Cyber Physical Systems and Internet of Things: Emerging Paradigms on Smart Cities

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***Abstract*—A city is smart when investment in traditional and modern infrastructure, human and social capital, fuel well being, high quality of life, and sustainable economic development. The Smart City paradigm is driven by technological evolution in the field of Information and Communication Technologies, and more specifically the paradigms of Internet of Things, Industrial Internet of Things and their confluence with Cyber Physical Systems. Smart Cities present a number of application domains that are related to their critical infrastructures, including energy and transport. These domains present needs similar to the industrial manufacturing environment utilizing smart devices and employing control automation for their applications. They could thus be labeled as "industrial domains" in the wider sense. This paper presents three application domains associated with Smart Cities, namely Smart Lighting, Smart Buildings / Energy, and Smart Urban Mobility, identifies their requirements and challenges and reviews existing solutions.**

***Index Terms*—Cyber Physical Systems, Internet of Things, Smart Cities**

I. Introduction

The smart city concept was originally introduced as an industrial marketing element by IBM a decade ago[1]. In this setting, smart city encompasses the perspective that cities will become more sustainable environments, improving the well-being and safety of citizens, by leveraging the potential of Information and Communication Technologies. Even though this technologically centered definition of smart city is criticized, in particular by social sciences, it has founded the "smart" wording that is used in many settings [1], [2]. Some would say over used. The smartness, as defined at that time, is very influenced by cybernetics and describes a system that has the ability to adapt (self-configure, self-heal, self-...) to inputs coming from the physical space where it is deployed [3], [4].

To provide these services, several entities must be monitored. Reliable data on the state of the city, its facilities, buildings, citizens' activities, etc are generated, collected and processed. This defines the technological context denoted IoT for 'Internet of Things" [5], [6], CPS for Cyber-Physical Systems [7] and their counterpart IIoT for 'Industrial Internet of Things' dedicated to the industrial domain [8]. The first and last term express the fact that all objects in our surrounding tend to be eventually connected to the Internet, generating data and sending them toward an infrastructure. The second captures the role of this technology which aims at bridging the physical world and the digitized one. Both capture overlapping realities that need to be properly defined.

Smart City covers several application domains with specific challenges or requirements. This paper spans some of them. But one can identify these challenges along the life cycle of data in a smart city application.

Data is generated at some place and time in the city. It can be by a sensor, CPS [7], or IoT device [6], a software running on a smartphone, or by any other means, but it usually has a spatio-temporal dimension [9]. The trustworthiness and availability of the devices and their data is one of the major challenges to be addressed.

Then, the data is collected and sent to a storage and computation facility. It can be a Fog or Edge distributed and networked infrastructure [10] or a centralized cloud

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[1] https://www.ibm.com/smarterplanet/us/en/smarter_cities/overview/

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data/computation center. Anyhow, most of the time, it needs a wireless connectivity to move the data from where it has been produced to where it will be processed. Wireless networks indeed enable dense and/or mobile deployments of devices that are needed in smart cities.

The design of the computation and storage infrastructure is mostly driven by cost, availability, and scalability trade offs. The placement of system functionalities close to the data production is often an argument for fog/edge design, since it can save significant amount of network bandwidth or storage [10], [11]. Versatility provided by virtualization, economies of scale and resource sharing preach for centralized cloud-based solutions [12], [13]. One of the major data-related challenge is the standardization of data representation, so as to enable their treatment by diverse algorithms. In terms of computation, efforts are put toward high bandwidth data-flows supporting algorithms.

In this paper, we focus on three iconic smart city application domains, namely smart lightning, smart building and energy, and smart urban mobility management. For each we describe the major challenges that are tackled in the literature and span prominent available solutions.

The rest of the paper is structures as follows. Section II describes the three aforementioned application domains and denotes their requirements. Section III deals with IoT, IIoT and CPS and presents the proposed relevant reference architectures. Section IV presents solutions and challenges for the three smart city application domains. Finally, section V offers discussion and conclusions.

II. Smart City Application Domains

A. Smart Lighting

Smart lighting is a system designed with the initial intent of decreasing energy consumption by adapting light intensity according to several parameters (e.g., natural light, occupancy) [14]. Studies have shown that replacing a legacy street lighting system with LEDs can reduce a municipality's energy bill by half. Moreover, integrating those lights with intelligent equipment can provide a further 30% in savings [15]. Furthermore, the same intelligent equipment can provide a platform for current and future smart city applications that can enhance public safety, traffic management, health, and comfort. A simulation of a smart lighting deployment in realistic urban environment for the city of Luxembourg, showed that replacing all existing lamps with LEDs and dimming light intensity in the absence of users in the vicinity of the lampposts drastically reduces energy consumption and can provide an economical return after the first year of deployment [16].

Another important factor that skyrocketed the interest in smart lighting is the study of light pollution, which results in: reduced visibility of the night sky, biodiversity loss, disturbance of circadian rhythms, and expansionary dynamics of global capital [17]. A recent study of satellite data showed that around 83% of the global population is affected by "artificial skyglow" (i.e. scattering of light in the atmosphere where the cumulative impact can reduce night sky visibility over vast areas), rising to over 99% of the population of Europe and North America [18]. Hence, reducing the street lighting in cities is of uttermost importance.

Advances in recent years in technology have considerably increased the intelligence of lighting systems, by making them capable of communicating with their environment, drastically changing traditional uses, and improving the life of citizens.

Each lamp is connected to sensors and wireless communication devices that can detect day/night cycles, the presence of people, direction of movement, and predict switching on/off and dimming of lights accordingly. Each lamp could be seen as a node in a local network, with an assigned IP address, collecting and sharing data inside the network, and even exchanging it with other local networks. A central controller can overlook the functioning of the whole system and remotely control, independently, each light pole. This prospect is made possible by the lowering cost of LEDs, environmental sensors, and wireless communication devices.

B. Smart Building/Smart Energy

As it is well-known, about one-third of total energy consumption can be attributed to buildings. So, to make a city smarter, under the energy perspective, it is mandatory to make buildings smarter [19]. That is why a variety of international regulations including EN 15232, the European Energy Performance of Buildings Directive (EPBD 2010), ISO 50001 and sustainability and energy certificates such as LEED or Energy Star have led to the creation of a wide technical literarture and to the design of specialized tools to optimize the energy efficiency of buildings.

The term Smart Building refers mainly to the above mentioned aspects. It goes beyond the basic building automation concept. Smart buildings are buildings that combine building automation techniques with advanced control techniques in order to dramatically improve their energy performance. They implement automatic centralized or cooperative distributed control over the building heating ventilation and air conditioning (HVAC), lighting and all other systems through an advanced building management system [20] [21].

Smart buildings often include a network of sensing and computing devices to better anticipate the impacts of disturbances in order to minimize the energy consumption and user discomfort. Designers also specify high-performance windows and extra insulation in the buildings structure to reduce the air leakage through the building envelope. Low-energy houses, as another interpretation of smart buildings, exploit on-site energy generation through renewable sources such as solar power, wind power or biomass which can significantly reduce the environmental impact of the building and increase dramatically its efficiency [22]. But, there is more. In the near future, smart buildings will also be able to follow a predefined electrical energy profile. As a matter of fact, the electricity national grid will be divided in many loosely interacting smart micrgrids, serving a city or even a quarter in large cities. A typical important node of a smart microgrid is actually the smart building, whose electrical consumption will necessarily follow the production through renewables. In this case, decoupling the thermal consumption from the electrical one is a way to assure comfort, quality and energy efficiency [23].

All the above pave the way to smart management system and complex real-time optimization techniques, which disclose new ways to optimize the building energy performance. In recent years, the largely increasing energy consumption in residential and commercial buildings has become a hot topic. In particular, heating, cooling and air conditioning systems are a foremost quota of energy consumption in building sector. This is why in the near future, there will be a convergence of the concepts of smart cities, smart buildings, distributed optimization, ubiquous sensing and computing.

C. Smart Urban Mobility Management

One of the major functions of a city infrastructure is to enable citizens (and visitors) to move around. Actually the mobility of inhabitants is a among the determinant factors of how they live in the city. There is a strong correlation between one's way of life and the urban fabric defining each metropolitan area: the availability of infrastructure and public/private services, the characteristics of the land use.

Urban mobility, before being managed, is measured and studied with a large number of techniques. While traffic flows can be estimated by different fixed sensors, the study of individual trajectories requires other methods. Of course, the omnipresence of geolocation systems has made it possible to collect traces of mobility. This has led to the emergence of the crowdsensing field, which is particularly useful for obtaining traces of pedestrian mobility [24], [25]. It has then been extended to the collection of data of all kinds, as long as a type of sensor can be embedded in a mobile device. These methods have methodological limits on the constitution of participant panels.

A more systematic method is to study the traces of cellular network usage. The urban pervasiveness of the network and the high level of equipment among the inhabitants of most major cities make this technique particularly effective [26]. It becomes possible to have a mesoscopic view of urban mobility: the accuracy is certainly less than GPS-based solutions, since the location is at the scale of the network cells, but the social and geographical coverage is incomparable. These studies have yielded remarkable results, particularly in the analysis of the urban fabric, and its use by the inhabitants [27].

However, it must be borne in mind that all solutions that make it possible to study the individual trajectories of inhabitants raise profound ethical questions about respect for privacy, security and respect for individual liberties.

With the densification of cities, traffic congestion problems are becoming increasingly worrying for municipalities as they generate frustration for citizens, air pollution and related diseases, and can, at times, totally paralyze urban infrastructure as on Route 110 around Beijing in 2010.

It is thus natural that intelligent urban mobility management solutions have been considered. One of the first directions taken was to try to predict traffic conditions, in particular to adapt the sequencing of traffic lights by trying to reduce traffic jams and accident situations [28], [29]. Beyond the performance of these approaches, the best solution to fluidify traffic is to reduce it.

In particular, it has been demonstrated that 30% of traffic jam is caused by vehicles cruising for parking [30]. This has motivated a large number of developments in the field of "smart parking". Many cyberphysical systems have been built for vehicle detection in parking spaces, first for parking lots, then for on street parking, ranging from optical or magnetic sensors to crowdsensing applications utilizing embedded car cameras. In a recent survey, more than 200 papers on smart parking have been identified [31].

Motor vehicles are not the only ones which in connectivity can make sense in a smart city. Bicycles and shared bicycle systems are among the solutions considered by many cities for congestion and pollution problems. Soft or active mobility makes it possible to reduce car traffic or the saturation of public transport and to contribute to public policies to improve health and stress. Understanding cycling mobility is an essential element in improving the cyclability of cities. The development of connected bicycles has therefore become an important subject [32]. This makes it possible to consider in particular environmental crowdsensing applications, based on bicycles, to measure where users make a physical effort and thus detect where public investment should be strengthened.

III. IoT, IIoT and CPS [ISI/ATHENA]

A. Internet of Things - IoT

The Internet of Things represents a novel paradigm that builds on top of such earlier technologies as embedded computing, sensor networks and pervasive systems. It moves beyond information systems and pervasive computing, by enabling the variety of things or objects around us to interact with one another and cooperate towards achieving common goals [33].

The market potential of IoT is significant. McKinsey Global Institute estimates IoT application potential economic impact between 3.9 and 11.1 trillion USD per year in 2025 [34]. The global number of IoT devices in 2018 reached 7 billion, while global number of connected devices is estimated to 17 billion [35].

The interconnection of billion of devices mandates a flexible architecture. Layered model architectures in literature define: the Objects or Perception layer comprising the physical things that IoT collects information from; the Object Abstraction Layer transferring data from things to the upper layers; the Service Management of Middleware layer receiving data, making decisions and pairing to services; the Application layer providing services requested by customers; and the Business layer managing overall system activities and services [36].

Different standards have been proposed to support IoT and facilitate its wide applicability. They are discerned into three categories: application protocols, service discovery protocols, and infrastructure protocols.

Constrained Application Protocols (CoAP) is an application layer protocol based on Representational State Transfer (REST). Unlike REST it utilizes UDP and not TCP, making it more suitable for IoT applications. CoAP enables low power IoT devices or things communication [37].

Message Queue Telemetry Transport (MQTT) is a messaging protocol aiming at connecting IoT devices and things with applications and middleware. Transition flexibility is ascertained by the publish / subscribe method [38].

Extensible Messaging and Presence Protocol (XMPP) is an open decentralized messaging protocol allowing device communication via instant messages. It provides cryptographic principles like authentication, access control and encryption [39].

Advanced Message Queuing Protocol (AMQP) represents an application protocol focusing on messaging. It safeguards reliable communication via message delivery acknowledgement primitives. It uses message queues for traffic avoidance and exchanges for routing purposes, while also supporting publish / subscribe model [40].

Service discovery protocols are required for discovering IoT device offered services and resources. Multicast DNS (mDNS) [41] and DNS Service Discovery (DNS-SD) [42] represent the predominant standards in this context offering dynamic and efficient service discovery. mDNS represents a Name Resolution type of service performing the task of unicast DNS server. DNS-SD actually performs discovery of desired services utilizing mDNS for pairing IP addresses with host names.

Routing Protocol for Low Power and Lossy Networks (RPL) represents an infrastructure protocol based on IPv6. RPL is designed to support routing requirements of devices with constrained resources [43].

IPv6 over Low-power Wireless Personal Area Networks (6LoWPAN) specifies mapping services required by IPv6 so that an IPv6 network is maintained over Low-power WPANs [44].

Zigbee/IEEE 802.15.4 is an infrastructure protocol offering a complete network protocol stack for Wireless Sensor Networks and aiming at low data rate services for devices with power constrains [45]. Bluetooth Low-Energy (BLE) represents an energy consumption efficient infrastructure standard [46].

Several challenges exist with reference to the Internet of Things. First of all there is a need for establishing smart environments. Their goal is to efficiently integrate devices enabling real time communication between them. Then the device data need to be integrated utilizing to this end a storage architecture. Energy management and reliability issues have to also be taken into account [47].

Security and privacy present a strong challenge for IoT systems [48]. Indeed, IoT systems tend to be less secure and more vulnerable than other systems due to different causes, including security design errors both in hardware and software. Insecure devices might attract IoT-based attacks like for instance denial-of-service attack. Plethora of devices that an IoT system consists of magnify security challenges throughout their lifecycle. Along with security, privacy challenges exist so that inference of private data from other data is limited. To this end, measures at the application, network and device levels are needed.

Heterogeneity is a characteristic of IoT systems as a large number of devices / things from different platforms need to be integrated. Middleware is essential to this end supporting functionalities like reliability, resource management, scalability, real-timeliness and security. Furthermore, it should support event management and code migration services. Finally, it should be adaptive to a dynamic and changing environment [47].

The generation of large amounts of data in IoT systems poses further challenges on how to efficiently store, retrieve, process and analyze all of it. Big data analytics can help extract knowledge out of this data that can be an asset for decision making in different application domains. Different computing paradigms can support in different ways storage and retrieval of this data. The cloud computing paradigm [49] represents a service model packaging IT resources required by the consumers as a service. The three cloud service models are Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). Fog computing paradigm [50] pushes computation closer to end nodes / devices attempting to solve the problem of billions of devices pushing their data to the cloud and operating solely when connecting to cloud servers. Use of shared computational servers and provision of Software as a Service (SaaS) model is promoted. Edge computing is a term used with two different meanings in literature [51]. By edge either devices at the edge of the network are meant, i.e. end nodes, or network elements connecting central nodes and end devices. Depending on the meaning adopted, edge compuring paradigm moves computation and storage locally utilizing end node resources, or to the network elements.

B. Industrial Internet of Things - IIoT

The Industrial Internet of Things represents a subset of the Internet of Things and is part of the general IoT evolution. Primarily addressing the industrial manufacturing domain it faces challenges that are unique with reference to IoT in general. Indeed, the industrial domain is characterized by the so called Operational Technology, comprising industrial networks, programmable logic controllers (PLCs), and Industrial Automation and Control Systems (IACS) of which Supervisory Control And Data Acquisition (SCADA) systems represent the larger sub group. Operational Technology has evolved independently of Information Technology, due largely to the nature of the systems in the industrial manufacturing domain posing such requirements as real-timeliness, continuity of operation, safety and reliability. Integration of OT and IT is a challenge for the emerging IIoT [52].

It should be noted that as a subset of IoT, IIoT bears great similarities. Both IoT and IIoT deal with interconnected devices / things that generate data, which have to be collected, stored, and analyzed, leading to decision making and service pairing provided to customers. What makes IIoT different is the hard requirements for real-timeliness, service continuity and safety, and the need of integrating OT [48]. As an example one could consider services associated with wearable devices e.g. activity tracking, in contrast to asset management services in an industrial plant. Both services involve sensing of physical signals, e.g. distance covered in the first case or manufacturing equipment vibration in the second, real time data collection and transfer, identification of anomalies and generation of alerts / alarms, and appropriate actuation / provision of feedback. Yet, the second service has much more stringent requirements, as its failure could be of higher cost both economic due to plant downtime and potentially with reference to safety of human lives, which is not the case in the first service at least for the general population.

The need to integrate IT and OT in the industrial manufacturing environment stems from the ever increasing capabilities of smart devices, such as advanced sensors and actuators, and embedded systems, having in many cases processing power and storage significantly higher that their OT counterparts, and thus enabling more advanced applications and new business models, e.g. Cloud Manufacturing. As IT and OT systems have followed different evolutionary paths their integration is a challenging task. As an example while in many cases OT systems have been managed independently by their owners and not connected to the outside world, IT is by default more open and interconnected, much more complex and thus much more vulnerable to failures and security threats. Efficiently integrating the two worlds has to generate a new paradigm maintaining the stringent requirements of OT while adopting the higher capabilities of IT.

Furthermore, the IIoT and the convergence of OT and IT that it brings, finds wider applicability than the pure industrial manufacturing domain. In fact a number of sectors bear similar needs to the industrial environment, utilizing smart devices and employing control automation for their applications. Critical infrastructures, such as energy production and distribution, transportation, and water management, as well as healthcare are among these industrial sectors. In this context IIoT becomes a unifying element for a number of domains that could be put under the label ”industrial domains”.

Smart Cities could fall under this label as well. With a number of applications comprising [53] building structural health, waste management, traffic management, city energy consumption, building automation, smart parking, smart lighting and environmental monitoring, Smart City domain is a good candidate as an industrial domain. In this context the application of IIoT in Smart Cities could lead towards new innovative applications and models.

C. IIoT, IoT and Cyber Physical Systems

IoT and IIoT as discussed in the previous sections represent a superset and a subset respectively, with the latter being an evolution of the former. It has also been argued that IIoT is extended to a number of industrial domains, comprising manufacturing, critical infrastructures and healthcare. In this context it goes beyond the pure industrial manufacturing domain.

Cyber Physical Systems (CPS) represent systems that comprise interacting physical and digital components, centralized or distributed, providing sensing, control and networking functions, so as to influence the real world through physical processes [54]. CPSs focus on controlling physical processes which discerns them from conventional Information systems. They provide digital descriptions of physical objects, extending the real world objects into the digital world. Thus, they lie at the cross section of physical and digital worlds, integrating physical processes and computer systems.

Application of CPS is thus associated with a digital counterpart of the physical world, which is called a Digital Twin (DT). A DT is virtual, comprises both static (design documents, process specifications) and dynamic (data acquisition, simulation) parts and addresses each and every instance of its physical world counterpart for its total lifecycle [55].

Applying CPS to the industrial domain and utilizing IoT / IIoT as an enabling technology led to what is known as the 4th Industrial Revolution or Industry 4.0 [56], a German initiative that has become a global buzzword. In this context, Industry 4.0 resides in the confluence of IoT and CPS, its pure manufacturing phase being at the confluence of IIoT and CPS [57].

D. IoT/IIoT Reference Architectures

The complexity of IoT applications derives from the fact that they are using a combination of cutting-edge technological achievements in the areas of networks, hardware and informatics [58]. Thus, only hierarchical, modular, loosely coupled, flexible and scalable system architectures can manage and coordinate such complex systems of heterogeneous hardware components, networks, data, and software.

In order to help the engineers that design IoT applications, reference architectures are developed, providing guidance for the development of systems, solutions and application architectures. A reference architecture provides common and consistent definitions in the system of interest and a common vocabulary for assisting the discussions on the specification of implementations, so that options may be compared.

To support the broad applicability of IoT systems, reference IoT architectures must be generic and remain at a high level of abstraction, so as not to enforce unnecessary restrictions to system applications. Preferably, they should oversee the limits of current available technologies, and so be able to identify technology gaps based on the architectural requirements.

Scalability is a critical aspect of IoT reference architectures, as they must be able to support a number of devices ranging from a few to millions, while remaining affordable for small deployments. They must also take into account the diversity of IoT devices, and the services they provide, such as data collection, analysis and actuation. As the IoT application will collect and generate data throughout its operation, a scalable storage system is highly demanded.

Usually, IoT applications are based on a large scale network deployment, where the connectivity and communication between all physical components is of utmost importance. Since most IoT devices are event driven, the communication protocols that support event-style communication must be utilized. In most cases, IoT applications manage vital infrastructures and systems supporting the living and privacy of the citizens. Thus, safety and security policies and measures must be able to be applied in all the aspects (network, software and hardware) of such complex systems.

Historically, the first attempts for IoT architecture definition have been inspired by the Service Oriented Architecture (SOA) adapting the idea that each system is able to expose its functionalities in terms of web services, which can be invoked by other systems over computer networks [59]. Although SOA was a good paradigm to support IoT application, new challenges such as the requirements for limited computational resources, low power consumption, networked devices distributed in a large geographical area, real-time and latency sensitivity, collection and processing of large amounts of data, new business models and social requirements, create the need for more flexible architectures that permit better data and resource management.

For a decade after the appearance of the first IoT applications, a lot of proposals have been put on the table, but none of them was widely supported in order to become a global IoT reference architecture. Most researchers, such as Masahl et al. [60], Mainetti et al. [61], with small differences and variations follow a three-layer approach which comprises:

i The *perception (or sensing) layer* representing the physical layer, where the IoT devices are installed. These devices are able to sense their environment and gather information about it, as well as interact with it.

ii The *network layer* representing both the physical communication between the IoT devices, network devices, and servers and the transmission and processing of data.

iii The *application layer* consisting of software applications that deliver IoT-based services to the end users.

The three-layer architectural was popular, mainly due to its simplicity, but as the IoT applications became bigger, researches identify that the complexity of orchestrating the large number of IoT devices, as well as the size of associated information, cannot be handled efficiently at the network or application layer. Thus, they moved to a four-layer architecture by adding one more layer (usually named as middleware layer), which provides mechanisms for the management of the hardware assets and the orchestration of information gathering and analysis. This optimization, has been adapted by ITU-T (International Telecommunications Union - Telecommunication Standardization Sector) in its Y.4000 Recommendation as a first attempt to define an IoT reference architecture [62].

The Industrial Internet of Things is part of the general IoT evolution. However, it faces challenges that are unique and differentiate it from the other systems and services of IoT, mainly due to the need to integrate the infrastructure of the Operation Technology (OT) with the typical Information Technology

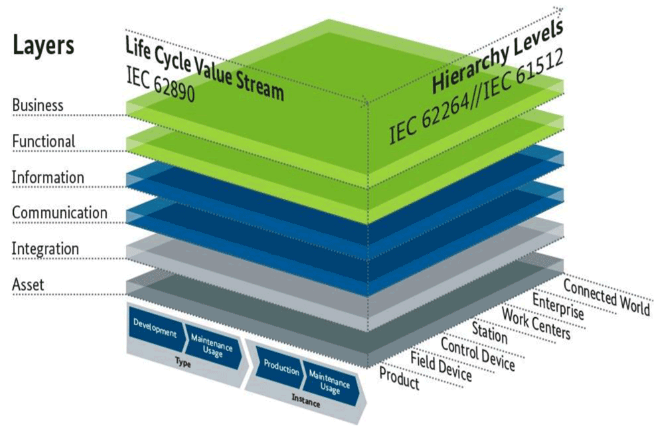

Fig. 1. RAMI 4.0 model. Source: Platform Industrie 4.0

(IT). This will create an integrated system that can manage the complete manufacturing hierarchy, from business processes to sensors, which provides significant flexibility and presents new opportunities to enterprises. Although the manufacturing environment is the primary and most important application domain of the IIoT, it is applicable in other domains as well, which characteristics and challenges are similar, including for instance critical infrastructure protection, transportation, energy and healthcare, being identified by the common term industry. In this context relevant reference architectures could be valuable for the Smart City paradigm.

Several initiatives deal with the adoption of IoT in industry, i.e. Industrial IoT (IIoT). The Industrial Internet Consortium[2] (IIC) and the Industrie 4.0 Platform[3] are two of the mainstream initiatives towards standardization of IIoT systems, supplemented by further initiatives such as Japans Society 5.0[4] and Made in Chine 2025[5]. The two aforementioned mainstream initiatives that have already produced Reference Architectures are briefly presented below.

Industrie 4.0 Platform (I4.0) is a high-tech strategy of the German Government, promoting computerization in manufacturing. Its scope is to connect/merge operation (production) technology with information technology and to enable higher, more flexible and efficient productivity and new services. In order to make this feasible, the Industrie 4.0 consortium proposed a reference architecture, the Reference Architectural Model for Industrie 4.0 (RAMI 4.0) [63], providing a common language to all stakeholders. RAMI 4.0 is a 3-dimensional map, that shows how to approach the issue of Industrie 4.0 in a structured manner. The reference model of the architecture is shown in Fig. 1.

The three dimensions of the RAMI 4.0 are *Hierarchy, Architecture and Product Life Cycle*. The first axis, Hierarchy, highlights the different approach that IIoT takes compared to previous models. Industrial IoT does not follow the hard-

[2]https://www.iiconsortium.org/
[3]https://www.plattform-i40.de/
[4]https://www.gov-online.go.jp/cam/s5/eng/
[5]https://en.wikipedia.org/wiki/Made_in_China_2025

ware based classical industrial environment hierarchy (Enterprise, Plant, Shop Floor, Field levels) but instead presents a flat and flexible hierarchy that distributes functions and integrates smart products, inspired by IEC62264/IEC 61512 standards. The hierarchy axis covers all the components from the Connected Word (upper level) to the Smart Factory to the Smart Product. The Smart Factory level consists of the interconnected components that allow the level of interactivity between systems and customer in order to build the future smart production, such as enterprise systems, work centers, stations, control and field devices. The Architecture Axis refers to the architectural layers of an IIoT application. The classical three-layer model is expanded in six layers (from bottom up):

i The *Asset* layer comprises the physical things in the real world.
ii The *Integration* layer contains the systems that "interpret" the sensing information of the physical things to digitized data.
iii The *Communication* layer consists of the network infrastructure which permits the access to the digitized data.
iv The *Information* layer defines the information that is available to the software application as it is formatted after pre-processing at the previous layers.
v The *Functional* Layer contains the asset management tools.
vi The *Business* layer consists of software applications of data processing depicting the organization and business processes.

Finally, the third axis is product life cycle. The life cycle of a product is broken down into 2 methods with two phases each. The first method, *Type*, refers to a product in the development or re-design phase. The second method, *Instance*, covers the production and facility management phases of the product life cycle.

At the core of the RAMI 4.0 application resides the I4.0 component. Between the physical asset and the communication layer of I4.0 lies the *Administration Shell*. The Administration Shell is the interface connecting I4.0 to the physical thing, which stores all data and information about the asset and serves as the network standardized communication interface. It is possible for a shell to refer to multiple assets that are related to each other. The Administration shell consists of the Manifest, which stores all data about the assets, and the Component Manager, which includes all necessary APIs to make services externally available. The structure of the administration shell is presented in Fig. 2.

The Industrial Internet Consortium (IIC) was founded in 2014 as an open membership organization aiming at bringing together industry players to accelerate the development, adoption and widespread use of Industrial Internet technologies. As a result the Industrial Internet Reference Architecture (IIRA) [64] was developed. IIRA deals with different industrial sectors ranging from manufacturing and transportation to energy and healthcare. The architecture is based on four viewpoints, each one associated with particular stakeholders and their

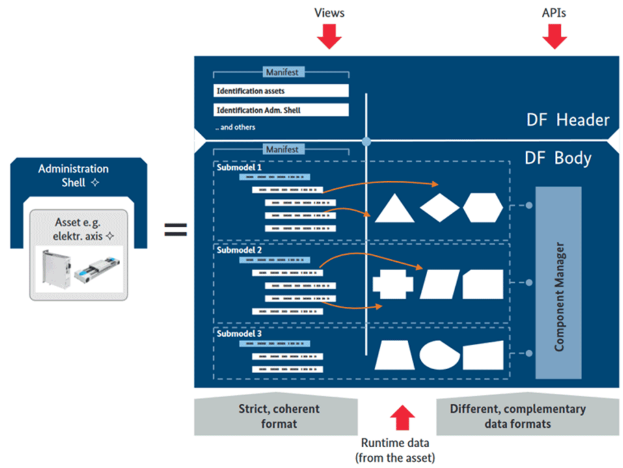

Fig. 2. Administration shell structure. Source: Platform Industrie 4.0

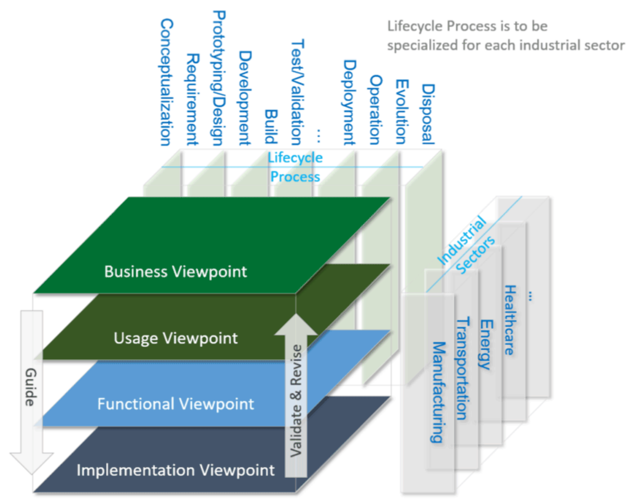

Fig. 3. IIRA viewpoint architecture. Source: Industrial Internet Consortium

concerns. It can also be related to product lifecycle process and be specialized according to the industrial sector in question. This is all presented in Fig. 3.

Business viewpoint refers to business-oriented concerns, such as business value, expected return on investment, cost of maintenance, and product liability. Stakeholders have a major stake in the business and strong influence in its direction. They include those who drive the conception and development of IIoT systems in an organization. Vision describes a future state of an organization or an industry and provides the business direction toward which an organization drives. Values reflect how the vision may be perceived by the stakeholders who will be involved in funding the implementation of the new system, as well as by the users of the resulting system. Key objectives are quantifiable high-level technical and ultimately business outcomes expected by the resultant system in the context of delivering the values. Key objectives should be measurable and time-bound. Fundamental capabilities refer to high-level

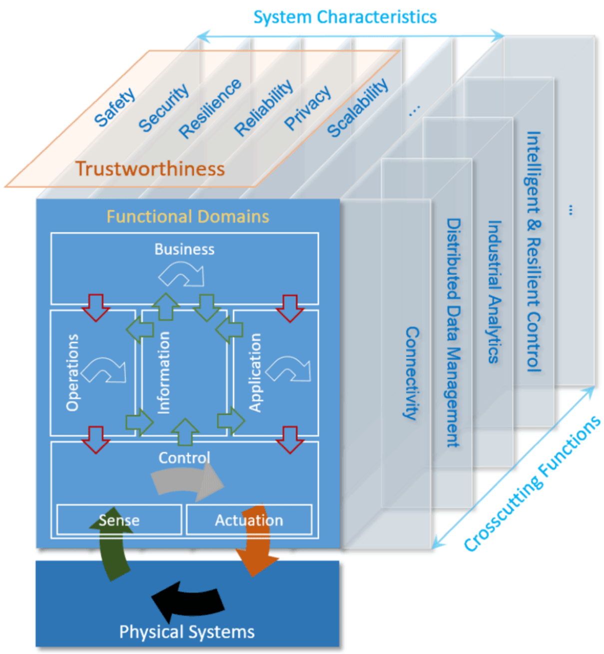

Fig. 4. IIRA functional viewpoint. Source: Industrial Internet Consortium

specifications of the essential ability of the system to complete specific major business tasks.

Usage viewpoint is concerned with how an IIoT system realizes the key capabilities identified in the business viewpoint. The usage viewpoint describes the activities that coordinate various units of work over various system components. The basic unit of work is a task which is carried out by a party assuming a role. A role is a set of capacities assumed by an entity to initiate and participate in the execution of, or consume the outcome of, some tasks or functions in an IIoT system as required by an activity. Roles are assumed by parties. A party is an agent, human or automated, that has autonomy, interest and responsibility in the execution of tasks. A party executes a task by assuming a role that has the right capacities for the execution of the task. An activity is a specified coordination of tasks (and possibly of other activities, recursively) required to realize a well-defined usage or process of an IIoT system.

Functional viewpoint (Fig. 4) focuses on IIoT System functional components, structure and interrelation, interfaces and interactions. It can be decomposed into five functional domains:

- Control domain which represents the collection of functions that are performed by industrial control systems. The core of these functions comprises reading data from sensors, applying rules and logic, and exercising control over the physical system through actuators.
- Operations domain which represents the collection of functions responsible for the provisioning, management, monitoring and optimization of the systems in the control domain.
- Information domain which represents the collection of functions for gathering data from various domains, most significantly from the control domain, and transforming, persisting, and modeling or analyzing those data to acquire high-level intelligence about the overall system.
- Application domain, which represents the collection of functions implementing application logic that realizes specific business functionalities. Functions in this domain apply application logic, rules and models at a coarse-grained high level for optimization in a global scope.
- Business domain, which includes functions that enable end-to-end operations of the industrial internet of things systems by integrating them with traditional or new types of industrial internet systems specific business functions including those supporting business processes and procedural activities.

Finally, the implementation viewpoint is concerned with the technical representation of an IIoT system and the technologies and system components required for implementing the activities and functions prescribed by the usage and functional viewpoints. IIoT system implementations follow certain well-established architectural patterns, such as:

- **Three-tier architecture pattern**. It comprises edge, platform and enterprise tiers. These tiers play specific roles in processing the data flows and control flows involved in usage activities. The edge tier collects data from the edge nodes, using the proximity network. The platform tier receives, processes and forwards control commands from the enterprise tier to the edge tier. It consolidates processes and analyzes data flows from the edge tier and other tiers. It provides management functions for devices and assets. It also offers non-domain specific services such as data query and analytics. The enterprise tier implements domain-specific applications, decision support systems and provides interfaces to end-users including operation specialists. The enterprise tier receives data flows from the edge and platform tier. It also issues control commands to the platform tier and edge tier.The three tiers are connected via different networks: a) The proximity network connects the sensors, actuators, devices, control systems and assets, collectively called edge nodes, b) the access network enables connectivity for data and control flows between the edge and the platform tiers, and c) the Service network enables connectivity between the services in the platform tier and the enterprise tier, and the services within each tier. The three-tier architecture pattern combines major components (e.g. platforms, management services, applications) that generally map to the functional domains (functional viewpoint). From the tier and domain perspective, the edge tier implements most of the control domain; the platform tier most of the information and operations domains; the enterprise tier most of the application and business domains.
- **Gateway-Mediated Edge Connectivity and Management architecture pattern**. It comprises a local connectivity solution for the edge of an IIoT system, with

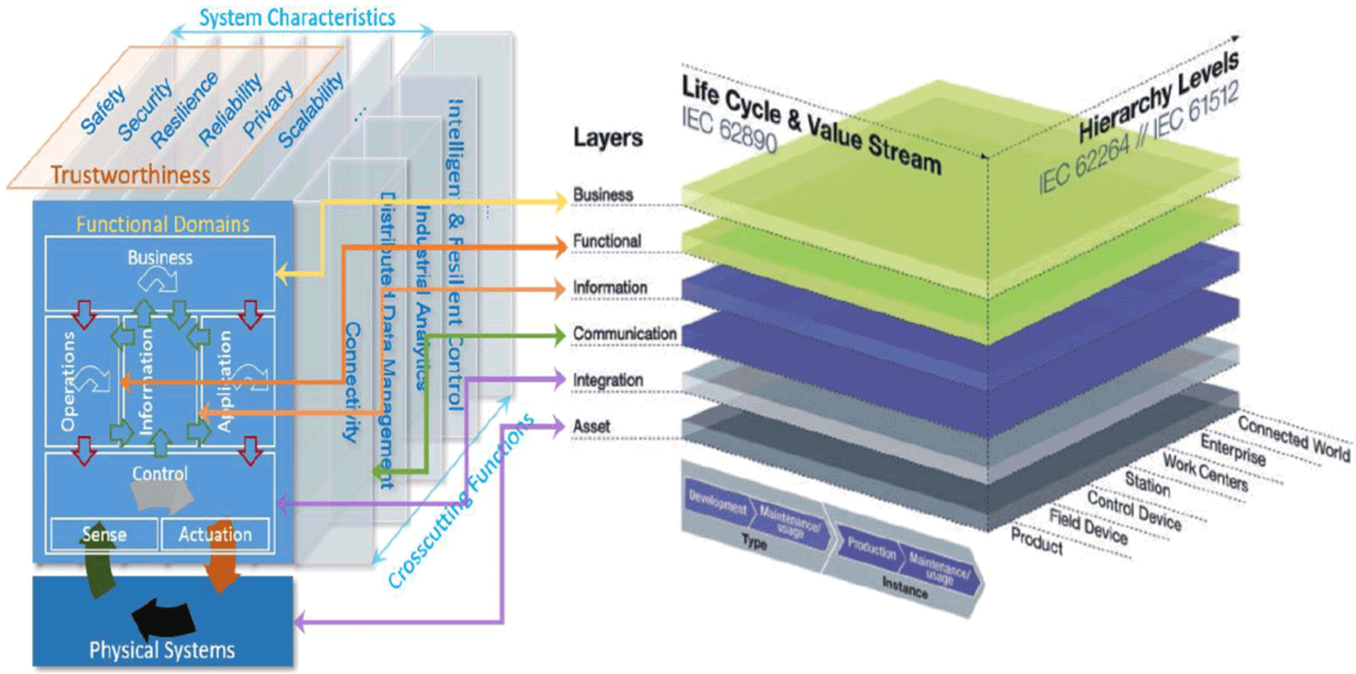

Fig. 5. Functional mapping between IIRA and RAMI 4.0. Source: Industrial Internet Consortium

a gateway, that bridges to a wide area network. The gateway acts as an endpoint for the wide area network, while isolating the local network of edge nodes. This architecture pattern allows for localizing operations and controls (edge analytics and computing). Its main benefit is in breaking down the complexity of IIoT systems, so that they may scale up both in numbers of managed assets as well as in networking.

- **Layered Databus pattern**. It provides low-latency, secure, peer-to-peer data communications across logical layers of the system. It is most useful for systems that must manage direct interactions between applications in the field, such as control, local monitoring and edge analytics. At the lowest level, smart machines use databuses for local control, automation and real-time analytics. Higher-level systems use another databus for supervisory control and monitoring. Federating these systems into a system of systems enables complex, Internet-scale, potentially-cloud-based, control, monitoring and analytic applications. A databus implements a common data model, allowing interoperable communications between endpoints at that layer. The databus supports communication between applications and devices. For instance, a databus can be deployed within a smart machine to connect its internal sensors, actuators, controls and analytics. At a higher smart system level, another databus can be used for communications between machines. At a system of systems level, a different databus can connect together a series of systems for coordinated control, monitoring and analysis. Each databus may have a different set of schema or data model. Data models change between layers, as lower-level databuses export only a controlled set of internal data. a logical connected space that implements a set of common schema and communicates using those set of schema between endpoints. Each layer of the databus therefore implements a common data model, allowing interoperable communications between endpoints at that layer.

There are efforts for a mapping between IIRA and RAMI 4.0 that recognize the commonalities between the two Reference Architectures [65]. The functional mapping of IIRA to the RAMI 4.0 architecture layers is shown in Fig. 5.

IV. Challenges and Solutions

A. Smart Lighting

The main aim of smart lighting systems is that lights turn on when needed, adjust their dimming in function of environmental lighting, and turn off when they are not needed. With the advancement of technology, numerous solutions like the use of LEDs, light and movement sensors, illumination controllers, dimmers, wireless communication devices, and Information and Communication Technology based designs have been proposed. We will review here the most important approaches.

One of the most widely proposed systems for implementing smart lighting solutions are the Wireless Sensors Networks (WSN). Yoshiura et al. propose a smart lighting system consisting of LEDs, brightness sensors, motion sensors, and short-distance communication networks (such as ZigBee or IEEE 802.15.4g) [66]. Mustafa et al. also use a WSN to detect the presence of vehicles along the road, and control lamps accordingly, in the context of a smart highway lighting management system [67]. According to simulation results, their proposed system can save up to 57.4% of power consumption compared to conventional lighting systems. The authors in [68] go a step further, and propose to also take into account the pedestrian and vehicle speed and rate of flow. However, an increased number of sensors is needed in order to implement this solution.

Castro et al. on the other hand, propose the use of emerging machine-to-machine (M2M) protocols and embedded Web services such as Constrained Application Protocol (CoAP) built over REST architecture [69].

Visible Light Communication (VLC) is another new technology that is getting a lot of attention for enabling smart lighting systems, be it denominated as LiFi, optical wireless, or Free Space Optics (FSO) [70]. Both theoretical and practical performances can be impressive [71].

In a nutshell, the idea is to use the high reactivity of LEDs to modulate the emitted light in a manner that is undetectable by human eyes, and which can be exploited by a dedicated hardware. The aforesaid modulation is then used to transmit digital signal. VLC systems have the advantage of working in the licence-free spectrum and being immune to radio frequency interference. However, there are still some downsides that need to be taken into account, such as: the possibility of uplink and downlink signal to interfere with each other, or the current level of energy consumption of such a solution.

A completely different approach to implementing smart lighting solutions is to integrate it in an existing Smart City platform, which covers the whole city and offers network coverage and system maintenance for several applications. In [72], wireless technology such as ZigBee is used at the communication level, and control and monitoring strategies are implemented as web services in the central software. Real-life use cases at test sites in Austria show an increased energy efficiency without compromising public safety. A different cloud-based solution is proposed by Merlino et al. [73], which integrates OpenStack[6], a widely used framework for infrastructure as a service. Their goal is to establish a smart city infrastructure interconnecting all the smart devices deployed in the city, and to provide it to smart lighting applications in a service-oriented, cloud-based fashion.

B. *Smart Building/Smart Energy*

As it is already mentioned, in the recent years the largely increasing energy consumption in residential and commercial buildings has become a concern topic. In particular, heating, cooling and air conditioning systems are a foremost portion of energy consumption in building sector. Hence, smart management of energy resources and optimizing the HVAC control systems in cities is of highest importance.

The smart buildings paradigm is nowadays well captured by the concept of nearly zero-energy buildings, which have very high energy performance. The low amount of energy that these buildings need comes mostly from renewable energy sources, while they have a yearly balance of produced and consumed energy close to zero. Since renewable sources are unpredictable and can not be scheduled, practical solutions include storing the excess energy produced by the renewables into thermal or electrical energy storages, which allow the decoupling of thermal and electrical energy profiles. However, some flexibility in user comfort requirements will not be an option. This mainly can be done through an energy resource management system, which takes into account the smart buildings as flexible loads by considering the energy storages, renewables and all operational constraints such as predefined agreement with main utility grid [20] [74].

From a computational and information perspective, this is enabled by the availability of energy-oriented Internet of Things crossed with intelligent analytics, which allow to monitor energy use and send it to the cloud to allow tracking and management of energy consumption via an online dashboard.

From a control point of view, a useful and powerful example methodology already in place in the most advanced solutions is model predictive control (MPC) [75], which is well suited to deal with a large amount of constraints of different types, variable user requests, and realtime optimization techniques. It is also specifically noted that MPC methods are well studied in building temperature control applications where the main contributions are mainly on the cost minimization and comfort satisfaction.

From an energy technological point of view, more efficient HVAC system can now be used, even in presence of high thermal loads. An air-to-water heat pump is an energy-efficient method of heating (or cooling), since it can convey heat from a heat source (ambient temperature) to a sink source (tank water) instead of generating heat directly, e.g. by using an electrical element. In this context, the heat pump performance can be significantly improved once used in energy management programs in order to be run when it is in high efficiency period. Heat pump systems can also be beneficial for demand-response applications, where the main focus is to shift demands from on-peak to off-peak periods. In this case, heat pumps are usually connected to a buffer hot water tank (HWT) both to increase the COP and to decouple the (thermal) load and the (electrical) heat generation [76].

Moreover, giving Smart Building technology suppliers and designers the flexibility to collaborate with their customers to create more targeted solutions is a hot debate topic. This may lead, for a single building, to thousands of sensors measuring various operating parameters in every corner of the building, including air temperature, humidity, occupancy, energy use, renewable energy productions, free capacity of the storage and many other parameters. These sensors collectively capture massive amounts of data that must be transmitted, stored, analyzed and acted upon, often in real-time, to provide a truly smart building experience. To this scope, smart metering in multi-tenant commercial and residential buildings is another challenging issue to optimize the number of sensors without

[6]https://www.openstack.org/

degrading the performance of the system in terms of occupancy and operational cost.

Finally, consider that near zero energy buildings i.e. the most efficient buildings nowadays have (among other characteristics) a yearly balance of produced and consumed energy close to zero. The next challenge it to scale down to the monthly and daily basis. This in turn requires even more accurate measurements of the level of energy storages distributed in the building and the level of comfort, when and where specifically needed. This will require some flexibility from the user side, so strong human interaction devices are needed.

C. Smart urban mobility management

Among the major challenges of intelligent urban mobility management are the collection of heterogeneous data and their processing, which is at the heart of many research projects. There are both general issues, including the management of V2V and V2I networks, crowdsensing or the processing of traces of mobility. There is also work focused on specific applications such as intelligent parking or autonomous vehicle management.

As said in section II-C, smart urban mobility management systems have been developed with the objective to leverage heterogeneous data into machine learning/AI algorithms forecasting the traffic and optimizing in "real time" the road infrastructure. To feed data to these prediction algorithms, several engineering and technical alternatives are available: cameras, magnetic detectors, etc. One of the challenges is then to be able to merge data of different origins, qualities and characteristics [77]. Traffic management on a more microscopic scale can also be done in a distributed manner between vehicles (V2V) or even with the support of an urban network infrastructure (V2I). It is no longer the urban system that estimates traffic and regulates infrastructure, but vehicles that collaborate with each other to manage their cohabitation in a nearby space: congestion detection, accident avoidance, sharing of environmental information. V2V/VI2 networks have been widely studied under the still false assumption of a high proportion of connected vehicles [78]. It is also one of the technological foundations of the operation of autonomous vehicles, which can rely on this collaboration to improve their decision-making capacities [79]. An additional technological challenge is to design similar systems that operate at low enough energy to be embedded in non-motorized vehicles such as bicycles. This would make it possible to further study the cyclability of cities and ways of adapting urban infrastructure to the practice of sustainable mobility [32], [80].

In the same trend, crowdsensing is for a few years a new way to gather information. Most smartphones and mobile operating systems provide applications which are able to sense and gather several data from the environment of the device. Thanks to this collected data, it is possible to combine information from several probes. A very common use case is the collection of network scans with location to help the localization feature of these devices. Nevertheless, most users are not aware of this spying. The collected data might represent infringements of privacy. One possible solution to keep gathering this data while maintaining privacy would consist in device-to-device communications in order to break the links between data and users. Several research projects have collected data from mobile users to combine location and network scan data to test the trade-off between accuracy and privacy [24]. It is also a challenge to design multiuser crowdsourcing system for geolocalization that can improve on the privacy of users. [25]

Mobility management also involves immobility management. Parking coordinates land use and transportation in urban areas, and it is also one of the most important assets, bringing revenues to cities. Manville and Shoup [81] surveyed the percentage of total parking areas in the central business district of different cities. Averagely, parking coverage takes 31% of land use in big cities, like San Francisco, and even more, 81% in Los Angeles and 76% in Melbourne, while at the lower end we find New York (18%), London (16%), and Tokyo (7%). Such a super high parking coverage density in Los Angeles can be a constraint on urban redevelopment and lead to an increase of vehicles, as well as a reduction of public transportation. The challenge, before its technical design, is then to define the objective of a smart parking system. If it is limited to the detection of free or occupied spaces, the utility of smart parking is limited to assisting police forces, who must enforce parking laws or to statically guiding motorists to areas where spaces appear free, with the risk that they will no longer be when the user arrives on site. To improve the efficiency of the guidance, a dynamic update is necessary and combinations of software and infrastructure for urban information dissemination have been studied [82].

V. Discussion

This paper presents the Smart City paradigm, a paradigm largely technology pushed by the evolution of Information and Communication Technologies. It more specifically addresses Smart City application domains that bear characteristics similar to the industrial manufacturing domain, representing critical infrastructures of the city. Such application domains are City Lighting, Smart Buildings / Energy, and Smart Urban Mobility. The nature of these domains mandates a huge number of interconnected smart devices and application of control automation for their appropriate management. Industrial Internet of Things, a subset of Internet of Things for the industrial domain, is thus applicable as an enabling technology. Its emerging reference architectures could thus pertain the Smart City set of application domains. The paper discusses the requirements, solutions and challenges associated with the aforementioned domains.

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