An Information Framework for Creating a Smart City Through Internet of Things

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Abstract—**Increasing population density in urban centers demands adequate provision of services and infrastructure to meet the needs of city inhabitants, encompassing residents, workers, and visitors. The utilization of information and communications technologies to achieve this objective presents an opportunity for the development of smart cities, where city management and citizens are given access to a wealth of real-time information about the urban environment upon which to base decisions, actions, and future planning. This paper presents a framework for the realization of smart cities through the Internet of Things (IoT). The framework encompasses the complete urban information system, from the sensory level and networking support structure through to data management and Cloud-based integration of respective systems and services, and forms a transformational part of the existing cyber-physical system. This IoT vision for a smart city is applied to a noise mapping case study to illustrate a new method for existing operations that can be adapted for the enhancement and delivery of important city services.**

Index Terms—**Information management, Internet of Things (IoT), network architecture, noise mapping, smart cities.**

I. INTRODUCTION

IT IS EXPECTED that 70% of the world's population, over six billion people, will live in cities and surrounding regions by 2050. So, cities need to be smart, if only to survive as platforms that enable economic, social, and environmental well-being. Smart city is the one that uses information and communications technologies (ICTs) to make the city services and monitoring more aware, interactive, and efficient [1]. Smartness of a city is driven and enabled technologically by the emergent Internet of Things (IoT) [2]—a radical evolution of the current Internet into a ubiquitous network of interconnected objects that not only harvests information from the environments (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analytics, and applications [3].

Fuelled by the adaptation of a variety of enabling devices such as embedded sensor and actuator nodes, the IoT has stepped out of its infancy and is on the verge of revolutionizing current fixed and mobile networking infrastructures into a fully integrated Future Internet. Wireless sensor networks (WSNs), as the sensing-actuation arm of the IoT, seamlessly integrates into urban infrastructure forming a digital skin over it. The information generated will be shared across diverse platforms and applications to develop a common operating picture (COP) of the city.

With urbanization breaking the 50% barrier, it is of paramount importance to understand the demand for service profiles to increase the efficiency of city management. Currently, few municipalities have platforms or systems for live monitoring and inferring of urban process parameters. The commonly employed strategy is data collection, offline analysis, and action; followed by system adjustments and repetition of the whole process. Data collection exercises are often costly and difficult to replicate. There is thus an increased demand on municipalities to incorporate smart technologies that collect the required data and analyze them for action, all in real time. Clearly, a large-scale, platform-independent, diverse-application IoT infrastructure can aid this process by including data processing and management, actuation, and analytics. With advanced sensing and computation capabilities, data are gathered and evaluated in real time to extract the information, which is further converted to usable knowledge. This will enhance the decision making of city management and citizens to turn the city smart.

The paper is organized as follows: the motivation for a smart city, especially from the perspective of city councils is first given in Section II. We then present the details of the IoT infrastructure for a smart city in Section III, and particularly focus on the design of network architecture in Section IV. Following that, the mapping of urban noise is presented as a case study in Section V. We also present future thoughts and current trends of smart city development in Section VI.

II. MOTIVATION

As mentioned, a smart city utilizes ICTs in a way that addresses quality of life by tackling urban living challenges encompassed by more efficient utilization of limited resources (space, mobility, energy, etc.). World leading municipalities, in terms of services and quality of life, have provided efficient services to their citizens by the forward thinking and use of technology in monitoring various environmental parameters. Most of these systems consist of sensor, data storage device, and computer at a base station where experts analyze the data.
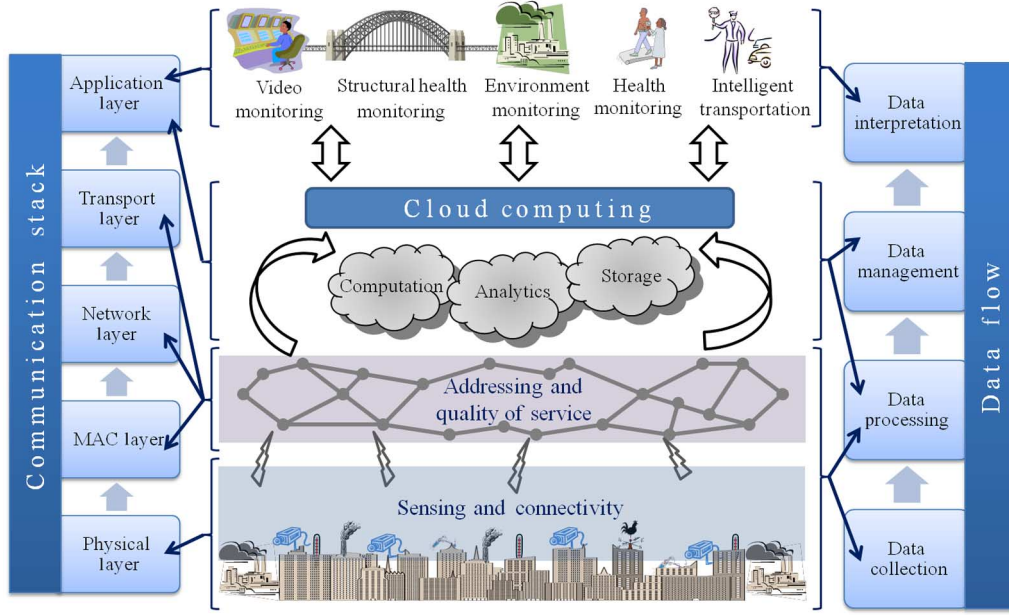
Fig. 1. IoT infrastructure from three different domains.

Our close interaction with the City of Melbourne has allowed us to unearth the vast ICT potential in making the entire system more efficient. From the technological perspective, the evolution of social networking in the past decade clearly shows the usability of ICT at an individual's level. Large-scale implementations at system level have made some progress in recent years. A fully integrated system of systems containing sensing, storage, analytics, and interpretation is required. The integrated system must have core capabilities of plug-and-play sensing, secure data aggregation, quality of service (QoS), and re-configurability. With an urban sensing system of systems in place, the ability to evaluate the impact of the preceding actions is readily available as the sensing cycle repeats.

A unifying information management platform delivers a capability across application domains critical to the city. While large volumes of data collection and interpretation are already performing at different levels within city councils using manual and semi-automated methods, it is mostly in isolation. As with any large organization, it is inevitable that large portions of these data remain disjoint in the time scales over which they are collected and the capacity for them to be integrated. An urban information framework enabled by IoT provides a means for consolidating these tasks and sharing of data between various service providers in the city.

The applications within the urban environment that can benefit from a smart city IoT capability can be grouped according to impact areas. This includes the effect on citizens (health and well-being), transport (mobility, productivity, and pollution), and services (critical community services). Several projects are already underway within the City of Melbourne that utilize sensor technologies to collect application-specific data. These include public parking monitoring, microclimate monitoring, and access and mobility (pedestrian, cyclists, cars, and freight vehicles). A number of specific application domains have also been identified that could utilize smart city IoT infrastructure to

service operations in health services (noise, air, and water quality), strategic planning (mobility), sustainability (energy usage), tourism (visitor services and tourist activity), business and international (city usage and access), and city safety.

III. IoT Infrastructure for Smart City

In this section, we will present the building blocks of smart city IoT Infrastructure. As the key technological enabler, IoT is introduced from three different domains: network-centric IoT, Cloud-centric IoT, and data-centric IoT, corresponding to communications, management, and computation requirements of smart city development and deployment (see Fig. 1).

A. Network-Centric IoT

The vision of IoT can be interpreted in two ways: 1) "Internet" based and 2) "Object" based. The Internet-based architecture will involve Internet services as the main focus while data are contributed by the objects. In the object-based architecture [4], the smart objects will take the center stage. In either case, networking is the fundamental issue. The proposed networking modules and their relationship with communication stack are shown in Fig. 1.

1) Sensing Paradigm: There are generally three sensing paradigms: RFID, WSN, and crowd sourcing. RFID technology offers automatic identification of objects to which the tags are attached. Passive RFID tags are not battery powered, but instead use the power from the reader's interrogation signal to communicate the ID to the RFID reader. This has resulted in many applications in retail and supply chain management. In the smart city, applications can be found particularly in transportation and access control.

WSNs enable the collection, processing, analysis, and dissemination of valuable information gathered in a variety of
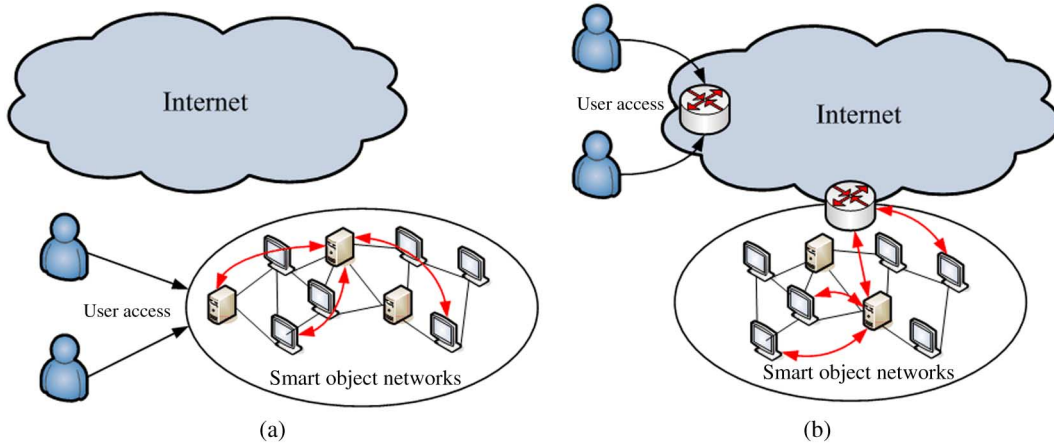
Fig. 2. Connectivity model. (a) Autonomous smart object networks. (b) Ubiquitous smart object networks.

environments [5]. With the availability of sensors that are smaller, cheaper, more intelligent, and widespread (e.g., embedded camera), WSN plays an important role in urban sensing applications.

Due to the progress in social networking, a new sensing paradigm has emerged by encouraging the citizens to contribute toward urban management. This is called participatory sensing, and it is set to play a major role in government–citizen interaction through advancement in smart-phone technology.

2) Addressing Scheme: Uniquely identifying objects is critical for the success of the IoT. This allows the recognition of hundreds of thousands of devices and the ability to control them remotely. In this case, every object that is already connected and those that are going to connect must be identified by their unique identification, location, and functionalities. The scalability of the device address in the existing network must be sustainable. The addition of networks and devices must not degrade the network performance and hamper the device functioning.

To address these issues, IPv6 provides a much needed option. The substantially increased address space provided by IPv6 ensures that the envisaged objects able to be connected can be assigned unique addresses. Also, its architecture is interoperable across devices and communication technologies, evolving and versatile while still stable, scalable, manageable, and simple enough that a resource-constrained smart object can easily run it [6]. In spite of this, IoT still faces a bottleneck at the interface between the Internet and smart object networks (that are termed here to generally refer to either RFID or WSN subnets).

3) Connectivity Model: Technically, the success of the Internet is partially due to the adoption of TCP/IP architecture. Meanwhile, it is interesting to note the transition of network architecture design for WSNs, which are considered as a subset of smart object networks since they share many of the properties such as low-power operation, the large scale of the networks, and resource constraints. Initially, the WSN community rejected the IP architecture with the assumption that it would not meet the challenges of WSN systems [7]. After several years, however, the community started to lean toward layered network architecture because of the benefits of modularity and separation of concerns [8], [9]. Many IP-based sensor networks have emerged now because of the interoperability with existing systems and

the well-engineered architecture adhering to the end-to-end design principle [10].

Based on the IP architecture, as shown in Fig. 2, connectivity models range from autonomous smart object networks, which are isolated from the Internet, to ubiquitous smart object networks, which are part of the Internet. In between, there are numerous models available depending on different applications. In Section IV, we will give more details in this perspective.

4) QoS Mechanism: Due to a variety of system protocols of wired, wireless, and hybrid type in a dynamic networking environment, heterogeneous IoT present different QoS requirements from conventional homogeneous networks. Heterogeneous networks are multiservice, providing more than one distinct application or service. This implies not only the existence of multiple traffic types within the network but also the ability of a single network to support all of these applications without compromising QoS for any of them. Very broadly, real-time network traffic can be categorized into two classes: throughput and delay tolerant *elastic* traffic and the bandwidth and delay-sensitive *inelastic* traffic, which may further be discriminated by data-related applications (e.g., high versus low-resolution videos) with different QoS requirements [11]. Therefore, as an end-to-end intelligent system that covers the entire acquisition–transmission–interpretation–action process, network algorithms, and/or protocols developed for IoT will need built-in QoS guarantees.

B. Cloud-Centric IoT

In order to integrate the ubiquitous urban sensing and the smart city applications, as well as to realize the full potential of Cloud computing, a combined framework with Cloud at the center is shown in Fig. 1. In this model, sensing service providers can join the network and offer their data using a storage Cloud; analytic tool developers can provide their software tools; and computational intelligence experts can provide their data mining and machine learning tools useful in converting information to knowledge. Cloud computing is able to offer these services as infrastructures, platforms, or software. Specifically, the data generated, tools used, and algorithms developed all disappear into the background, with focus given to various application domains of IoT. According to our vision for Cloud-centric IoT

TABLE I
COMPARISON OF CHARACTERISTICS OF IoT NETWORK ARCHITECTURE CLASSIFICATION

Network architecture	Autonomous	Ubiquitous	Application-Layer overlay	Service-Oriented
Design approach	Evolutionary	Evolutionary	Evolutionary	Clean-slate
Connectivity model	IP-compatible	IP	IP	IP-compatible
Network hierarchy	Yes	Yes	Yes	No
In-Network processing	No	No	Yes	Yes
QoS complexity	Low	High	Low	High
Progress in defining QoS	Intermediate	Intermediate	Advanced	Early stage

[12] (as shown in Fig. 1), the Cloud integrates all facets of ubiquitous computing by providing scalable storage and computational resources to build new businesses. Moreover, the core objective of the Cloud to efficiently model cost based on supply and demand offers a unique opportunity to create an efficient IoT business model.

C. Data-Centric IoT

It is not surprising that there will be a massive amount of data generated in a fully functioning IoT. Data-centric IoT emphasizes all aspects of data flow, including collection, processing, storage, and visualization.

1) Data Collection: Efficient heterogeneous sensing of the urban environment needs to simultaneously meet competing demands of multiple sensing paradigms. It also has implications on network traffic, data storage, and energy utilization. Importantly, this contains both fixed and mobile sensing infrastructures as well as continuous and random sampling. A generalized framework for data collection is required to effectively exploit spatial and temporal characteristics of the data, both in the sensing domain and associated transform domains.

Besides common sensing paradigms, such as RFID and WSN, participatory sensing is emerging as a novel sensing paradigm, where people, rather than deployed sensors, take the responsibility for collecting and sharing sensory data [13]. It offers the possibility for low-cost timely sensing of the environment localized to the user, complementing data from a fixed infrastructure. A salient feature of participatory sensing is that people are not obliged but voluntary or incentivized to perform the sensing tasks. As such, it is difficult to guarantee the quality of data being contributed. In [11], we have defined a metric to evaluate the quality of data contributed through participatory sensing. At the same time, systems for ensuring privacy and trust are yet to be adequately addressed.

2) Data Processing and Management: Extraction of meaningful information from raw data is nontrivial. It usually involves preprocessing and event detection. Events need to be detected in long multivariate time-series data. For a smart city, adaptability and robustness of algorithms to compare data at large scales of time and space are essential—this is data-to-information analytics. To further make sense of the information and convert it into knowledge, state-of-the-art computational intelligence techniques such as genetic algorithms, evolutionary algorithms, and neural networks are necessary [14]. They will help achieve automated decision making and provide useful policy. Meanwhile, due to the unprecedented amount of data available, storage, ownership, and expiry of them become critical issues. The data have to be stored and used intelligently and energy-efficiently.

3) Data Interpretation: For smart city applications, visualization is important for data representation in user-understandable form, allowing interpretation by the users. It is indeed challenging to visualize heterogeneous sensory data in a temporally varying 3-D landscape. New display technologies facilitate creative visualization. For instance, the evolution from cathode ray tube (CRT) to plasma, liquid crystal display (LCD), light-emitting diode (LED), and active-matrix organic light-emitting diode (AMOLED) displays have given rise to highly efficient data representation (using touch interface) with the user now better able to navigate data. Moreover, visualization schemes could be improved by plugging into other Geographic Information System (GIS) platforms and integrating geo-related information.

IV. DESIGN OF NETWORK ARCHITECTURE

By further focusing on the networking aspect of IoT, in this section, we will design and construct appropriate network architecture for different smart city applications as well as define their corresponding performance metrics.

In general, there are two main design approaches for network architecture: 1) an evolutionary approach and 2) a clean-slate approach [15]. The evolutionary approach makes incremental changes to the current network architecture to reuse as many components as possible from existing networking solutions. From this perspective, an IoT could be viewed as an extended architecture evolved from the Internet. On the other hand, the clean-slate approach advocates a redesign of network without being constrained by the current structure. It means, in order to cope with next-generation network challenges, new architecture and protocols will be developed according to disruptive design principles. Indeed, an ongoing debate about these two approaches has engaged in the networking research community over the past several years. Ultimately, individual researchers have their own styles, often a unique blend between them as the applications dictate [16].

In the following, we will present four most common network architectures in the smart city domain, that is, autonomous network architecture, ubiquitous network architecture, application-layer overlay network architecture, and service-oriented network architecture. They are all given in three parts devoted to architecture description, applications, and QoS requirements, respectively. Table I summarizes the characteristics of each network architecture in terms of different features, namely, design approach, connectivity model, network hierarchy, in-network processing, QoS complexity, and progress in defining QoS.

A. Autonomous Network Architecture

1) Architecture Description: Fig. 2(a) illustrates the connectivity model of autonomous networks. As suggested by the

name, autonomous networks are not connected to the public networks, and there are several such use cases in reality. However, it does not necessarily mean that the Internet access is forbidden; it is in fact possible via gateway if required. While designing autonomous networks, though not mandatory, IP protocol suite is still commonly adopted due to its scalability and flexibility. What is more important, the large address space provided by IP is desired in most cases.

2) Application—Automatic Parking Management: Automatic parking management, as a direct example, is a useful service city councils may provide to its citizens. By collecting the information regarding the parking bay occupancy wirelessly, the council can provide parking vacancy information to the users on a visualization platform like a smart-phone. It will also enable the council to apply fine in case of parking infringements. Due to the technological advances and relative simplicity of application, a few commercial systems are available based on this wireless technology (e.g., [17]). Most of the systems work autonomously in a three-tier mode where the lowest tier motes are attached to sensors (usually glued to the ground), the middle tier contains forwarders (connected to light poles), and the uppermost tier contains base stations connected to an Internet-enabled device [18]. With developments in antenna engineering and availability of motes with long range, formation of star network will be made possible bypassing the intermediate forwarders.

3) QoS: The QoS requirement in this case is indeed application-dependent. For the above automatic parking management, sensor coverage, reliability, and system responsiveness are the major concerns.

B. Ubiquitous Network Architecture

1) Architecture Description: For ubiquitous networks, the connectivity model is as shown in Fig. 2(b), where smart object networks are a part of the Internet. Through the Internet gateway, authorized users will have access to the information provided by smart object networks either directly fetching from the device or by means of intermediate servers. Usually, the servers act as the sinks in smart object networks to collect data from each object. Taking scalability and resource conservation into account, the user access through the servers is probably more preferable.

By taking a close look at the interface between the Internet and smart object networks, Fig. 3 captures a detailed view of ubiquitous network architecture. Instead of abstracting as smart object networks as previously, we are now referring to the specific networks. The feature of ubiquitous network architecture includes:

Multitier: The network architecture is hierarchical, comprising both wireless multi-access networks and wireless multi-hop networks. In particular, wireless multi-hop networks could be in the form of WSNs or vehicular ad-hoc networks, with respect to the applications in Sections IV-B2 and IV-B3.

Multiradio: It is not uncommon nowadays to have a number of radio access technologies available to connect to the Internet, either covering the same or complementing geographical areas. These networks could be WLAN, WiMAX, macro-cellular, femto-cellular, or even ad-hoc. The synergy and integration of different networks in multi-access and
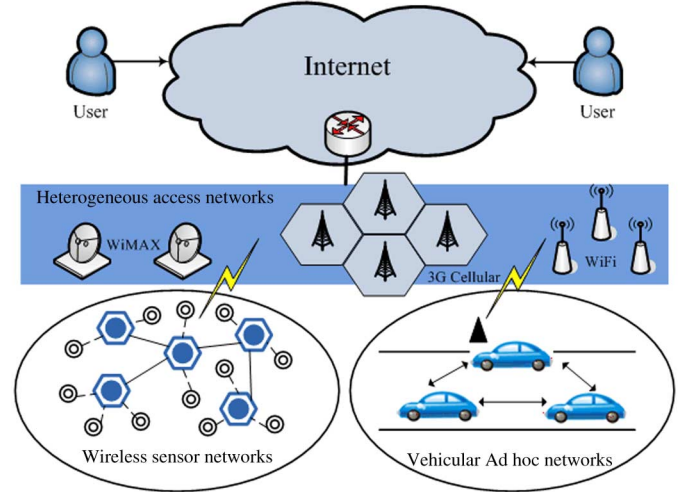

Fig. 3. Ubiquitous network architecture.

multi-operator environment introduces new opportunities for better communication channels and an enhanced quality of provided applications and services.

2) Application—Structural Health Monitoring: A typical application of WSNs for smart cities is structural health monitoring. The city is full of stationary structures—some small, some huge, others new, most of them very old—such as buildings, dams, or bridges [6]. They are actually part of our life: bridges are used by humans and vehicles, and people are living and working in the buildings. The health of these large structures is clearly critical; any damage may cause life-threatening situations and serious financial loss. To monitor their health level, passive wireless sensors will be embedded within a concrete structure, and send a radio signal of suitable amplitude and phase characteristic periodically using the radio frequencies in the unlicensed Industrial Scientific and Medical (ISM) bands. The data collected at the sink are then used to detect any anomalies that could be a sign of abnormality for early warning or damage prevention.

3) Application—Traffic Congestion and Impact Monitoring: Urban traffic is the major contributor to traffic noise pollution and one of the major contributors to urban air quality pollution and greenhouse gas emissions. Traffic congestion directly imposes significant costs on economic and social activity in cities: congestion in Australia's metropolises cost the nation $9.5B in 2005, and is forecast to cost $20.4B in 2020. In addition, supply chain efficiencies and productivity, including "just-in-time" operations, are severely impacted by this congestion causing delays to freight vehicles and failures to meet delivery schedules.

There are a variety of sensors available for measuring pollution levels and traffic delays and queuing, either stationary at fixed locations or mobile mounted in vehicles. Via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, they are able to form ad-hoc vehicular networks, which allow online monitoring of travel times, origin-destination route choice behavior, queue lengths and air pollutant and noise emissions, as well as predict possible accidents. Together with information gathered by the urban traffic control system, valid and relevant information on traffic conditions can also be presented to travelers.
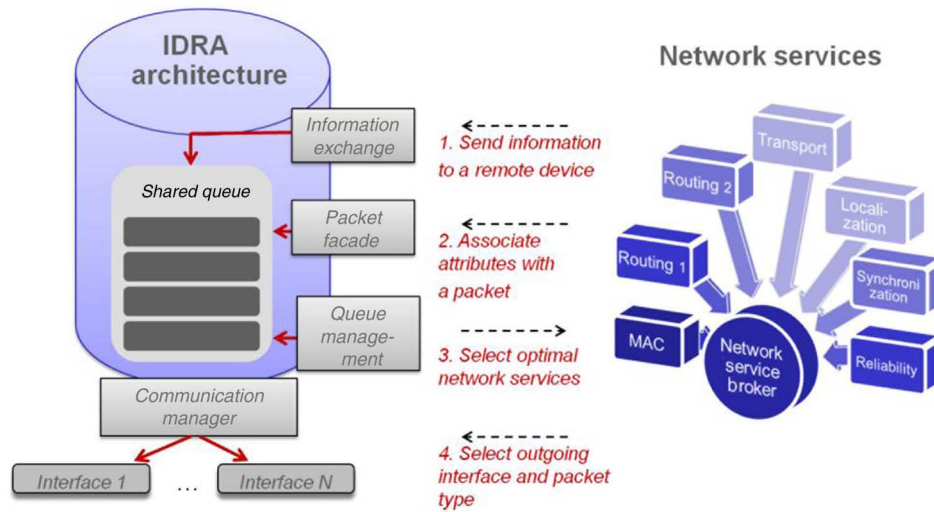
Fig. 4. Service-oriented network architecture [20].

4) QoS: In such multi-access multi-hop wireless networks, providing QoS guarantees is unsurprisingly challenging and an emergent discipline. The shortage of a standardized end-to-end protocol for establishing QoS, the complexity of network dynamics, and the difference of QoS requirements to be achieved cause this hard situation. Specifically, structural health monitoring mainly requires reliable data delivery from each node to the sink. The QoS requirement of traffic congestion and impact monitoring is relatively stringent in terms of throughput and delay, due to the involvement of real-time data information.

C. Application-Layer Overlay Network Architecture

1) Architecture Description: Similar to WSNs, the most common operation of IoT is to collect data from hundreds of thousands of nodes. Because of the multipoint-to-point nature of data flows, it is easily observed that traffic congestion occurs more likely near the sinks, which would not only degrade the QoS, but also increase energy consumption of these nodes.

Statistically, the spatio–temporal data are correlated unless something unusual happens. Thus, in-network data processing, e.g., data aggregation, data fusion, or rule-based feature extraction, will greatly help reduce the amount of data transmissions and prolong system lifetime. Thanks to the network virtualization technology [19], the idea can be realized by forming an application-layer overlay network, consisting of selected nodes (e.g., cluster heads) running in-network data processing tasks.

2) Application-Compressive Sensing for Environmental Monitoring: The above architecture is readily applied to city-wide environmental monitoring application. By deploying large-scale environmental monitors, the data from these will be relevant to rapid urbanization and climate change adaptations, and enable continuous monitoring of the city environment for ensuring appropriate environmental health and safety standards. More specifically, parameters including hydrocarbons and oxides of nitrogen—the basic ingredients of photochemical smog, carbon dioxide, carbon monoxide, ammonia, and benzene will be monitored to reflect the air quality in the deployed area of interest. In addition, microclimate sensing

will also be achieved through the deployment of temperature and humidity sensors. Overall, urban sensing is able to improve the quality of life and productivity for a more sustainable city.

3) QoS: The data traffic for environmental monitoring is elastic in nature. It implies that bandwidth is the primary concern; delay and packet loss are tolerable to some extent.

D. Service-Oriented Network Architecture

1) Architecture Description: Heterogeneity is the most distinguished characteristic of the IoT, which often contains a variety of subnetworks adopting different communication technologies. To enable communication between these subnetworks, traditionally, a complex gateway device needs to be installed in order to translate different network protocols. Because of the inherent complexity of the translation gateway and the lack of flexibility and scalability, it is clearly not an efficient solution. To remedy this situation, revolutionary network architecture, named IDRA (Information DRiven Architecture), is developed in [20].

The IDRA is based on a clean-slate design approach, with its conceptual presentation given in Fig. 4. The key idea is to implement different network functions (such as addressing, naming, synchronization, routing, etc.) as a standardized, technology-independent component called *network service*. Network service can also be used to build either a full network protocol (e.g., transport protocol) or a simple operation (e.g., MAC for controlling the timing and sending the packets). In this case, different communication technologies are simply different services that will be understood by the communication manager. Regarding information exchange, a special packet is created and maintained by IDRA, whose metadata is associated with different network services required. For simplicity, IDRA uses a single system-wide queue for storing and processing all the packets. In summary, the major advantages of IDRA [20] include: 1) IDRA enables direct communication between subnetworks even with different communication technologies, without the need of translation gateways and 2) IDRA supports backward compatibility with IP architecture.

2) Application—Combined Noise Mapping and Video Monitoring: One immediate IDRA application for smart cities is combined noise mapping and video monitoring.

The well-known implications on health, well-being, and quality of life associated with noise pollution provide a significant challenge to city councils in managing noise and its effects. A reliable system for measuring noise and responding to noise issues is the strong motivation in development of acoustic sensor network within a municipality. Video sensor network, on the other aspect, integrates image processing, computer vision and networking to perform dynamic scene analysis. Detecting the cause of noise helps the council to take action and reduce noise in urban environment. With the coexistence of acoustic sensor network and video sensor network, they can be further combined together to empower noise-activated video monitoring for obtaining a fine-grain real-time COP. This will offer the city council an unprecedented practical opportunity to understand dynamic noise pollution profile, assess its impact on health and well-being and better plan for noise reduction and desirable urban soundscape.

3) QoS: Both audio and video data are categorized as inelastic traffic, which are generally delay sensitive and have strict QoS requirements. Unlike elastic traffic, they have an intrinsic bandwidth threshold because the data generation rate is independent of network congestion. The degradation in bandwidth may cause serious packet drop and severe performance degradation. To ensure the QoS of inelastic traffic, rate control and admission control is hence necessary to guarantee that they will receive sufficient bandwidth, at least greater than the threshold.

V. NOISE MAPPING—A CASE STUDY

In order to produce a sustainable urban environment and an increase in the associated quality of life, long-term strategic planning by the city council is required. Among many issues, noise pollution and its management are a critical concern [21]. Extended exposure to excessive noise is known to have negative health effects. City councils mostly depend on public complaints to define the issue of noise rather than the best practice method of noise mapping, leaving a gap in the ability to effectively manage and prevent increases in excessive noise.

The conventional approach to noise monitoring and analysis has relied on acoustic consultants manually measuring noise levels. Adding further complexity is the sharing of enforcement of noise limits across different bodies (e.g., council, police, traffic authorities). The associated cost and labor-intensive nature of this process means, it is applied only to specific areas and on a one-off basis. As a case study of utilizing the IoT technology, in close coordination with the City of Melbourne, we have developed a new approach for noise monitoring and mapping, which addresses the above limitations and helps to understand the noise pollution and city soundscapes together with the impacts on health, well-being, and quality of life.

A. Noise Mapping Architecture

The proposed noise mapping architecture shown in Fig. 5 (based on SmartSantander IoT architecture [22]) contains both fixed and mobile infrastructure [23]. Fixed infrastructure is a

realization of WSN in urban sensing. The WSN platform facilitates deployment flexibility to incorporate diverse sensing modalities for continuous monitoring, providing baseline reference data and validation capabilities. The platform also incorporates a mobile WSN extension, providing the capability from short- to medium-term deployments in target areas or where higher spatial resolution of data is required. Where there is greater activity or variation in sound levels in a given area, measuring sound levels at more closely spaced locations provides a more accurate picture of the soundscape. This provides greater accuracy in identifying potential noise sources.

The mobile infrastructure includes scope for sensors mounted on vehicles, mobile phones, and other handheld devices. These sensors enrich data collected from fixed infrastructure by filling gaps in spatial data and help citizens in filing noise complaints where fixed infrastructure facilities are not available. In this case, although data from participatory sensing are no longer continuous or completely reliable, the people-centric sensing platform indeed provides a mechanism for engaging citizens, as well as obtaining valuable feedback and an understanding of the public perceptions of noise and urban sounds. This in turn assists in identifying local soundscapes and the desirability and usability of urban spaces.

Specifically, the three-tier IoT architecture consists of the following elements (also illustrated in Fig. 5).

1) *Bottom tier*: Sensor nodes positioned sufficiently above ground on public properties such as street lights, traffic lights, or building facades, to alleviate multipath fading effects due to reflections.
2) *Middle tier*: Relay nodes to collect and buffer measurements from sensor nodes, and forward the data across multiple hops to a gateway. Relay nodes are equipped with more memory than sensor nodes for buffering measurements, as well as a low-jitter crystal oscillator for high-precision time synchronization.
3) *Top tier*: Gateways to collect measurements from the relay nodes and send them via the Internet to the Cloud. While relay and sensor nodes communicate on IEEE 802.15.4 links, there are several options for gateway nodes depending on cost and availability.

The multitier architecture presents a natural differentiation of functions, and hardware/software requirements.

B. An Urban Information Framework

While the focus of this case study is the development of an IoT infrastructure that addresses the noise-related issues, it is able to extend to a more generic urban information framework built on technology that enables efficient data collection. The capability to achieve measurement, understanding and visualization of multiple urban environment parameters is a key criterion in developing a smart city. In order to validate this framework, a lab-based testbed has been created with custom-designed sensor boards capable of capturing noise levels and other environmental parameters. At the physical layer, Crossbow's iMote2 and IRIS motes are used as sensor interface. A low-cost A-weighted filter has been designed that outputs noise level (in dBA). The output analog signal is converted into a digital format using the Imote2 sensor board (ITS400), which samples the signal at 2 Hz.
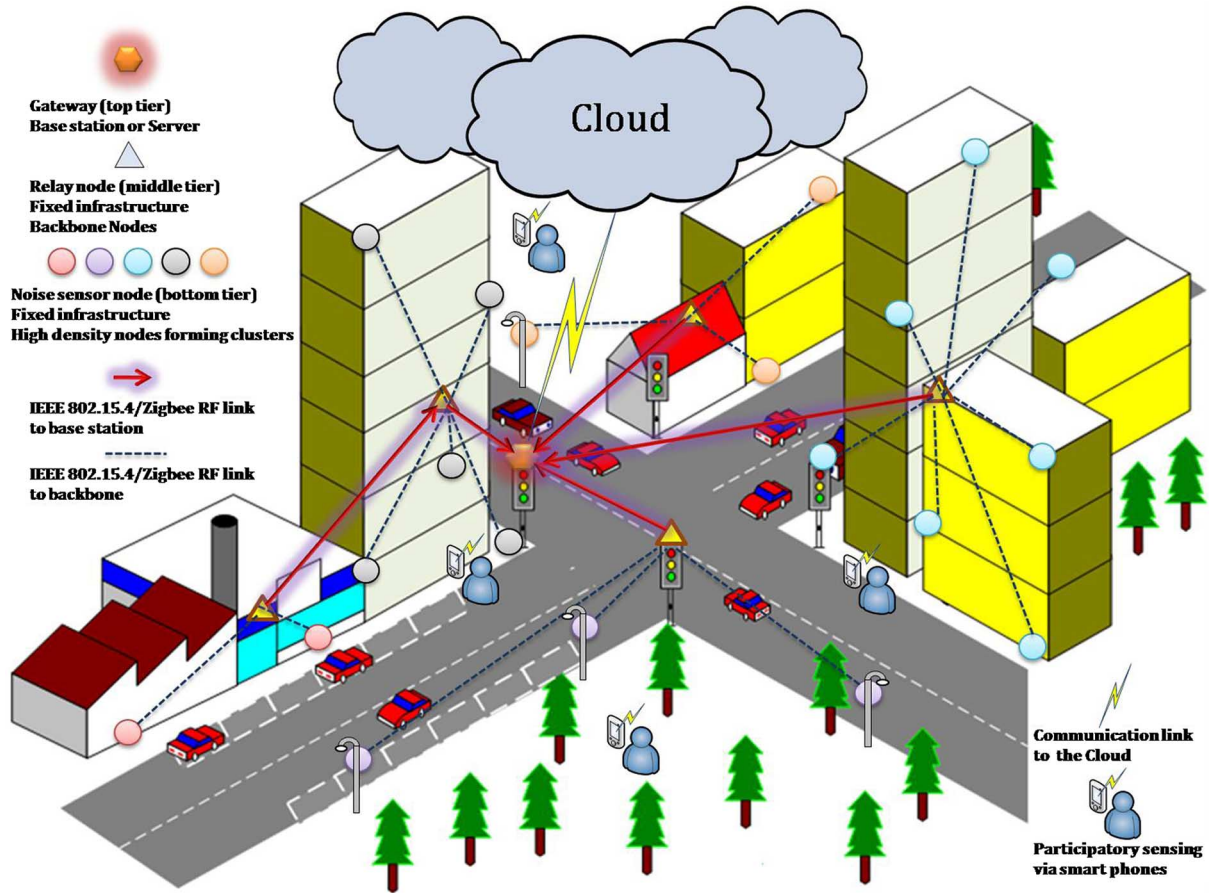
Fig. 5. IoT architecture for noise mapping.

Two modes of network architecture were implemented. In the low-density data mode, IRIS nodes were used using mesh network (Crossbow's XMesh) for data collection. In high-density mode, Imote2 was used in star configuration. Depending on the deployment requirements, the mode was chosen. In large-scale deployment, the combination of two modes is feasible.

Cloud is defined as a type of parallel and distributed system, consisting of interconnected and virtualized computers that are dynamically provisioned and presented as one more unified computing resources based on service level agreements established through negotiation between the service provider and the consumers [24]. Cloud computing can offer three basic services as Infrastructures (for storage), Platforms (for computation), and Software (for delivering IoT services). In our framework, Cloud computing forms the core integrating unit [12]. In the first instance, Xively (previously Cosm and Pachube) was used for data storage. In the second instance, we have demonstrated the usefulness in combining the Microsoft Azure and Manjrasoft Aneka [24] Cloud platforms in order to implement on-the-fly analytics provisioning. Moreover, use of the Aneka platform will enable interaction between public and private Clouds through its InterCloud model.

All data from the fixed infrastructure and mobile infrastructure are time stamped and stored in the storage Cloud. The data are visualized using geo-spatial maps on handheld devices for the end users. In our implementation, Google Maps-based web application programming interface (API) has been developed to visualize the noise map (more details in [23]).

C. Business Model

Data and technology capabilities provided by the IoT inform the determination a suitable business model for this emerging technology. To establish the business model for a smart city IoT platform, the value chain of the system can be framed to define the end-to-end system, from data capture to analysis to reporting. The seamless transition from a collection of raw urban data to translate into meaningful information that will inform decisions or actions is delivered via this urban information framework. In creating a sustainable business model for laying out large-scale infrastructure, the following challenges need to be addressed: 1) ownership and system construction; 2) maintenance and management; 3) data utilization; and 4) data markets and revenue streams. Identifying the data market and the revenue streams is highly critical for the IoT system to be sustainable. For instance, parking sensors IoT subnet can generate revenue in the form of parking fees and parking infringements, while microclimate monitoring may not generate revenue directly. Hence, an efficient business model is required. For the City of Melbourne deployment, we have developed a possible business model including modes of revenue generation [25].

VI. Current Trends and Future Thoughts

Along rapid urbanization, making the cities smart becomes imperative. It is fair to say, WSN is evolving into the IoT. As a result, the WSN testbed activities of the last decade have provided valuable information about the architecture, security, networking, and data handling critical to large-scale IoT implementation. Most of these testbeds address targeted applications and their communication backbone and other resources are not shared [26]. This obviously leads to high costs and complexity, nevertheless providing valuable information about large-scale deployments.

More recently, IoT activities are gathering momentum around the world. Europe is becoming the contact point of IoT research with the establishment of Internet of Things European Research Cluster (IERC), which is a cluster of European Commission 7th Framework Program (EU-FP7) funded IoT projects. Key projects have included CASAGRAS2, Internet of Things Architecture (IoT-A) and the IoT Initiative (IoT-I). A city-wide smart city testbed development is now complete in Spain (Santander) that is laying out a testbed for research and service provision. China has established an IoT Center in Shanghai to study technologies and industry standards. A group of 60 telecom operators (key drivers of the technology) have initiated "Sensing China" project. Similar activities are underway in Japan, Korea, USA, Australia, and India, where various stakeholders are collaborating to advance the capabilities toward an IoT.

Melbourne is one of the few cities to embrace this technology very early. It is a part of the C40 cities (climate leadership group) and the Melbourne City Council has undertaken various studies in the implementation of IoT style applications (noted earlier). With these studies, the need for common communication, data storage, and processing infrastructure is quite clear. Moreover, the ease of data sharing between various departments within the council can easily be facilitated using emerging IoT. In a recently concluded workshop, several new spatial temporal high resolution data to be collected were identified in the domains of environment, traffic, biodiversity, utilities, infrastructure, and social media.

The end goal of smart city IoT platform is to have plug-and-play smart objects that can be deployed in any environment with an interoperable backbone allowing them to blend with other smart objects around them. In order to realize this goal, there are many technological hurdles including architecture, energy efficiency, security and privacy, QoS, Cloud computing, data analytics, and GIS-based interpretation. Standardization of frequency bands and protocols plays an important role in accomplishing this goal. Several projects and activities detailed above are addressing these critical challenges in the next decade, a clearer picture regarding the usefulness of IoT in making the city smart will emerge. Due to the scale of activities, participation of large companies and the Government will play a pivotal role in the success of this emerging technology.

VII. Conclusion

With rapid development in the emerging IoT technology, we give, in this paper, a comprehensive blueprint of developing a smart city using IoT, which is actually motivated and strongly demanded from city councils as they seek to ensure the provision of essential services and quality of life for city inhabitants. In this context, we identify the key IoT building blocks of smart cities, as well as provide the approaches and resolutions to meet their respective communications, computing, and computation requirements. Furthermore, IoT-enabled noise mapping work in association with the City of Melbourne is presented as a case study to highlight the practical usage and merit of our proposed framework. Finally, in order to push the development forward, the proper business model of smart city is believed to be equally important as technological advancement.

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