Network Architecture and QoS Issues in the Internet of Things for a Smart City

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***Abstract*—The emerging Internet of Things (IoT) that effectively integrates cyber-physical space to create smart environments will undoubtedly have a plethora of applications in the near future. Meanwhile, it is also the key technological enabler to create smart cities, which will provide great benefits to our society. In this paper, four different IoT network architectures spanning various smart city applications are presented and their corresponding network Quality of Service (QoS) requirements are defined. Furthermore, as the beneficiary of smart city, we have the responsibility to actively participate in its development as well. A new network paradigm, participatory sensing, is thus discussed as a special case to highlight the way people may be involved in the information acquisition-transmission-interpretation-action loop.**

***Index Terms*—Internet of Things, Smart Cities, Network Architecture, Quality of Services, Participatory Sensing.**

I. INTRODUCTION

By 2050, 70% of the world's population - over 6 billion people - is expected to live in cities and suburbia. To survive as platforms that enable economic, social and environmental well-being, a city needs to be smart, i.e., one that "uses information and communications technologies to make the critical infrastructure components and services of a city - administration, education, healthcare, public safety, real estate, transportation and utilities - more aware, interactive and efficient" [1]. This is technologically predicated on the emerging Internet of Things (IoT) [2] - a radical evolution of the current Internet into a network of interconnected objects that not only harvests information from the environment (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analytics, applications and communications [3]. The new integrated Sensor-Actuator-Internet framework will form the core technology around which a smart city will be shaped.

Fuelled by the prevalence of devices enabled by open wireless technology such as Bluetooth, radio frequency identification (RFID) and near field communications (NFC) as well as embedded sensor and actuator nodes, the IoT has stepped out of its infancy and is at the verge of transforming the current static Internet into a fully integrated Future Internet. If Internet provides anytime connectivity for anyone leading to social networking, IoT provides anytime connectivity to anything leading to multitude of applications in the cyber physical world.

The paper is aimed at addressing the communications and networking issues of an IoT, by first identifying and constructing network architecture for potential smart city applications, and then defining and satisfying the corresponding performance metrics. Due to a variety of system protocols of wired, wireless and hybrid type in a dynamic networking environment, IoT presents different Quality of Service (QoS) requirements from conventional homogeneous networks. Being an end-to-end intelligent system that covers the complete acquisition-transmission-interpretation-action loop, network algorithms and/or protocols developed for IoT will need built-in QoS guarantees. Indeed, QoS is one of the fundamental networking problems that have received substantial attention in both wired and wireless networks [4]. The main Internet Engineering Task Force (IETF) activity in the QoS area has focused on the definition of end-to-end QoS-signaling protocols and resource reservation control mechanisms. In wireless networks, there is substantial ongoing research focussed on the involvement of radio interface and the implications imposed by interference [5].

The IoT networking environment is strongly characterized by the *heterogeneity* of networks. Heterogeneous networks feature multi-service, 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 [6]. Very broadly, network traffic can be categorized into two classes: throughput and delay tolerant *elastic* traffic, and the bandwidth and delay sensitive *inelastic* (real-time) traffic, which may further be discriminated by data-related applications (e.g., high-vs.-low resolution videos) with different QoS requirements. Therefore, in this paper, QoS requirements are particularly defined and discussed in the context of dedicated network architecture and relevant applications.

The rest of this paper is organized as follows. In Section II, we describe two network architecture design approaches and IP-based connectivity models of IoT. Section III presents four different network architectures along with the related applications and QoS requirements. In order to encourage people to actively participate in the smart city development, participatory sensing as an emergent network paradigm that

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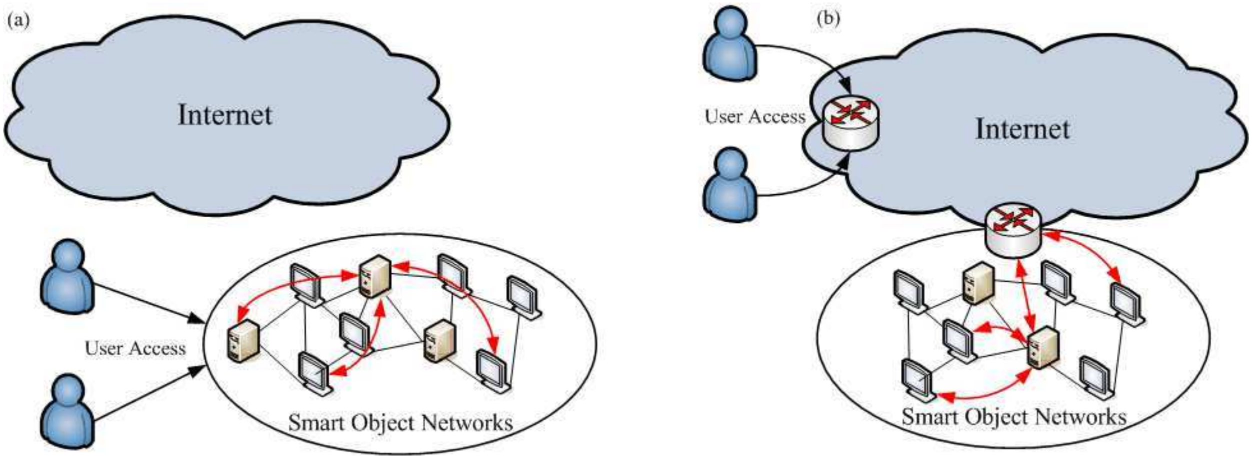

Fig. 1. Connectivity models: (a) autonomous smart object networks. (b) ubiquitous smart object networks.

involves people in the loop, will be separately discussed in Section IV. Finally, we draw the conclusions in Section V.

II. Design Choice of Network Architecture

A. Network Design Approach

There are two main design approaches for network architecture: (1) an evolutionary approach; (2) a clean-slate approach [7]. 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 re-design 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 [8].

B. IP-based Connectivity Models

The focus hereafter will be on the network architecture of the Internet of Things. In terms of network elements, IoT is generally made up of the Internet and smart object networks. Technically, the success of the Internet is partially due to the adoption of TCP/IP architecture. Also, as shown in [9], the IP architecture is interoperable across devices and communication technologies, evolving and versatile while still stable, scalable, and manageable, and simple enough that a resource-constrained smart object can easily run it. All these facts make IP architecture a reasonable choice for the emerging IoT.

Meanwhile, it is interesting to note the transition of network architecture design for wireless sensor networks, 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 wireless sensor network community rejected the IP architecture with the assumption that it would not meet the challenges of wireless sensor network systems [10]. After several years, however, the community started to lean toward layered network architecture because of the benefits of modularity and separation of concerns [11], [12]. 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 [13], [14].

Based on the IP architecture, as shown in Fig. 1, 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, depending on different applications, there are numerous models available that are developed using either an evolutionary approach or a clean-slate approach.

III. Network Architecture

In this section, we will present four different network architectures in the smart city domain, namely, 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.

A. Autonomous Network Architecture

1) Architecture Description: Fig. 1(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 the Internet access is forbidden; it is in fact possible via gateway if required. While designing autonomous networks, though not mandatory, IP

TABLE I
COMPARISON OF CHARACTERISTICS OF THE PROPOSED 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

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 visualisation platform like a smartphone. 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., [15]). Most of the systems work autonomously in 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 [16]. 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. 1(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. 2 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 wireless sensor networks or vehicular ad hoc networks, with respect to the applications in the following two subsections.

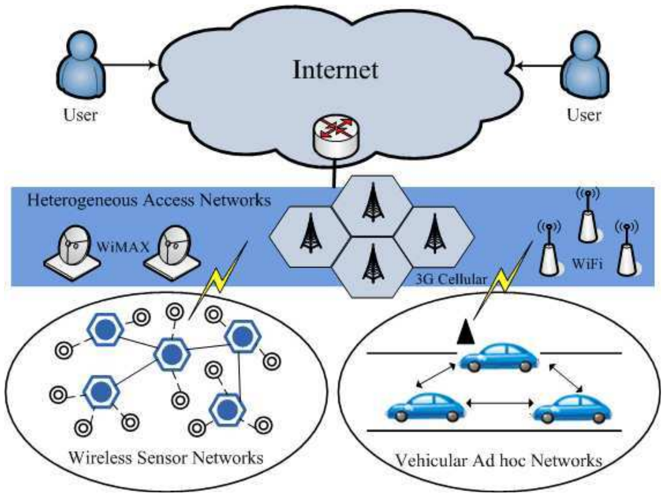

Fig. 2. The Ubiquitous Network Architecture.

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 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 wireless sensor networks 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 [9]. They are actually part of our life: brides 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.

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 wireless sensor networks, 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 [17], 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 task.

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.

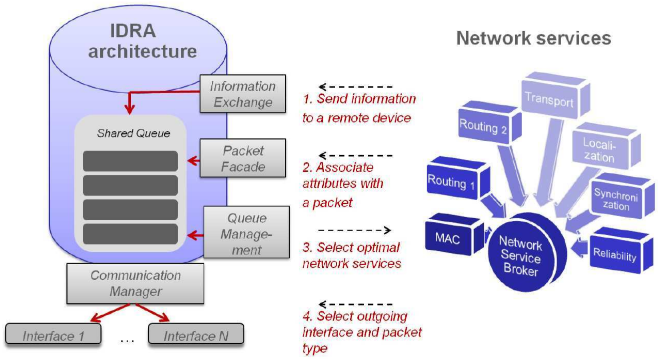

Fig. 3. The Service-Oriented Network Architecture [18].

3) QoS: The data traffic for environmental monitoring is elastic in nature. It implies that bandwidth is the primary concern; delay and packet loss is 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 sub-networks adopting different communication technologies. To enable communication between these sub-networks, 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, a revolutionary network architecture, named IDRA (Information DRiven Architecture), is developed in [18].

The IDRA is based on a clean-slate design approach, with its conceptual presentation given in Fig. 3. 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 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 [18] include: (1) IDRA enables direct communication between sub-networks even with different communication technologies, without the need of translation gateways; (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, monitoring 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 do dynamic scene analysis. Surveillance, the most widely used video monitoring application, helps track a person, identify suspicious activities, detect left luggage and unauthorized access.

With the co-existence 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 common operating picture (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 sound-scape.

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.

IV. PARTICIPATORY SENSING - A SPECIAL CASE

Different from four network architectures identified above, participatory sensing emerges as a new network paradigm of IoT, in which people, rather than deployed sensors, take the responsibility of collecting, analyzing, and sharing sensor data [19]. In this section, we present participatory sensing separately as a special case, in order to highlight its unique human-centric nature and further reveal its great potential to involve people in the smart city development.

A. Network Architecture

The unique "human-as-a-sensor" feature of participatory sensing dictates certain network architectures. As human behaviors are highly mobile, erratic, and unpredictable, the most common network architecture is one in which participants connect to a central server directly, via a reliable wireless technologies such as WiFi, GPRS, or 3G, instead of relying on other users as relay nodes. Therefore, unlike ad hoc, mesh, or traditional sensor networks, the interaction between nodes (users), if any, will have to be intermediated by the central entity. This is essentially a star as opposed to a mesh or hierarchical architecture. Nonetheless, in certain confined spatial-temporal context (e.g., a conference), where a certain group of people rendezvous for a pre-scheduled period, a clique (or multiple cliques) could be formed and a cluster-based architecture be applied. Because of the common interest of the participants, most message exchanges would be intra-cluster only. Thus, a cluster-based structure would be more cost-efficient, and save substantial bandwidth and energy resources.

Applications of participatory sensing broadly span from environmental monitoring to transportation, and from healthcare to lifestyle, among many others. With the vast penetration of smartphones, such emergences will definitely play a significant role in the process of creating a smart city. For instance, ear-Phone [20] is a developed participatory sensing system that collects noise samples from microphones on Nokia N95 and HP iPAQ mobile devices carried by common people. By complementing the deployed on-spot noise detectors, it offers an alternative way to recover a city noise map. Citizens participation does reflect their comfort levels that will be critical in policy decision making particularly in smart city applications.

B. QoS

In spite of various benefits participatory sensing brings along, there are tremendous research challenges when applying to the real life. In realistic settings, people are generally non-altruistic, lazy, error-prone, privacy-concerned, and sometimes even misbehaving. The idea of turning them to be the sheer source of data, is bound to encounter challenges in the aspect of incentive, trustworthiness, privacy, QoS etc. In the following, we are going to focus on the QoS issues. Rather than defining QoS in terms of conventional networking performance, it makes more sense for participatory sensing to define QoS in terms of data quality contributed by the participants.

A salient characteristic of participatory sensing is that the participants are not obliged but are *voluntary* or *incentivized* to perform the sensing tasks [21]. As such, there is hardly any guarantee on the quality of data contributed by them; the accuracy, resolution, frequency and timeliness can vary greatly due to erratic user behaviors and different sensing devices. Even worse, forged data can originate from misbehaving users. Therefore, the QoS of participatory sensing would be unacceptable if there lacks an effective way to control the quality of contributed data.

The key to address the problem is to, in the first place, evaluate the quality of contribution, which we denote by ψ_i for a contribution made by user i. In general, QoS as an aggregated performance metric of the whole system and denoted by Ψ, would be a function of ψ_i from all the users. Although the exact expression would be application dependent, one may think of it as $\Psi = \sum_i \psi_i$ or $\Psi = \sum_i e^{-\Delta t_i} \psi_i$ for an intuitive understanding without loss of generality. In the latter, Δt_i is the time between the time of evaluation and the time when the contribution ψ_i was made, which captures the effect that timelier data bears more value than outdated data.

To evaluate ψ_i, we propose to assess it according to its *intrinsic* value or *extrinsic* value. The intrinsic value is conveyed by the contributed data itself. For a generic example, consider an application that estimates a parameter $\mathbf{x}$ (such as travel speed or target location), and user i's contributed measurement denoted by $\mathbf{y}_i$. Then ψ_i can be defined as the *reduction of uncertainty* in estimating $\mathbf{x}$ by incorporating $\mathbf{y}_i$. A formal definition can be found in [22] that is based on *information utility*. Another similar example is the value of information (VoI) [23].

On the other hand, the extrinsic value is an external attribute associated with the contributed data but cannot be conveyed by the data itself. User reputation, signal strength, and sensor accuracy all belong to this category. The extrinsic value usually pertains to the contributing entity (such as user or device) or the context (such as time or location), and is especially useful when actually obtaining the data involves additional cost or evaluating intrinsic value is difficult. For example, in decision making applications, a user's contribution (e.g., decision on the presence of a phenomenon of interest (PoI)) can be evaluated by the user's historical performance (how accurate were his decisions) without knowing his current decision. This can be formulated as a *likelihood ratio* and a formal definition can be found in [24]. Another example is *Mahalanobis distance* [22] that characterizes how likely a user is to provide the most useful information (i.e., the most reduction of uncertainty) without actually obtaining the contributed data.

V. CONCLUSIONS

In the domain of smart city development, this paper is focused on the communications and networking aspect of the IoT. We identify and propose a variety of network architectures for smart city applications, and also define their corresponding performance metrics in order to maintain QoS guarantees. As a special case, participatory sensing, as well as its related network architecture and QoS, is separately presented. This new network paradigm will include people in the information acquisition-transmission-interpretation-action loop, and therefore enable them to make active contributions towards the future smart city.

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REFERENCES

[1] J. Belissent, "Getting clever about smart cities: new opportunities require new business models," 2010. [Online]. Available: http://www.forrester.com/rb/Research/getting_clever_about_smart_cities_new_opportunities/q/id/56701/t/2

[2] L. Atzori, A. Iera, and G. Morabito, "The Internet of things: a survey," *Computer Networks*, vol. 54, no. 15, pp. 2787–2805, 2010.

[3] "Smart sensored objects and Internet of things," Association Institutes Carnot White Paper, Greece, 2011.

[4] H. El-Sayed, A. Mellouk, L. George, and S. Zeadally, "Quality of service models for heterogeneous networks: overview and challenges," *Annals of Telecommunications*, vol. 63, pp. 639–668, 2008.

[5] Q. Zhang and Y. Q. Zhang, "Cross-layer design for QoS support in multihop wireless networks," *Proceedings of the IEEE*, vol. 96, no. 1, pp. 64–76, January 2008.

[6] R. Wood, *Next-Generation Network Services*, 1st ed., ser. Networking Technology. Cisco Press, 2005.

[7] M. Conti, S. Chong, S. Fdida, W. Jia, H. Karl, Y.-D. Lin, P. Mahonen, M. Maier, R. Molva, S. Uhlig, and M. Zukerman, "Research challenges towards the Future Internet," *Computer Communications*, vol. 34, no. 18, pp. 2115–2134, December 2011.

[8] J. Rexford and C. Dovrolis, "Future Internet architecture: clean-slate versus evolutionary research," *Communications of ACM*, vol. 53, no. 9, pp. 36–40, September 2010.

[9] J.-P. Vasseur and A. Dunkels, *Interconnecting Smart Objects with IP: The Next Internet*. Elsevier, 2010.

[10] J. Heidemann, D. Estrin, R. Govindan, and S. Kumar, "Next century challenges: scalable coordination in sensor networks," in *Proceedings of the fifth annual ACM/IEEE International Conference on Mobile Computing and Networking*, Seattle, WA, 1999, pp. 263–270.

[11] A. Dunkels, F. Osterlind, and Z. He, "An adaptive communication architecture for wireless sensor networks," in *Proceedings of the fifth ACM Conference on Networked Embedded Sensor Systems (SenSys 2007)*, Sydney, Australia, November 2007.

[12] J. Jin, Y. W. Law, W. H. Wang, and M. Palaniswami, "A hierarchical transport architecture for wireless sensor networks," in *Proceedings of the fourth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*, Sydney, Australia, December 2008.

[13] J. Hui and D. Culler, "IP is dead, long live IP for wireless sensor networks," in *Proceedings of the sixth ACM Conference on Networked Embedded Sensor Systems (SenSys 2008)*, Raleigh, NC, November 2008.

[14] B. Priyantha, A. Kansal, M. Goraczko, and F. Zhao, "Tiny web services: design and implementation of interoperable and evolvable sensor networks," in *Proceedings of the sixth ACM Conference on Networked Embedded Sensor Systems (SenSys 2008)*, Raleigh, NC, November 2008.

[15] SmartGrains. [Online]. Available: http://www.smartgrains.com

[16] S. Lee, D. Yoon, and A. Ghosh, "Intelligent parking lot application using wireless sensor networks," *Collaborative Technologies and Systems, 2008. CTS 2008. International Symposium on*, pp. 48–57, 2008.

[17] N. M. M. K. Chowdhury and R. Boutaba, "Network virtualization: state of the art and research challenges," *IEEE Communications Magazine*, vol. 47, no. 7, pp. 20–26, July 2009.

[18] E. D. Poorter, I. Moerman, and P. Demeester, "Enabling direct connectivity between heterogeneous objects in the Internet of things through a network-service-oriented architecture," *EURASIP Journal on Wireless Communications and Networking*, 2011.

[19] M. Srivastava, T. Abdelzaher, and B. Szymanski, "Human-centric sensing," *Philosophical Transactions of the Royal Society A*, vol. 370, no. 1958, pp. 176–197, 2012.

[20] R. Rana, C. T. Chou, S. Kanhere, N. Bulusu, and W. Hu, "Ear-phone: an end-to-end participatory urban noise mapping system," in *Proceedings of the ninth ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2010)*, Stockholm, Sweden, April 2010.

[21] T. Luo and C. K. Tham, "Fairness and social welfare in incentivizing participatory sensing," in *Proceedings of IEEE SECON*, 2012, to appear.

[22] M. Chu, H. Haussecker, and F. Zhao, "Scalable information-driven sensor querying and routing for ad hoc heterogeneous sensor networks," *International Journal of High Performance Computing Applications*, vol. 16, no. 3, pp. 293–313, 2002.

[23] A. Krause, E. Horvitz, A. Kansal, and F. Zhao, "Toward community sensing," in *Proceedings of the seventh ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2008)*, St. Louis, MO, April 2008.

[24] H.-X. Tan, M.-C. Chan, W. Xiao, P.-Y. Kong, and C.-K. Tham, "Information quality aware routing in event-driven sensor networks," in *Proceedings of IEEE INFOCOM 2010*, San Diego, CA, March 2010.