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Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities

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ABSTRACT

Smart city is an application of Internet of Things (IoT) notion. Unceasing growth of population and urbanization have intensified innovative ways to handle urbanization with minimal impact on environment, citizen lifestyles, and governance. Initial integration of information communication technology (ICT) into city operations have promoted telicity, information city, and digital city concepts. Later, the conception of IoT has founded the smart cities, which support the city operations intelligently with minimal human interaction. Smart city emerged as a solution to address the challenges arise with exponential growth of urbanization and population. However, smart city concept is still evolving and not mainstreamed throughout the globe due to technological, economical, and governing barriers. Therefore, this paper aims to deliver the essence of smart cities. The paper presents a brief overview of smart cities, followed by the features and characteristics, generic architecture, composition, and real-world implementations of smart cities. Finally, we present some challenges and opportunities identified through extensive literature survey on smart cities.

1. Introduction

The concept of connecting everyday objects via the existing networks became highly favorable with the emergence of smart devices and their recent advancements. Internet of Things (IoT) resulted from the evolution of conventional networks that connect zillions of connected devices. Technological advancements in ubiquitous computing (UC), wireless sensor networks (WSN), and machine-to-machine (M2M) communication have further strengthened the IoT notion (Silva, Khan, & Han, 2017a; Khan, Silva, Jung, & Han, 2017). Facilitating UC via uniquely identifiable smart devices without or minimal human interaction is being the de-facto principle of IoT (Gubbi, Buyya, Marusic, & Palaniswami, 2013; Khan, Silva, & Han, 2017). Moreover, connected smart devices share own information and access authorized information of other devices to support contextual decision-making (Vermesan et al., 2015). Owing to the extensive attention gained from various interest groups, IoT notion has pioneered striking applications with its expansion i.e. smart home, smart city, smart warehouse, smart health, and so forth (Islam, Kwak, Kabir, Hossain, & Kwak, 2015; Jabbar, Khan, Silva, & Han, 2016; Jin, Gubbi, Marusic, & Palaniswami, 2014; Khan, Silva, & Han, 2016). Smart city has become the spotlight in last few decades, due to dramatic urbanization all over the world. Performing city operations with aid of ICT made cities efficient in various aspects. However, incorporating ICT to perform city operations does not fully interprets a smart city (Hollands, 2008). Smart city has been favored among other urban models i.e. telicity, information city, and digital city, since it represents the abstraction of all other models (Mohanty, Choppali, & Kougianos, 2016). The smart city is an application of the IoT (Silva et al., 2016), hence it inherits the underlying operational mechanisms from IoT. As shown in Fig. 1, IoT provides essential building components for smart cities i.e. data generation, data management, and application handling.

In generic terms, smart city is an urban environment that utilizes ICT and other related technologies to enhance performance efficiency of regular city operations and quality of services (QoS) provided to urban citizens. In formal terms, experts have defined smart city considering various aspects and perspectives. A popular definition states that a smart city connects physical, social, business, and ICT infrastructure to uplift the intelligence of the city (Harrison et al., 2010). In another comprehensive definition smart city is defined as an advanced modern city that utilizes ICT and other technologies to improve quality of life (QoL), competitiveness, operational efficacy of urban services, while ensuring the resource availability for present and future generations in terms of social, economic, and environmental aspects (Kondepudi, 2014). The utmost goal of initial smart cities was to enhance the QoL of urban citizens by reducing the contradiction between

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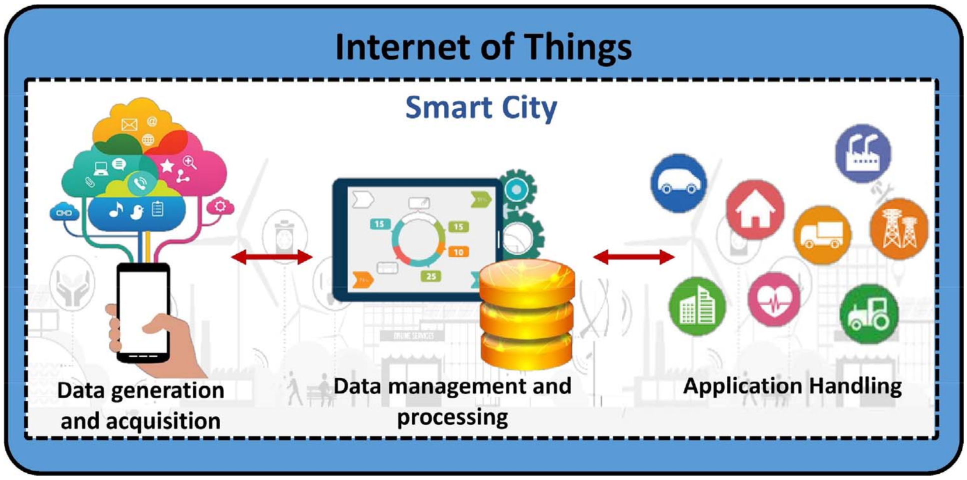

Fig. 1. Contribution of Internet of Things In building Smart City.

demand and supply in various functionalities (Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014). Accommodating QoL demands, modern smart cities especially focus on sustainable and efficient solutions for energy management, transportation, health care, governance, and many more, in order to meet the extreme necessities of urbanization (Ejaz, Naeem, Shahid, Anpalagan, & Jo, 2017).

The United Nations (UN) projected that 66% of the world population will be urban by 2050 (United Nations, 2014). In this era a large portion of resources of the world is preoccupied by cities, as a fact in modern world, 75% of the total energy is consumed by the cities (Mohanty et al., 2016). This perpetual energy consumption generates nearly 80% of the greenhouse gases that causes unfathomable adverse effects on the environment (Nam and Pardo, 2011a). Considering the fact, experts in both industry and academia agreed upon smart city as the ideal solution to address the challenges occur from drastic urbanization, population growth, deterioration of energy sources, environmental pollution, etc. Nevertheless, not every smart city are essentially similar in requirements, contributions, components, and characteristics. Therefore, International Organization for Standardization (ISO) provides globally agreed standards to assure the quality, safety, and performance of a wide range of smart cities. Hence, we can claim that adherence with smart city standards offer innumerable benefits in deploying and managing smart cities, while facilitating real-time performance monitoring (The British Standard Institution, 2014).

The research community came up with a plethora of experimental and real-time smart city solutions owing to expedience and significant attention drawn towards sustainability during the recent past. However, a majority of the proposed works belongs to experimental lab based testbed category. Transforming a testbed scenario into the real world is a laborious and a complicated task, since testbed limitations i.e. limited scalability, lack of user environment, mobility restrictions, and lack of heterogeneity preclude the practical implementation. Even though, Oulu smart city architecture (Ojala, 2010) and Citysense (Murty et al., 2008) offer service provision and experimental testbed, these architectures lack in compensating heterogeneity of IoT devices, scalability, and mobility support. Some testbed experiments (e.g. Kanseigenie (Sridharan et al., 2010)) serve heterogeneity of IoT devices, though the deployed environment is extremely different from the actual urban environment. Hence, direct extension of original tools and mechanisms used in testbed setting is not feasible in real-world deployments. WISEBED (Coulson et al., 2012) is another testbed based solution that provides a comparatively large heterogeneity in IoT devices. Moreover, SmartSantander testbed was proposed to offer mobility experiments exploiting a large-scale IoT device framework, which involves real urban citizens in the experiments (Sanchez et al., 2014).

The rest of the paper is organized as follow: Section 2 elaborates on different features of a smart city. Following to thorough analysis of recent works, in Section 3 we present a generic smart city architecture, which confirms with many proposed architectures. Section 4 elaborates on the composition of a smart city. Real-world implementations of smart cities around the world are presented in Section 5 and challenges and future trends are identified in Section 6. Finally, the conclusions are presented in Section 7.

2. Features of a smart city

Smart city comprises of attributes, themes, and infrastructure. Attributes of a smart city are also known as characteristics of smart city. Since the continuous progression of a smart city relies on themes, they are also called as pillars of the smart city. In fact, infrastructure is an essential feature for any smart city, which provides the operational platform. This section elaborates on aforementioned features considering a generic smart city deployment.

2.1. Characteristics of a smart city

Composition of multiple attributes builds a smart city. According to Saruja et al., a majority of smart city proposals consists of four main attributes i.e. sustainability, QoL, urbanization, and smartness (Mohanty et al., 2016). Few sub attributes are concerned under each attribute. Infrastructure and governance, pollution and waste, energy and climate change, social issues, economics, and health are the sub attributes that come under sustainability. The ability of a city to uphold the balance of eco system in all aforementioned aspects, while serving and performing city operations is known as the sustainability. Emotional and financial well-being of urban citizen indicates the QoL improvement. Urbanization attribute focuses on technological, economical, infrastructural, and governing aspects of the transformation from rural environment to urban environment. The smartness is defined as the desire to improve social, environmental, and economic benchmarks of the city and its inhabitants.

From 1980s, sustainability has been considered as a predominant paradigm in urban development. In fact, prevalent attention on sustainability played a major role in the emergence of smart cities. Sub attributes of sustainability adhere to the triple bottom line notion (Barton, 2010; Rydin, 2012; Wheeler & Beatley, 2014). The triple bottom line concept contemplates about interrelationship and interdependence among sub attributes shown in Fig. 2. Cities of the modern world are increasingly developing by utilizing natural resources. Thus, it is crucial to scrutinize the ramification of scarcity of non-renewable energy sources. Consequently, safe guarding natural heritages and energy sources has become a compelling demand in maintaining

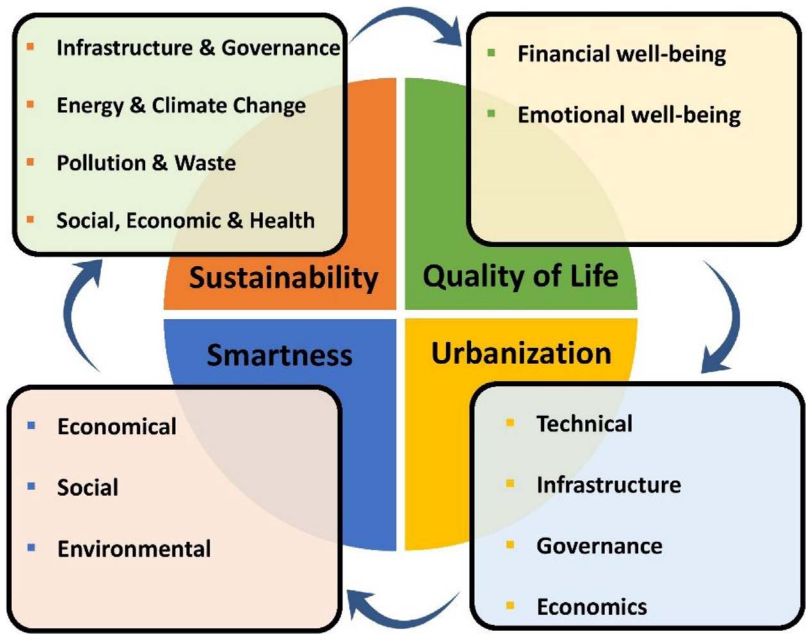

Fig. 2. Characteristics of a Smart City.

sustainability of smart cities (De Jong, Joss, Schraven, Zhan, & Weijnen, 2015).

In the past, smart cities were proposed with the ultimate goal of improving QoL. Improvements in QoL level of citizens are made by including innovative solutions, which reduces social learning restrictions and social participation barriers. Moreover, the modern city councils introduce well-defined social policies to recognize and to employ skilled citizens. Consequently, quality of city service provision is upgraded, while augmenting the QoL and financial state of skilled employees. Ultimately, financial and emotional well-being of both employees and citizens satisfy QoL enforcement. Similar attempts have made in various cities to improve the QoL. For example, City of Yokohama, Japan has implemented an artists' circle to gather artists and organize exhibitions, workshops, and performances (Sasaki, 2010) to improve social values. Moreover, in Chicago, healthcare service campaigns were organized to improve the services offered to underprivileged citizens in the city (Oakley & Tsao, 2007).

Modern world perceives smart cities as the new urban utopias (Datta, 2015). Experts claim that smart city is the ideal solution to manage challenges arise with drastic urbanization. Some of the major challenges followed by urbanization are waste management predicament, air pollution, traffic congestion, adverse human health effects, resource scarcity, and infrastructure aging (Borja, 2007; Toppeta, 2010; Washburn et al., 2009). Urbanization is categorized by the purpose i.e. industrialization-led urbanization and entrepreneurial-led urbanization, in order to provide resilient management. Enhancement of economic growth and interrelation between policy formulation and realization are at the focal point of entrepreneurial urbanization. Astounding advancements of technology has changed the conventional concept of urbanization into a more sophisticated view. Various studies were performed to understand the connection between urbanization and smart city. Smart city and urban development concepts i.e. culture, science and technology, urban policies, and social and economic development of City of Melbourne, Australia have been evaluated in Yigitcanlar, O'connor, and Westerman (2008). Similarly, the authors of Caragliu, Del Bo, and Nijkamp (2011) studied the correlation between urbanization and smart cities by exploring smart cities in Europe. The authors identified numerous factors i.e. attention to urban environment, level of education, accessibility to ICT, and use of ICT in public administration that positively influence the urban wealth. Revolving around these positive aspects, experts claimed that urbanization as a core attribute of smart city notion.

Smartness of the city aims on improving the living standards of urban community in terms of economic, social, and environmental aspects. Caragliu et al. analyzed partial correlations among human capital, e-government, length of public transport network, per capita gross domestic product (GDP), and employment in the entertainment industry to measure smartness of smart cities in Europe (Caragliu et al., 2011). Without mentioning the smartness concepts, researchers conducted studies to determine the correlation between ICT infrastructure and economic growth for the last two decades (Röller & Waverman, 2001). Alawadhi et al. performed a case study covering four cities in North America to understand the smartness of a city with reference to the smart city initiatives framework (Alawadhi et al., 2012).

2.2. Pillars of smart city

Institutional infrastructure, physical infrastructure, social infrastructure, and economic infrastructure are considered as the four pillars/themes of a smart city (Mohanty et al., 2016). The European Union (EU) adopted a well-established approach with six pillars, which resembles the four pillars mentioned above (Giffinger & Gudrun, 2010). Four-pillar constitution of a smart city is illustrated in Fig. 3.

Governance of smart cities comes under the institutional infrastructure. It associates with participation in decision making, public and social services, transparent governance, and political strategies and perspectives (The Government Summit, 2015). Careful and sensitive consideration on political perspectives made governance of a city a lot easier. Gaining the maximum benefit of human capital is essential for the betterment of a smart city. Involving and working with citizens have significant positive influence on utilizing human capital. Governance has remarkable role in coordinating between citizens and administrative bodies. The institutional infrastructure liaise with regional governments and central government to maximize the benefits of smart city. The institutional infrastructure of a smart city integrates public, private, civil, and national organizations when necessary to provide interoperation between services. In fact, this consolidation of different administration bodies serves citizens more reliably, efficiently, and effectively. Technocratic governance is another key feature of institutional infrastructure that presumes all city services and features are

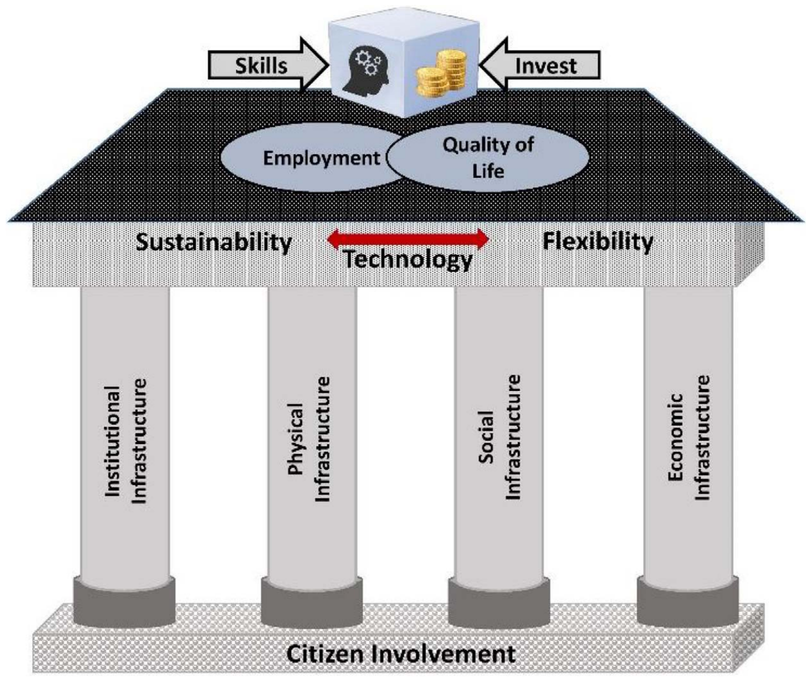

Fig. 3. Four-pillar constitution of a generic smart city.

addressable through technical solutions (Kitchin, 2014). Thus, complex social issues can be optimized through computational abilities of the smart city, which adheres with instrumental rationality (Mattern, 2013) and solutionism (Morozov, 2013).

Physical infrastructure consists of natural resources and manufactured infrastructure. Physical infrastructure pillar ensures sustainability of resources to continue city operations at present and future (Mohanty et al., 2016). The quality of ICT infrastructure leverages the performance of a smart city (The Government Summit, 2015). In addition to the ICT infrastructure, the quality and availability of smart object network has a similar importance in realizing smart cities. Physical infrastructure is further extended to green buildings, green urban planning, renovation of buildings and amenities, and smart energy (The Government Summit, 2015). Owing to these significant benefits, smart city is seen as the solution for the scarcity of natural resources. Hence, a majority of smart city initiatives focus on conserving natural resources of the city i.e. waterways, green spaces, and sewers (Bowerman, Braverman, Taylor, Todosow, & Von Wimmersperg, 2000; Vasseur & Dunkels, 2010). As stated in Section 2.1, smart city utilizes technology to serve better management, while increasing the sustainability of natural resources.

The social infrastructure of a smart city comprises of intellectual capital, human capital, and QoL. Citizen awareness, responsibility, and commitment plays a key role in popularizing the smart city concept. Hence, social infrastructure become crucial for the evolution and sustainability of a smart city. Even though the smart cities are well organized, utilize advance technologies, and equipped with sophisticated equipment, the sustainability is not guaranteed without social awareness. Since utilizing ICT to improving living standards of citizens comes under the social infrastructure pillar, we can claim that social infrastructure immensely influence the QoL of urban citizens. As social infrastructure pillar concerns about people and their relationships, it has been considered as an essential asset for any smart city (Nam & Pardo, 2011b). Comparative to a conventional city, smart city serves human to utilize and grow their potential to live a quality life. Consequently, competent and better educated citizens tend to gather around smart cities, which on the other hand encourage the growth of the city (Glaeser & Berry, 2006). Hence, knowledge based urban development is considered as a key factor in modern smart cities (Yigitcanlar et al., 2008). The experts in both industry and academia have declared that social infrastructure is a core pillar for any smart city owing to its immeasurable importance.

Existing literature provides multiple definitions for economic infrastructure of smart cities. Unceasing and steady economic growth and job growth, which flourishes a smart city is identified as smart economy in Mohanty et al. (2016), Kondepudi (2014). According to The Government Summit (2015), smart economy is a concept that reaches the boundaries of both micro and macro economy. In generic perspective, utilization of best practices and applications of e-commerce and e-business to escalate the city productivity is known as smart economy. In addition, smart economy comprises of novel innovations in ICT, manufacturing and service provision related to ICT, and integration of advanced technologies that uplift the reliability and performance of economic management. Lombardi et al. analyzed economic infrastructure of a smart city with aid of a revised triple helix model and performance indicators (Lombardi, Giordano, Farouh, & Yousef, 2012). Public expenditure on research and development (R&D), GDP per head of city population, gross inland energy consumption indicator, percentage of projects funded by civil society, and employment rate in various industries (Lombardi et al., 2012) are some of the key indicators used to evaluate the performance of economic infrastructure.

3. Smart city architecture

Researchers earnestly work on defining an apparent smart city architecture to alleviate real-world deployment of smart cities. However, feasibility of defining a universal smart city architecture for real world deployment is far from reality, though theoretically feasible. Drastic variations in the required features restrict the universal architecture to be speculative, but not realistic.

After thorough analysis of multiple existing architectures, we derived the bottom-up architecture illustrated in Fig. 4 that is common with a majority of proposed works. This architecture comprises of four layers i.e. sensing layer, transmission layer, data management layer, and application layer. Sensitive data protection is a key concern of any smart city, thus security modules have been integrated to each layer. Data collection from physical devices is the main responsibility of sensing layer, which reside at the bottom of the architecture. Via

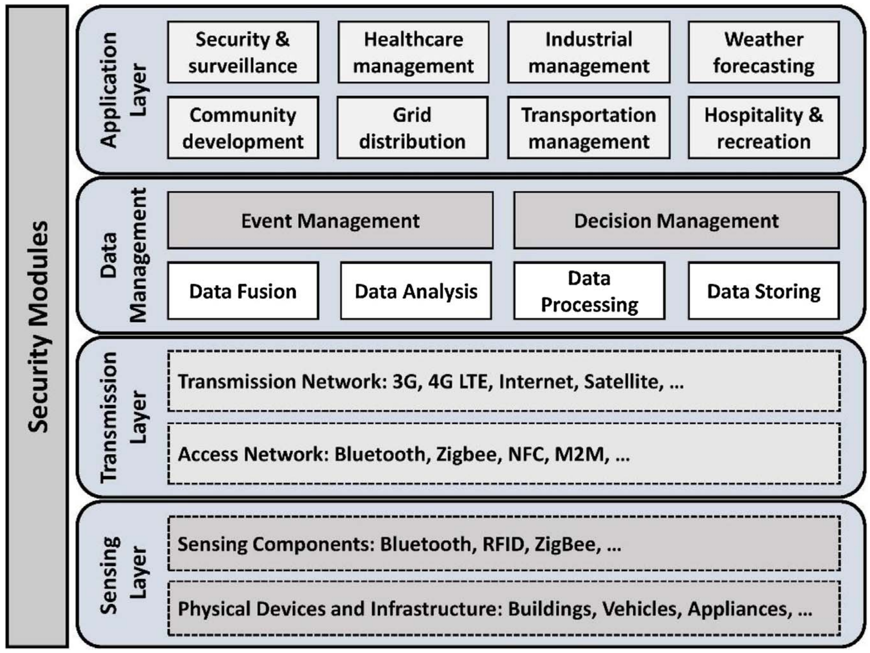

Fig. 4. Layered architecture of a generic smart city.

various communication technologies, transmission layer carries data to the upper layers. Data management layer processes and stores valuable information that are useful for service provision offered by various applications at the top layer.

3.1. Sensing layer

A real world smart city comprises of colossal amount of data, complex computations, information storage, and intelligent decision-making abilities. The practitioners have claimed that smart city implementations rely upon all forms of data and computations, due to their importance in decision-making (Wenge, Zhang, Dave, Chao, & Hao, 2014). On one hand, data collection is considered as the most important role as it controls rest of the operations of a smart city. On the other hand, data collection is considered as the most challenging task due to the immense heterogeneity among data. Data acquisition mechanism and technology are tightly bound with the type of data and the context. In fact, smart city consist of disparate data that results from diversified city operations i.e. appliance controlling in a smart home to load balancing in a smart grid, personal health monitoring to epidemic disease management, waste management in communities to disaster management, etc. Thus, we can claim that divergence among city operations create extremely heterogeneous data. Furthermore, prodigious data generation intensify the complexity of data collection.

As illustrated in Fig. 4, the bottom layer represents the sensing/data collection layer. Smart devices, WSN, and other data capturing devices build the sensing layer. Literally, it captures all types of data from all types of sensors and devices (Deshpande, Guestrin, Madden, Hellerstein, & Hong, 2004).The sensing layer offers various techniques to enhance data capturing efficiency in different contexts. The sensor network of the sensing layer collects various data parameters i.e. humidity, temperature, pressure, light, etc. For this purpose, practitioners use multiple sensing equipment, such as Zigbee, Bluetooth, and radio frequency identification (RFID) sensors, actuators, cameras, and global positioning system (GPS) terminals (Bandyopadhyay & Sen, 2011; Mulligan & Olsson, 2013; Silva et al., 2016). Maximized network coverage facilitates ubiquitous accessibility and smartness, in addition to extended data capturing abilities (Wenge et al., 2014). According to existing literature reports, the smartness of a city increases with the coverage of sensor networks (Kim et al., 2012; Sanchez et al., 2014). In addition to deployed sensors, the sensing layer gathers data from various physical devices and infrastructures, which consequently increase the number of connected devices in the smart city network. However, wider coverage cannot ensure smart ness and reliable data transmission entirely. Henceforth, perceptual models are defined to link actions with the objects or sensors to mitigate uncertainty of gathered data (Aguirre & González, 2003; Saffiotti & LeBlanc, 2000).

3.2. Transmission layer

Connecting data sources with management stations, transmission layer act as the backbone of any smart city architecture. The transmission layer is a convergence of various communication networks. Therefore, innumerable devices connected to a single network satisfies routing via unique addressability (Silva et al., 2017a). Transmission layer consists of various types of wired, wireless, and satellite technologies. Considering the coverage aspect, transmission layer is further divided into two sub layers i.e. access transmission and network transmission. Bluetooth, Zigbee, near field communication (NFC), M2M, RFID, and Zwave are known as access network technologies that provide comparatively short-range coverage. Similarly, technologies that offer wider coverage i.e. 3G, 4G long-term evolution (LTE), 5G, and low-power wide area networks (LP-WAN) are known as transmission network technologies. Various communication technologies used in smart city deployment are illustrated in Fig. 5.

RFID technology use radio frequency (RF) portion of the electromagnetic spectrum to uniquely identify an object, a person, a vehicle, or an animal. In fact, RFID shares similarities with barcode systems. However, it performs well in identifying things from a distance compared to barcode systems (Want, 2006). NFC is an access network technology that facilitates communication between two devices apart from 10 centimeters (Want, 2011). NFC performs identification, while sharing information between NFC enabled devices (Chavira, Nava, Hervas, Bravo, & Sanchez, 2007; Ohmura, Takase, Ogino, Okano, & Arai, 2013). Bluetooth is another popular access network technology that significantly reduces energy consumption on communication, owing to its short wavelength radio signals (Lee & Su, 2007; Jung, Kim, Seo, Silva, & Han, 2017). ZigBee offers low power communication among ZigBee enabled devices within a range of 10 m. Most importantly, ZigBee leverages self-organized, reliable, and multi-hop mesh

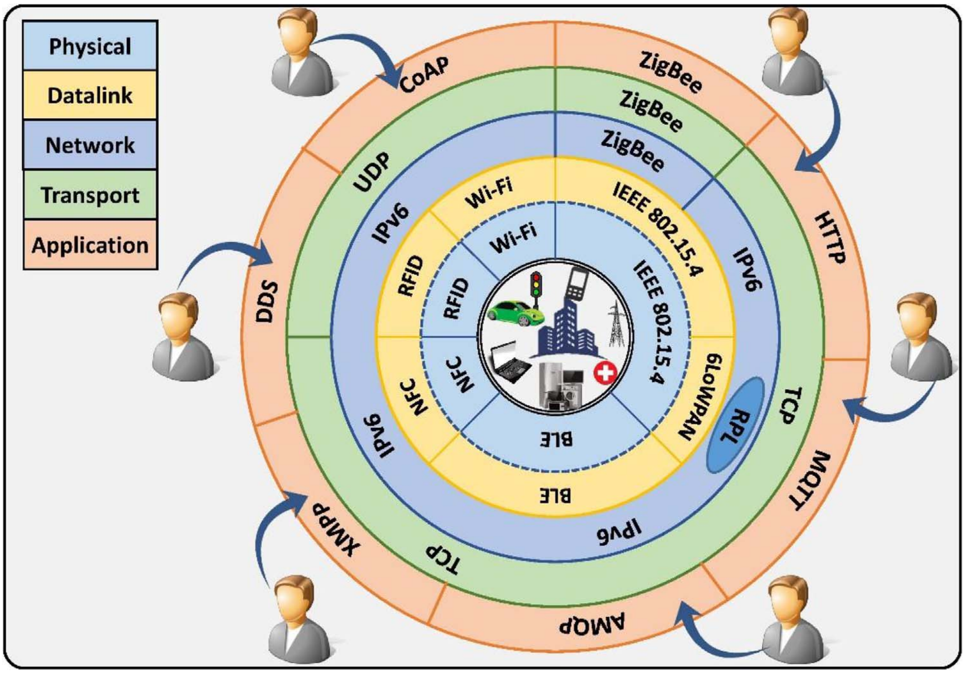

Fig. 5. Communication technologies and protocols used in smart city deployment.

networking together with long lasting battery life (Lee, 2006).

Unceasingly growing number of smart devices, mobility, and wide area aspects have promoted the demand for wireless wide-range networks in smart city designing and implementation tasks. In fact, the demand for ubiquitous access has further augmented the usage of wireless technologies (Zander, 1997). LTE is a leading 4G wireless service that has confirmed its superiority over 3G, Wi-Fi, and WiMax in terms of higher throughput, higher bit rate, and lower latency (Huang et al., 2012). In transmission network layer, 3G and 4G play an important role in mobile networks. However, fifth generation (5G) cellular network is the buzzword in modern telecommunication. In 5G networks, large number of massive multi-input multi-output (MIMO) antennas are embedded into base stations to transfer gigabit level wireless traffic (Ge, Tu, Mao, Wang, & Han, 2016). Mobile service providers utilize licensed spectrum band to offer mobile services, whereas Wi-Fi occupies unlicensed spectrum band. Wi-Fi is the most widely known wireless local area network (WLAN) technology that belongs to IEEE 802.11 family of specifications. In fact, Wi-Fi offers a comparatively higher bandwidth. However, Wi-Fi communication is adversely affected from interference due to its operation on unlicensed spectrum in 2.4 GHz (Lehr & McKnight, 2003). LP-WAN is a novel transmission networking paradigm that aims to enhance energy efficiency of industrial networking (Sanchez-Iborra & Cano, 2016). Hence, LP-WAN is seen as a promising candidate for future smart cities as it satisfies wide range coverage, while facilitating low energy consumption. Light fidelity (Li-Fi) is another trending transmission network technology that utilizes surrounding light emitting diodes (LED) for data transmission (Khare, Tiwari, Patil, & Bala, 2016). Owing to its availability in the spectrum and potential high speed, Li-Fi is seen as the future of wireless communication (Saini, 2012). Table 1 presents featured characteristics of widely accepted network layer technologies.

3.3. Data management layer

Data management layer is the brain of any smart city that resides between acquisition layer and application layer. This layer performs a variety of data manipulating, organizing, analyzing, storing, and decision-making tasks (Silva, Khan, & Han, 2017). In fact, efficiency of the data management layer is vital for a sustainable smart city, since service performance of smart city operations rely on data management. The basic task of the data layer is to maintain the vitality of data, which focus on data cleaning, evolution, association, and maintenance (Wenge et al., 2014). Data management layer can be further categorized into data fusion, data analysis, data processing, data storage, and event and decision management.

In data fusion, data from heterogeneous data sources are combined together to enforce accuracy and to generate explicit decisions without relying on a single data source (Hall and Llinas, 1997). The functionality of data filtration is to enhance the data processing efficiency of smart environments. Existing literature followed many techniques and approaches to perform data fusion. In Silva et al. (2017b), the authors have introduced Kalman filtering technique at the data management layer to perform data fusion. Similarly, practitioners occupied data analysis and processing mechanisms to reveal valuable data that are unknown and hidden in the surface (Han, Pei, & Kamber, 2011). For this purpose, experts suggest utilizing data mining techniques (Kitchin, 2014).

In Al Nuaimi, Al Neyadi, Mohamed, and Al-Jaroodi (2015), Khan, Anjum, and Kiani (2013), Rathore, Ahmad, Paul, and Rho (2016); Silva et al. (2017b), authors have proposed consolidating Big Data analytics for efficient and real-time data analysis and processing of data from smart city platforms. Data storing plays a major role in smart city deployment, since data analysis and data processing themselves do not guarantee the performance improvement of a city. Hence, we can claim that data storages are bound to support reliable and scalable accessibility for complex and massive amounts of data. Owing to the importance, experts in the domain revealed the significant impact of cloud storage architectures, large-scale storage systems, large-scale hybrid systems, and dynamic data managing architectures to attain mass data storing purposes of smart urban architectures (Alvarez et al., 2001; Golubchik, Khuller, Kim, Shargorodskaya, & Wan, 2006; Khan et al., 2013; Lin, Zha, & Xu, 2013).

Intelligent operations of the smart city are performed by event management and decision management components. In accordance with gathered data from heterogeneous data sources and retrieved data from data storages, the decision management component conceives appropriate decisions. Since decision-making is crucial for the continuous operation of any smart city, this area is being studied

Table 1
Concise descriptions of network layer technologies in terms of transmission medium, coverage, benefits, and limitations (HF- high frequency, Trans- transmission layer).

Technology	Layer	Medium	Range	Benefits	Limitations
RFID (Wireless)	Access	RF (Forster, 2007)	3–10 m	Identification Line of Sight is not demanded	No information on object condition (Liu, Bolic, Nayak, & Stojmenovic, 2008) Privacy threats (Ohkubo, Suzuki, & Kinoshita, 2005)
NFC (Wireless)	Access	HF band 13.56 MHz (Want, 2011)	10 cm (Want, 2011)	Identification	Narrow coverage Security threats
Bluetooth (Wireless)	Access	2.4 GHz in ISM band	0–10 m (Golmie & Mouveaux, 2001)	Low power Low cost	Co-interference Slow connection (Krco, 2002) Low scatternet support (Krco, 2002) Lower bandwidth
ZigBee (Wireless)	Access	2.4 GHz, 915 MHz, 868 MHz (Park & Rappaport, 2007)	0–20 m (Park & Rappaport, 2007)	Low cost Low power Mesh and tree networks (Mainetti, Patrono, & Vilei, 2011)	Limited communication (ZigBee) ZigBee network Low throughput
Wi-Fi (Wireless)	Trans	2.4 GHz	30 m (Silva et al., 2017a)	Data rate (Tronquo, Rogier, Hertleer, & Van Langenhove, 2006) Ease of setting up Flexibility and Mobility	Coexistence interference Security threats of wireless communication Black spots with no coverage
Li-Fi (Wireless)	Trans	LED	10 m (Cisco and Cisco Router, 2017)	Wider spectrum High data rate up to 10Gbps (Saini, 2012) Low cost	Interference from external light sources Light waves cannot penetrate through objects Point-to-point topology
Ethernet (Wired)	Trans	Copper cables	50–70 km	High data rate High reliability High security (Meddeb, 2005)	Require physical backbone Crosstalk with longer cables
LP-WAN (Wireless)	Trans	2.4 GHz, 868/915 MHz, 433 MHz, and 169 MHz (Centenaro, Vangelista, Zanella, & Zorzi, 2016)	10–15 km in rural 2–5 km in urban (Centenaro et al., 2016)	Long range Low power Low cost (Lee & Yi, 2016)	Lack of resource scheduling Absence of user mobility consideration (Centenaro et al., 2016)
3G/4G (Cellular)	Trans	1800–2200 MHz band (3G) 700, 800, and 2600 MHz bands (4G) (Varshney, 2012)	Up to 100 km (Ideal conditions)	High data rate Wider coverage Higher data security -UMTS encryption (3G) -IMT advanced (4G)	Data rate depends on the device (Hwang, Consulta, & Yoon, 2007) RF interference
5G (Cellular)	Trans	Millimeter wave spectrum (30–300 GHz)	2 km (tested by Samsung)	Very high data rate Low latency Ultra-density management Wider coverage	Multi-hop relay optimization(Ge et al., 2016)
xDSL	Trans	Copper cable Twisted pair	Up to 4 km (Esmailzadeh, 2016)	High data rate (Esmailzadeh, 2016)	Asymmetric communication

extensively. In various approaches, decision management components have utilized various algorithms and techniques to derive precise and real-time decisions. As the concluding task of the data management layer, derived decisions are conveyed to the application layer to execute accordingly.

3.4. Application layer

The application layer is the top layer of smart city architecture that mediates between urban citizens and data management layer. The performance of application layer highly influences user perspective and user satisfaction of smart city operations, as it directly interacts with citizens. In fact, citizens are concerned about the intelligent behavior of the city that offers intelligent services to them e.g. smart weather forecasting. The application layer consists of various components in multiple domains. The composition of a smart city is discussed elaborately in Section 4.

The key application layer services include community development, grid distribution, smart transportation, weather forecasting, etc. Application layer escalates city performance via numerous applications that utilize processed and stored data. Nevertheless, deploying isolated smart applications have minimal benefits over the performance enhancement of city operations. Hence, enabling information sharing among different applications is seemed as a promising approach for the evolution of smart cities. Table 2 represents a summary of few frameworks proposed as experimental works.

The smart applications are liable for decision execution that are transferred from data management layer. As mentioned in Section 3.3, data management layer cleanses and processes gathered data to opt the ideal intelligent decision that fits with the context. Consequently, the application layer executes decisions upon receiving them from the data management layer. As citizens are not aware about intermediate data management layer, user perspectives on performance improvement solely depend on the outcomes of application layer. Hence, smart systems at the top layer should analyze certain and uncertain needs of citizens and serve with utmost accuracy, while retaining interoperability among other smart applications. Moreover, the practitioners realized and claimed that encompassing advanced and sophisticated technologies is inadequate to attain user satisfaction in realistic smart cities. In order to attain these demands, more research work is encouraged in terms of design challenges, optimization of requirement analysis, security perspectives, and standards.

4. Composition of a smart city

Fig. 6 illustrates a few from various components that constitutes a smart city. Smart community, smart energy, smart transportation, and smart healthcare are some of those key components. However, the smart city composition varies from one smart city to another depending on the areas of interest. For example, a particular smart city might consider including a disaster management system to the smart community, while another city plans to integrate a waste management system. Following sub sections discuss few components that are common to a majority of smart cities.

4.1. Smart community

Smart community aspires to uplift citizen satisfaction and well-being of urban citizens. In this context, smart community converges large number of smart buildings, water management systems, and waste management systems. Smart buildings include smart homes and other business infrastructure i.e. offices, schools, data centers, factories, warehouses, etc. As stated in Section 3, standalone components cannot achieve much in terms of performance. Hence, smart community is connected with various other components to maximize the benefits of smart city.

Table 2
Comparison of testbed based, simulation based, and generic smart city architectures in the literature.

Architecture	Sensing Layer	Network Layer	Data Management Layer	Application Layer
Harrison et al. (2010)	Cloud based loosely coupled sensor implementation	Horizontal communication capabilities	Real-time and historical data analysis	Guided or automated policy driven decisions
Zanella et al. (2014)	Deployed a sensor network	A communication approach using constrained application protocol (CoAP)	Applied an averaging filter for 10 readings to process data	Proposed HHTP-based interface for each IoT node
Silva et al.(2017b)	Proposed deploying a sensor network	Occupied various transmission mediums to gather data	Proposed a Kalman filter optimization based Big Data analytics approach	Proposed a partitioned application layer to optimize event execution
Al-Hader, Rodzi, Sharif, and Ahmad (2009)	Proposed a geographic information system (GIS)	–	Proposed application, business and information management approach	–
Anthopoulos and Fitsilis (2010)	Represented public and private data creation and storage	Incorporated various transmission mediums	Introduced enterprise architecture, policies and rules	Provide information and services without information replication
Lugaric, Krajcar, and Simic (2010)	Data acquisition via physical grid	Agent based modelling for communication infrastructure	Agent based modelling for data exchange and decision-making	–

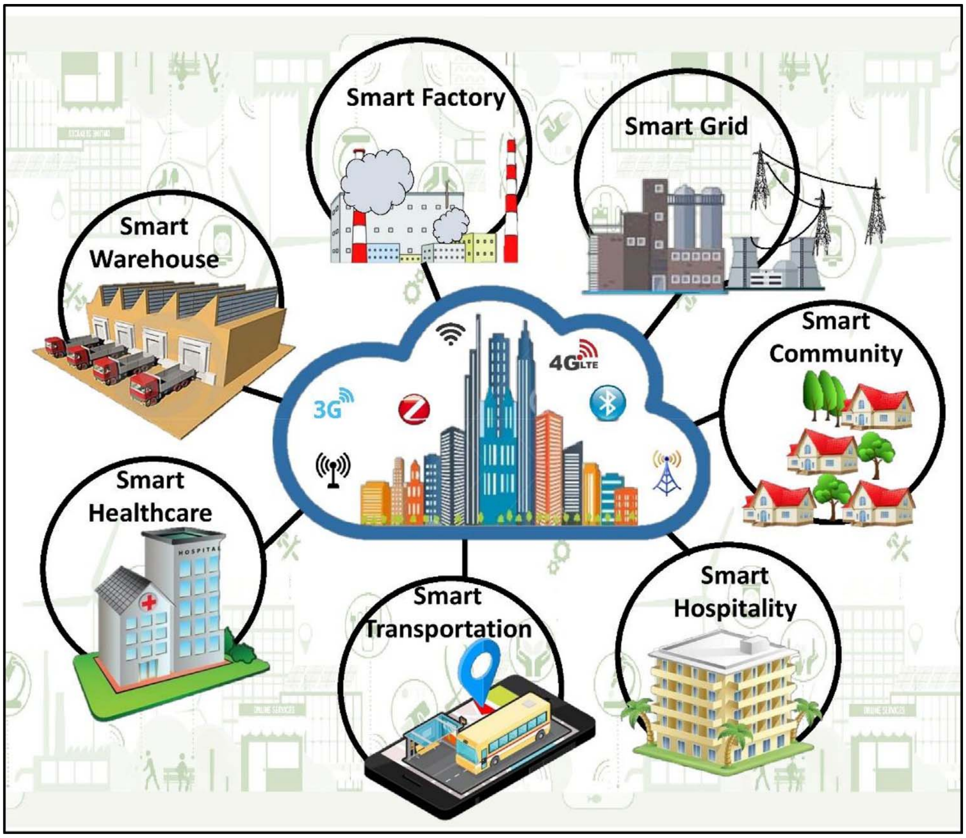

Fig. 6. Generic composition of a smart city architecture.

Smart appliances, sensors, and dedicated software and hardware are embedded into generic smart buildings. Smart buildings and green buildings share common motive in terms of energy management. In fact, green buildings focus on optimizing energy consumption and reducing carbon footprint (Eichholtz, Kok, & Quigley, 2010). Nevertheless, energy management of smart buildings follows a distinctive strategy to enhance energy efficiency by connecting smart buildings with smart grids and natural energy plants via existing network. Most importantly, data-driven decision-making ability of smart buildings maximizes energy efficiency and minimizes operational cost. However, smart buildings are not only about energy efficiency. Smart buildings are further connected with other components to manage security, surveillance, lighting control, automated operations, and so forth. Moreover, utilization of knowledge discovered through available networks enable the smart buildings to enhance quality of services offered to habitat. Owing to these benefits, inclusion of smart buildings in a smart community immensely influences smart city operations. Smart homes, smart offices, smart warehouses, etc. perform their tasks efficiently and accurately, in order to offer high quality services to citizens. For example, a smart home controls home appliances, energy consumption, surveillance, lighting control, and many more to uplift the quality of life of residents (Khan, Silva, Jung, et al., 2017; Khan, Silva, Han, et al., 2017; Khan et al., 2016; Han, Choi, Park, Lee, & Kim, 2014). Smart warehouses increase the productivity of supply chain management, which benefits the stake holders of the community (Jabbar et al., 2016).

Further, modern world perceives smart waste management as an important inclusion for any smart community. Waste generation is increasing exponentially due to extreme urbanization and industrialization. Smart waste management effectively manages the waste generated by people, public city services, and private offices (Neirotti, De Marco, Cagliano, Mangano, & Scorrano, 2014). Waste management operates in four key stages i.e. collection of waste, disposal, recycle, and recovery. Waste management is crucial for the sustainability of smart cities, since mismanaged waste disposal causes dilemma on human health and environment (Rathi, 2006; Sharholy, Ahmad, Mahmood, & Trivedi, 2008).

4.2. Smart transportation

Transportation has been a necessity for human from the beginning of civilization. The technological evolution has extended this requirement to road transportation, water transportation, train transportation, and air transportation. Conventional transportation mediums of the world were not intra-connected or inter-connected. However, the concept of connecting everyday objects has revolutionized the conventional transportation systems into inter-connected modern transportation systems.

As a result, modern transportation mediums are embedded with various communication systems and navigation systems. Thus, each particle of a particular transport type is connected with each other. Extending the connections within same medium, disparate transport mediums are inter-connected with each other to offer global transportation system. Vehicular ad hoc networks (VANET) gained much attention with the notion of intelligent transportation systems (ITS) (Naumov, Baumann, & Gross, 2006). Recently, VANETs are widely used to manage traffic congestion in city suburbs using vehicle-to-vehicle (VV) communication, and vehicle-to-infrastructure (VI) communication capability. Owing to real-time communication capabilities, transport systems became capable of acting efficiently based on real-time data. Furthermore, smart transportation systems convey information regarding congestion level of streets, alternative routes, alternative transportation mediums, etc. to passengers. Moreover, safety and security measures for passengers and pedestrians are enforced in smart transportation systems together with performance improvement. Accordingly, modern systems offer global airway hubs, intelligent road networks, intercity train networks, subway and metro train networks, safety embedded public transportation, protected cycle routes, and protected pedestrian paths (Mohanty et al., 2016). In summary, integrating smart transportation systems into smart cities improve operational efficiency of cities, while optimizing time, cost, reliability, and safety of city transportation.

A conflict detection algorithm for next generation air transportation was proposed by Hwang and Seah (2008) to predict and avoid air traffic accidents by exchanging aircraft data with each other. The rail traffic management system proposed by Mazzarello and Ottaviani improves punctuality and fuel consumption and prevents conflicts by giving real-time guidelines on travelling speed (Mazzarello & Ottaviani, 2007). Similarly, many other researchers worked on managing conflicts and congestion in rail networks (Corman, D'Ariano, Pacciarelli, & Pranzo, 2012; Mazzarello & Ottaviani, 2007; Şahin, 1999). Numerous studies were performed on road traffic management (Foschini, Taleb, Corradi, & Bottazzi, 2011; Vasirani & Ossowski, 2009; van Katwijk, van Koningsbruggen, De Schutter, & Hellendoorn, 2005) and road safety (Durbin et al., 2001; Tighe, Li, Falls, & Haas, 2000). In addition, novel transportation applications include RFID enabled toll collection, parking management, passport control at the airports, and renting and tracking taxis via mobile applications. Integrating these new dimensions of transportation systems leverage the QoL of urban citizens, while ensuring sustainability of the city.

4.3. Smart healthcare

Exponential population growth rate creates numerous healthcare challenges in modern world. As a result, conventional medical practices are insufficient to handle healthcare demands of world's population, thus become obsolete and invalid. The condition gets worsen, as the number of medical practitioners in healthcare domain does not grow proportionally with the population. Subsequently, increase the risk of prescribing wrong medication, risk of receiving inappropriate diagnosis, and risk of misinterpreting infectious and epidemic diseases. The gap between expectation and reality of healthcare is furthered by shortage in resources and superfluous demand. As a solution, smart healthcare systems were introduced to bridge this gap between healthcare demand and supply, while maintaining efficiency, accuracy, and sustainability.

The convergence between conventional medical practices with sophisticated medical intervention approaches i.e. medical equipment, sensors, wearable devices, emergency services, and ICT is known as smart healthcare. In order to serve the demands and improve the quality of services, modern intelligent healthcare services utilize sensor network, ICT, cloud computing, fog computing, smart phone applications, and powerful data processing mechanisms (Catarinucci et al., 2015; Demirkan, 2013; Roy, Pallapa, & Das, 2007; Stantchev, Barnawi, Ghulam, Schubert, & Tamm, 2015). Smart healthcare services expose sensitive patient data to authorized users i.e. doctors, nurses, and laboratory technicians via secured hospital system network to facilitate real-time decision making on patients' condition. Moreover, centrally managed electronic health records (EHR) empower real-time decision-making based on latest information.

An IoT aware healthcare system that automatically monitors and tracks patients, medical practitioners, and biomedical devices was proposed by Luca et al. (Catarinucci et al., 2015). The proposed smart hospital setting occupies RFID, WSN, and smart mobile technologies that are interconnected through CoAP. Another smart healthcare framework was proposed by Demirkan in (Demirkan, 2013), which conceptualize a data driven mobile and cloud supported smart healthcare system. In order to handle ambiguities in different contexts, Roy et al. proposed a context-aware data fusion smart healthcare framework (Roy et al., 2007). Solanas et al. (2014) proposed a new concept of context-aware mobile health in smart cities. Improved healthcare services imply heightened QoL of urban citizens. Thus, integrating smart healthcare into smart cities is foreseen as a major breakthrough in global realization of smart city notion.

4.4. Smart energy

Energy is an essential element to perform any sort of operation. Highly diversified energy sources can be either renewable or non-renewable. Unlike non-renewable sources e.g. fossil fuel, renewable sources i.e. solar, wind, and geo-thermal do not deplete with consumption owing to the nature of regeneration. For the past few decades, experts of have promoted smart energy (Lund, 2014), green energy (Midilli, Dincer, & Ay, 2006), and sustainable energy (Chu & Majumdar, 2012) concepts to raise awareness and publicize energy consumption best practices. Green energy aims on consuming energy with minimal impact on the environment. The utmost goal of sustainable energy is to sustain non-renewable energy sources for the consumption of current generation and future generations. Smart energy concept is more appealing among others as it promotes a holistic approach that consolidates green energy, sustainable energy, and renewable energy. In other words, smart energy aims to serve energy demands incorporating renewable energy sources to maintain sustainability of non-renewable energy sources, while minimizing adverse effects on environment e.g. reducing carbon footprint.

As stated before, the renewable nature of renewable energy sources makes them excellent fits to meet the world's energy demands (Herzog, Lipman, & Kammen, 2001). Along with the increasing energy demands, popularity of renewable energies has been increased over the past few decades. As a result, many studies were conducted to embed renewable energy sources to smart buildings. In some cases, renewable energy sources are attached to smart buildings and in other cases, renewable energy plants are integrated with smart grids. An energy management system for a microgrid that incorporates advanced photo voltaic (PV) generators and storage units was proposed by Kanchev, Lu, Colas, Lazarov, and Francois (2011). A similar architecture, which utilizes solar energy and wind energy was proposed for a home environment in (Han et al., 2014). Boynuegri et al. proposed a home energy management algorithm that concerns customer comfort level, while introducing renewable energy sources (Boynuegri, Yagcitekin, Baysal, Karakas, & Uzunoglu, 2013). In addition to the integration of renewable energy sources, various studies have been conducted to achieve efficient energy management in smart environments. Young et al. proposed a home energy management system (HEM) based on power line communication (PLC) to optimize power consumption and to facilitate intelligent controlling of appliances (Son, Pulkkinen, Moon, & Kim, 2010). Pipattanasomporn, Kuzlu, and Rahman (2012) proposed a demand response (DR) analysis based intelligent algorithm for HEM to manage household appliances with high-energy demands.

In fact, a large number of energy management systems are proposed for home environments, since it creates an extreme impact on total energy consumption. According to forecasted energy reports, domestic energy demand will increase up to 24% in succeeding few decades (Erol-Kantarci & Mouftah, 2011), hence managing energy consumption at the base level seems to be promising in extending energy management at city level with sustainability. In order to improve energy utilization, researchers expanded their work to manage smart grids. A game theory based energy consumption scheduling approach was proposed in Mohsenian-Rad, Wong, Jatskevich, Schober, and Leon-Garcia (2010). This strategy successfully reduced the total energy demand, total energy cost, and cost of daily electricity usage per person. Similar scenario was addressed in Erol-Kantarci and Mouftah (2011), to attain efficient demand supply balance, reduce energy expenses, and to reduce carbon emission. Introducing HEM with grid energy management maximizes energy utilization at city level.

4.5. Integration and inter-operation

The realization of smart city notion relies on integration and inter-operation of aforementioned components. Interactions among different components assist in improving performance, efficiency, QoS, and intelligent decision-making. For example, a smart home scenario included in smart community interacts with renewable energy plants and smart grid to optimize energy utilization of smart home. Similarly, smart grids interact with smart buildings to manage DR and real-time pricing. Consequently, unnecessary energy consumption is prevented in smart buildings of smart cities. Once this strategy is applied in all smart buildings, the energy conservation phenomenon is extended to community level, city level, regional level, and to global level.

However, the integration of multiple smart components is not an easy task, in other words integration could be the most challenging task when deploying a real world smart city. Each component consists of innumerable heterogeneous devices and sensors. Enormous heterogeneity among devices results extensive platform incompatibilities that hinder interoperation and intercommunication within and among smart city components. Therefore, addressing the issues arise with incompatibilities is another major concern of integrating smart city components. In Silva, Khan, and Han (2017c), have proposed a web of things (WoT) based smart city architecture to enhance the interoperability of smart city components.

5. Smart cities in the world

5.1. Smart city rankings

Smart city deployment is ascertained to improve the competitiveness of cities, in order to enhance the sustainability and livability of real-world smart cities. Cities in motion index (CIMI) was introduced to scrutinize 77 city indicators covering 10 dominant categories in urban life i.e. the economy, technology, human capital, social cohesion, international outreach, environment, mobility and transportation, urban planning, public management, and governance (Berrone & Ricart, 2016). Exploiting CIMI, Berrone et al. evaluated 181 cities in more than 80 countries to determine the smartest cities around the world. According to the index results, City of New York (USA), London (UK), and Paris (France) topped the list respectively, while San Francisco (USA), Boston (USA), Amsterdam (Netherland), Chicago (USA), Seoul (South Korea), Geneva (Switzerland), and Sydney (Australia) round out the top 10 (Berrone & Enric, 2016). New York City topped in economy index with strengths in human capital, governance, and technology. However, it ranked extremely poor at 161 in social cohesion parameter. London has topped the list in the category of human capital followed by strengths in economy and international outreach. Similar with the New York City, social cohesion index of London was poor and ranked at 129. Paris topped in international outreach metric. Moreover, Paris was recognized to be comparatively strong in social cohesion and urban planning than New York and London. Fig. 7 represents the distribution of top 50 smartest cities according to the CIMI metric. As the figure illustrates, the distribution of smartest cities is significantly bounded within Europe and USA. Few from widely tested real-world smart cities are discussed in the following sub sections. We have selected these cities based on the availability of literature, real world deployment aspect, and coverage of the components mentioned in Section 4.

5.2. London, United Kingdom

London is placed as the second smartest city in the world according to CIMI (Berrone & Enric, 2016). The city of London is constantly changing to accommodate projected one million population growth over the next decade (Board, 2016). The London data store is considered as the first platform that provided open accessibility to public data that can be utilized in innovative application development. London city is renowned for its exceptional passenger management and transportation systems. The transportation system of London has introduced congestion management from number plate recognition, which has efficiently reduced vehicle congestion during peak hours. Moreover, it includes Wi-Fi connectivity on the Tube, intelligent road management, and cycle renting schemes.

In addition, London city widely accepts digital money to enhance efficiency in savings. The city of London invests enormously on technological advancements that explore on betterment of future cities. In order to create smart infrastructure that satisfy London's requirements, the municipal of London closely works with numerous research institutes. Furthermore, Smart London Plan has proposed to utilize waste as a resource by stimulating new market opportunities for efficient waste management. Aggregating technology and creativity, London's data are linked to an iPad wall at city hall that enables the mayor to visualize city performance in real time. Similarly, citizens of London are encouraged to rate and give feedback on their experiences, which will be used to shape services according to citizens' requirements.

The architectural layout of London closely aligns with the generic architecture that we have presented in Section 3, which encompasses a heterogeneous data collection layer, a data management layer, and an application layer. London city consists of all architectural layers mentioned in Section 3 including a widespread data collection network, openly accessible data storage, and various innovative applications that serve Londoners. The components of Section 4 belongs to the top layer of generic architecture. Smart transportation system of London is highly recognized as one of the most advanced transportation systems in the world. In addition, London consists all other key components i.e. smart community, smart energy, and smart healthcare.

5.3. San francisco, United States of America

San Francisco (SF) has been renowned as the greenest city in Northern America according to US and Canada green city index (Environment, 2016). SF utilizes technology to improve operational performance of buildings, extend transportation system, centralize waste management procedures, and reduce energy consumption. In other words, SF includes smart transportation, smart energy, and smart community as its main components that serve citizens of SF. Innovative waste management approaches of municipal are considered as the main smart community aspect that upholds the title "greenest city".

The vision of shared, electric, connected, and automated vehicles (SECAV) was promoted by the SF municipal transportation agency to replace single occupant vehicles. Subsequently, SECAV vision has resolved the issues arose with time consuming and expensive transportation system within city suburbs (Municipal Transportation Agency, 2016). Moreover, SF municipal implemented a series of revolutionary acts to attain the mission of generating zero landfilling waste by 2020. In order to accomplish the mission, SF offers online tools to increase the accessibility to recycling and composting (Environment, 2016). Another key feature of SF is that 41% of urban energy demands are fulfilled by renewable energies. This approach was initiated to reduce 25% of greenhouse gas emissions by 2017. Furthermore, city municipals initiated a street light conversion project to replace high power streetlights with ultra-low power light emitting diodes (LED). Owing to the adaptation of smart energy concept, SF municipal reduced the energy consumption by 50%, while reducing the cost incurred from maintenance.

Data collection of SF smart city is extensive and broad in many aspects. Extended data collection consists of data from connected high occupancy vehicles, smart traffic signals, and connected safety corridors for pedestrians. The SF Municipal Transportation Agency (SFMTA) plays a major role in smart transportation initiatives of SF smart city. Innovative waste management approaches of municipal are considered as the main smart community aspects that uphold the title "greenest city". As stated afore, smart energy, smart community, and next generation payment systems are a few from the services offered to SF citizens. Worthy to note that all these service are offered at the application layer of the architecture described in Section 3. Moreover, these services also become the building components of SF smart city.

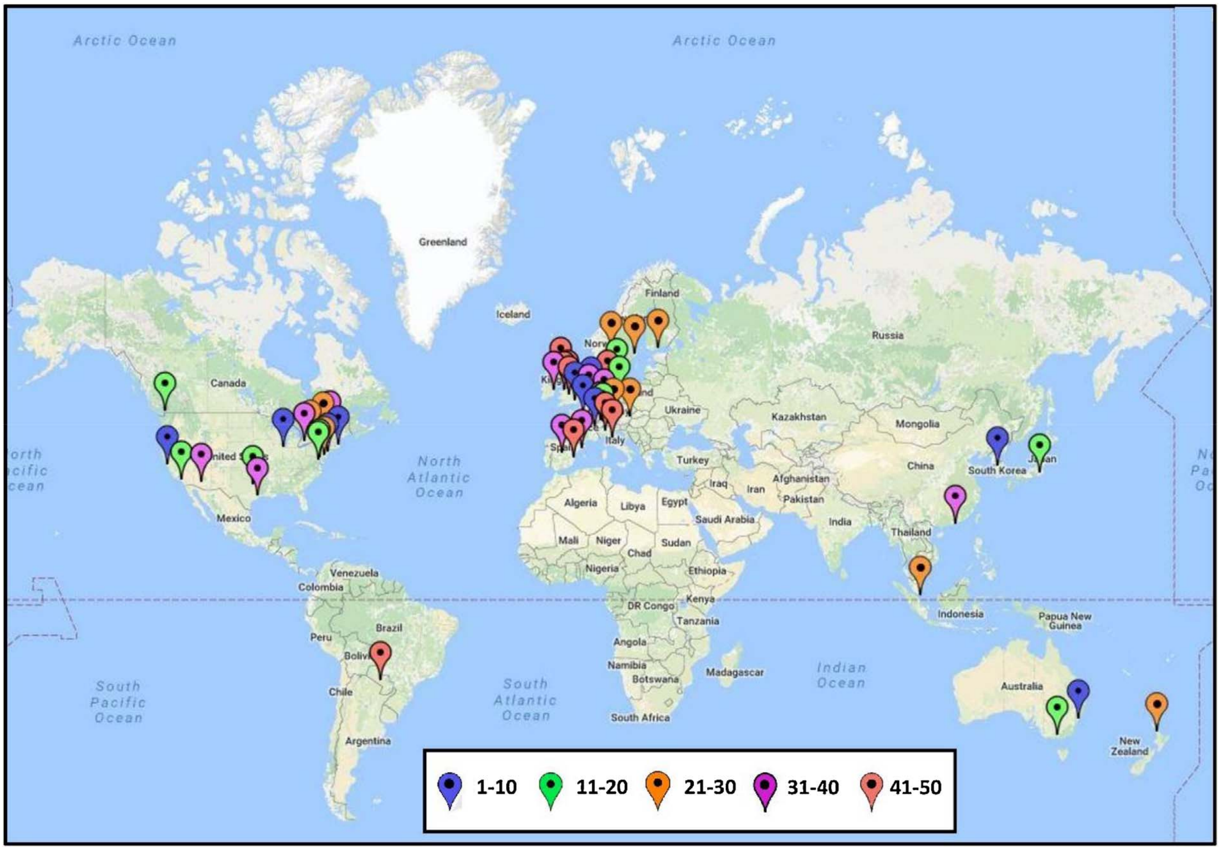

Fig. 7. Dispersion of top 50 smartest cities around the word according to CIMI metric.

5.4. Barcelona, Spain

Barcelona tops among the best smart cities in Europe as well as in the World, despite of its downfall in 2008. As the second largest city in Spain, Barcelona is considered as the industrial spotlight owing to its knowledge intensiveness, tourist attraction, and main port. In the process of transforming Barcelona, the utmost goal was to utilize ICT in business processes and public administration to enhance the accessibility, transparency, and efficacy of services. Infrastructure, information, and human capital are identified as the main assets of the smart city of Barcelona (de Barcelona, 2012; Leon, 2008). In order to attain smart city standards in economics, green infrastructure, mobility, science and technology, quality of life, and housing, certain districts of Barcelona are engaged with 22@Barcelona district project (Bakıcı, Almirall, & Wareham, 2013). Considering the facts, Barcelona city infrastructure has been remodeled to alleviate ICT integration.

The smart city of Barcelona comprises various novel services i.e. internal government services, citizens' daily life improving services, and citizen-to-citizen services. Internal government services assist municipal councilors to make better decisions and to design policies with aid of useful information provided through public workers. The city model distributes updated information to offer better services that make citizens' daily life more comfortable. In order to meet these deeds, Barcelona city is equipped with a corporate fiber optical network, Wi-Fi mesh network, multipurpose and multivendor sensor network, and a public Wi-Fi network (Bakıcı et al., 2013). In summary, Barcelona smart city model has improved public services, accessibility to knowledge, infrastructure plan, job opportunities with high creativity, etc. With reference to the architectural composition of Section 3, the transmission layer of Barcelona is dazzling with its wide broadband coverage that enable broadband economies (Zygiaris, 2013). Highly dense sensor network of Barcelona further enhances real-time data generation that support real-time service manipulation of the city. As stated for other cities, service provision for citizens is carried out by various applications i.e. smart transportation, smart healthcare, smart community, and smart energy. Upgrading the street lighting system for energy saving has been a successful stepping-stone towards smart energy management. Moreover, occupying space vacancy sensors in multistoried car parks has increased the efficiency of finding a parking space as well as the revenue. Barcelona smart city is a rapidly evolving to serve citizens with most innovative smart solutions in all aspects of life.

5.5. Santander city, Spain

Santander city was implemented as a part of SmartSantander project supported by the European Commission to facilitate an extremely large framework for research experiments on smart cities and IoT. This is known as the largest testbed for IoT deployment (Sotres, Santana, Sánchez, Lanza, & Muñoz, 2017). In addition, it supports generic services and operations of a smart city (Sanchez et al., 2014). Since Santander city was deployed as a service provision framework and an experimentation infrastructure, it offers experimentation facilities on heterogeneity of IoT devices, scalability, and real-time mobility scenarios. Santander city has integrated a variety of properties to overcome existing limitations in executing emerging smart city research. Moreover, live testbed of Santander offers experimentation realism that requires for real world deployment. Furthermore, Santander adheres with the multi-tier architecture of SmartSantander project, which defines a separate device tier. The device tier manages heterogeneous devices connected via various network technologies to serve data collection/aggregation. Contrasting to other IoT testbeds, Santander considers user responses in serving IoT enable services to citizens.

The infrastructure of Santander city provides scalable, heterogeneous, and trustworthy experimentation facility. Santander city is well known for its widespread IoT network that includes more than 12,500 sensors. These sensors monitor no of pedestrians, available parking spaces, remaining volume of trash containers, etc. The focus of the Santander city was to implement smart transportation and smart community by utilizing the deployed IoT network. The smart transportation enables congestion management, outdoor parking management, driver guidance, etc., while smart community facilitates waste management, environmental monitoring, participatory sensing, and precision irrigation (Sanchez et al., 2014). Collected data are processed in the data management layer, in order to utilize at the application layer. Consequently, Santander city offers best services to city's citizens and tourists.

5.6. Nice, France

Nice in France is well known as the first European smart city, which adopted NFC technology to execute payment transactions (Anttiroiko, Valkama, & Bailey, 2014). They accepted NFC to handle payments on trams, buses as well as in galleries, shops, etc. Nice collaborated with Cisco to acquire potential advanced benefits of Internet of Everything (IoE) (Mitchell, Villa, Stewart-Weeks, & Lange, 2013). Moreover, they performed evaluations to validate the IP-enabled architecture of Nice smart city to identify social benefits of IoE. Similar to afore mentioned smart cities, Nice adheres with the generic architecture described in Section 3.

Furthermore, this project offered four main services to the city i.e. smart waste management, smart transportation, smart environment monitoring, and smart lighting. With this initiation, the city of Nice has started utilizing valuable information across different services. For example, transportation data become useful input to efficient parking management of the city. Smart transportation of Nice offers driver guidance and parking management service. In 2012, Nice smart city deployed a smart parking management system using the network of sensors that are attached in public roads. These information are conveyed to drivers and then direct them towards the best route via GPS based mobile application (Daniel & Doran, 2013). Another important component of Nice is the grid demonstration project, which is acclaimed as Nice grid. Nice grid creates a smart solar neighborhood in city areas by converging distributed electricity, thermal storages, solar power generation forecasts, and load management (Michiorri, Girard, Kariniotakis, Lebossé, & Albou, 2012; Lannez et al., 2013).

Nice's residents are benefited from its expanded sensor network that has been deployed to monitor environmental data i.e. air, sound, humidity, energy, etc. Gathered data are processed on real-time basis to provide accurate real-time overview as well as more precise forecasting features. Among all other smart services and applications, smart energy has become the key component of Nice smart city. It encourages energy consumption reduction by scheduling electricity consumption at residential and business premises (NICE CONVENTION BUREAU, 2017). Smart waste management optimizes trash collection process. Furthermore, Nice offers interactive information on parking and traffic via smart mobility component. Moreover, smart transportation of Nice facilitates driver guidance and parking management service.

5.7. Padova, Italy

Padova smart city is implemented as a joint venture between Padova municipality and Padova University employing both IPv4 and IPv6 at the network layer. Meanwhile, occupied a WSN gateway to collect data from the deployed WSN (Perera, Zaslavsky, Christen, & Georgakopoulos, 2014). The primary goal of Padova city is to adopt open data and ICT in public administration tasks (Zanella et al., 2014). The city monitors environmental parameters and public street lighting. In order to monitor these, heterogeneous sensors were placed on street light poles and were connected with the WSN gateway to facilitate seamless data collection. As stated in Section 3, Padova smart city operates in three levels, data collection, data processing, and services.

The sensors are deployed to gather data regarding temperature level, humidity, noise, carbon monoxide level, and light intensity. Light intensity parameter assist in streetlight monitoring simply, but accurately. Lighting monitoring can be performed periodically or upon request (Cenedese, Zanella, Vangelista, & Zorzi, 2014; Zanella & Zorzi, 2014). Despite of its simplicity, smart lighting system of Padova has significantly improved the QoS by reducing the duration to recognize failures and repair, which simultaneously reduce the cost of manual inspection procedure of the street light system. Smart energy has been the key concern of Padova city. For that purpose, the smart city aims on upgrading renewable energy production, which on the other hand reduce the carbon emission. Furthermore, smart mobility and smart community components are designed to enforce low-emission environment (C.n.o.t.C.o. Padua, 2016).

6. Smart city challenges and opportunities

Even though smart city concept is widely accepted and practically implemented in real world, addressing existing issues in certain areas has become crucial to achieve further improvement. This section provides a brief discussion on challenges and promising opportunities for realistic implementation of smart cities. The challenges were identified through extensive literature review performed on recent research on smart cities. Similarly, the opportunities were identified through existing works and hands on experience on smart city research.

6.1. Challenges for smart cities

The realistic implementation of smart cities is challenged throughout design, implementation, and operation stages. Cost of design and operation, heterogeneity among devices, enormous data collection and analysis, information security, and sustainability are some of the major challenges. Fig. 8 illustrates few main concerns in designing a realistic smart city.

Design and maintenance cost is one of the major challenges for realistic smart city implementation. Cost is categorized as design cost and operational cost. Design cost is the financial capital for deploying the smart city. Hence, smaller the design cost, higher the probability of real-world implementation. Operational costs incur due to daily city operations and maintenance tasks. Minimal operational costs are highly demanded to assure the sustainability of service provision without additional financial burden on municipal. However, the cost optimization throughout the lifetime of a smart city is still a quite challenging task.

Heterogeneity is another key concern of smart city architectures. Smart cities consist of multi-vendor and multi-purpose sensors, appliances, devices, etc. The realization of smart city notion relies on the ability to integrate all these heterogeneous things at the application layer. However, platform incompatibilities result from heterogeneity hinder the ability to integrate and inter-operate at the application layer. Although facilitating universal access is a tedious and challenging task, smart cities focus on designing, identifying, and purchasing hardware and software that enables aggregation of these heterogeneous sub systems. Though high security incurs additional expenditure on design and maintenance, infrastructure security and information security are highly enforced in smart cities. Technological advancements create revolutionary changes in major cities around the globe. Cities adapted technology to improve lives of residents, visitors, and businesses. Nevertheless, parallel growth of technology and malicious threats have caused a huge controversy about securing smart cities and their operations from possible attacks. An attack on a city management system (CMS) that coordinates myriads of tasks gives a wide range of options to cause adverse effects. For example, a gas pipeline explosion has been occurred on June, 2010 in Johnson County, Texas due to confusions about location and construction progress remarks on the CMS. Similarly, attack on Illinois water utility control system in 2011, has destroyed a water pump and cut off water supply for 2200 residents. Hence, infrastructure security and information security are highly

Fig. 8. Common challenges for practical implementation of smart cities.

enforced in smart cities, even though high security incurs additional expenditure on design and maintenance.

The urban network gathers a variety of data including highly sensitive citizen data, which are vulnerable for numerous security threats i.e. side channels, cross-site scripting, and data leakage (Papadimitriou & Garcia-Molina, 2011; Vogt et al., 2007; Yang, Wu, & Karri, 2004). Hence, data privacy is another pivotal feature of any smart city structure. In fact, privacy, trust, and data confidentiality come with a price. Citizens communicate with core smart city services via computers smart phones, and other smart devices. Hence, it is essential to manage privacy issues e.g. eavesdropping. Therefore, maintaining these security measures to ensure safety of citizens' data has become a highly challenging and essential task.

Consequent to the unceasing data generation from innumerable devices, smart city data volumes tend to grow instantly and exponentially. Hence, transfer, store, recall, and analyze bulks of data is vital for uninterrupted and seamless operation of an intelligent city. Therefore, smart cities yearn to discover new realms and appealing strategies to deal with its Big Data generation and analysis.

Preserving city environment and resources for future generations by minimizing carbon footprint and efficiently utilizing resources are key concerns of modern smart cities. Therefore, modern cities are focusing on renewable energy sources to reduce the carbon footprint, while ensuring the sustainability of city operations and non-renewable energies. Owing to the importance of energy utilization, maintaining sustainability, and reducing carbon footprint, Greater London Authority (GLA) extensively discussed on improving the efficiency of power networks of London in smart opportunities for London report (ARUP, 2016).

Waste management is another critical issue in modern smart cities due to environmental pollution and land filling. The utmost goal of smart waste management is to expedite collection and separation processes (ARUP, 2016). GLA states scarcity of resources and population growth are the main issues to be addressed for successful waste management procedures.

Failure management is also a key concern for any smart city development project. Failures can occur subsequent to natural disasters i.e. floods, earthquakes, tornados, etc. and system failures such as infrastructure breakdown and network unavailability. Designing sustainability defines immediate recovery strategies to overcome a failure and to revert the city operations back to normal. Nevertheless, identification and implementation of recovery strategies and fault tolerance strategies increase both design cost and operation cost. The challenge would be to implement failure recovery mechanisms with minimal effect to cost and operational efficiency.

6.2. Future trends and opportunities

Smart city notion is still evolving and experimentation and implementation are limited within the boundaries of developed countries. Singapore has taken initiatives on utilizing citywide sensor data to monitor everyday living. The Smart Nation Program (SNP) of Singapore has incorporated existing technology infrastructure to connect all communities online. However, the benefits of smart cities are versatile and applicable to any urban environment. Therefore, further studies on cost efficient designing and implementation is highly desired to popularize the smart city approach around the world. Incorporating renewable energy sources is another compulsory approach to ensure sustainability of city operations and to manage scarcity of non-renewable energy sources.

Smart devices generate enormous amount of data that require large data storages. As a result of Big Data generation, conventional data processing methods and techniques have become obsolete for use in modern smart city architectures. Hence, it is essential to explore and integrate Big Data analytics into smart city environments. In fact, few studies attempted to address this challenge. However, most of them are proposals and not experimented on real world scenarios. Therefore, proposing and experimenting Big Data analytics in actual smart cities is a promising research opportunity for future smart cities. Preserving security of sensitive data is demanded in connected environments. If citizens are not convinced about the security of sensitive data, they simply tend to avoid using ICT platform of smart cities, which hinders sustainability and reliability of city operations. Thus, introducing universal security measurements for smart cities is an essential necessity that requires further investigation.

Exploiting benefits of heterogeneous devices is another key area for research. Smart cities integrate various sub systems at the application layer to offer timely and reliable services. Aggregation at the application layer is worthy to explore further. Web inspired WoT notion is seen as an ideal candidate to integrate heterogeneous applications owing to its universal accessibility. As a result, smart city components will be able to communicate with each other despite of the incompatibilities in operational platforms and communication technologies.

7. Conclusions

Smart city concept emerged as an application domain of IoT. Among various concepts that utilize ICT in urban environments i.e. digital city, green city, sustainable city, intelligent city, etc. smart city stands out owing to its holistic vision. In other terms, smart city act as a composition of other forms of urban environment management strategies.

This paper presented fundamentals of a smart city in terms of definitions, standards, and implications. The characteristics and features are described in a simple manner to understand the gist of smart city notion. Moving on to more technical details, generic architecture of a smart city is described after thorough examining among proposed smart city architectures. Smart city is a system that facilitates interoperability among various sub systems to improve the QoL of urban citizens. Henceforth, to acknowledge the importance of the composition, major components that builds a smart city are described elaborately. The literature survey identified that the realization of smart city highly relies on expedite data processing, ubiquitous accessibility, and platform dependent interoperability among devices. Real-world implementations of smart cities are presented towards the end of the article along with some latest statistics. Even though, smart cities has become a buzzword in modern world, it still faces some serious challenges and issues due to prodigious data processing demands and heterogeneity of connected smart things. In order to enrich the knowledge base and to provide guidance for future research, we described some challenges identified and opportunities for improvements.

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