Smart City Sensing and Communication Sub-Infrastructure

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***Abstract*—Significant recent research activities and initiatives by local governments to establish resilient smart city infrastructures signal that time is right for smart cities in the near future. For example, sensors deployed within a city could monitor traffic patterns, perform environmental measurements and determine optimum traffic routing, when deployed in areas that have a power infrastructure. In this paper, we conceptualize the deployment of such nodes, which we term Smart Boxes, in a part of the city where there is no existing or currently functional energy and communication infrastructure. We envision our proposed smart boxes incorporating a multi-source energy harvester (e. g., wind/solar). Eliminating the infrastructure requirement allows our smart box to act as an emergency cell phone network in any part of the city, thereby forming an emergency sub-infrastructure. To improve scalability, we use a Software Defined Radio (SDR) within the box. The contribution of this paper is to provide an architectural map of the box and a proof-of-concept experimental demonstration of its LTE network capabilities. Our experiments show that the box is capable of serving three cellular users and can be powered from a 50–100 W solar panel and a 50-100 W wind turbine, thereby confirming its feasibility as a Smart City node.**

***Index Terms*—Smart City, Software Defined Radio, Cellular Networks, IoT, Autonomous Systems.**

I. Introduction

Recent progress made in conceptualizing resilient smart city architectures has triggered an avalanche of interest in municipal authorities and academic disciplines that study both the technical aspects [1]–[3] as well as the crisis management and cyber-security aspects of the smart city concept [4]. An example is the smart city bill passed by president Obama [5]. Envisioned developments aim to improve operational efficiency in a variety of city operations [2], [6] or monitor environmental conditions [3]. For example, camera-based monitoring of city traffic can reduce traffic congestion and consequently, air pollution. In this application, monitoring nodes will be needed throughout the city that incorporate a camera, multiple air quality sensors, and an embedded computer [7]. The acquired data from the sensors and the camera are pre-processed by the embedded computer and transmitted into the city's cloud infrastructure, where an algorithm determines optimum traffic routing.

The aforementioned applications assume an existing power infrastructure for the monitoring nodes – an assumption that often does not hold in the context of disasters and emergencies [8], in which accidents, attacks, or natural hazards may

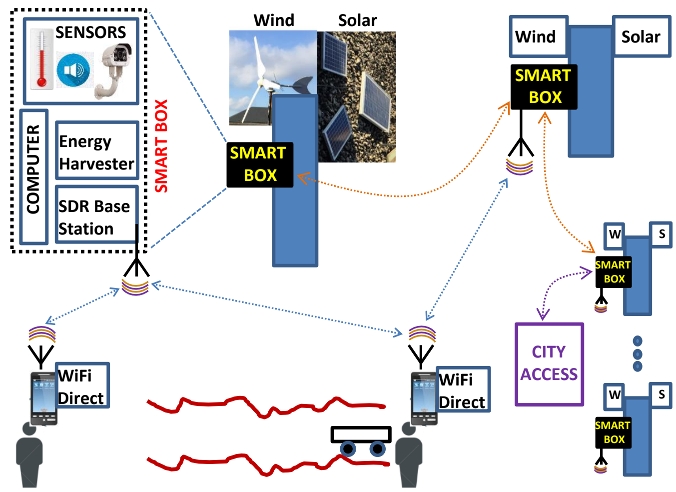

Fig. 1. High-level architecture of distributed network of smart boxes. Each Smart Box is an IoT node and is equipped with a camera and multiple sensors such as temperature, noise level, NO_2, and O_3. They can harvest energy from multiple energy sources, such as wind and solar, to operate maintenance free. They are able to serve multiple cell phone users using a Software Defined Radio (SDR) and do not require an existing LTE carrier; they can also reach neighboring boxes via other users' cell phones.

cause critical power and communication systems to fail [9]. Furthermore, a high availability network connection to the city is assumed either via wired or wireless networks. Unfortunately, such assumptions inherently limit the populations that can be served by smart infrastructures and often leave unserved the most vulnerable residents. To bridge this gap, we conceptualize and prototype a smart city emergency sub-infrastructure that is self-powered, self-healing, and independent of existing infrastructure. At the heart of our design is our smart city node dubbed *Smart Box*. These boxes connect to each other and the Internet to form an independent, yet globally-connected overlay network for smart and connected cities. Our *Smart Box* has two modes of operation – (i) *regular* and (ii) *emergency*. In *regular* mode, the *Smart Box* performs a rich variety of routine monitoring functions such as air quality control [1], noise pollution detection [3], and traffic monitoring [2]. In *emergency* mode, the *Smart Box* transforms into a self-configuring and self-healing LTE network that beyond urban sensing, can provide communication services in the face of a disaster.

In both operational modes, energy harvesting from multiple energy sources continues [10], [11], although the operational priority of the box shifts towards providing a cellular network for the residents affected by the disaster. One of the most important aspects of the box is easy deployment and low-maintenance, to enable the city to deploy a significant amount of them to improve coverage. This poses non-trivial research/design challenges for the realization of the box. Our proposed architecture integrates open hardware (such as SDRs and general purpose PCs) and open-source software to implement reliable and flexible sensing and communication infrastructure. Furthermore, we envision the box to incorporate advanced energy-aware computation algorithms [12] to avoid energy starvation during emergency scenarios when power is needed the most.

The contribution of this paper is to prototype and evaluate *Smart Box*. In Section II, we provide the technical/architectural details of our proposed Smart Box. In Section III, we provide *Smart Box* operational details that allow these boxes to form an overlay network sub-infrastructure. We evaluate our design with a preliminary study using an open source implementation of the LTE cellular stack called OpenAirInterface and provide concluding remarks in Section IV.

II. Infrastructure design considerations

In this section, we provide key *Smart Box* design considerations and detail the energy harvester. Because the design of the box and the overlay network – that is composed of many boxes – are inextricably intertwined, the operational details of the box in regular and emergency modes are provided within the context of the network architecture in Section III.

Autonomous Energy Harvesting Capability: Because the network availability is a crucial operational concern for the Smart Box, energy harvesting capability is necessary to ensure operation in locations that lack a power infrastructure. While solar energy harvesting is a viable alternative to sustain operations [10], harvesting form multiple energy sources such as solar and wind provides energy redundancy due to the complementary nature of these two energy resources, thereby improving the functional robustness of the box [11].

Cyber Attack Resistant Operation: Undoubtedly, one of the biggest concerns in the design of the Smart Box is ensuring its resistance to Cyber attacks. These attacks can be either system-level or crypto-level; in either case, they attempt to either disrupt the operation of the box or take over control [13].

Easy Deployment: The density of the deployed boxes in a localize area has a drastic effect on the quality of the service it provides in the *emergency* mode, therefore, these boxes must be inexpensive and should not require technical expertise to be deployed. Their solar and wind panels should be fairly easy to install; ideally this hybrid energy source should be constructed as single unit with a horizontal wind turbine and a solar panel on top.

Self-configuration: As the density of the deployed smart boxes increases, the concern of controlablity arises. We propose to have a software architecture in each box that incorporates self-check and self-configuration features. Each box should be controllable and accessible by city employees and should be able to accept new firmware revisions through software uploads. This will enable instant operational improvements of network and sensory capabilities, which are mostly controlled by software-based components to begin with.

TABLE I

Smart Box FUNCTIONS DEPEND ON ITS OPERATION AND POWER MODES.

Energy/Operation	Regular	Emergency
Strong	Sensing, Backhaul	Sensing, Last mile, Backhaul
Normal	Sensing, Backhaul	Sensing, Last mile
Weak	Sensing	Sensing or Last mile

Maintenance-free Operation: While easy deployment reduces the initial cost, recurring expenses must also be reduced to limit long-term costs. Incorporating hardware redundancy introduces the *self-healing* feature into the box; continuous operation must not be interrupted by small hardware failures that are expected in the proposed environments. Functionality of the box should degrade gradually with each failing component.

III. Smart Box Overlay Network

Our overlay network leverages the *Smart Box* to create a blanket coverage for a smart city. The purpose of this network in regular operation is to provide a sensing and control environment. In disasters, the network transitions from a passive sensing infrastructure to a hybrid sensing and communication infrastructure that can both aid in determining the severity of a disaster and in helping the disaster relief efforts by providing a communication infrastructure in the affected areas. In this section, we first provide details on our *Smart Box* design, components of which are shown in Fig.1. The box features a set of sensors, a general purpose processor, a hybrid harvester, a software-defined radio and a suite of open-source software used for sensor control, data analytics and cross-functionality switch in the two operation modes. We then detail how our *Smart Box* nodes are interconnected in an overlay smart city network.

A. Smart Box design and implementation

Our *Smart Box* maintains three key functions: (i) sensing to collect environmental data, (ii) last-mile communications to provide user connectivity and (iii) backhaul for interconnect across *Smart Box* devices. These functions are prioritized in importance depending on the operation mode of the node (*regular* or *emergency*) and its energy level (strong, normal or weak) as detailed in Table I.

In *regular* mode, the Smart Box performs a variety of environment monitoring functions. Commercially-available inexpensive air quality sensors that measure NO_2, CO, CO_2, and O_3 can aid air pollution monitoring. For example, NO_2 pollutant is introduced by combustion and can be an indicator for the degradation in air quality caused by traffic congestion. *Smart Box* is designed with heterogeneous sensor capabilities; we envision that deployment of our *Smart Box* reflects the sensing and communication diversity of common smart city applications [7]. Consequently, assuming that different hardware revisions of the box can incorporate a variety of evolving sensors, the capability of the software to adapt to this heterogeneity via the capability of each box to register itself in the global network is necessary. We propose that boxes "cache" and know the capabilities of their neighbors through continuous communication, either with the city or by one another.

Of particular importance to our system is its ability to sense failure in existing communication infrastructure and augment the communication services in that area. To this end, we harness our previous methodology [14] that monitors the control channels of commercial networks in order to determine the degree of congestion at a base station or a backhaul failure. Additionally, the boxes can detect outages in city lighting using simple photo-detectors or power-grid outages using Hall sensors that measure current flow through power lines.

In *emergency* mode, *Smart Box* provides combined sensing and communication functions. Each *Smart Box* node will feature functionality to determine the occurrence of a disaster in its immediate vicinity. Where indications of a disaster scenario (e.g., power outages, communications network disruptions, impacts of extreme weather) are detected, the node will notify the center (denoted "City Access" in Fig. 1) and will transition to *emergency* mode. Depending on whether the disaster affects existing communication infrastructure or not, it will activate the *Smart Box* LTE base station capabilities. Activation of the LTE base station will launch the SDR and will execute the associated software to spawn the LTE base station.

Our system makes use of an open source implementation of LTE dubbed OpenAirInterface (OAI) [15]. OAI employs an SDR, such as the USRP B210, as a radio front-end. Simultaneously, it runs an eNodeB and an Evolved Packet Core (EPC) network on a commodity computer in order to evoke both the base station as well as the LTE core. OAI implements the 3GPP-defined LTE standards and thus allows users to access *Smart Box* for communication services with their existing unmodified cell phones. A key advantage of the OAI setup is its modularity. Specifically, an EPC can run collocated with the base station, virtually creating a mobile network in a box. This network can either serve its users in isolation or perform a centralized coordination across multiple EPCs in order to establish a multi-base-station network. This enables high resilience of communication services, whereby in the worst case, the network can provide real-time services within a cell and delay-tolerant services across cells. Where cross-cell connectivity is available, the *Smart Box* network can provide a wide-area communication service.

B. Energy harvester

For the Smart Box to provide an uninterrupted operation during unpredictable and harsh environmental conditions, capability to harvest energy from multiple complimentary energy sources is necessary. For example, having only solar harvesting capability will not allow the box to operate at night, unless it has a large energy buffer. This buffer can be implemented with rechargeable batteries or supercapacitors [10], both of which have advantages and disadvantages [16]. While supercapacitors have substantially higher life expectancy, rechargeable batteries embody nearly an order-of-magnitude higher energy density, thereby allowing the box to be built on a smaller footprint. Harvesting from multiple complementary energy sources provides a steady level of supply, reducing the dependence on size of the buffer [11]. Therefore, a Smart Box has to incorporate a multi-source energy harvester, e.g., solar/wind.

C. Overlay Network/Software Architecture

As shown in Fig. 1, the network of *Smart Box* nodes are designed to operate individually or as part of an overarching network. We envision a combination of real-time and delay-tolerant backhaul to establish the links that interconnect our *Smart Box* nodes. The real-time interconnect will be established through long-distance microwave links. The delay-tolerant backhaul will be leveraged when the real-time backhaul fails, which can happen if infrastructure is failing or unable to provision enough energy to sustain its backhaul links. This delay-tolerant backhaul will be established in a device-to-device fashion between users phones using Wi-Fi Direct[1]. As user move, they will haul information across cells.

The sensor network will connect to a centralized processing unit controlled by authorized city personnel. This software is proposed to run in the cloud that is owned – or rented – by the city. In addition to providing a user interface to the city personnel, the cloud software also manages the automation of sensory data gathering by accessing individual *Smart Box* data and aggregating it. This data is fed into algorithms that predict anomalies in traffic conditions, weather conditions, or environmental conditions. In regular operation, the data can be used as environmental information, whereas when a disaster is detected, the surrounding boxes must be alerted to switch their operation mode to *emergency*. These algorithms must take into account the fact that the availability of individual boxes cannot be guaranteed.

IV. Experimental Evaluation

In this section we evaluate *Smart Box*. We are particularly interested in understanding whether the box can serve multiple cellular users and whether our hybrid energy harvester can power the node. To evaluate our setup, we use the aforementioned OpenAirInterface (OAI) [15]. The eNodeB portion of OAI runs on a Core i7-6700K based PC with Ubuntu 14.04 (Kernel 3.19) OS and 16 GB of RAM. The EPC portion runs on a Lenovo Thinkpad X250. We use USRP B210 as a radio front-end and a Nexus 5 smartphone with Android 5.1.1. as an LTE client.

We envision an i7-6700K motherboard and a power supply to be a part of our Smart Box construction, although the power supply can be replaced with a DC harvester in a field setting. Therefore, our reported power consumption levels are conservative. We use a P3 Kill-A-Watt device to measure instantaneous power consumption of the system once per second

[1] http://www.wi-fi.org/discover-wi-fi/wi-fi-direct

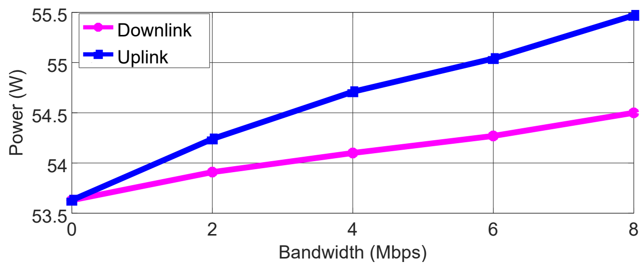

Fig. 2. Average power consumption vs. bandwidth of a single device that uploads/downloads data to/from the base station.

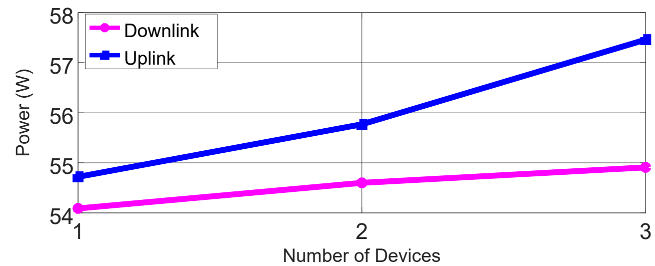

Fig. 3. Average power consumption when multiple nodes, each transferring data at 4 Mbps, are connected to the eNodeB.

and average these samples over two minutes. We evaluate the i) energy consumption of the entire system without SDR and ii) the incremental power consumption incurred due to the LTE functionality including the SDR. We disable all peripherals such as the discrete graphics card, all unused SATA devices, Intel Turbo Boost, and the X Server.

Figure 2 shows the processing node power consumption as the client bandwidth grows from 0 to 8 Mbps with a single cellular user. The idle system power consumption is 47.24 W and increases by another 6.36–8.26 W, depending on the load. We observe that uplink is more power-hungry than downlink; as user demand grows to 8 Mbps, power consumption increases by 0.9 W for downlink and 1.9 W for uplink.

We further study the effects of increasing number of users on energy consumption. The current implementation of OAI supports up to 4 simultaneous users and we conduct our experiments with a maximum of 3 users. We measure the power consumption with increasing number of users that require 4 Mbps each. Figure 3 presents our results. Adding two more users incurs a 0.82 vs. 2.74 W increase for downlink vs. uplink power, a pattern that is similar to the previous figure.

V. Conclusions

In what follows from Fig. 2 and Fig. 3, we conclude that a *Smart Box* harvester with a 50–60 W power output can realize our concept. A proper solar panel and wind turbine provisioning for this scenario can power this node using a 50–100 W solar panel and a 50–100 W wind generator [10], both of which have a manageable physical size for deployment [12].

For future work, we claim that the system power consumption could be drastically reduced by two design changes: i) the only required DC voltage levels for a PC motherboard are ± 12 V, ± 5 V, and ± 3 V and can be supplied from a solar/wind harvester [10], thereby eliminating the 10–20% inefficiency incurred by the AC-DC conversion of the PC power supply. ii) in both single- and multi-user experiments, we observe that the CPU load is only $\approx 20\%$. Such workloads can be run power-efficiently on modern CPUs, such as the 14 nm Intel Atom X5-E3940 @9.5 W Thermal Design Point (TDP), as opposed the i7-6700K @91 W TDP. These improvements will reduce the required solar panel and wind generator capacities, and consequently their size.

Acknowledgment

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