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Smart city in crisis: Technology and policy concerns

Tolga Soyata[a], Hadi Habibzadeh[a,*], Chinwe Ekenna[b], Brian Nussbaum[c], Jose Lozano[d]

[a] Department of Electrical and Computer Engineering, University at Albany, Albany, NY 12222, USA
[b] Department of Computer Science, University at Albany, Albany, NY 12222, USA
[c] College of Emergency Preparedness, Homeland Security and Cybersecurity (CEHC), University at Albany, Albany, NY 12222, USA
[d] Biological Energy, Inc. Spencer, NY 14883, USA

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ABSTRACT

Any effective smart city application proposal must consider both the technological and policy challenges to be optimally beneficial to the city; and not only in functioning of the narrow area of application during normal operations (lighting, parking, etc.), but also the utility of these systems and data in disasters and emergencies. In this paper, we propose a conceptual redundant mesh network of smart devices (termed “smart boxes”), which are capable of harvesting their own energy from off-grid sources and operating in two modes: in normal mode, smart boxes act as data collection devices and enable smart city data to be shared through traditional IT services. Alternatively, during a catastrophic event in the city, smart boxes switch to emergency mode and provide a communication channel to first responders via the redundant overlay network they establish, without requiring any power from the grid. We provide a detailed research map to realize such a conceptual network, both from technology (i.e., communication, hardware) and policy aspects (i.e., institutional and personal policy adoption), including extensive suggestions for assessment of both technical and policy success, and incorporation of non-traditional smart city customers for smart city application data and services like first responders and emergency managers.

1. Introduction

Smart city deployments are growing rapidly (Collotta & Pau, 2015; Guelzim, Obaidat, & Sadoun, 2016; Lee, Chong, & Lee, 2017; Mokhtari, Zhang, Nourbakhsh, Ball, & Karunanithi, 2017), however at this point their technology deployments are often siloed, poorly coordinated across agencies, and are typically not designed to offer additional functionality beyond their normal state of operations. Smart city application deployments typically target narrow functional areas such as smart lighting or smart parking, which are generally funded, built, and managed individually. Such a narrow focus often results in the deployment of dedicated hardware that only serves a single intended application, resulting in a patchwork of systems that is often not optimally integrated, or even inter-operable. These individually deployed systems are typically run and controlled by single components of a city government with no common planning or strategy across the municipality. Often, city governments do not know what data and smart systems they have, and certainly do not catalogue them for other potential users; this lack of insight into what “smarts” are produced by smart city applications are even more pronounced with fields like emergency management and first responders who are not typically part of integrated smart city discussions. Additionally, since many of these systems have unused or underused capacity or capabilities that could serve the city agencies in emergency situations, clearer technical and organizational integration of these disparate agencies and data is key to smart cities living up to their potential utility. This paper suggests that infrastructure can behave differently in emergency state operations than it does in normal state operations, particularly in smart cities, could be beneficial across multiple infrastructure sectors.

Of the 16 infrastructure sectors defined by the Department of Homeland Security, this paper focuses on the Emergency Services Sector and the Communications sector, and the dependency of the former on the latter. It addresses this dependency by creating and by deploying *smart boxes* (introduced in Habibzadeh, Xiong, et al. (2017) originally) that leverage the fact that the communications sector and information technology sectors use similar hardware and software to underpin their efforts. This paper exploits that technical overlap to offer up a possible improvement in the ability of first responders to communicate in disaster situations.

According to the United States Department of Homeland Security

* Corresponding author.
E-mail addresses: tsoyata@albany.edu (T. Soyata), hhabibzadeh@albany.edu (H. Habibzadeh), cekenna@albany.edu (C. Ekenna), bnussbaum@albany.edu (B. Nussbaum), jll13@cornell.edu (J. Lozano).

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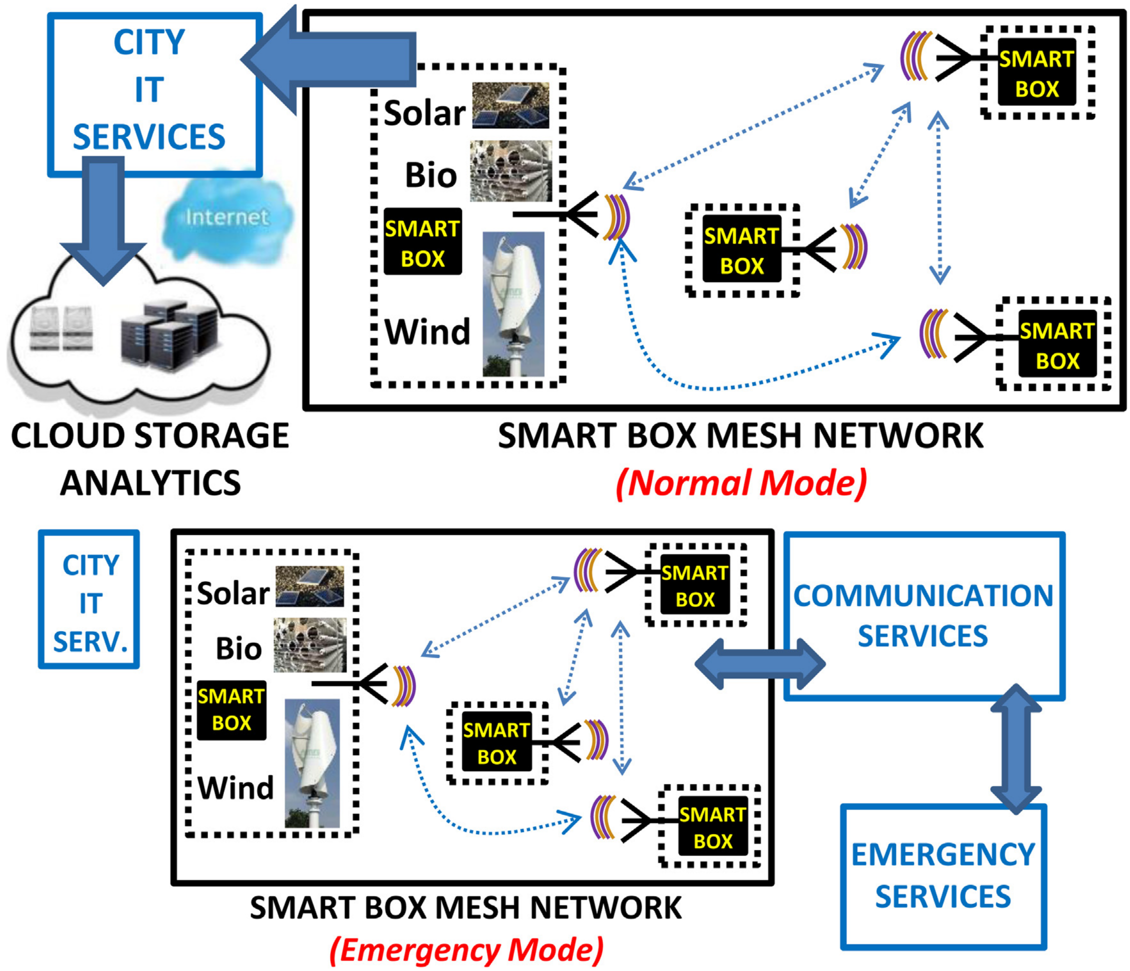


Fig. 1. An example smart box mesh network is capable of working in **normal mode** and **emergency mode**. Smart boxes harvest their own energy from redundant power sources, such as wind, solar, and bio, making them operationally self-sufficient. This allows the mesh network of smart boxes to be independent of the power grid, which, in turn, enables the first responders to utilize them during a catastrophic event in the city.

(DHS), "There are 16 critical infrastructure sectors whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof" (https://www.dhs.gov/critical-infrastructure-sectors). This paper proposes incorporating two of these sectors directly, Emergency Services and Communications, by deploying a mesh network of *smart boxes* as shown in Fig. 1.

The conceptualized system shown in Fig. 1 collects environmental data—through the sensors built into each smart box—and analyzes it using data analytics algorithms in **normal mode** to provide the city decision support; it switches to a totally different operation mode (**emergency mode**) during emergencies or catastrophic events by providing a communication network for first responders. Each smart box uses its dedicated solar panels, wind turbines, or biofuel cells (or a combination of these in hybrid energy harvesting) to power its operation (Habibzadeh, Hassanalieragh, Ishikawa, Soyata, & Sharma, 2017; Habibzadeh, Hassanalieragh, Soyata, & Sharma, 2017). This makes the system independent of the power grid and/or the commercial communication infrastructure. Hence, it effectively becomes an alternative communication medium, which is owned by the city, that avoids overloading the federal resources (e.g., the national guard) during situations when there are multiple such events in adjacent cities.

The proposed implementation and analysis leverage the technical overlap between the communications and information technology sectors, but its primary focus is on the intersection of the emergency service and communications sectors; that said, it also touches on the information technology sector, and even the water sector. The connection to the water sector is a bit more peripheral (wastewater serving as a power source for the "smart boxes"), but the connection between the communications and information technology sectors is central and important. By examining the crucial dependency of emergency services on communications infrastructure, and especially by examining how the information technology sector could potentially use existing smart city IT deployments to offer redundant communications capabilities (partially powered by the water sector), this paper presents a novel study of the interdependencies across several key sectors.

Any smart city project must consider the technology, people, and process aspects of the deployment. There is a clear consensus that having technology that works is not sufficient for that technology to be adopted, integrated, and accepted by an organization or institution (Nussbaum & Lewis, 2017). This is because any technology deployment is actually a constellation of the technology, the people who use it, and the processes that exist for the users to integrate it into their business or operations. In the context of a smart city, this three-part framework is laid out in Table 1. While a rich body of technical studies exists within the context of smart city applications, policy aspects of these projects are under-studied, which can hinder their applicability due to potential policy hurdles, such as ones regarding user privacy concerns or organizational capacity to adopt such smart applications.

The remainder of this paper is organized as follows. In Section 2, we propose a research roadmap to realize our proposed system in multiple

Table 1
Components of an effective technology deployment.

Technology	People	Process
Hardware	Individuals	Decision making
Software	Organization (agencies)	Technology adoption
Infrastructure	Jurisdiction (city)	Technology integration

distinct research threads. In Section 3, we review existing research and technologies that are related to this paper. In Section 4, we provide a detailed description of the operation of our proposed smart box mesh network, along with its sensing and communication infrastructure. The hardware (including energy harvesting) and software architectures Sections 5 and 6, respectively. We provide a policy research roadmap in Section 7. We conclude our paper in Section 8.

2. Proposed analytic approach

In this section, we highlight the fundamentals of the proposed research map to the realization of our redundant mesh network of smart boxes. We address at least three specific questions that are under-explored. Our first aim is to address issues concerning the smart box design, i.e., proposing a system of smart boxes and their components to do what is required to operate as smart city IT in normal state operations, and operate as an emergency communications mesh network in emergency mode, all while remaining independent of the electrical grid by harvesting their own energy. Our second aim is to address the software and algorithm infrastructure for the smart box network. In this case, the goal is to ensure that the boxes are in fact valuable components of a smart city network, including ensuring proper communication among the boxes and other smart city applications, the proper storage, sharing, and utilization of data, and the ability to conduct predictive analytics that are useful both to the smart boxes (for automated decision making) and the city (for human decision making). Thus the emphasis here is mostly on the normal state of operations. Finally, our third aim is to offer a way of looking at the policy and institutional implications of this work. By focusing on adoption and decision making at the jurisdictional (city) level and the level of the organization (city agencies), and focusing on both regular IT disciplines like the CIOs office but also on first responders and emergency services, this thrust is concerned both with the boxes' normal operations as well as with their emergency operations.

2.1. Smart box mesh network

Our proposed smart box network is conceptually depicted in Fig. 2; this system will be capable of self-energy harvesting from three different energy sources (solar, wind, and bio-fuel, although not necessarily simultaneously) and provide a communication link for the first responders. For the communication network, either box-to-box-only communication (without the help of smartphones) or a peer-to-peer (P2P) network, which utilizes smart boxes as well as the smartphones of the contributors (either volunteering residents or city employees), will be studied. We detail the operation of our proposed smart box-based mesh network and provide design details for its sensing and communication infrastructure in Section 4.

The hardware architecture of our system is based on previous work that implemented a self-sufficient data-intensive field device that is nearly maintenance-free and is capable of solar energy harvesting (Hassanalieragh, Soyata, Nadeau, & Sharma, 2014, 2016), which was extended to include hybrid solar/energy harvesting and the initial ideas of our proposed mesh network was published in Habibzadeh, Xiong, et al. (2017). We provide a detailed study of the energy harvesting infrastructure of our proposed smart box system in Section 5.

2.2. Data collection, database, and decision making system

The software infrastructure goal of this study is to propose a software architecture (Application Programming Interface – API) that is capable of storing, providing and classifying sensor data, during normal state, to third-party smart city applications that the city can purchase, and to investigate the feasibility of performing predictive analysis important for the city's infrastructure e.g., predicting power line outage due to a bad combination of wind, temperature and precipitation from data collected from the smart boxes. Our proposed software architecture is detailed in Section 6.

2.3. Policy research objectives

The policy implications of our proposal are broad and far-reaching. While focused specifically on the adoption of smart city technologies and their utility for first responders, it speaks to broader areas of policy research around technology adoption and crisis or disaster management. The key to understanding these dynamics will be a program of interviews with decision makers and technology end users, an analysis of documents that illustrate city and agency decision making and processes, and coordination of these sources with technical and usage data collected by the systems themselves. When this data is combined with

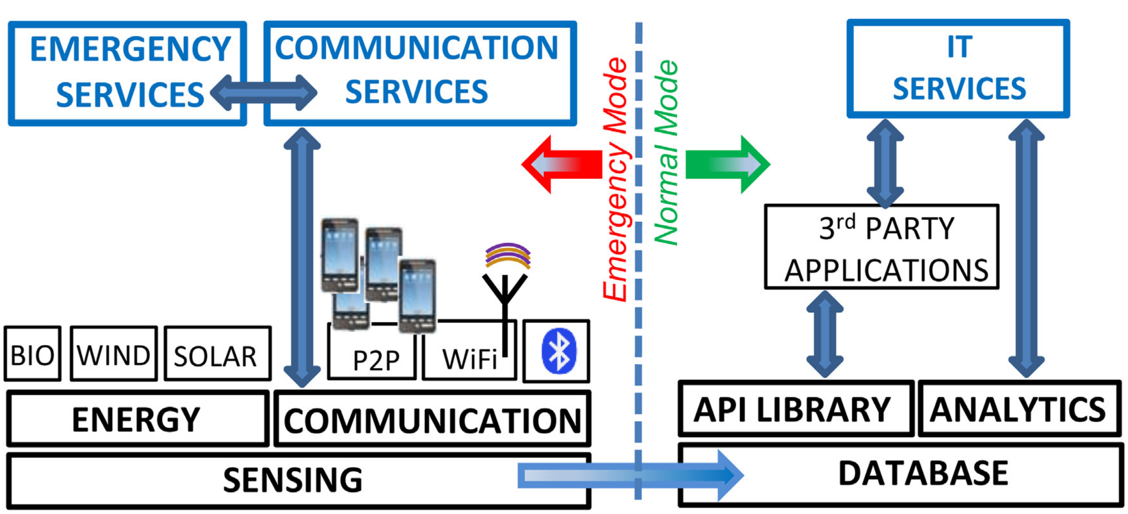


Fig. 2. Example smart box hardware (left) and software (right) architecture.

the data created and collected in mechanisms like disaster simulations and other real-world event usages, it will be possible to document how a city adopts smart city technology, what organizations hurdles exist, and what insights (best practices or process improvements) might inform other jurisdictions moving forward.

The potential contributions of this data collection, analysis, and dissemination are far-reaching. First, by gaining an understanding of how these technologies are adopted, accepted and utilized at the level of both the jurisdiction (the city) and the organization (particular city agencies), the policy findings and implications will contribute both to a broad policy and technology literature about the diffusion of innovation, as well as a narrower public administration and policy literature about municipal adoption of technology. Secondly, this will contribute to a nascent—but quickly expanding—literature about how embedded computing and "smart city" technology impacts important areas of government service provision, notably public safety and emergency management. First responders and emergency managers have historically been, at best, an after thought in most smart city projects. This need not be the case moving forward. The collection of interview and documentary evidence in this work would assess first responder data needs, and look at how smart city data collection might contribute to shrinking those knowledge gaps. We investigate the technical aspects of the system in Section 4, Section 5, and Section 6. We detail our proposed policy research in Section 7.

3. Background and related work

In this section, we review existing research and technologies that are related to this work.

3.1. Mesh network data collection systems

Efficient and reliable data collection in smart cities is primarily hampered by meager power availability of sensing nodes and their embedded communication modules. When coupled with other major requirements such as mobility, scalability, and interoperability support, this limitation inexorably inclines developers toward low-power mesh wireless network (Habibzadeh, Soyata, Kantarci, Boukerche, & Kaptan, 2018). WiFi, IEEE 802.15.4, and its many variants (such as ZigBee and WirelessHART) are the prime candidates for implementation of such networks. Although reliable and low power, ZigBee suffers from substantial performance reduction in coexistence with WiFi (Yang et al., 2016). It also provides limited throughput and offers poor scalability (Ndih & Cherkaoui, 2016). WiFi can be superior to ZigBee in terms of the aforesaid requirements; however, its considerably higher power consumption hinders its widespread application in power-scant implementations. The high energy demand for reliable connectivity can be counterbalanced by ambient energy harvesting solutions. Various energy sources from RF to vibration to thermal are investigated in the literature (Shaikh & Zeadally, 2016; Soyata, Copeland, & Heinzelman, 2016); nonetheless, wind and solar energy harvesting remain the primary power sources for medium and high power systems.

IEEE 802.11s is a viable candidate for implementing wireless mesh networks. Unlike the common architecture of WiFi (IEEE 802.11), this amendment is configured for multi-hop topologies, which do not rely on central APs and wired communication backhaul. In IEEE 802.11s, multiple WiFi-enabled stations connect to each other in a peer-to-peer fashion to create a mesh basic service set. One or more selected stations in each cluster acts as gateways to provide *global* connectivity for the mesh service set. This facilitates the realization of large scale peer-to-peer networks, which are particularly of interest for emergency communication. The disaster recovery system (DRS) proposed in Hepner, Muenzner, and Weigel (2017) utilizes the embedded WiFi modules of smartphones and other portable devices to establish a battery-powered mesh network. The traffic is directed through the network to eventually reach gateways with broader access (e.g., internet connectivity). Indeed, relying on battery-powered devices limits the life of the network even in the presence of energy saving solutions (e.g., duty cycling). The main advantage of IEEE 802.11s can be associated with its ubiquity and convenient deployment, however, the complexity of the routing mechanism can degrade the performance in large networks (Minh, Shibata, Borcea, & Yamada, 2016).

3.2. Peer to Peer (P2P) communication networks

Avoiding single failure points and providing alternative routes are the primary advantages of mesh networking topology, which is the de facto standard of emergency management systems, for sensitive data collection scenarios. E-SPONDER (2000) provides real-time data collection and communication among First Responders (FRs) in emergency situations. Considering that the existence of functioning communication infrastructure is not guaranteed in these scenarios, E-SPONDER utilizes IEEE 802.11-based mesh networks to establish person-to-person and person-to-group communication in Incident Area Networks (IAN) (Palmieri, Ficco, Pardi, & Castiglione, 2016a). Another resilient self-organizing emergency network is detailed in Aloi et al. (2015), which aims to establish a multi-hop uniform network by connecting normal end-devices such as smartphones and tablets via WiFi connectivity. The reliability of the network emanates from its mutation, cooperation, and evolution capabilities. *Mutation* allows each node to autonomously assume a specific role such as gateway or access point. *Cooperation* ensures intra-network behaviors based on swarm intelligence, and *evolution* enables individual nodes to change their role automatically through software upgrades (e.g., changing from AP to 3G/WiFi gateway). An emergency network for extensively-damaged areas is investigated in Nemoto and Hamaguchi (2014). This network uses WiFi and WiMAX-based mesh networks with satellite connectivity. A fleet of Unmanned Aerial Vehicles (UAV) are used as intermediary nodes to relay signals between the satellite and mesh networks. Finally, first introduced in the LTE Release 12 (R-12), LTE Proximity Services (ProSe) adds direct device-to-device communication capability, where no intervention from eNB is required. ProSe is particularly developed by the 3rd Generation Partnership Project (3GPP) for public safety and emergency applications (Lin, Andrews, Ghosh, & Ratasuk, 2014). Upgraded in R-13, LTE ProSe now provides support for multi-hop connectivity as well (Lien et al., 2016).

In emergencies and crises, UAVs are expected to play a pivotal role in assessing and controlling the situation. These devices are easy and inexpensive to deploy, cover a large area, and when enabled with artificial and swarm intelligence, can provide autonomous and perpetual operation. The deployment of a UAV as a flexible sensing node, however, faces various challenges. Chief among these are communication and package delivery difficulties. The radius of operation and high-speed mobility of UAVs inevitably increase the package drop rate. This can be alleviated by establishing back-up paths. However, multi-path routing adds to the communication overhead, which translates to additional computational costs and curbs the scalability of the system. The literature includes multiple solutions to address this problem. Particularly, using particle swarm optimization and exploiting the hierarchical structure of the sensing networks, viable K-disjoint path routing solutions can be developed (Al-Turjman & Alturjman, 2018c).

The emerging Vehicular Area Networks (VANET) also provide a viable alternative for establishing emergency communication. VANET can help with dispersing urgent messages about failures in transportation infrastructure. If these messages arrive on time, they can warn drivers and maintenance units in advance and hence prevent potential accidents. The inherent fast-pace nature of transportation, however, substantially complicates the QoS requirements of the service. Additionally, establishing a robust network that remains reliable during emergencies is costly and time-consuming. These requirements can be partially addressed by employing a hybrid approach, which combines the benefits of WSN and VANET. WSNs (using multi-hop routing

(Hasan, Al-Turjman, & Al-Rizzo, 2018)) can relay data from the Road Side Units (RSU) to vehicles on the road (that are not in range of that RSU). Hence the connectivity can be established even if the coverage of RSUs is not comprehensive. This substantially decreases the implementation cost and improves the reliability of the network (Al-Turjman, 2018).

3.3. Smart city wireless communication technologies

With the fifth generation of cellular networks on the horizon, the future of smart city communication is subject to profound changes. In 5G technology, the burden of communication is outsourced to smaller communication cells (termed *femtocells* in the literature), which are powered by relatively less resourceful APs. This approach paves the way for more fine-grained management of the network; an objective which is mostly in line with the increasing heterogeneity of smart city communication (Habibzadeh, Boggio-Dandry, et al., 2018). A typical femtocell base station includes a power supply, transceiver, and computing components and provides various communication services (in terms of QoS) for indoor and outdoor applications (Al-Turjman, Ever, & Zahmatkesh, 2018). The femtocell-oriented architecture of 5G is expected to become preponderant in the coming decade. Hence, it is important for future communication technologies to adopt a similar implementation, which facilitates their potential synthesis with 5G technology.

Security remains a critical hindrance against the widespread application of wireless communication in future smart cities. An effective authentication that does not add to the complexity of the system and does not involve users in a cumbersome procedure is still required in the field. To this end, the work in Al-Turjman and Alturjman (2018a) proposes context-sensitive seamless identity provisioning (CSIP), as a cloud-based authentication method compatible with both CoAP and HTTP. CSIP minimizes the risks of identifying theft by analyzing and learning access patterns. This paves the way for convenient and automatic authentication. Notwithstanding its critical role, protecting network security involves more than authentication. In fact, in addition to authentication, authorization and access control, a comprehensive solution must involve all components of the system (routers, switches, firewall, etc.) to effectively avoid and detect possible threats. Merely relying on encryption is oftentimes inadequate to safeguard the system, implying that a robust security preserving solution must be implemented as a framework (Al-Turjman & Alturjman, 2018b; Alabady, Al-Turjman, & Din, 2018).

Another aspect of the shifting paradigm of smart city communication can be associated with the gradual expansion of multimedia traffic share, which has led to the emergence of so-called Wireless Multimedia Sensor Networks (WMSN). Harnessing the sundry challenges of real-time WMSN requires numerous adaptations in routing mechanisms. Especially, multi-path routing protocols play an integral role in fulfilling many QoS requirements of WMSNs as they improve the odds of packet delivery, add to the network's reliability, and balance the network's load. It is also possible to make multi-path routing algorithms cognizant of the network's energy availability, where packets are forwarded based on the energy budget of each node (Hasan, Al-Rizzo, & Al-Turjman, 2017). This is particularly important to sensor nodes with energy harvesting capabilities, where their dynamic energy availability entails adaptive energy-aware routing protocols.

3.4. Smart city data analytics and application API

Unraveling the entangled dynamism of smart city applications hinges on the existence of a strong machine intelligence substrate. Advanced data analytics techniques such as emerging machine learning and deep learning solutions, when coupled with resource abundance of the cloud, can well satisfy this requirement. Particularly, in the context of crisis prevention and management, these solutions can provide a reliable framework for effective resource management and prediction. For example, the research conducted in Gupta, Kambli, Wagh, and Kazi (2015) utilizes Support Vector Machine (SVM) to compute the correlation between past data and real-time load distribution of power lines to efficiently predict the outset of a blackout in smart grids with the impressive accuracy of 100%. Another study (Hasenfratz et al., 2015) uses Land-Use-Regression (LUR) to formulate the dependence of air quality on historical explanatory data parameters such as traffic, road status, and industrial density. By circumventing the requirements for expensive centralized stations, this approach paves the way for inexpensive fine-grained air quality monitoring and prediction (when fed with expected explanatory data). Utilizing the existing symbiosis among different machine learning solutions, the study carried out in Wu and Peng (2017) conflates Back Propagation Neural Networks (BPNN) with *k*-means to estimate expected output power of wind turbines. An ensemble of researches in the literature has also studied distributed analytics implementation (Kim, Stankovi?, Johansson, & Kim, 2015; Patwary et al., 2012; Qin, Fu, Gao, & Zheng, 2017). A wide spectrum of commercial products provides IoT *Platform-as-a-Service* (*PaaS*), which can reliably host a diverse range of smart city services while ensuring their security, scalability, and interoperability. For example, Google's PaaS, Google Cloud IoT service (Google LLC), offers various APIs for device management, access control, data storage and delivery, etc. as well as tools for data analytics, machine intelligence, and data visualization. Alternatively, Microsoft Azure IoT Suite (Microsoft Corp.) makes available a rich collection of APIs and SDKs for device management and configuration to developers. Other notable existing PaaS products include IBM Watson IoT (IBM Corp.), GE Predix (GE Inc.), and Amazon AWS IoT (Amazon Inc.).

3.5. Hybrid solar/wind energy harvesting

Most of the existing ambient energy harvesting sources in the literature such thermal (Lu & Yang, 2010), RF (Honan et al., 2015), vibration (Moss, Payne, Hart, & Ung, 2015), and acoustics (Li, You, & Kim, 2013) are tailored for low power devices ($\leq$1W). For more demanding systems such as the proposed smart box with a nominal power of $\leq$10 W, solar and wind energy harvesting are the most suitable options. Due to its solid-state implementation, predictable power generation behavior, and impressive power density (28.5 mW/cm^2) solar energy remains the primary solution for such autonomous systems (Hassanalieragh et al., 2016; Zhu et al., 2018). Wind energy is inherently more erratic, outputs AC signals, and includes mechanical parts, all of which render it less applicable to many applications. Nonetheless, the extensive study conducted in Habibzadeh, Hassanalieragh, Ishikawa, et al. (2017) underlines the benefits of hybrid solar/wind energy harvesting. The authors show that exploiting the complementary availability of solar and wind cannot only reduce the downtime but also the energy storage size (by almost a factor of two). This improves the energy-availability, cost, and the form factor of smart boxes. The cited study also proposes a resilient hybrid harvester with capabilities such as auto-wake up and self-healing features, which are crucial to our mission-critical application.

We envision our smart boxes to be equipped with hybrid solar/wind harvesters proposed in Habibzadeh, Hassanalieragh, Ishikawa, et al. (2017), which are particularly developed for medium-power (1–10 W) autonomous devices. Based on the application, the harvester proposed in these two works can be implemented in three architectures: *independent*, *cooperative*, and *time-multiplexed*. These architectures offer trade-offs among cost, complexity, reliability, and availability of the system, which add to the resilience of our smart boxes.

3.6. Bio-energy harvesting

Relying on electro-chemical activities of microorganisms, Microbial Fuel Cells (MFCs) are proven effective for wastewater bio-energy harvesting. Regarding the nominal power, MFCs cannot surpass relatively more conventional energy sources such as wind or solar, however, they can provide a steady and predictable energy inflow. This allows the system to continue its most basic options even in the absence of wind and sunshine; a crucial requirement for our mission-critical smart box. The maximum achievable power of an MFC relies on various aspects such composition of wastewater, temperature, physical dimensions of substrates and their chemical structure (Pandey et al., 2016). The power density ranges from 14 mW/m^2 (Sulonen, Kokko, Lakaniemi, & Puhakka, 2015) to 2770 mW/m^2 (Catal, Li, Bermek, & Liu, 2008). However, output power density typically changes inversely with a working volume of MFCs, implying that increasing the physical dimensions of the substrate yields diminishing returns (Dewan, Beyenal, & Lewandowski, 2008).

3.7. Smart city policy

The current state of affairs in research at the intersection of smart cities and policy or organizational concerns could be characterized as rapidly expanding, but still underdeveloped and fragmented. That is, there are numerous streams of research that have not yet coalesced around a set of key problems, and that have neglected some important topics leaving lacunae unaddressed. Much like smart city deployments, smart city literature tends toward narrow focus and narrow application rather than broad cross-disciplinary approaches. As Nam and Pardo note: "… infusing intelligence into each subsystem of a city, one by one transportation, energy, education, health care, buildings, physical infrastructure, food, water, public safety, etc. is not enough to become a smarter city." (Nam & Pardo, 2011b). It is interesting, and perhaps telling, that they mention public safety here. Public safety, first responders, and emergency managers remain an important urban and municipal constituency that is under-addressed in the smart city literature. While there are a few attempts to address questions of public safety and disaster response directly (Asimakopoulou & Bessis, 2011), the more common occurrence is for such issues to be peripherally mentioned in pieces focused on other kinds of smart city deployments or efforts (Washburn et al., 2009). In fact, even when the concept of disaster or emergency in the smart city are addressed, they are often framed as technological challenges to be managed rather than problems for which technology could provide part of the solution. See for example "The components, systems, networks, and architecture are all important to the security design and reliability of the Smart City communications solution. But it's inevitable that an incident will occur at some point and one must be prepared with the proper Incident Response plan." (Bartoli et al., 2011). This focus on smart city technology as the object of disaster, rather than a part of the solution to disaster response is one key constraint of the current literature that this paper hopes to address. The application of smart city technology to questions of disaster response and emergency management is one key area of focus for this paper.

Interestingly, there is a large literature around disaster communication and first responder communication networks (Manoj & Baker, 2007; Philpott, 2008; Sawyer, Tapia, Pesheck, & Davenport, 2004), however, it is overwhelmingly focused on radio communications, interoperability, and specific technologies like RFID (Guerrieri et al., 2006) or problems like location sensing (Rantakokko et al., 2011). There is a paucity of work directly integrating first responder communications with the smart city and IoT literature. There is some thought given to the topic (Bartoli, Fantacci, Gei, Marabissi, & Micciullo, 2015; Palmieri, Ficco, Pardi, & Castiglione, 2016b), but the literature is underdeveloped and what does exist focuses overwhelmingly on technological questions—like architecture—rather than organizational and policy questions. While attempts to grapple with these issues exist in narrow areas, like disaster health care (Malan, Fulford-Jones, Welsh, & Moulton, 2004), they too tend to focus more on technology than organizational questions, and integration across disciplines is largely unexplored.

The second area of focus is the set of questions around smart cities being more than just about technology deployments, but rather part of municipal and urban reorganization and related changes in governance. Nam and Pardo have spoken of the smart city being a constellation of "technology, people, and institutions" (Nam & Pardo, 2011a), which it is, and so while the literature has a strong grip on the technology, the people and institutions (how they adopt such technologies and incorporate them into their jobs and organizations) remain under-examined. They go on to illustrate that this results in important policy questions, Nam and Pardo (2011b) suggesting that smart cities cannot properly be understood without a better understanding of "management, policy, and context." While there is an understanding of the importance of integrating technology and organizational issues—like coordination (Toulmin, Givans, & Steel, 1989) and culture (Marincioni, 2007)—in disaster communications, such insights are still just beginning to grow in the smart city literature.

4. Smart box mesh network

In 2012, the Department of Homeland Security conducted a major study of cyber risks to the Emergency Services Sector (Department of Homeland Security, 2012), which reports seven potential scenarios that could interrupt emergency services crucial operations. At least four of the seven scenarios of most concern to the sector in the cyber realm involve the interruption of data and/or voice communication to, or among, first responders. Such challenges range from "Natural Disaster Causes Loss of 9-1-1 Capabilities" to "Overloaded Communications Network Results in Denial of Service Conditions for Public Safety and Emergency Services Communications Networks." What is clear from the report is that there are serious challenges to the provision of emergency services that arise from the interdependencies that the sector has with the communications sector; and particularly the fact that so much of regular emergency communications rides on the same infrastructure as commercial communications. Disasters put first responders and emergency managers at the risk of becoming metaphorically blind, deaf, or mute, when communications networks are impacted by malicious, accidental, or natural disasters. This inter-dependency, and the vulnerabilities that emerge from it, are a key animating force behind the architecture of the smart box network described in this paper.

This paper includes an emergency mesh network (Fig. 1), a software architecture for this network, and a comprehensive approach to assess the adoption, usage, and costs and benefits of these networks to the cities that employ them. The paper seeks to demonstrate the technical capability of the devices and network, their usage by municipal partners, and the policy and organizational hurdles and best practices to their introduction into the smart city environment. Our mesh network is capable of working in two different modes; in ***normal mode***, the network collects environmental data such as CO_2, O_3, noise, NO_2, and vibration levels and transmits them to the IT services (through long-range WiFi) for storage and data analysis, and ***emergency mode***, in which the network completely shuts down its sensing operations and provides a communication network for first responders through its WiFi network.

The network is composed of small ($1.5\,\text{ft} \times 1.5\,\text{ft} \times 1\,\text{ft}$) boxes (termed **smart boxes**), which are capable of harvesting energy from solar and wind sources (as well as bio-energy, when deployed at a waste water treatment site). They continuously harvest energy and use long-range (1–2 km) WiFi communication to send their data to the IT services, as well as communicate with each other; furthermore, they use auxiliary smartphones of volunteering city residents (or city officials) to extend the range of the WiFi network. Successful development and deployment of the hardware, software, and policies will have a transformative impact on the design of advanced smart city application deployments, as the implementation can be inexpensive, effective, and holistic archetype for the potential needs of future smart cities.

Fig. 3. A long-range (2 km) WiFi device.

In the rest of this section, we detail the sensing and communication infrastructure of the smart box network.

4.1. Sensing infrastructure

The primary *engineering challenge* in building the sensing component of the smart boxes is determining which sensors to use to provide the highest information content—for environmental conditions—at the lowest cost. Commercially-available inexpensive sensors provide measurements for noise levels (by using microphones), vibration levels (by using accelerometers), location (by using GPS devices), temperature, and a slew of air-quality-related metrics, such as NO_2 (a by-product of combustion), CO_2, and O_2. Furthermore, because of incorporating solar and wind power sources for energy harvesting, smart boxes are capable, by definition, of measuring wind speeds and solar irradiation levels. This level of sensing capability can enable a rich set of smart city applications. Research challenges to address in this thread are:

4.1.1. Implementing crowd-sensing

A sensing network of volunteering city residents or city employees' smartphones can be used to perform environmental sensing, which is termed *crowd-sensing* (Pouryazdan, Kantarci, Soyata, & Song, 2016); the goal of crowd-sensing is to augment the sensing capabilities of the smart boxes by incorporating the sensor data from the participating smartphones by continuously communicating with the nearby smartphones and collecting their data, merging this data into the smartbox-collected data and sending them to the city IT center. Recent research investigates the quantitative metrics, utility, and feasibility of *crowd-sensing* (Pouryazdan et al., 2016; Pouryazdan, Kantarci, Soyata, Foschini, & Song, 2017). Smart cities already use various smart city applications (some of which use a smartphone app that is downloaded by their residents), which reflects their initiatives to involve their volunteering residents. We propose to incorporate crowd-sensing techniques into the embedded software design within the smart boxes; note that the practicality and utility of this, along with the adoption by citizens, is a challenge in crowd-sensing (Pouryazdan, Fiandrino, et al., 2017). Furthermore, one of the most important research challenges in incorporating crowd-sensing into the smart box design is making the participation in the crowd-sensing network energy efficient to avoid draining the battery of the volunteers' smartphones.

4.1.2. Implementing sensor substitution

This research thread departs from the hypothesis that the information obtained from a sensor can be *emulated* by using one or more completely different sensors. A recent case study of this was published in Kaptan, Kantarci, Soyata, and Boukerche (2018), which investigates the feasibility of emulating (substituting) a GPS sensor using a microphone and accelerometer. The case study is conducted by measuring sound levels (using a microphone in a smartphone) and vibration levels (using the accelerometer in the same smartphone) inside a bus during its ride along a static route. The idea is that the vibration levels follow a certain pattern due to the pots and imperfectnesses on the road, as well as the stop-start patterns of the bus along that static route, which gives statistically-relevant clues about the location of the bus. Similarly, the sound levels provide information about the number of passengers along the route, which is statistically-correlated to the location of the bus. The study reports between 80–90% accuracy (depending on the bus route) in predicting the location with two completely different sensors.

Based on the sensor substitution idea, we will formulate a machine learning platform to predict *asthma symptoms* in Section 6.3; our idea is to compute *pollen count* by using completely different sensors, such as temperature, wind, etc.

4.2. Communication infrastructure

Typical WiFi communication range of a tablet or a smartphone is approximately less than 100 m, however, specialized long-range WiFi devices (such as the PowerLink device shown in Fig. 3) allows WiFi communication up to 2 km. The power consumption goes up substantially when communicating over longer ranges; while a smartphone uses up to $\approx$0.7 W for its WiFi link (Carroll & Heiser, 2010), the Powerlink device consumes 3.5 W to transmit and 2 W to receive within the 2 km range. This is perfectly acceptable for purposes of smart box development, because extending the communication range to 2 km allows a much less dense smart box deployment scenario within a smart city. A city with an area of 28 km^2 (close to 4 km × 7 km) can be completely covered with by using a handful of smart boxes, theoretically. However, in practice, closer to 20–30 smart boxes will provide much better coverage and redundancy, because WiFi interference from ambient cell phone traffic as well as the obstacles among smart boxes reduce the signal-to-noise ratio (SNR).

In the emergency mode, the group of deployed smart boxes establishes a mesh wireless network of access points using their embedded long-range WiFi modules. Increasing the deployment density of smart boxes creates alternative paths, which improves the network's reliability and also helps with a more uniform energy consumption among APs (using energy-aware routing algorithms). Alternatively, a surrogate path can be established through a multi-hop connection of users' WiFi-enabled devices (as shown in Fig. 4). This, however, requires the presences of a large number of users in the area. Besides, all users' devices should be set up to become compatible with WiFi mesh networks. As long as two entities (citizens or first responders) are in the range of any of these smart boxes, they can use their conventional WiFi-enabled devices to communicate with each other. Any disruption in existing paths between two smart boxes divides the network into two isolated clusters. The disconnected clusters cannot exchange data packages, nonetheless, they can still provide local connectivity services.

Each smart box can be built within a budget of $\leq$1000. Powerlink devices connect to the tablet through a USB port. The energy harvester is capable of powering the tablet, as well as all external devices, such as the Powerlink device. While the *engineering challenge* is to design a functioning smart box, the *research challenge* in smart box design is establishing a WiFi network that is capable of using the nearby smartphones to extend its range, as shown in Fig. 4, which depicts a scenario where the smart boxes use volunteer smartphones to provide a link between an emergency ambulance and a firefighter.

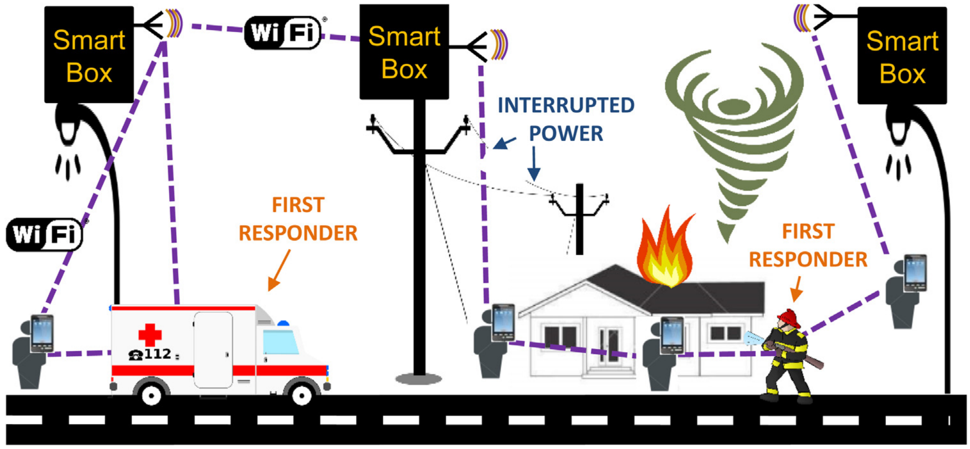


Fig. 4. Smart boxes use volunteering smartphones to establish a long-range WiFi network among first responders.

5. Hardware design and energy harvesting

Our first aim involves the conceptualization of the hardware architecture for the smart box network, as shown on the left side of Fig. 2; this hardware architecture includes four distinct components: **(i) the main unit**, which is the primary computational unit, including a rechargeable battery, **(ii) energy harvesting**, which is the circuitry that is capable of turning solar irradiation, wind power, or bio-fuel into usable electrical energy by the hardware inside the smart boxes, **(iii) sensing**, which is the hardware that measures environmental quantitative parameters, such as noise, Ozone, and Oxygen levels, and **(iv) communication**, which is the hardware that provides a communication link among smart boxes, as well as first responders. Fig. 5 shows an example deployment of the proposed smart box in the field. This box is powered by a solar panel and captures real-time video streams using a conventional camera. A generic smart box can incorporate any sets of sensors and a combination of solar, wind, and biofuel energy harvesting units. All three of these components require addressing research challenges for their development and incorporation into the smart box design, as detailed below.

5.1. The main unit

The *engineering challenge* in designing a smart box is to make it sufficiently inexpensive to the point deploying them at a mass scale (e.g., 10 s or even 100 s throughout the city) is affordable. This will shift the redundancy focus towards "system level redundancy" rather than "redundancy of each box." The smart boxes should be able to function from the buffered energy inside their rechargeable Li-Ion battery in the event no power source is available. For example, in a night when no solar energy is available and it is not windy, no energy can be harvested. Assume that there is an emergency at sunset. In this case, the smart box must be able to function overnight, until there is sufficient sunshine at sunrise. This is approximately 8–12 h of operation, depending on the deployment location. Each long-range WiFi consumes 2–3 W and the entire power consumption of the box is estimated to be 3–4 W, based on previous deployments (Zhu et al., 2016, 2018). This means that 12 hours of operation will require an energy buffer of at least $E = P \cdot t = 12 \cdot 3 = 36$ W-h.

To perform the duties of a smart box, a *tablet* is perfectly sufficient. A modern 7″ tablet includes a quad-core CPUs and incorporates a 21 Wh Li-Ion battery (e.g., Samsung 8″ for $159), while a large 13″ tablet includes a 41 Wh battery (e.g., Ipad Pro for $700). For deployment, the internal LCD and WiFi must be shut down to reduce power consumption and external WiFi (through the PowerLink) must be used. Some case study deployments can be found in Zhu et al. (2016), Zhu et al. (2018). The *research challenge* in the design of the main unit is to develop energy-aware algorithms to use the energy frugally to avoid premature energy depletion.

5.2. Energy harvesting

The most important functionality of a smart box is its capability to harvest its own energy continuously; this capability makes a smart box independent from the power grid, which can be interrupted during a catastrophic event. While a smart box itself can be destroyed as part of the emergency, having a substantial amount of smart boxes throughout the city (e.g., 10 s or 100 s) substantially reduces the reliance of the

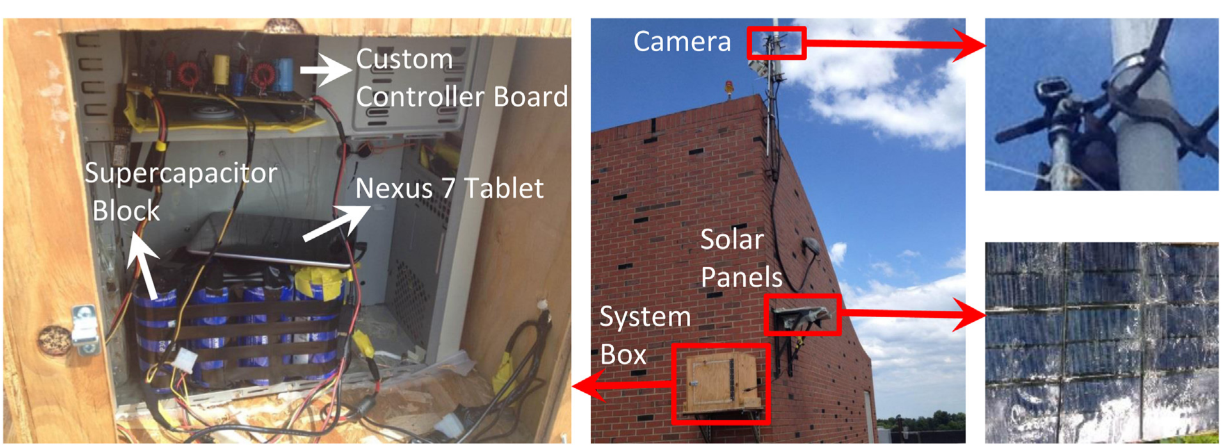


Fig. 5. An example deployment of smart box in the field. This picture is borrowed from Zhu et al. (2018) with the authors' permission.

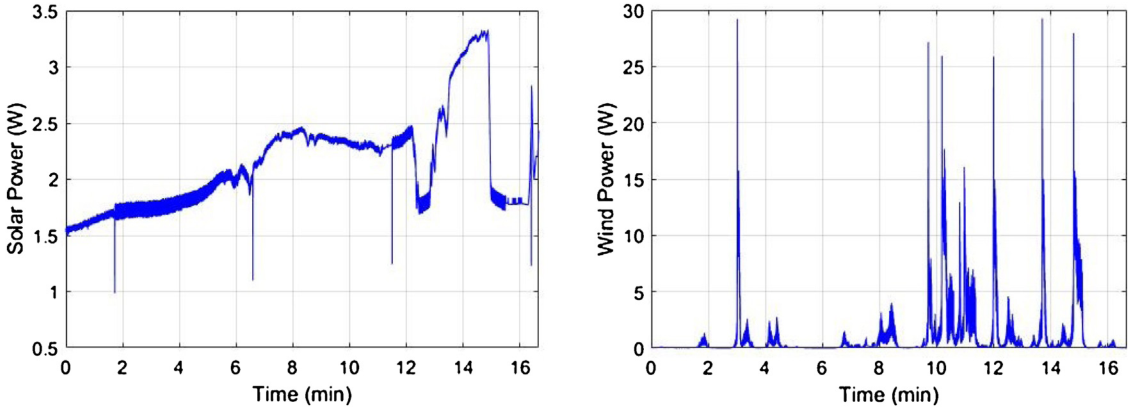


Fig. 6. Spontaneous power from solar and wind sources in a hybrid solar and wind energy harvester.

system on any individual smart box. Furthermore, a smart box is designed so that even if one of its energy sources is interrupted (e.g., by falling on the ground and the wind turbines "getting stuck" and not being able to produce energy from wind), the solar source may still provide energy due to the solar panels being exposed to sunshine.

5.2.1. Solar/wind energy harvesting

Because the Samsung tablet does not have any energy harvesting circuitry built-in, previous designs must be improved and adapted to the smart box network; these designs include solar-only (Hassanalieragh et al., 2014, 2016) and hybrid solar/wind harvesters (Habibzadeh, Hassanalieragh, Ishikawa, et al., 2017; Habibzadeh, Hassanalieragh, Soyata, et al., 2017). Fig. 6 depicts the instantaneous power generated by solar and wind in hybrid harvesting. The data collected on November 5th (a cloudy day), 2016 in Rochester, NY. The solar energy harvester included three solar panels (a parallel combination of a single 30 W and two 10 W panels). The wind turbine had a nominal output power of 50 W. During this experiment, wind harvester generated an average power of 0.81 W, while the solar panel delivered 2.28 W. This amounts to an aggregate average harvested power of 3.09 W for the hybrid harvester.

5.2.2. Bio fuel energy harvesting

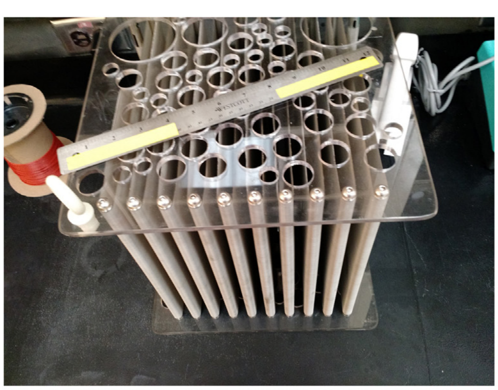
The *research challenge* in this thread is to incorporate bioenergy generation into the smart box design and investigate the energy consistency when this third (and highly diverse) energy source is included.

Fig. 7a shows the biofuel energy harvesting apparatus used to power the smart box. Fig. 7b depicts the load voltage of the device. To generate this data, the apparatus was deployed in the Ithaca Wastewater treatment facility for approximately two and a half months. During this experiment, the output load was set to 1 KΩ. As demonstrated in this figure, the amount of generated power does not compare with wind or solar sources, nonetheless, the biofuel harvester could deliver a stable 0.6 V output amounting to approximately 36 mW. Fig. 8 depicts the attained power density of the device over a course of two months. The data points (blue) represent the measurements, whereas the red line presents the average. As evident in the figure, the average power density reaches a peak of $\approx 70\,\mathrm{mW/m^2}$ and typically hovers around $\approx 30\,\mathrm{mW/m^2}$.

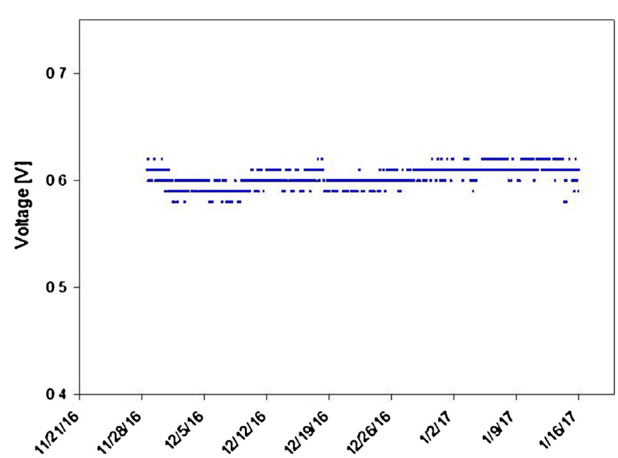
Biofilms can interact electrochemically with the surfaces they are growing on. Manganese (MnO_2) and iron (Fe III) reduction can be done by Shewanella oneidensis (Myers & Nealson, 1988). If a biofilm grows on an electron acceptor substrate the bacteria closest to it become specialized in respect to those growing at the surface of the biofilm. Well defined oxido-reduction potentials, ORP, gradients have been reported on biofilms growing on electroactive surfaces (Yuan, Zhou, & Tang, 2013). The bacteria growing in close proximity to the substrate, de facto an electrode will have access to an unlimited source of electron acceptors (Nealson & Finkel, 2011). A mature biofilm will have an aerobic surface and an anoxic core with a net flow of electrons to the substrate. In the anodic volume of the biofilm organic compounds are oxidized anaerobically, according to the following reaction, for Glucose as an example (Menicucci et al., 2006):

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-,$$

While in the cathodic volume of the biofilm, O_2 is reduced according



(a) 3D bio-energy harvesting apparatus.



(b) Output voltage at 1 kΩ load

Fig. 7. Bio fuel energy harvester (left) and its harvesting performance (right).

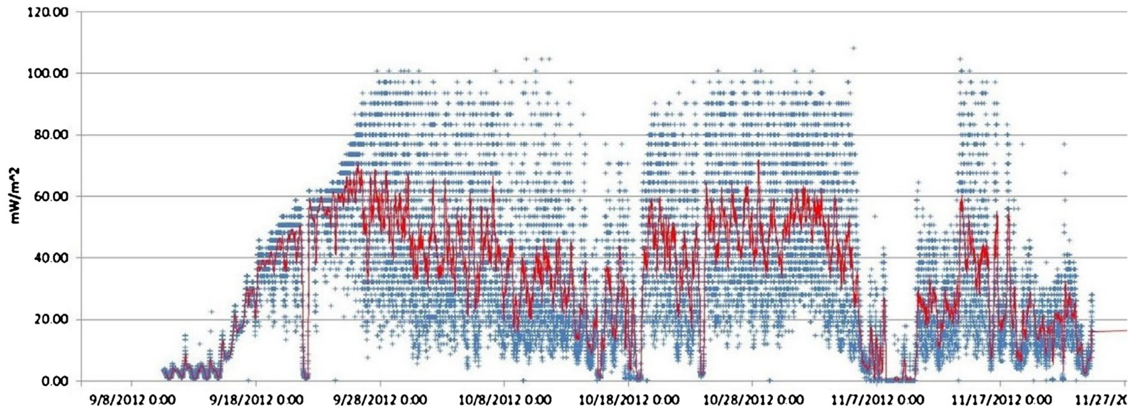


Fig. 8. Achieved power density of biofuel energy harvester.

to: $O^2 + 2H^2O + 4e^- \rightarrow 4OH^-$.

Fig. 7a shows the apparatus that is capable of generating bio-energy from waste water using a long sheet of metal bio-film that is wrapped around 10 times; this 1 ft × 1 ft × 1 ft device generates 110 mW on average and is demonstrated to peak at 1.35 W. We propose to deploy this device outside the smart box (inside a wastewater tank) and connect it to the smart box through a power line. These measurements were taken using a fixed load, which are not optimal. Our proposed research thread is to implement an automated Maximum Power Point Tracking (MPPT) algorithm (Fahad et al., 2012; Habibzadeh, Hassanalieragh, Ishikawa, et al., 2017), which is able to adjust (vary) the load based on the available power. We expect this to substantially increase the generated power (to about 200–300 mW). Using a large number of these cubes (50–100, arranged in a 7 × 7 or 10 × 10 array) will allow us to generate power that is sufficient for the smart box operation (15–30 W). The cost of this array is expected to be $2000, which can be further reduced by experimenting with larger cubes with a higher number of wrapped metal film.

6. Software architecture and application programming interface (API)

Intelligent infrastructure is becoming the bedrock to the success of any smart city framework and architecture as noted in the recently released news print by the Computing Research Association. Intelligent infrastructures combine intricate details of sensing, communication and computing capabilities into making any smart city concept realizable. Our second aim addresses the infrastructure needed to formulate a data collection, storage, and decision making system, which will be realizable by building a software architecture—API to handle the intricacies of making this successful. Enterprise systems are typically customizable and integrate application software that enables the fusion of various important component of any enterprise e.g., a city (Chofreh, Goni, & Klemeš, 2018; Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014). Commercially available software using enterprise resource planning (ERP) exists that integrates every function i.e., data representation, fusion, transmission, storage, integration, prediction but these are very expensive and proprietary to third party companies (Ahmad & Mehmood, 2015; Seethamraju, 2015). Specialized software architecture using the ERP methodology—which is tailored to cater to the city's pertinent needs—will be presented in this paper.

6.1. Data collection and integration

Sensors on the smart boxes will be collecting data as required by the city. Our inquiries from an existing smart city confirmed their interest in sensors such as wind, temperature, seismic vibrations, NO_2, O_3 and CO_2 toxic levels. This data will need to be collected and forwarded to a central back-end unit for further processing. However, due to the heterogeneity of the sensor and data being collected, issues such as unbalanced energy consumption could affect efficient collection and fusion of data collected (Vaidyanathan, Sur, Narravula, & Sinha, 2004).

Sensor Model Language (SensorML) (Botts & Robin, 2007) provides a standard modeling paradigm to build ontology frameworks for expressing the collected data. We propose to use SensorML, because it will enhance and automate the utilization of the data irrespective of the number of third-party applications bought by the city. SensorML is a data model in UML that helps capture relationships common to all sensors via the creation of classes and functions to help facilitate processing and integration of the observed data from the different sensors we have available on the smart boxes.

Data collected should be efficiently transported to the back-end (e.g., database) for further processing (such as delivery to third-party vendor applications procured by the city) and further utilization of the data for specific predictive analysis local to the city's unique needs and interests (e.g., prediction locations in the city where people are prone to have asthma) and the possible reasons behind it. Data transmission protocols abound (e.g., UDP, TCP, CoUDP), which handle the transmission of media during network congestion that impedes data flow. Wireless communication interface best suited for projects of this nature should meet the research underlying motivation i.e., dependable, low cost, portable and cross-platform.

6.2. Data storage and management

Data collected daily from the sensors on the smart boxes need to be stored efficiently. How these data are isolated, distributed, and stored is very important. Data being collected have to be stored in such a way that their relationships can be harnessed and manipulated for predictive analysis and third-party smart city applications. Existing platforms such as RDBMS, DBMS, NOSQL are based on the Hadoop HDFS (Hadoop, 2009; Rashid, Gondal, & Kamruzzaman, 2017) and allow for creation of new data elements with low impact on the application (Rodrigues et al., 2018). However, there is still a need for flexible solutions that can account for changes in the data or the applications which graph databases can handle efficiently (Cathey & Dailey, 2002; Cattuto, Quaggiotto, Panisson, & Averbuch, 2013). Graph databases are essential to discovering, capturing and making sense of complex inter-dependencies within collected data. Fig. 9 gives a description of our approach.

6.3. Predictive analysis

6.3.1. Asthma and sensor substitution

Our inquiries from an existing smart city confirmed their concern about the rise of asthma. They are interested in a model that determines areas in the city with a high pollen count, which will eventually help

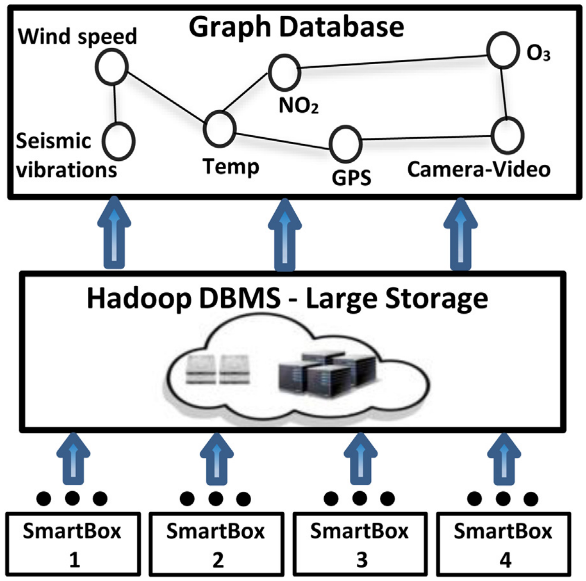


Fig. 9. Example database schematic.

them in terms of designing building codes. Predictive analysis and sensor substitution (see Section 4.1 for details on sensor substitution) are an ideal means to gather intelligent information and facilitate decision support for city officials. According to the World Health Organization (WHO), asthma allergic conditions are worsened by pollen present in the air but till date, pollen counts are still manually collected in a time consuming and tedious process. According to the Allergy Bureau, there are only 48 stations in the united states where pollen counts are located (Liu et al., 2017). This leaves local communities at a disadvantage. Local information received from the sensor to predict pollen counts provides an ideal way to get much-needed information within the locality of interest.

There are no sensors that detect "pollen count," but smart boxes incorporate sensors that detect wind speed, temperature, dew point, rainfall, etc. Innovating a "virtual pollen sensor" is one essential and novel contribution to make. Table 2 shows preliminary investigations using meteorological data taken from the national weather service and the pollen level from the American Academy of Allergy Asthma and Immunology (AAAAI) data repository. This preliminary study indicates that there is a high correlation between pollen count and this meteorological data like temperature, dew point, and humidity. We propose to use machine learning techniques to elucidate this fact to predict pollen counts from this meteorological data, as formulated in Eq. (1); we can compute the correlation of existing sensor information using random forest algorithms to determine the pollen count for the city.

$$\mathrm{Sensor}_{(\mathrm{PollenCount})} = F_{\mathrm{randomforest}}(S_1, S_2, S_3, \ldots S_n) \quad (1)$$

Random forests are supervised classification machine learning methods that build multiple decision trees and output classes or behaviors most prevalent in all the trees developed. Random Forests are multivariate, non-parametric function with N input variables and so best suited for this sensor substitution. Successful implementation of

Table 2
Correlation between sensor data and pollen levels.

Correlations	Temp	Dew	Humidity	Wind	Pollen
Temp	1				
Dew point	0.87	1			
Humidity	0.09	0.55	1		
Wind	−0.10	−0.25	−0.23	1	
Pollen	**0.73**	**0.49**	**-0.25**	**0.002**	**1**

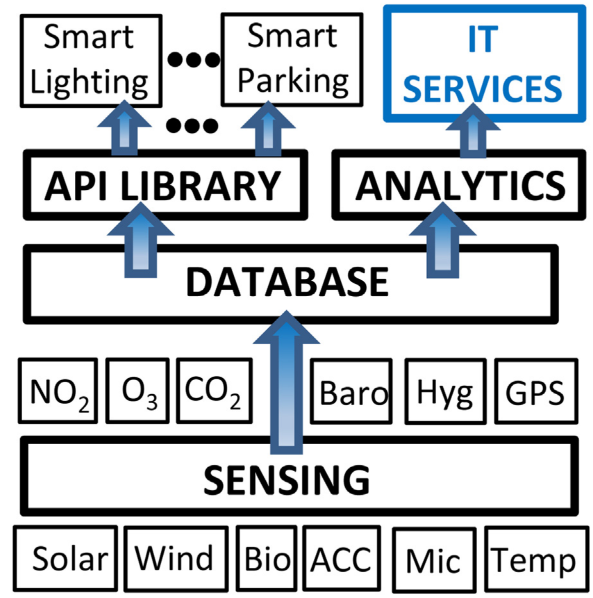


Fig. 10. Example software architecture.

this sensor substitution can provide a much-needed service to the city and can be part of the IT services from this work as shown in Fig. 10. Furthermore, this shows an archetype to *emulate sensors* by using only the existing ones and holds the promise to substantially expand the information that is provided by the smart boxes.

6.3.2. Power line outage prediction

One important aim of this work is to investigate the importance and impact of local sensor information being collected and comparing it to publicly-available and highly crude (i.e., quantitatively averaged) regional data. This is of particular interest because power line outage and disruptions are a huge problem in the Northeast due to weather conditions ranging from heavy snowfall to flooding caused by rainfall and melting ice. This can be mitigated by real time analysis on some smart box-collected environmental information during normal mode operations to keep the city and first responders better informed. Existing research shows the correlation between outages and weather in the long term (DeGaetano, 2000; Degelia et al., 2016; Kankanala, Das, & Pahwa, 2014), however real time prediction can meet the city's immediate needs by using smart boxes and predictive analysis. Providing a predictive analysis as an added intelligent framework for the city's software infrastructure is essential. We propose to use a combination of sensor readings for wind speed and temperature will be used to develop prediction algorithms for the likelihood of power outages due to downed electric lines or power poles.

7. Policy research

One of the key challenges with policy assessments of smart city applications is that they have often—as the applications themselves have—been limited to the deploying agency or agencies. In order to conduct a comprehensive and complete policy assessment around smart city applications, the aperture of analysis needs to be expanded. The idea that such applications need to be assessed at the municipal level, across many agencies with varying levels of connection to the application, is true; but even more pronounced if the application, like the smart box, is to leverage the technical overlap between communications and information technology to offer both normal and emergency mode capabilities. What then might a process for doing a cross-agency municipal level policy assessment for a smart city application look like?

The use of qualitative methods—including interviews, document analysis, observation, and others—to study urban environments in general (Bracken, 2014) and smart cities in particular (Caragliu, Del Bo, & Nijkamp, 2011) is widely accepted. For many kinds of institutional study, political assessment, and policy analysis, quantitative assessments are either incomplete, or even misleading. While qualitative analysis is sometimes harder to interpret or to draw sweeping conclusions from, it remains a key tool for many kinds of policy analysis and is one that can be done rigorously (Baxter & Eyles, 1997). Interviews and interview data can be powerful tools for policy analysis (Leech, 2002) and understanding organizational or management issues (Qu & Dumay, 2011). Another key qualitative method for addressing policy issues (Ritchie & Spencer, 2002), institutional questions, or even policy evaluation (Pershing, 2002) is document analysis (Bowen, 2009). These two methods are often combined in qualitative analysis of policy issues (Owen, 2014).

The methodological approach proposed to guide the policy research component would remain similar throughout—gathering insights from users, potential users, and organizations—however the goal would be to target those methods at numerous key areas of study across phases of a smart box implementation. The goal of a policy assessment process like this would be to understand the institutional and organizational perspectives on this technology, and its implications for policy, across several continua or characteristics. The first is across disciplines and agencies in city government, with a focus both on the deploying agencies, as well as on first responders and emergency management agencies. The second is across steady state or normal operations, and emergency or disaster operations. And finally, looking at these issues across time from the exploration phase, to the adoption phase, to the usage phase, and ultimately to the evaluation phase. By asking the same organizations questions across time, across space, and across bureaucratic boundaries, the goal is to understand how these technologies do, and can, shape city operations and disaster response. As noted in Table 3, doing this will require numerous approaches to data gathering across phases of implementation.

7.1. Initial phase

The initial phase of the research and evaluation process would focus on a series of questions about the adoption and usage of smart city technologies in general. First, it would examine—using documents, interviews, and other data from the partners—how the agencies involved in the project adopt and deploy smart technology. It would focus on decision-making processes, coordination across disciplinary and agency boundaries, and the various costs and benefits that are assessed for such projects. In any deployment locations, there would likely be a series of meetings, observations, and requests for documents that will provide a corpus of data for analysis. This would have to include the agency partners doing the deployment directly, but also target the cities more broadly, such that there is an understanding of the political and institutional environment in which this adoption and decision-making take place. Also in the initial phase, there would be an engagement with first responders about their data usage, data needs, and how they might benefit from data collected from smart city deployments. Such analysis of how smart city applications could provide useful data to organizations other than those deploying them is understudied for unsurprising reasons; but is a key to improving the policy and response relevance of smart city data. This kind of exploratory research would be intended to understand how much these agencies have thought about smart city technology, how incorporated the agencies are into municipal discussions of these technologies, and what their data needs to look like. All of this is designed to assess how existing and future smart city deployments might be able to assist first responders, both in their day-to-day operations, but also in the emergency state when disasters occur.

7.2. Assessment phase

The goal of the data collection in the subsequent years would be less about framing the organizational, policy, and disciplinary constraints on smart city adoption and usage, and be more about beginning to assess systematically how the cities, and city agencies, are using the data from the smart boxes during steady state operations, and how they could or would use the communications capabilities the boxes provide in the emergency state. While continuing to rely on interviews, documents, and internal usage of the data and capabilities provided by this work, the goal of this phase would be to assess the quality of the data provided from an organizational perspective, understand how that data is shared and used, and to assess the integration and adoption of the technology in agencies, and across the municipality. This would involve several discrete pieces. One is a focus on the deploying organizations themselves; a second on their partner agencies in municipal government, and finally, a third is assessment by city first responder agencies and emergency managers. In each of these three cases, there will have to be separate assessments of the contribution these smart boxes make in their steady state, as well as what they could contribute in the emergency state, at least for the responders. One of the key ways in which this approach could uniquely contribute to answering these key questions is by planning and executing disaster simulations utilizing the smart box infrastructure. These simulations would provide both technical performance data and user interview data that could be collated and compared to assess whether technical and organizational or policy-level success appear to be linked, disconnected, or whether there are intervening variables are at play. Finally, at the end of this phase, this work would include both interviews and a brief survey to participants to assess the quality of adoption and usage for the smart boxes, what the city partners believe the boxes did (or could) contribute to their growth as smart cities, and whether there are key or best practices that emerged from their experiences with the smart boxes.

7.3. Presenting and leveraging the data and assessments

The goal of the data collection and assessment efforts detailed above, and of the broad blueprint to both deploy the technology and conduct parallel technical and organizational assessments is ultimately to better integrate the smart city technologies and the agencies using

Table 3
Policy research approaches across the implementation process.

Cycle	Method	Area of interest
Initial phase	Document analysis interviews meeting observation	“decision making processes, coordination across disciplinary and agency boundaries.”
	Document analysis interviews meeting observations	“assess the quality of the data provided from an organizational perspective, understand how that data is shared and used, and to assess the integration and adoption of the technology in agencies, and across the municipality.”
Assessment phase	Disaster simulations	“whether technical and organizational or policy-level success appear to be linked, disconnected, or whether intervening variables are at play.”
	Interviews user survey	“quality of adoption and usage for the smart boxes, what the city partners believe the boxes did (or could) contribute to their growth as smart cities, and whether there are key or best practices that emerged from their experiences.”

them. A proper outreach strategy across academic and importantly practitioner disciplines would be key to taking the information collected, and communicating it to decision makers and practitioners. This would certainly include conferences, journals, and popular venues that target smart city and technology specialists, but would be incomplete without a parallel outreach effort to first responder communities and general city and government agency managers. The truth is that in just a decade or so there have already been several generations of smart city and IoT technologies created and deployed in various ways and places; but most cities using these technologies still have organizational structures (like civil service job titles) that might be 40 or 50 years old, and feature agencies particularly first responder agencies that have cultures that are slow to adapt not just to technology, but even to the idea that decision making should be driven by data (Uluturk, 2012). These organizational, structural, cultural, and policy impediments to broad integration and optimization of smart cities are not only real, they are a key factor to fulfilling the vision of what a smart city can be. Improving or even perfecting - the technology without acknowledging the room for improvement and imperfections that exist at the jurisdictional level is a sure way to smart cities being less smart than they could be otherwise.

8. Summary and concluding remarks

This paper has offered up a proposal for a unique smart-city technical application, the smart box mesh network that has both normal and emergency modes, and a unique socio-technical process for assessing both the performance of the technology as well as municipal integration into policy and operations. In that regard, it proposes two important new approaches to thinking about smart city applications. One that integrates such applications across kinds of incidents (steady state vs. crisis), and one that integrates such applications across a broader than usual array of municipal stakeholders, with a focus on viewing first responders and emergency managers as key customers of smart city data and smart city hardware and software capabilities. The paper, hence, proposes a holistic three-dimensional approach to the realization of smart box mesh network system. The first dimension accommodates the design of the smart box; the core hardware/software building block of the system. The second dimension uses long-range WiFi connectivity to form a unified mesh network of smart boxes. The last dimension holds a spectrum of APIs that help with municipal decision making and address the various challenges pertaining to data heterogeneity.

- **Smart Box Implementation.** Each smart box incorporates four underlying modules. The *main unit* provides on-site processing capabilities typically using a tablet or minicomputer. The *energy harvesting unit* powers the system using either solar, wind, or biofuel energy sources, depending on the deployment site of the smart box. This paves the path for the autonomous operation of the device, which is critical during catastrophic events. To ensure uninterrupted operation, the energy unit buffers the excess energy in embedded supercapacitor-based storage blocks, allowing the device to cope with environmental irregularities and their effect on power availability. A 2.25 ft^3 box can readily accommodate a large enough energy storage unit for a medium-power system. The *sensing* unit comprises sensors that measure various environmental parameters, depending on the application and deployment location of the box. The *communication* module uses long-range WiFi connectivity to pass data to a sink node through a multi-hop network of smart boxes.
- **Smart Box Mesh Network.** Two orthogonal services partition the functionality of this mesh network. The *normal mode* provides both conventional dedicated sensing services and emerging crowd-sensing. An occurrence of a significant even triggers the *emergency mode*, where the network switches its functionality to supply a surrogate emergency communication infrastructure for first responders. The backbone of this network involves individual smart boxes that use their long-range WiFi modules to connect to each other and establish a unified mesh network. Increasing the number of deployed boxes increases the number of alternative routes, which in turn improves the reliability of the system. If there is no path between two nodes of the network (e.g., due to some of the smart boxes being damaged during the emergency), the network splits into isolated stand-alone cells. No communication can happen between two disconnected cells, nonetheless, the network can still guarantee within-cell communication. Further augmenting the capabilities of the network, volunteers can use their WiFi-enabled devices to set up multi-hop connectivity.
- **Software Architecture.** The smart box network relies on a flexible software core to handle the intricacies of city-wide data collection, storage, and decision making. Data collection depends on ontology-based frameworks (e.g., SensorML) to cope with the sensing heterogeneity of both the city and individual smart boxes. The challenges of heterogeneity also evince themselves in data storage solutions. Smart box network, hence, relies on graph databases to better detect intricate inter-dependencies among the data. Finally, the included APIs provide various predictive analytics solutions to facilitate decision making. Particularly, the paper investigates two likely scenarios, where the APIs utilize the underlying correlation between environmental factors to predict pollen count and possible power outages.

The two approaches taken in this paper are departures from the current general realization of smart city applications—like the smart parking meter operated by a municipal parking agency—which have tended to focus instead on dedicated hardware and software with singular applications, that are operated and feeding information to relatively narrow disciplinary agencies. Only a small leap of imagination is needed to see that multi-mode and cross-municipal smart city applications are possible, and one proposed example is spelled in both policy and technical detail here. From implementation to assessment, blue sky day to disaster, and from IT specialist to firefighter, the future of the smart city is much broader than it's present.

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