer. Each site is interconnected to the testbed server via MANDa, the metropolitan area network of the city of Darmstadt. Domain differences between sites of a federated testbed require alternative networking solutions for the support layer. While one site exploits the available Ethernet infrastructure, others need to resort to a wireless off-band channel for performing management tasks (cf. site 1 and 2, respectively, in Fig. 1). This infrastructure can also provide power to the sensor nodes, e.g., through USB cabling. Yet, in

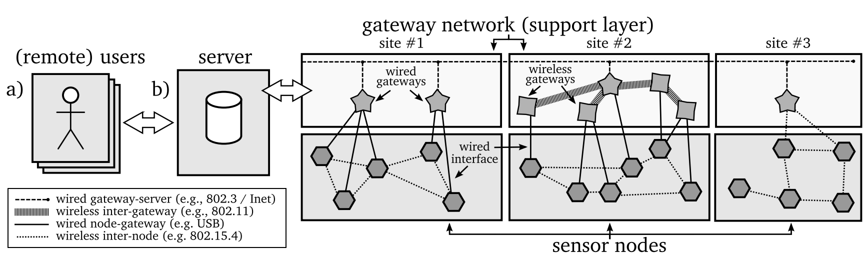

Fig. 1. High-level Testbed Architecture

other sites, this ideal, dual layer instrumentation might be impossible/unfeasible (site 3), having to resort to in-band testbed service protocols, like Deluge, for reprogramming, and CTP for collecting data, and even to solar power, ensuring mobile nodes have energy for certain periods of time.

Experimentation through a testbed requires fine grain control of the test jobs. This includes definition of job execution times, selection of sensor and node types, network topology and geographical node distribution, among others. TUDμNet adopts the concept of *scopes* [6] to specify groups of nodes. Each user might have access to a different set of sites, or scopes, which together with a time quota enables spatio-temporal sharing of the overall system.

3.2 Deployment on Streetcars

In order to generate a micro climate map for Darmstadt, we deployed a testbed of six wireless sensor nodes on the trams. By using mobile vehicles we can capture a large area using only a small amount of nodes. The six wireless nodes, manufactured by Libelium in Spain, are equipped with an 868 MHz transceiver for a metropolitan scale wireless range of over one kilometer.

The nodes are equipped with a temperature sensor, GPS for accurate localization, and most importantly solar cells (cf. Fig. 2). By using energy-efficient algorithms and an adaptive sampling rate [11], we are able to allow almost perpetual network operation even though the nodes are battery powered. A base station located in the city center collects all measurements as the trams pass by. They are then transmitted to the da_sense platform via GPRS.

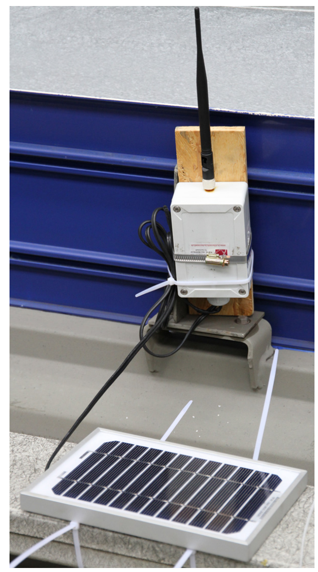

Fig. 2. Sensor node deployed on a streetcar in Darmstadt.

3.3 Piloty Building Deployment

This testbed deployment is located in the building of the CS Dept. of the TUD, a 3-story building consisting mainly of office rooms. The site currently spans 30 offices at the north wing, each with 2 to 4 sensor nodes: TelosB and Zolertia Z1, equipped with an MSP430 MCU, an 802.15.4 radio operating at 2.4GHz, 48 to 92 kB of ROM, and 8 to 10 kB of RAM (respectively). The sensors attached to the nodes can measure temperature, humidity, light intensity, acceleration and CO_2. Figure 3 depicts a typical deployed office. In each, a Buffalo WZR-HP-G300N acts as gateway (green), which bridges departmental ethernet with the nodes (red) through a USB backchannel (red lines). This rather unconstrained environment has shown its own challenge: the USB backchannel.

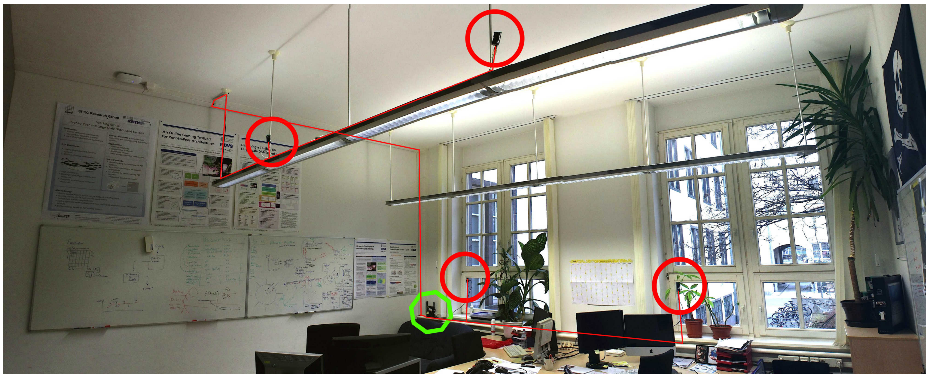

Fig. 3. An office at the CS building, with installed wireless sensors (red circles) that are also attached to a gateway (green circle) for quick reprogramming.

3.4 Data Integration and Management

In order to organize the information produced in our deployments, we have developed a lightweight data layer, da_sense [1], that connects different sensor sources and allows visualization and correlation of all the data sources available through a standardized API. da_sense integrates most of the data streams described in this paper and offers an open API to further innovate on the data. It also correlates different data streams (e.g. sound pressure and traffic density) to create virtual sensor nodes. Additional data sources can also be plugged into it. An example directly related to the traffic management application are Darsmtadt's street intersections, which are equipped with a large number of inductive loops that monitor the number of cars passing by and the utilization of the sensor in a 15-minute interval. We receive this data at da_sense, make it available for public consumption, visualize it (cf. Fig. 4) and correlate it with other data sources, leading to overall better optimizations.

4 Outlook

In this paper we have presented our ongoing work in designing, deploying and federating sensor network testbeds in domains that present great potential for reducing energy consumption and CO_2 levels. The data sets produced so far are gaining attention, and the testbed has already seen its first users external to the TUD. The streetcar deployment is being replicated in Hanoi, Vietnam, to enable online monitoring of traffic-generated pollution data, which further evidences the usefulness of the overall system. In the future, we plan to develop a number of applications to further exploit each site's sensors and which will run as permanent test jobs at TUDμNet.

[1] http://www.da-sense.de

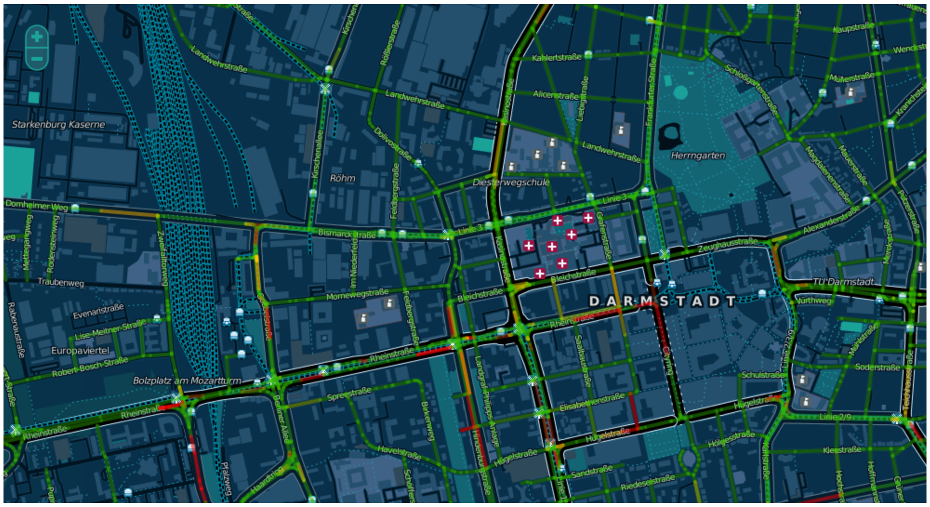

Fig. 4. Traffic data from inductive loops in Darmstadt's intersections

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