Smart Cities for Promoting a Sustainable Urbanization

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***Abstract*—This paper highlights the significance of modernizing urban architectures towards establishing smart cities in populated metropolitan areas of the world. The paper first summarizes the ongoing efforts for modernizing urban infrastructures, while underlining the role of information and communication technologies and citizen-government collaborations in the management of smart cities. After exploring the possibility of performing holistic planning and operation of interdependent and interoperable smart city infrastructures, the paper presents a hierarchical control and management framework that takes into account big data analytics and software-defined networking technologies for facilitating the implementation of smart city infrastructures. An interactive simulation scheme based on a multi-agent system is proposed for evaluating the sociotechnical and socioeconomic performance of smart city infrastructures. The paper also elaborates on potential social, economic and technological challenges encountered in smart city infrastructures, including human-machine partnership and cyber-physical security. It is concluded that smart city infrastructures will play a critical role in attaining the global sustainability considering economic, social, cultural, ethnic, and political constraints facing our planet.**

***Index Terms*—Smart cities, urban infrastructures, holistic planning and operation, cyber-physical systems, socio-technical systems, hierarchical control and management.**

I. The Need for Establishing Smart Cities

Cities with substantial population growth are increasingly encountered with economic, social, and environmental challenges in their daily operations. Fig. 1 shows the trend in the growth of urban population. Currently, above 55% of the globe's population lives in major cities, which is almost quadrupled in headcount as compared with that in 1950s. The global urbanization is expected to grow to cover about 70% of the world population by 2050 resulting in an unprecedented increase in the consumption of existing resources [1],[2].

Fig. 2 shows the substantial growth in the green gas emission around the globe from 1995 to 2015, which has resulted in a unanimous public outcry and forced well-versed societies to curb their dependence on fossil fuel consumption for restraining the excessive global warming. In fact, major cities contribute to the 75% usage of global energy resources and account for 70% of global greenhouse gas emission, even though they only occupy about 5% of the total land mass [3],[4]. The rapid urbanization also contributes to multiple types of serious environmental pollutions (e.g., air, soil, water), which affect the health and the quality of life of citizens. Fig. 3 shows the possible contamination of urban water resources when industrial chemicals and sewage are drained into waterway.

The optimal management of major cities could play a key role in orchestrating the global response to challenges posed by rapid urbanization. A prosperous society manages a collection of smart city infrastructures that supports sociotechnical and socioeconomic initiatives and celebrates cultural and ethnic diversities.

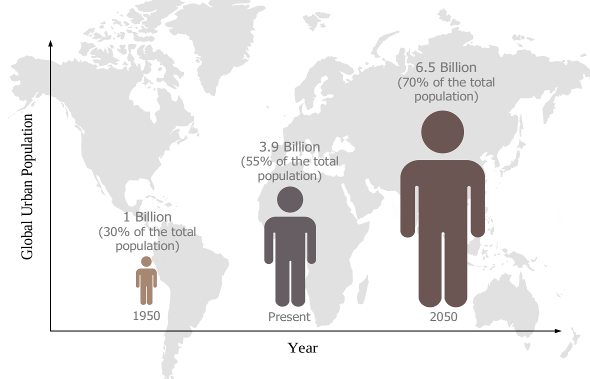

Fig. 1 Growth in urban population

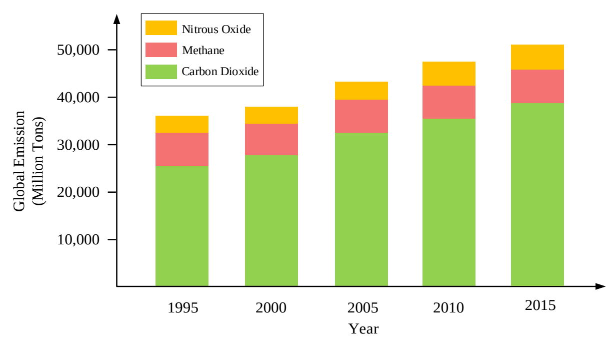

Fig. 2 Growth of greenhouse gas emission

Fig. 3 Urban water contamination

However, urban infrastructures in many cities suffer from a series of critical issues including capacity insufficiency, functional deterioration and deferred maintenance, and technological obsolescence that place legacy infrastructures under perpetual stress for providing better civil services and promote a higher quality of life and socio-economic competitiveness. In particular, a significant increase in urban population places massive pressure on constrained city infrastructures (e.g., public and private transportation and mobility), poses various types of concerns pertaining to daily lives of individuals, and potentially lead to significant economic losses and lack of preparedness in critical and disastrous circumstances.

Fig. 4 depicts a typical traffic congestion in developing countries. Meanwhile, well-developed urban areas like Chicago also represent some of the most overcrowded transportation hubs in the world. In such locations, the individual driver's economic opportunity is estimated at $24/hour culminating in over 302 million hours of travel delays with a total congestion cost of $7,222 million in Chicago in 2014 [5]. These numbers could sum up quickly to highlight significant elapses in economic productivity and social contentment considering the number of cities with major traffic congestion in North America.

Fig. 4 Severe traffic congestion

Fig. 5 Leak in the legacy water supply infrastructure

For example, about 25% of the water supply in major U.S. cities is lost through leaks in legacy water pipes (see Fig. 5) indicating that water supply systems in several cities require a major overhaul [6]. Likewise, the vast majority of inner city power distribution lines (see Fig. 6) were constructed in 1950s and 1960s, which have already surpassed their 50-year life expectancy [7]. The legacy electric power infrastructure has already proved its frangibility, especially as it faces extreme weather events. On Aug. 14, 2003, New York City was severely hit by a power blackout resulting from cascading failures of electric power system components, in which eight million local citizens suffered prolonged power outages. Fig. 7 shows the mostly dark skyline in New York City during the blackout. Again in October, 2012, New York City experienced a widespread power outage caused by Hurricane Sandy, which left millions of citizens without electricity for several days [8].

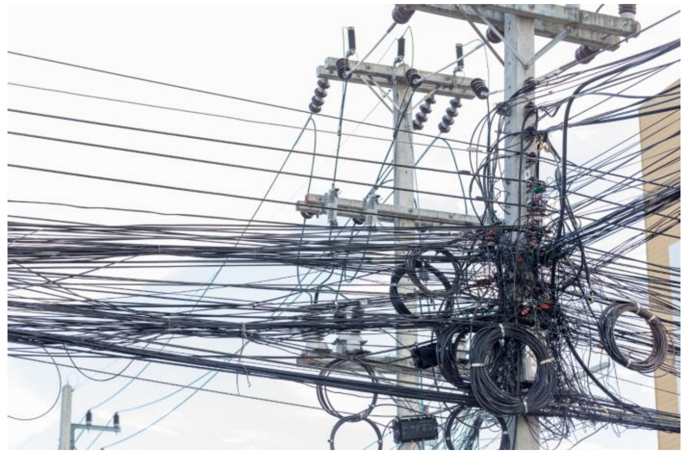

Fig. 6 Aging power distribution infrastructure

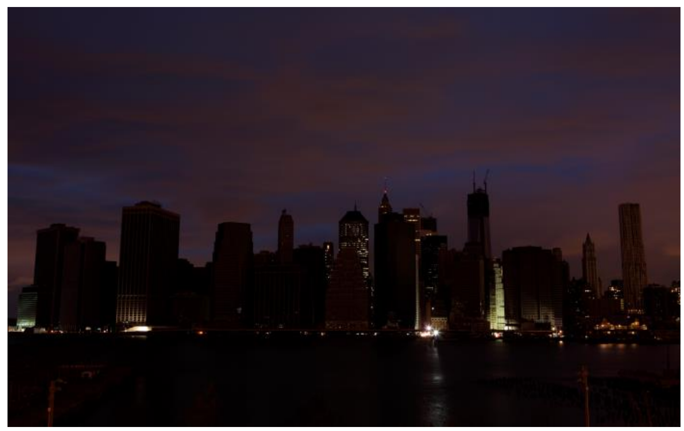

Fig. 7 Power blackout in New York City

II. What is a Smart City?

A smart city is an urban center that integrates a variety of innovative solutions to improve infrastructural performances in order to achieve a sustainable urban development. In particular, the adoption of smart city solutions represents a key factor in the consumption of resources for improving the efficiency of services and meeting individual citizens' needs, as urban population grows and resources become scarce. A smart city therefore depends on underlying urban infrastructures to create necessary services for its citizens to develop their professional, social and cultural activities.

As migrations to major cities are considered by individuals in pursuit of a more secure and economically viable conditions, citizens of large cities have greater and more sophisticated demands for a better quality of life. Smart city solutions, which can potentially remedy some of the shortcomings stemming from urbanization, have already spurred increasing interests among citizens, city authorities, and technology vendors for addressing critical economic, social, and environmental concerns in metropolitan areas [9]–[11]. In such cases, cities are experimenting various smart city alternatives for maintaining

Fig. 8 A hierarchy of services in a smart city

the safety, security, welfare, convenience, and comfort of their citizens [12]–[14]. The development of a smart city is commonly regarded as a natural strategy to fulfill desired city functions that meet citizens' expectations.

A smart city includes a collection of urban infrastructures with a common goal of enabling certain objectives, among which energy, transportation, and municipal infrastructures which represent the backbone of a city's efficient, livable, and sustainable operations. Fig. 8 shows a typical version of critical smart city infrastructures which provide vital services for the economic and social processes in a smart city, including electricity and natural gas supply systems, district heating system, traffic management system, public transportation system, water supply system, water and waste management system, street lighting system, and public safety system. Although these smart city infrastructures consist of their own service territories and jurisdictions, their operations are interdependent and often coordinated in a smart city.

Since a smart city utilizes innovative solutions to connect social, economic, and infrastructural objectives for addressing specific public mandates, the development of smart cities is expected to play a key role in achieving the urban sustainability. As such, the successful transition to smart cities is intricately linked to the modernization of urban infrastructures that could meet the specific requirements posed by smart city objectives. However, it is technically challenging and economically expensive to build from scratch new urban infrastructures that meet various requirements of smart cities. Instead, significant efforts should be invested in maintaining and upgrading legacy urban infrastructures for increasing the functionality and intelligent operations of smart city components.

In Fig. 9, urban sustainability conceptually rests on three pillars of economic, social, and environmental sustainability [15],[16]. Economic sustainability is the city's ability to support a desired level of economic productivity and growth indefinitely; social sustainability is the city's ability to maintain the well-being of social functions (e.g., security, reliability, resilience) at a desired level indefinitely; environmental sustainability is the city's ability to harvest renewable resources at a desired level without hampering the ecosystem integrity indefinitely. Accordingly, smart city solutions will not only enable efficient use of the natural environment and the built environment, but also guarantee to meet the needs of present and future citizens in economic, social and environmental aspects [17].

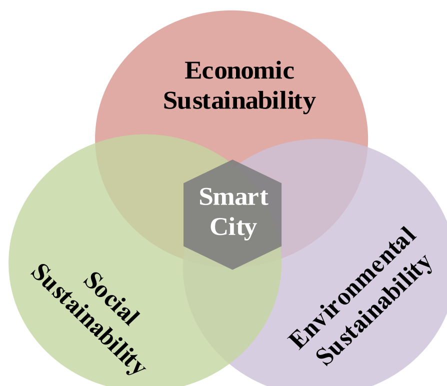

Fig. 9 Pillars of urban sustainability

In this paper, the implementation of interdependent smart city infrastructures is regarded as the outcome of technological, economic, and social innovations which are developed as part the transition to smart cities, which are detailed as follows. Section III present the role of information and communications technologies (ICTs) and citizen-government partnerships in the modernization of urban infrastructures, and exemplifies three ongoing projects associated with smart city infrastructures. Section IV explores holistic planning and operation of smart city infrastructures in order to provide designated services in smart cities. Section IV proposes a hierarchical control and management framework in accordance with the sustainable urbanization objectives, which facilitates the coordination and integration of independent smart city infrastructures and promotes the collaborations between the government and citizens. Section V presents an interactive scheme for performance evaluation, guiding the implementation of smart city infrastructures, and refining the specific urban services provided by these infrastructures. Section VI analyzes the risks rooted in the implementation of smart city infrastructures from social, economic, and technological perspectives. Section VII concludes the key role of smart city infrastructures in facilitating a sustainable urbanization.

III. MODERNIZING URBAN INFRASTRUCTURES

Smart city promotes the vision of sustainable urbanization for improving the performance of city operations. Cities constantly validate and deploy effective solutions to maintain, upgrade and expand their infrastructures in support of a more sustainable, efficient, and livable urban society. In Fig. 10, technological and social innovations delivered through smart city development, and management offer a new wave of opportunities for modernizing urban infrastructures while striking a balance among social, environmental and economic sustainability.

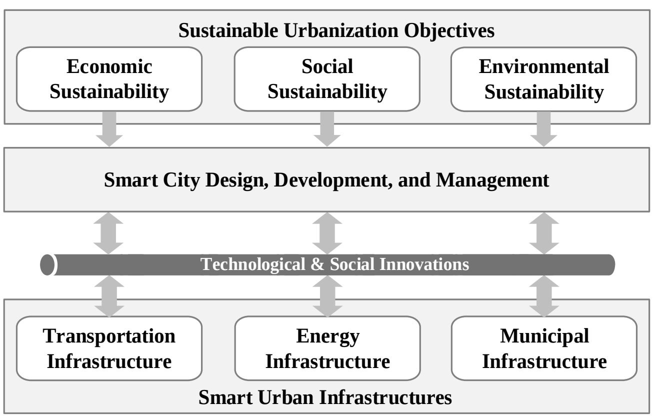

Fig. 10 Smart city solutions for modernizing urban infrastructures

The introduction of smart city solutions into urban infrastructures for transforming citizens' lives has resulted in numerous opportunities which are discussed below.

III.A Smart City Operations via ICTs

A smart city infrastructure is a cyber-physical system that comprises a series of networked physical elements, including embedded sensors, computation devices, communication media, and actuators. The adoption of ICTs for networking a combination of heterogeneous smart city infrastructure components in a coordinated manner is regarded as the enabler of smart city infrastructures. The emergence of ICTs in legacy smart city infrastructures endorses economic prosperity, environmental protection, and social welfare.

ICTs play a key role in helping city authorities increase the understanding and the control of smart city infrastructure operations with optimized use of resources for city functions. ICTs catalyze the situational awareness and the real-time decision making of smart city infrastructure operations and enable city authorities to implement necessary infrastructural adjustments more effectively in extraneous operating conditions.

In fact, cities are increasingly adopting scalable solutions that benefit from the advances of ICTs to increase the efficiency, sustainability, reliability, and resilience of their urban infrastructures. In particular, the emergence of internet of things (IoT) technologies [18], including radio frequency identification (RFID) [19], near-field communications (NFC) [20], and wireless sensor networks [21], has contributed to the inclusion of advanced information technologies into the optimal operation of legacy smart city infrastructures.

IoT technologies manage to interconnect machines, applications, and services across all facets of citizens' lives and facilitate the implementation of machine-to-machine communications and human-machine interactions at very large scales. Accordingly, IoT technologies create a seamless integration of physical objects and the digital representation of city operations, providing tremendous opportunities for cities to improve their functions (e.g., spurring local economic growth through technological advancements, increasing citizens' well-being by offering a more resilient, reliable, secure, and sustainable city environment) [22]–[24]. For instance, global positioning system (GPS) sensors installed on snow plows feed real-time positioning data to a "plow tracker" map that identifies and displays the locations of snow plows and salt spreaders during snow storms [25]. The implementation of such an IoT project allows the city to keep streets clear within shorter time by optimally guiding the use of existing equipment.

III.B Promoting Man-Machine Collaborations via Smart Cities

Cities are developed by humans and a successful transition to smart cities hinges upon the man-machine interface which encompasses human behavior and technological advances in such cities. Fig. 11 shows the potential operations of a smart city, where humans, processes, and machines are linked by the underlying smart city infrastructures via ICTs that results in extensive interactions among citizens and the city government. Accordingly, the modernization of urban infrastructures can foster additional collaborations among citizens and the government in normal and emergency conditions. Only when technological implementations are in sink with human behavior, can interdependent infrastructures in smart cities reach their full potentials for serving local citizens.

In Fig. 11, the man-machine interface for the modernization of urban infrastructures requires a balance between top-down and bottom-up approaches which are driven by technological and social innovations, respectively. On the one hand, the interface requires strong top-level leadership and top-down execution processes for city authorities to implement innovative technological solutions with high confidence. For example, authorities collate extensive information generated by smart sensors deployed at various sites in order to develop sophisticated applications to serve citizens better. On the other hand, bottom-up governance, including citizen-driven innovations and co-creation, is becoming the defining characteristic of smart city infrastructures, as the role of citizens is changing from passive end-users to active co-providers of services, activities and other facilities involved in smart city operations. For example, it is increasingly common for citizens to produce energy from renewable sources at residential sites and send it back to the electric utility grid for enhancing the power grid reliability and economics in a smart city.

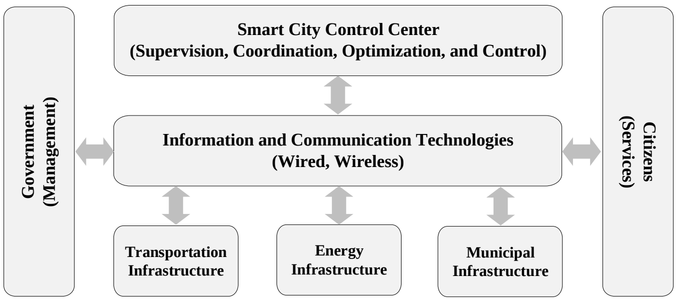

Fig. 11 Holistic view of man-machine interface in smart city operations

However, current practices in implementing smart city infrastructures are often faced with criticism for being more concerned with technologies than humans by following top-down approaches [14],[26],[27]. In order for urban infrastructures to reach their full potential in smart cities, citizens should be encouraged to participate at large in decision making processes of city operations. Such active participation allows urban infrastructures to be modernized in a human-driven bottom-up fashion that is in parallel with more traditional technology-driven approaches. As ICTs act as innovators in the provision of smart city infrastructures, city authorities and citizens are provided with immense collaboration opportunities to achieve higher excellence in city operations.

Advances in ICTs give birth to a variety of innovative platforms and applications that engage citizens actively in the real-time monitoring and control of city operations. City authorities monitor individual citizens' behaviors and share the real-time information on city operations with citizens over social media, websites, or hotlines, when citizens are motivated to respond to respective signals from city authorities and adapt their behaviors to the evolving urban settings in a smart city. In that case, both citizens and city authorities have access to increased intelligence on city operations for situational awareness which promote more collaborative efforts in achieving the urban sustainability. With the provision of a good knowledge on city operations corresponding to citizens' behaviors, city authorities can also collaborate with technology vendors to develop customized platforms and applications for further enhancing the citizens' work and living environments.

Advanced metering infrastructure (AMI) is a good example of how citizens enjoy the transparency and efficiency of electric power services [28]. AMI employs smart electricity meters to measure, store, and transmit energy usage data associated with electronic appliances at citizens' sites. Meanwhile, AMI allows electric utility companies to guide citizens' power consumption by monitoring, tracking, and influencing energy usage across smart meters. Accordingly, citizens are enabled to perform demand response in order to optimize their energy usage based on the dynamic pricing information obtained via smart meters [29],[30]. Waze [31] is another example of how smart cities can benefit from citizens' active participation in traffic management. Waze users can report accidents and traffic jams on individual routes via their cellphones, and this information is shared with other users and local traffic management authorities for improving the overall traffic efficiency in certain regions.

III.C Practices for Coordinating Smart City Infrastructures

Given the economic and the societal significance of smart city infrastructures, many cities are adopting innovative smart city solution to modernize their urban infrastructures which can sustain improvements in city services and enable the infrastructure resilience to catastrophic events. Modernization efforts are continuously made for making individual infrastructures smart before integrating them in a smart city.

Energy, transportation, and municipal infrastructures depicted in Fig. 8 are building blocks of smart city infrastructures in a smart city. Hence, smart city solutions should first be experimented and demonstrated on these infrastructures. The following subsections will detail three prototype attempts, which have been initiated on the main campus of Illinois Institute of Technology (IIT), for making these infrastructures smart in the City of Chicago.

III.C.1 Smart Energy Infrastructure in a City

The modernization of urban energy infrastructures relies on innovative technological and social solutions, including advanced sensors and meters, sophisticated dispatch and control tools, to automate and optimize the entire process of energy generation, distribution, consumption, and storage. Ongoing efforts invested in developing smart energy infrastructures include [32]–[36]: improve the overall energy efficiency in generation, transmission and distribution; accommodate a higher penetration level of renewable energy resources; reduce environmental pollutants resulting from energy generation and consumption; enhance reliability and resilience of energy system operations; promote demand-side management for citizens to get more efficient decision making of energy consumption.

The widespread implementation of ICT-based technological innovations provides an extended network of intelligent energy services across the city, enabling a detailed view of energy generation and consumption patterns along with a sophisticated decision-making process of allocating available resources for sustaining energy balance. Moreover, a growing number of distributed energy resources (DERs) has become active participants in the provision of energy services, which will continue to flourish the use of distributed energy systems (e.g., microgrids, nanogrids).

Distributed energy systems are small-scale self-controllable energy systems clustering DERs and loads, which promise to dramatically improve the survivability and efficiency of local energy services by taking advantage of on-site DERs.

Distributed energy systems can also be networked to further improve the economics, efficiency, security, sustainability, reliability, and resilience of energy services supplied to local citizens. In that regard, conventionally centralized energy infrastructure will be logically replaced with a host of distributed, interoperable and intelligent systems that are capable of handling two-way energy and information flows.

The Keating Nanogrid [37], which is a self-sufficient building-level electric power system sited at the sports center on IIT campus, is a good example of distributed energy systems that lay the solid foundation for smart energy infrastructures. Fig. 12 presents the flexible configuration of the nanogrid which is a hybrid AC and DC power system for utilizing solar energy in conjunction with energy storage devices.

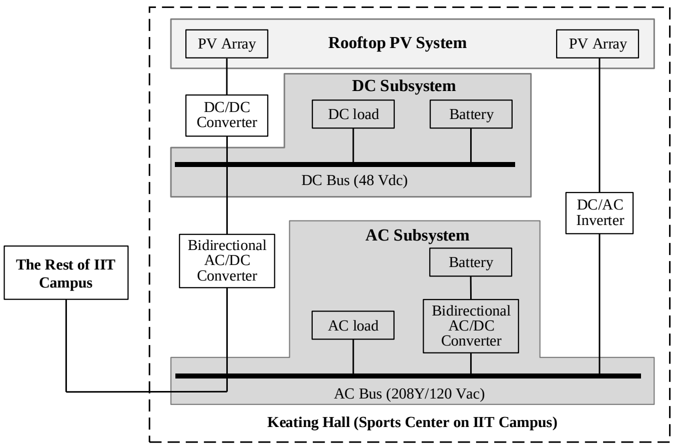

Fig. 12 Configuration of the Keating nanogrid

With the support of the sophisticated ICT implementation (e.g., remote lighting control, battery status monitoring), the nanogrid is a self-controlled entity equipped with strategic supply-side and demand-side management solutions, thereby maintaining a guaranteed high level of operation efficiency and resilience. In normal conditions, a nanogrid can take full advantage of on-site resources to serve the building load with minimized import energy from the adjoining electric utility grid. At certain hours, the nanogrid will feed the excess power generated by PV arrays back to the IIT campus for improving the energy consumption efficiency at a larger scale or and store it in on-site storage devices for turning the lights on after the sun has set. In case of power outages, the nanogrid can intentionally island itself from the rest of the IIT campus and continue to power the critical building loads by utilizing available PV and storage resources inside the nanogrid.

Fig. 13 presents the field results on an average summer day, when the nanogrid will harvest solar energy for demand response, which is based on the optimal utilization of installed PV arrays and batteries. When the power output of PV arrays varies significantly from 7 am to 9 pm and peaks at around 2 pm, batteries are strategically controlled to level out the variability of PV power output and firm up the nanogrid operation. Specifically, batteries are charged when the PV power output exceeds the building load and they are discharged when the PV power output is inadequate for supplying the building load. The implementation of the nanogrid reduces building energy cost and adds more flexibility to the operation of the localized electric power system. This nanogrid design could be applied to other critical infrastructures including the surgery department within a hospital campus.

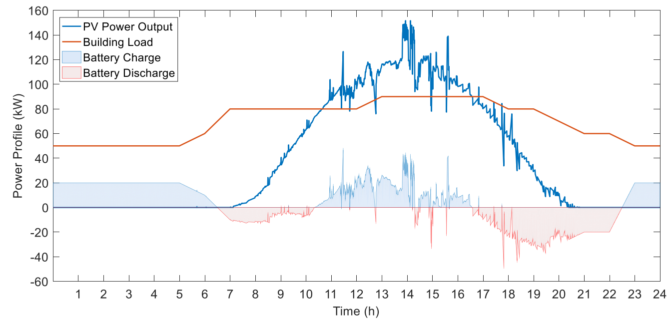

Fig. 13 Power generation and consumption of the Keating nanogrid

III.C.2 Smart Transportation Infrastructure in a City

The modernization of urban transportation infrastructures requires a seamless integration of automobiles, sensors, actuators, telecommunications, and analytics with legacy transportation infrastructures so as to release the constrained urban mobility. Ongoing efforts invested in developing smart transportation infrastructures include [38]–[42] which enable a fully automated and completely reliable remote traffic management system; achieve the real-time visualization of the road traffic conditions; automate the detection of offences and hazardous conditions on roads; identify accurate traffic patterns based on contextual observations (e.g., weather condition, type of day, special event); predict traffic volumes on different time scales; automate the diagnosis and preventive maintenance of public transit vehicles; prioritize emergency and public transit services based on online traffic flow analyses.

In this regard, advanced ICTs are increasingly utilized to interlink vehicles, drivers and transportation infrastructures in the urban traffic management system that aims at improving traffic flows and travel times on city streets and highways while satisfying citizens' travel requirements. Particularly, vehicular wireless communications such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications enable drivers to communicate with each other and with the traffic management authority. In Fig. 14, V2V allows vehicles to communicate with one another within a short range, whereas V2I allows interactions between vehicles and neighboring transportation infrastructure components (e.g., traffic light signal controller) that are under the control of the traffic management authority. The resulting real-time information sharing enables both drivers and the traffic management authority to gain increased situational awareness on the dynamics of traffic conditions so that potential traffic emergencies and road congestions can be predicted and managed more effectively [41],[43].

Considering that congested street intersections often signify the bottlenecks for boosting the overall efficiency of the urban traffic management, researchers in the Robert W. Galvin Center for Electricity Innovation at IIT have attempted to employ vehicular wireless communications in optimizing the sequence and durations of traffic light signals at street intersections [41], [42]. The proposed innovative signal optimization mechanism promotes the coordination between drivers and the traffic management authority in decision making processes for identifying individual driver's optimal travel routes. Here, the traffic management authority makes decisions on setting traffic light signal durations that mitigate traffic congestions (i.e., minimize the total travel time), and drivers use the corresponding signals provided by vehicular wireless communications to identify fastest travel routes.

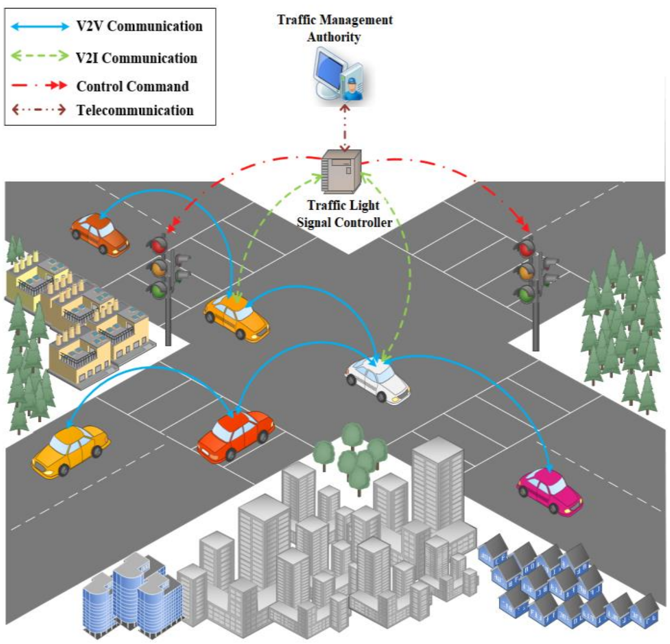

Fig. 14 Vehicular wireless communications for urban traffic management

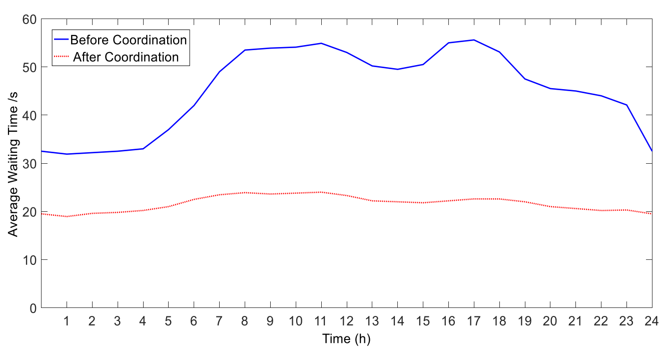

Fig. 15 Comparison of the average waiting time at the intersection

The IIT researchers have validated the effectiveness of the proposed signal optimization mechanism for coordinating drivers and the traffic management authority by conducting a series of high-fidelity microscopic traffic simulation. Fig. 15 shows the corresponding reduction in the average waiting time at the intersection of 33rd & State Streets on the IIT campus. The simulation results also revealed that vehicular wireless communications help drivers determine optimal travel routes based on traffic dynamics which curb congested hotspots by adjusting traffic light signals at designated intersections. Hence, the signal-based coordination and optimization is expected to be a promising solution to improve the overall traffic efficiency in a smart city.

III.C.3 Smart Municipal Infrastructure in a City

Municipal infrastructures are linked tightly to various aspects of citizens' daily lives and their modernization lays the foundation for improving the social welfare in a smart city. Ongoing efforts invested in developing smart municipal infrastructures include [44]–[48] which improve the cost-effectiveness of facility planning, operation and maintenance (e.g., optimizing the expansion of water purification plants, optimizing the routes for waste collection vehicles); enhance the situational awareness of the entire service cycle (e.g., pressure loss in water flows, filling waste containers, identifying the location of waste collection vehicles); promote closed-loop economies (e.g., waste water treatment, solid waste recycling); automate comprehensive control of the service cycle (e.g., water treatment, purification, and distribution, waste collection, separation, and treatment); enable fast detection and identification of anomalies (e.g., leaks and physical damages to water distribution pipes, hazardous substances in waste containers); provide incentive-based programs with citizens for reducing the stress on the natural environment (e.g., solid waste reuse, water conservation).

After augmenting legacy municipal infrastructures with innovative technologies (e.g., a network of IoT sensors and actuators), city authorities are more willing to take on challenges posed by growing social concerns (e.g., water scarcity, solid waste management). Meanwhile, modernized municipal infrastructures become innovation platforms for smart city services and functions that benefit citizens' lifestyles to a larger extent.

As a part of a prototype street light project in smart cities, a networked street lighting system which utilizes light-emitting diode (LED) lights was installed at IIT campus [24]. Compared with traditional street lights that used high pressure sodium lights, the newly installed LED lights on IIT campus are dimmable and between 25-80% more efficient, and have a life expectancy that is between 3 and 25 times longer, presenting immense potential to reduce energy consumption costs. Fig. 16 compares the ambient lighting conditions of high pressure sodium (left) with LED lights (right) in one of the campus streets at IIT, which signifies the role of LED lights in enhancing the campus public safety.

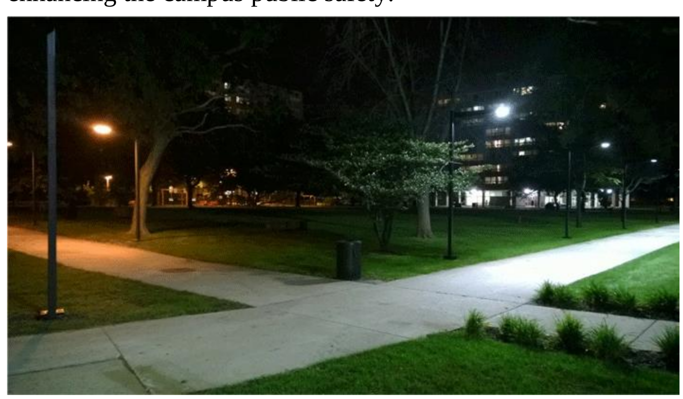

Fig. 16 Comparison of the lighting condition

The LED lights are integrated with intelligence through the installation of sensors, cameras, and networking components. Fig. 17 shows the detailed control configuration of on-campus street lights at IIT. The resulting smart street lights utilize a low-cost mesh communication network infrastructure which makes it very convenient to locate lights that need to be repaired and schedule the on/off status of individual lights in special circumstances and physical locations.

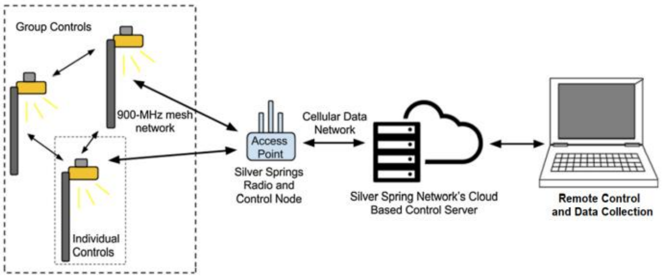

Fig. 17 Configuration of smart street light

In order to enhance the campus safety, the smart street lighting infrastructure can be connected to various IoT devices and public data sources (e.g., traffic, weather), which opens new venues for innovative applications in smart cities. At IIT, an emergency response application is developed which links the street lights with the on-campus 911 emergency contacts; a mobile application has been designed for generating the safest walking path on campus by supplying the street lights with numerous pedestrian-counting video sensors. In addition, controlled street lights at IIT can be used to guide the residents to evacuate the campus effectively and expeditiously in emergency situations.

IV. Holistic Planning and Operation of Smart City Infrastructures

As city operations aggregate various flows of resources and services corresponding to professional, social and cultural activities of local citizens, the underlying smart city infrastructures would also maintain citizens' convenience and lifestyle. Accordingly, the flows should be managed strategically for improving the overall efficiency, sustainability, reliability, and resilience of smart city operations. The holistic planning and operation scheme presented in this section will optimize the flows of resources in a globally optimal way, resulting in a multitude of benefits (e.g., more effective use of underutilized resources, a balance between the use of built and natural environments) that will be reaped by the development of smart cities. Accordingly, holistic planning and operation processes in smart cities will merit various aspects of enhancing urban infrastructures, as discussed below.

IV.A Interoperability of Infrastructures in a Smart City

Historically, urban infrastructures were planned independently and operated individually, leading to domain-specific silos that lack flexibility and interoperability [49], [50] in providing services to citizens. For example, electricity, transportation, and waste management infrastructures are currently managed separately by different city authorities without any mutual communications. However, infrastructure services become increasingly interdependent and tightly coupled as electric trucks are further introduced in the transportation infrastructure and used for waste management in smart cities. When electric trucks are utilized for waste collection, the overall collection efficiency depends on routing decisions which are increasingly dependent on traffic volumes and locations of charging stations. Accordingly, an integration scheme for orchestrating the planning and operation of various urban infrastructures is critical as the optimal operations of smart city infrastructures tend to be progressively intertwined and interdependent. It is demonstrated that city infrastructures will otherwise be inefficient and more costly if they are not planned nor operated in tandem for maintaining a greater socioeconomic sustainability.

The holistic planning and operation scheme for smart city highlights the need for interoperability among infrastructures which can be closely managed for operational savings, cost-effective risk management, improved asset utilization, and prompt response to emergency incidents. However, urban infrastructures have been isolated for distinct purposes which allow them to utilize dedicated, private, and domain-specific communication and control systems, which add difficulties to making these infrastructures interoperable. The vastly discrete hardware and software requirements pose great challenges for the aggregation and fusion of operation information of infrastructures stemming from heterogeneous data sources embedded in their operation systems.

Interoperability among smart city infrastructures should be continuously maintained for achieving a coordinated operation. Theoretically, interoperability among infrastructures can be achieved either physically (which necessitates extra physical facilities for converting and linking services in different domains) or logically (which relies on digital technologies to exchange services and integrate functionalities in an abstract form). Smart city infrastructures can thus be interoperable at the following three levels:

- Technical and syntax level: this level concerns physically and logically basic connectivity, message exchanges and data structure of messages.
- Informational and semantics level: this level concerns the information and concepts contained in messages exchanged among smart city infrastructures.
- Administrative and organizational level: this level concerns operational processes as well as strategic and tactical objectives shared among smart city infrastructures.

The process of adding interoperability among smart city infrastructures is in concert with advances in ICTs. In fact, automation tools and techniques enabled by advanced ICTs facilitate logical interactions among smart city infrastructures without posing limitations on their scopes. When technological, economic, and social innovations successfully break down domain-specific infrastructural silos, the collection of interoperable smart city infrastructures can be expanded optimally and maintained holistically, leading to more efficient use of smart city resources and more flexible provision of city services. For instance, the extensive interoperability among energy, transportation, and municipal infrastructures is expected to insure more efficient water distribution and waste water treatment, more affordable and available supplies of energy services, and more efficient and cleaner transportation activities at the same time.

IV.B Refinement of Services and Functions in a Smart City

The holistic planning and operation introduces interoperability among smart city infrastructures for harnessing their full potentials. Then, city authorities are able to collect, integrate, and analyze the real-time data from metering devices dispersed among infrastructures. Correspondingly, long-term planning decisions and short-term operation strategies of smart city infrastructures are optimized closely in close coordination, which can improve city operations, ensure the well-being of citizens, and meet the expectations for urban sustainability.

The output of smart city infrastructures is ptresented as city and civil services. Thus, the holistic view of smart city operations introduces additional opportunities to discover new relationships among infrastructures so that smart city services can be coordinated more comprehensively to better serve citizens. Meanwhile, the refined services present new opportunities for optimizing the planning and operation of smart city infrastructures in newly specified control domains. For example, when electric buses are utilized for public transit services, they become control resources associated with the electric power infrastructure (for battery charging) in addition to their conventional role in transportation infrastructure. Thus, electric buses can work closely with the electric power infrastructure to minimize the impact of charging batteries at peak load hours, minimize charging time delays for delivering optimal services to transportation customers, and deliver ancillary services (e.g., frequency regulation) to the electric power infrastructure when buses are not in service.

In order to refine city services in the context of smart city infrastructures, operational technologies (OTs), which apply optimal operation strategies for controlling and managing the physical process, should be adequately emphasized for further improving the efficiency and quality of city services. The sophistication of OTs should keep up with that of ICTs, as ICTs provide OTs with more opportunities for fine-grained control and management in smart cities. Cities can leverage OTs to create additional values for implementing smart city infrastructures by coordinating their decision making processes as they deliver city services. Thus, there is an urgent need to develop a holistic multi-disciplinary OT approach for capturing dynamic relations among smart city people, policies, and deliverables. The potential return, in terms of near-term operation cost savings and the long-term urban sustainability, will more than justify the effort.

Energy hub [51]–[54] is a good example for using OTs to solve shared challenges of multiple urban energy infrastructures which are designated with a common goal of enabling a smart city. An energy hub is a localized energy system where multiple types of energy services are provided through a single modularized implementation, resulting in considerable savings of urban space and operation costs. Fig. 18 exemplifies an energy hub that integrates three energy carriers (e.g., heat, electricity, gas) in the local area. The optimal planning and operation of energy hubs take full advantage of synergies among corresponding forms of energy, which in turn provide immense opportunities for refining energy services for local citizens. Accordingly, generation, conversion, distribution, storage and consumption processes of the associated energy carriers are coordinated strategically within an energy hub. Since electricity plays a critical role in converting various energy forms, microgrids provide a promising platform for implementing energy hubs. In that regard, microgrid master controllers [55]–[57] assumes the burden of integrating, coordinating, and optimizing the operation of the associated local energy carriers, and take the responsibility of improving the overall efficiency, sustainability, reliability, and resilience of local energy services.

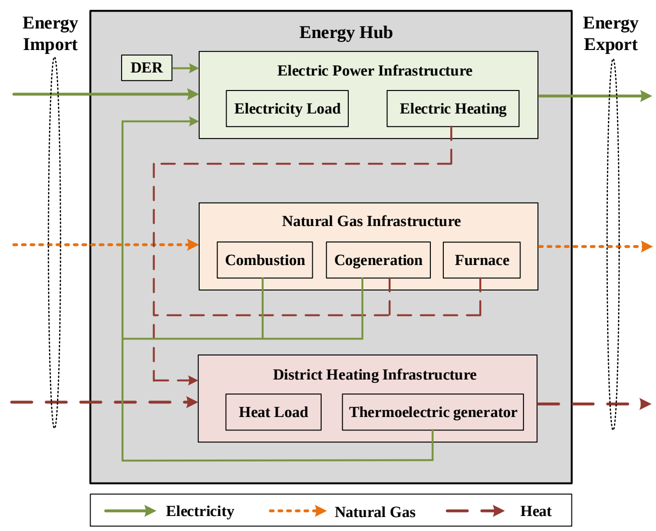

Fig. 18 Energy hub configuration

V. Hierarchical Control and Management of Smart City Infrastructures

Smart city infrastructures take advantage of both ICTs and OTs for achieving a higher degree of excellence in city operations. Therefore, a comprehensive control and management framework should be developed in smart cities for harmonizing ICTs and OTs initiatives. This section presents a data-centric scalable framework for controlling and managing the optimal interdependent operation of a collection of smart city infrastructures in a dynamic urban environment. The proposed framework, which is discussed below, enables heterogeneous resources and functions across smart city infrastructures to be interlinked seamlessly as smart city operations are controlled and managed holistically for satisfying various quality-of-service requirements.

V.A Data-Centric Approach to Harmonize the Utilization of Innovative ICTs

Data flow is the lifeblood of smart city operations, so the development of smart cities is based on high-speed, high-reliability and high-availability data flows that can be utilized for optimal decision making in smart city operations. To thrive in the transition to a smart city, a city thus needs to utilize the state-of-the-art ICTs such as IoT technologies to facilitate data flow management throughout city operations.

IoT augments smart city infrastructures with intelligence, interconnection, and instrumentation, after enabling the data sharing and exchange among a diversity of sensors and actuators across buildings, roads, networks, and utilities. Pervasive sensors, as the backbone of IoT, automatically monitor and detect changes in city operations in real time, when low-cost communications (e.g., Zigbee, Bluetooth), as the driving force of IoT, can simplify data flows and reduce the cost of gathering and sharing data by enabling convenient and affordable data flows. It is also of practical importance to select proper IoT technologies for different physical infrastructure in a cost-effective manner, by considering their unique technical and social features (e.g., electricity usage metering, water leakage monitoring, intersection traffic regulation).

However, IoT technologies produce massive amounts of raw data across smart city infrastructures, which provides city authorities with major difficulties in making rapid and shrewd decisions for optimizing city operations. Considering an unprecedented volume and variety of data involved in smart city operations, big data analytics can play a significant role in improving the performance of city operations [18]. In particular, big data analytics manage to translate the collected raw data into actionable intelligence which facilitates real-time decision making in smart city operation. Accordingly, big data analytics support city authorities' goal of boosting the efficiency, economics, reliability, resilience, and sustainability of smart city operations.

Cloud computing [58] allows data to be retrieved and processed in real time which offers a convenient way to perform big data analytics. In essence, cloud represents an group of networked computers and servers which are easily assessible over the Internet. Cloud computing thus provides pathways for dealing with large volumes of data in cost-effective manners. Existing IoT-driven cloud computing platforms include Amazon Web Services [59], GE Predix [60], Google CloudPlatform [61], Azure IoT Suite [62], and Salesforce IoT Cloud [63].

However, there have been several limitations blocking the widespread deployment of cloud computing applications. In addition to concerns on bandwidth limitations and processing delays, one major challenge is tied to heterogeneous data sources included in IoT technologies. For example, some IoT devices generate analog data with proprietary timing and structural characteristics, which necessitate additional protocol translations before any data transmission to cloud. More important, privacy leakage is another common concern in applying cloud computing together with IoT technologies [64]. For example, smart electricity meters may reveal citizens' sensitive personal information (e.g., domestic energy usage) which prefer local data processing rather than cloud-based services.

Edge computing (or fog computing), acting as an extension of cloud computing to the utmost edge, is a promising solution for analyzing localized data with maximized resolution and minimized latency [65]. Hence, it is considered as an alternative to keep data storage, processing, and analysis in a more localized manner at edges of the cloud. Similar to cloud computing, edge computing utilizes of semantic intelligence (natural language processing and machine learning) and computational intelligence (i.e., advanced mathematics). But different from cloud computing, edge computing enables more efficient data analysis by employing local computing resources.

The combination of cloud computing and edge computing merges the merits of both technologies in order for city authorities to make data-driven decisions in a rapid and proactive manner. Therefore, city authorities should utilize flexible data flow management mechanisms to customize the use of IoT technologies for specific applications, with a tradeoff between the reliability and efficiency of city operations and the privacy and security of citizens.

V.B Hierarchical Control and Management Framework for the Implementation of Smart City Solutions

The hierarchical control and management framework is proposed for merging the merits of both technology-based centralized (i.e., top-down) approaches and human-based distributed (i.e., bottom-up) approaches for making urban infrastructures smart and secure. In Fig. 19, the proposed framework is divided into three functional hierarchies with distinct requirements on operation timescales and communication bandwidth.

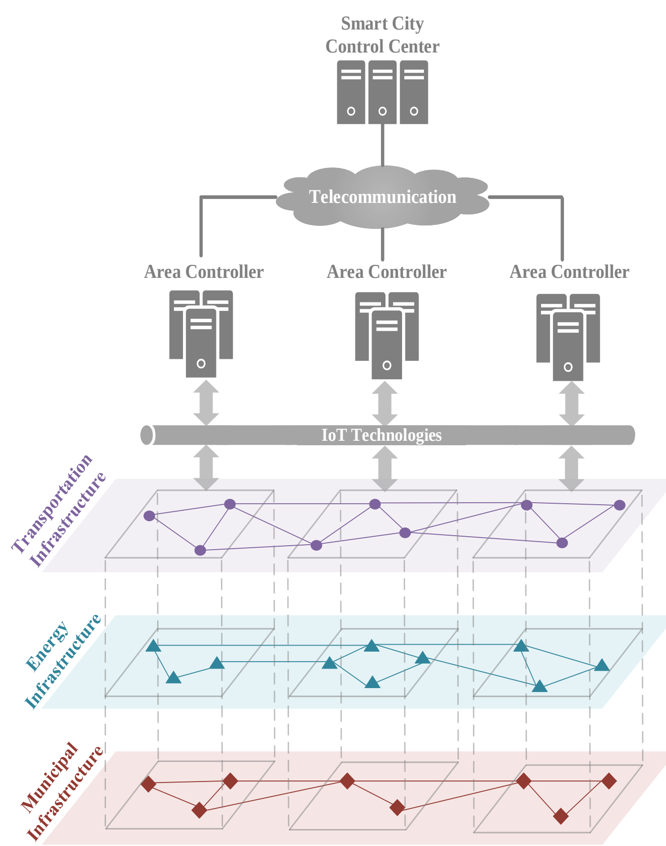

Fig. 19 Hierarchical control and management framework

The three levels are detailed as follows:

- Field device level. Sensors and actuators are networked with IoT technologies, which promotes more efficient integrations of emerging context-aware sensors and devices, ultimately improving the situational awareness in city operations. Sensors embedded into the collection of smart city infrastructures collect the monitoring and the measuring information in real-time and report it to the smart city control center via a wired or wireless telecommunication infrastructure.
- Area control level. Local controllers realize data capture, processing, storage, and analytics at distributed points across the city, which reduces architectural complexity and boosts scalability. With the utilization of edge computing technologies, local controllers increase their responsiveness to real-time and context-critical information.
- Control center level. The control center helps discover and maintain a registry of data sources and their characteristics such as periodicity, liveliness, and quality, and make them available for subsequent analyses. Application-specific analytics based on cloud computing can also be deployed in the control center for facilitating pattern mining and predictive analytics.

The proposed framework is expected to ensure data integrity, localization, and confidentiality, while enhancing availability, flexibility, and elasticity to meet targeted performance requirements (e.g., transmission rate, delay). On the one hand, the framework features a hybrid communication strategy, which collects data from dispersed field devices through short-range wireless technologies and delivers real-time data to the smart city control center (i.e., cloud-based) via long-range backhauling communication technologies. On the other hand, the proposed framework strikes a balance between immediacy and depth of insight for data processing, which analyzes most time-sensitive data at the local level and sends selected data to the smart city control center for more extensive processing and longer-term storage. Hence, the proposed framework acts as a unified platform for orchestrating all parts of the city to work together, which ensures the collection of smart city infrastructures so that they can work in harmony rather than running as separate entities. Since the proposed framework promotes synergies between ICTs and OTs, it is expected to not only boost efficiency, reliability, and resilience of smart city operations but also enhance the quality of life, well-being, and safety of citizens.

When the framework is friendly to prevalent applications of ICTs like IoT technologies, it is also compatible with emerging innovations in ICTs like software-defined networking (SDN) technologies [66], [67]. SDN is an innovative networking design that allows the control of a communication network directly programmable by transferring the network control logic from underlying switches to a logically centralized controller (i.e., SDN controller). Therefore, SDN breaks the conventional vertical integration and makes the communication network globally visible and directly programmable to the SDN controller. The global visibility facilitates the implementation of more efficient management of network-wide data flows, while the runtime programmability enables the SDN controller to reroute data flows in a timely manner.

The integration of SDN with the proposed framework leads to the decoupling of city services provisions and their locations on the underlying smart city infrastructures. Accordingly, the framework has additional capabilities to incorporate and regulate resources and services independent of their geographical locations and without concerns on the stringent quality-of-service requirements. In this way, logical interoperability among these infrastructures can be dynamically constructed and adaptively configured, resulting in more value-added service innovations. Hence, the proposed framework drives smart city infrastrcutures to become a multifunctional platform for developing innovative smart city solutions.

VI. Interactive Performance Evaluation of Smart City Infrastructures

The modernization of urban infrastructures has significant environmental, economic, and social impacts on city operations, so there is an urgent need for evaluating the true value of urban infrastructures in a smart city. The operational performance of smart city infrastructures can be iteratively evaluated using a high-fidelity human-in-the-loop simulation that models extensive interactions among technologies, processes, and humans in a flexible manner. Such an interactive simulation scheme is helpful for deepening the conceptual understanding of the convergence of technologies, processes, and humans in a transition toward smart cities. Moreover, simulations provide empirical results for smart city operations, allow the derivation of guidelines, and facilitate radical transformations of current practices applied to the design, deployment, and management of smart cities. For example, simulation results lay foundations for establishing regulations, policies and technological strategies applied to smart cities in accordance with specific local requirements. Hence, smart city operations can harness the power and forces behind sustainable urbanization more effectively.

VI.A Automated Interactions Enabled by Multi-Agent Systems

Since the operation of smart city infrastructure is characterized as a highly distributed and evolving process, the real-time strategic control and management of these infrastructures can be configured as a multi-agent system (MAS). MAS is an integration of agents (i.e., computer systems) that are capable of achieving the assigned goals without human interventions [68], [69]. In MAS, each agent interacts and collaborates with other agents for a global coherence, and perceives and responds quickly to potential changes in the local working environment for achieving its design goals.

The automation functionality provided by MAS is robust, resilient, flexible and self-organizable [70], [71]. Considering a high level of flexibility in configuring and coordinating agents, MAS is proved as a practical solution to automated and interactive decision making in complex and dynamic operating conditions [37]-[40]. In particular, MAS reduces the computation complexity of controlling and managing smart city operations, because each agent is capable of making locally optimal decisions in near real time. More specifically, MAS is deployed with a host of reliable, robust and high-performance agents. These agents manage to efficiently simulate the dynamic decision-making capabilities of functional components in various control domains (e.g., area controllers, smart city control center) while fully capturing the behaviors of citizens and city authorities on smart city operations.

Considering the complex interactions among agents pertinent to distinct smart city infrastructures, universal modeling language (UML) [76], is utilized as an object-oriented language to represent complicated smart city operations by recognizing citizens' requirements, infrastructure' operation states, and the sequence of events in the operation of smart city. After converting UML constructs into executable models, MAS automates both static interdependencies and dynamic interoperations of smart city infrastructures, as well as interactions among citizens and city authorities for optimizing city operations. Meanwhile, extensible markup language (XML) [77] is employed to wrap operating states initiated from heterogeneous data sources and represent them in a universally standard manner. When an operating state can be described without a huge overhead in XML, each agent is responsible for understanding and parsing XML files received from the functional components within its own control domain.

The combined utilization of UML and XML makes the operating states of smart city infrastructures to be more routinely developed. Therefore, MAS present a strong position in automating data collection, fusion, and decision making even for asynchronous interactions. Besides, the fidelity of automated interactions can validate theoretical analyses and empirical observations pertaining to interactions among technology implementation and human behaviors in smart city operations.

VI.B Human-in-the-Loop Cyber-Physical Co-Simulation

Smart city infrastructures are complex systems with extensive cyber-physical interdependencies in which exchanges between digital components and physical objects can be easily abstracted as interactions between agents. When MAS considers the behaviors and the activities of citizens and city authorities in the closed-loop simulation, it opens the door to human-in-the-loop simulation [78], [79] representing smart city operations. The human behavior is modelled as an effective feedback control signal, given the various processes that denote citizen-government collaboration and human-machine partnership in a cyber-physical representation of smart cities.

The co-simulation of human-in-the-loop and cyber-physical systems consists of three main elements including physical elements representing infrastructure components involved in the physical process of city operations, cyber elements representing communications and computing capabilities, and human elements representing the human response and intelligence in decision making for the smart city operation. When co-simulation relies on existing simulators for various aspects of smart city operations, individual simulation processes are managed within separate simulators and coordinated with a common simulation goal. Due to inherent differences in the simulation mechanism (e.g., time-continuous versus event-driven), simulators are placed in a common platform for realizing the strict time synchronization and efficient data exchange among individual simulation processes [67], [80].

Fig. 20 exemplifies the configuration of the co-simulation platform, when municipal solid waste management relies on electric vehicles in a smart city. The Java Agent DEvelopment framework (JADE) environment [81] is employed to model the inherent functionality of agents and their interactions in MAS. OMNet++ [82] is a discrete event simulation environment for representing various means of communication inside and among smart city infrastructures. OpenDSS [83] is an electric power distribution system simulator that supports nearly all frequency domain analyses related to grid modernization, and renewable energy research. Simulation of Urban MObility (SUMO) [84] is a time-discrete microscopic traffic simulator rendering simulation results consistent with real-world scenarios, where vehicle movement can be simulated based on car-following and lane-changing theories. Solid waste management is implemented in Java [85] to support the calculation of substance flows, environmental impacts, and costs of waste management [86]. The human behavior models, which are derived from management science and behavioral science experiments, are abstracted as knowledge learned by MAS in JADE. Hence, such a co-simulation platform facilitates the performance evaluation of smart city infrastructures.

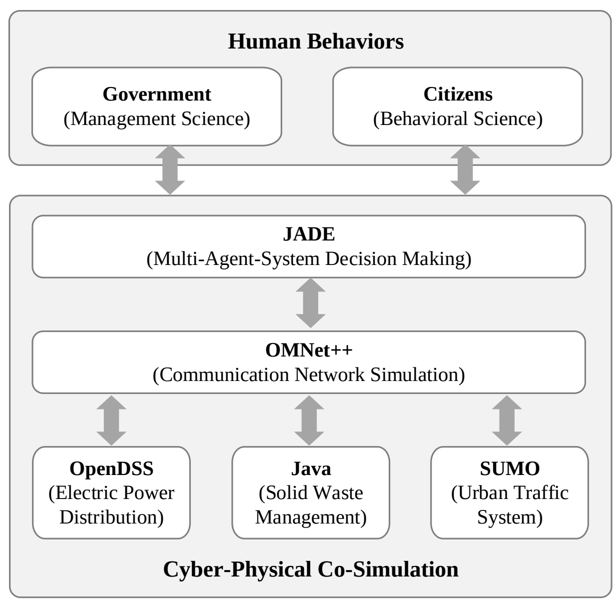

Fig. 20 MAS-based simulation platform for smart cities

VII. SOCIOTECHNICAL RISK ANALYSES IN SMART CITIES

With ubiquitous interactions among social and technical elements of smart city operations, infrastructures are not only sociotechnical systems but also represent cyber-physical systems. Accordingly, technological, economic, and social innovations for modernizing urban infrastructures may raise new risks and concerns as part of implementation. Hence, a thorough understanding and an in-depth analysis of risks imbedded in innovative smart city solutions is the key to maintaining the role of smart city infrastructures in achieving the urban sustainability.

VII.A Human–Machine Partnership as a Workforce Strategy

With the proliferation of technological innovations, humans and machines will coexist and continue to interact for enabling smart cities. In essence, a smart city infrastructure assembles intelligent, interactive, and highly networked machines with which humans share intelligence in order to accomplish the stated goals more comprehensively (i.e., less risky, less costly, faster, more resilient, etc.). Hence, the operation of smart city infrastructures will benefit from pervasive human-technology collaborations.

Machines are good at automating repetitive tasks, and moreover new breeds of intelligent machines have increasingly replicated human capabilities, including gathering and analyzing data automatically and providing recommendations for next course of actions. Thus, it is envisioned that the implementation of smart city infrastructures will change the landscape for job markets, which will inevitably impact the citizens' lifestyle in a smart city.

While technology is an integral part of smart city solutions, it should only be seen as an enabler to meet the citizens' needs. Machines excel at precision, scale and consistency, but humans are better suited for creativity, contextual understanding and complex communications. Correspondingly, intelligent machines will eliminate repetitive low-skill jobs, but smart cities would introduce additional creative and high-skill jobs. In other words, human-machine partnership does not necessarily mean a net job loss in a smart city. Moreover, human workforce is expected to conduct more cognitive work and make better decisions based on prevailing circumstances at it engages the maximum support provided by intelligent machines. That is, human-machine partnership increases skill requirements but extends individual contributions of human workforce. Consequently, traditionally inflexible human workforce should be transformed into knowledge-based workforce that is able to handle complex tasks intelligently and efficiently in a flexible environment.

When intelligent machines work collaboratively with human workforce in a smart city, there exist a range of work opportunities to further improve the performance of city operations. The ultimate goal is to achieve higher levels of safety and excellence in the operation of smart city infrastructures which exceed the levels attainable by either skilled human operators or completely autonomous machines acting alone. Even if intelligent machines will eliminate repetitive rules-based positions, human workforce should be re-deployed to higher-value tasks and complete these more challenging tasks with the help of intelligent machines. Furthermore, new work opportunities will engage all groups of citizens and promotes gender inclusivity. For instance, present vulnerable groups such as women, the elderly, and persons with disabilities will participate more actively in smart cities' future work scenarios with the help of intelligent machines. There is unavoidably an urgent need to educate certain groups of human workforces to develop unique human skills for performing abstract, creative, and non-routine tasks that will not be replaced by intelligent machines.

VII.B Managing Cyber-Physical Security Risks

The application of innovative solutions based on ICTs in the modernization of urban infrastructures is both beneficial and problematic. ICTs offer a host of opportunities for increased efficiencies and greater convenience, but at the same time expose the smart city infrastructures' cybersecurity vulnerabilities extensively to cyber threats. Cyber threats are realized in terms of deliberate cyberattacks, inadvertent human errors, defective equipment or software, or even natural disasters. Since smart city infrastructures are considered cyber-physical systems where software components and physical objects are deeply intertwined, cyberattacks can cause significant physical damage to the infrastructures, leaving severe consequences on social services enjoyed by citizens. In particular, certain physical components in smart city infrastructures (e.g., underground water pipes) disabled by cyberattacks may be more difficult to diagnose or replace. The consequences of cyberattacks can be exacerbated by physical incidents if executed during a natural disaster or a terrorist attack.

At present, energy, transportation, and municipal infrastructures in urban areas are hardly immune to cyberattacks. Attackers may launch cyberattacks on urban energy infrastructures after compromising the supervisory control and data acquisition (SCADA) system that are developed based on off-the-shelf operating systems. In fact, most SCADA systems are configured without inherent security management solutions and thus vulnerable to remote intrusions. For example, the security firm Symantec uncovered in 2014 that the hacking group Dragonfly had repeatedly gained access to the SCADA system of several energy companies [87]. By compromising the SCADA system, physical damage can be easily inflicted by cyber means on energy infrastructures. For example, three regional electricity distribution companies in Ukraine suffered power outages due to cyberattacks on Dec. 23, 2015 [88]; attackers took control of SCADA systems (through backdoors opened by the malware BlackEnergy) to manipulate the operating states of networked devices; consequently, at least 30 substations were disconnected from the bulk power system and at least 225,000 citizens lost electricity services for about six hours.

Meanwhile, the implementation of advanced metering systems for urban energy infrastructures exposes a network of smart meters to potential attackers in which attackers can easily get access to these meters for mounting cyberattacks. Attackers may tamper with smart meters to alter energy usage information for reducing utility bills. In 2009, FBI uncovered a widespread fraud in Puerto Rico where around 10% of smart meters at residential sites were tampered to underreport electric energy consumption, causing the electric utility company a $400 million revenue loss [89]. Attackers may even access smart meters to observe citizens' whereabouts, habits, or personal and financial information, thereby hampering citizens' privacy, safety, and security. For example, a low energy usage shown in a smart meter could be an indicator that the citizen is not at home.

Attackers may remotely launch cyberattacks to curtail the performance of urban transportation infrastructures. On the one hand, attackers may directly compromise transportation components (e.g., traffic light signal controller) to increase the traffic congestion in specific areas. A pilot security awareness project [90] has demonstrated the possibility of seizing control of over 100 traffic signals by using readily available hardware that costs less than $100. Correspondingly, attackers can manipulate traffic signals at multiple intersections across a smart city, causing city-wide catastrophic traffic congestion. As a real-life example, two lanes on the George Washington Bridge were unexpectedly closed in November 2013, resulting in severe traffic congestion which lasted several hours and resulted in a direct economic loss of more than $7 million [91]. On the other hand, attackers may compromise V2V and V2I signals to reduce the safety of traffic flows; they may block V2V data for causing sudden braking, acceleration, lane change, or conceal individual vehicle actions to other drivers; they may compromise V2I devices to disseminate inaccurate information to individual vehicles on road conditions, including lane merges, sharp turns, or dangerous conditions ahead.

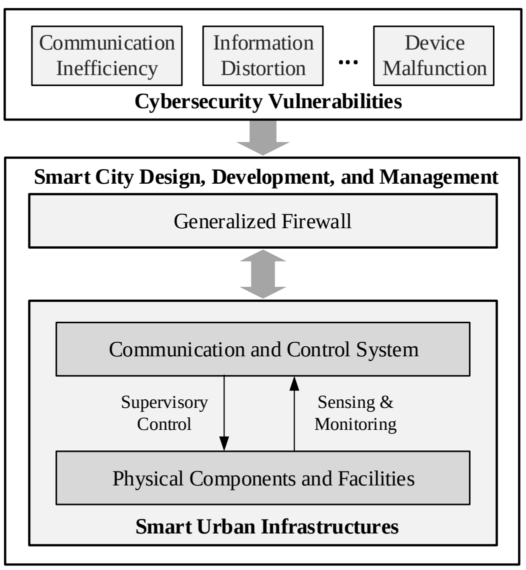

Fig. 21 Generalized firewall for smart city operations

Attackers may remotely launch cyberattacks on smart city infrastructures by disabling water alarms that would disrupt flows in water distribution pipes; manipulating pump actuators that would feed inappropriate levels of chemicals and endanger the public health; reporting false meter readings that would mask dangerous conditions; compromising water storage facilities that would drain a smart city's water resources, creating flood conditions, or hindering emergency services (e.g., fire emergency services); closing pipe valves that would prevent the transportation of storm water away from at-risk areas; manipulating pumps that would reroute storm water towards at-risk areas. Such critical incidents would have severe consequences in real life. For example, a disgruntled employee in Australia used insider knowledge in 2000 to access a wastewater treatment plant's SCADA system and succeeded in spilling over 200,000 gallons of sewage into streets, rivers, and buildings [92].

Therefore, smart cities necessitate a generalized firewall (shown in Fig. 21) that works interactively with smart city infrastructures and protects city operations from a variety of cybersecurity vulnerabilities. The design, deployment, and management of firewall relies on a clear understanding of cyber-physical interdependencies and interoperability of infrastructures, and man-machine collaborations for smart city operations.

VIII. CONCLUSIONS

Smart cities motivate innovative solutions that act as key drivers for enhancing the management and operation of smart city infrastructures. The emerging smart city solutions will introduce invaluable opportunities to help smart city infrastructures converge to more flexible, efficient, and sustainable city operations. The realization of urban sustainability around the globe relies on extensive collaborations among citizens, technology vendors, and city authorities. These individuals create, validate, and demonstrate technological and social innovations in smart city infrastructures, and promote comprehensive understanding of scientific, social, and human behavior aspects of urban development.

On the one hand, smart city infrastructures are cyber-physical systems that integrate a hybrid of hardware and software components including field devices (e.g., sensors, actuators), low-cost IoT communications, high-speed telecommunications, and real-time big data analysis. Based on an efficient, adaptive, and service-oriented control framework for facilitating the integration and coordination of independent smart city infrastructures, the smart city control center will make holistic planning and operation decisions for historically isolated smart city infrastructures to achieve a higher degree of operational excellence. Although ICTs promise to make smart city infrastructures more intelligent for real-time decision making, these technologies unintentionally expose city operations to a host of cyber security issues that will potentially hamper the efficiency of smart city services and the well-being of citizens' lives. Accordingly, risks associated with technologically innovative solutions deployed in smart city infrastructures should be first identified and then managed for contributing to the urban and the global sustainability in a truly synergistic and secure fashion.

On the other hand, smart city infrastructures are sociotechnical systems that take full advantage of human-machine partnerships. To continue providing comfortable and affordable citizen-centric services, smart city infrastructures should be modernized to respect potential symbiotic relationships between humans and machines within the context of smart cities. This modernization process necessitates the combination of a bottom-up human-driven approach with a top-down technology-driven approach, which hinges on the knowledge of information and operation technologies together with experiences of behavioral and social sciences in developing and managing smart cities. Hence, cross-disciplinary research should be promoted to expedite the evolvement of urban infrastructures for meeting the strict requirements of smart city development. In that regard, cities around the globe will manage to maintain the well-being, security, and safety of citizens under various environmental and regulatory conditions by improving the efficiency, sustainability, reliability, and resilience of citizen-centric services.

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