Coupled with high flexibility and ease of deployment, IoT-based solutions can be easily adopted for different application scenarios. However, there are many challenges that system designers would need to consider before employing large-scale IoT deployment.

Firstly, dealing with big data in IoT systems is a significant concern. According to Statista [2], the number of IoT devices is expected to arrive at 30.9 billion by the year 2025, tripling the number of non-IoT devices then. These IoT devices will produce data at an unprecedented rate, which our traditional systems were not designed to accommodate. This problem of massive data flow contributes to our interest in the concept of “Big Data”, characterized by the high volume, velocity, and variety of data. To better leverage IoT in the data-driven society, the current infrastructure has to quickly adapt to handle the big data in the system efficiently. Moreover, the smart components in the IoT-enabled smart cities have to supply the interoperability for cross-functional performance and the cognitive capacities in our systems.

In order to solve the potential incompatibility between the traditional systems and big data, emerging technologies appear to adjust and accommodate, each contributing to the development of our smart city landscape in different ways. When coupled with realistic assumptions of real-world situations about system security and a comprehensive examination, such solutions can be very promising.

However, these emerging technologies are not perfect. The adoption of these emerging technologies may lead to the downside of another problem. Blockchain is a potential candidate for securing distributed networks, eliminating the need for a central agency, and improving scalability and efficiency. Blockchain enables decentralized data storage by encrypting and disseminating transactions across all participants. Furthermore, every legitimate transaction in the system is appended to each participant’s ledger, making these transactions immune to malicious modification, thus safeguarding system data integrity. However, data privacy and computational overhead have become key problems with blockchain, due to the transparency of the transaction ledger and the necessity for transaction validation. Likewise, the millimeter-wave (mmwave) could support a high data transfer rate to accommodate large data flow in the 5G scenario. It is expected to alleviate the congestion problem in the currently congested radio frequency spectrum. However, mmwave suffers from high penetration loss and is vulnerable to changes in the physical environment. Furthermore, the massive amount of data transfers puts a pressure on the security of communication channels, mandating the development of more reliable and robust technologies.
secure protocols to deal with communication security.

Most importantly, we have to consider the new security context brought about by the IoT-enabled intelligent systems, which raises new security concerns. There are two primary sources of new security concerns: the different capabilities of IoT devices, and the deployment environment.

Firstly, it is common to have IoT devices of varying capabilities cooperating in a single system. Unlike centralized and sophisticated commercial systems, most IoT devices are low-cost end-point devices that operate in open environments. Due to resource constraints, they are largely limited in their ability to deploy traditional security mechanisms, and it is hard to guarantee their physical security in the open deployment environment. Thus, security issues associated with these low-end IoT devices are difficult to address with conventional approaches. Another common type of IoT device is the complex cognitive IoT, capable of sensing and cognitive decision-making. Such a device exhibits high network heterogeneity and requires dynamic spectrum access of IoT devices, contributing to security risks that might not be accounted for by traditional security approaches. For example, sensitive information can be easily leaked and attacked during sharing and broadcasting in the massive heterogeneous network and across platforms.

Another major source of new security concern is the deployment environment of IoT systems. The traditional industrial systems operate in highly controlled environments, where the enterprise security can always be guaranteed. However, the scope of cybersecurity for IoT systems has expanded beyond typical information technology (IT) systems to encompass protection for security needs of operational technology (OT) systems such as industrial control systems and cyber-physical systems, which involves more external devices that may be in the untrusted environment of the open Internet. Thus, the security requirements for IoT-enabled smart city systems differ significantly from the traditional implementations due to new expectations diverging from our traditional understanding of system architecture. Moreover, the security requirements of systems that operate in the open environment are largely context-dependent and application-specific. As a result, new adaptations of the existing security mechanism or new solutions will be needed for the IoT-enabled smart cities to fill the gap between the security needs and capabilities.

Given the widespread deployment and high physical accessibility of these IoT devices, regardless of their system capabilities and deployment environments, we have to consider a new spectrum of security risks to avoid these IoT devices from becoming the weakest link and the largest attacking surface in our system. As aforementioned, there exist several security challenges for IoT-enabled smart cities. Common security challenges include integrity, confidentiality, availability, decentralization, authentication, secure communication, end-to-end security, identity management, access control, privacy, system resilience, scalability, and interoperability. There are some recent survey papers that cover the relevance of these topics. Some focus on IoT security, and some pay more attention to the requirements that provide insights on the current security challenges in IoT.

Nonetheless, many of the existing surveys focus on IoT security in general, rather than reviewing and providing specific studies for different smart city developments. As such, they may not provide sufficient examples to gain a deeper understanding of the security challenges and requirements for new smart city proposals using emerging technologies. Therefore, we review the works related to the topic of IoT security from a more comprehensive perspective, and summarize the security concerns separately according to the characteristics and requirements of different smart applications. The main contributions of this paper are summarized as follows:

- We highlight the common properties and challenges among smart city applications and provide a relative comparison for domain-wise characteristics.
- We present some of the latest innovations in IoT-enabled smart cities, such as cloud, edge, and more. We also highlight the common security challenges associated with these emerging technologies. In addition, we summarize some of the popular research topics grouped by domain and their main security focus.
- We review recent cryptographic security implementations for IoT-enabled smart cities.
- We analyze the major security challenges of present IoT deployments using the Activity-Network-Things (ANT)-centric security reference architecture. This will promote the understanding of the new security challenges arising from the emerging smart city context.
- We also propose a set of specialized security requirements for IoT-enabled smart cities, illustrated using the ANT architecture. By providing this set of security guidelines, we aim to encourage developers to incorporate more security considerations for protecting the digital ecosystem.
- Besides, we provide a discussion on the potential prospect for IoT and IoT security in smart cities, highlighting the potential of “cognitive IoT”.

The structure of this paper is in accordance to the following: Section II presents an overview of IoT-enabled smart city applications, technologies, and domain-wise characteristics. Section III introduces cryptographic proposals for IoT-enabled smart cities. Section IV explains the common security challenges for smart city applications in an ANT-perspective, which differs from traditional security challenges. Section V summarizes a set of specialized security requirements for IoT-enabled smart cities, illustrated using the ANT architecture. Section VI discusses the potential prospect for IoT and IoT security in smart cities. Section VII concludes our works in this paper.

II. OVERVIEW OF SMART CITY APPLICATIONS

The intelligence of a city is supported by the combination of physical and technical intelligence, where the IoT serves as the backbone to provide data for large-scale insight generation. Smart city developments aim to achieve higher efficiency, flexibility, and sustainability than their current counterparts and will bring drastic changes to the way people live and work. To unleash their full potential in the respective domains, the current systems and architectures will need to undergo...
structural transformation to adapt themselves to the new era of big data. Moreover, new sets of standards and regulations have to be ruled out for governing the new norms.

An illustration of the major smart city developments can be found in Fig. 1. In this scenario, the central authority, the public community, and the service providers are the major players involved in controlling and maintaining the city. While smart devices and applications create a bidirectional data network in which any participant can ingest or contribute data. These data exchanges can be done via various communication protocols, and the cloud is likely to be employed to handle such massive data traffic.

Furthermore, smart city applications are highly context-dependent. Understanding the common properties of smart city applications, and the challenges arising from these properties can be very useful for system evaluation. The common properties and challenges among smart city applications are summarized as below:

**Common properties among smart city applications:**
- High connectivity throughout the system with rapid information flow periodically or constantly, it may exchange data with external parties.
- Most of the applications relies on cloud storage directly or indirectly, for storing the massive data incurred.
- Devices with varying capabilities and resource constraints participate in the same system.
- Different types and volumes of data can be collected and used for insight generation.
- Many devices are deployed in open environments.

**Common challenges among smart city applications:**
- Securing data communication between systems and between devices of varying capabilities in implementing security mechanisms.
- Allowing heterogeneous devices to interact in a safe and efficient manner.
- Giving adequate protection for sensitive information throughout its life cycle.
- Using a unified representation of the heterogeneous data collected.
- Providing solutions for remote mass updates and system recovery in the event of an attack/intrusion.

In addition, while developed nations strive to be among the first to embrace the latest developments, it is important to consider the varying levels of social and technological advancements among different societies, to broaden the feasibility of these applications for benefiting a wider range of audiences. For example, existing smart transportation research has mostly focused on fully digital metropolitan societies. While traffic congestion and road safety are just as serious in developing countries, they are less capable of participating in a brighter image of smart transportation due to a lack of high-quality road and telecommunication infrastructure, as well as the absence of adequate traffic monitoring systems.

Nevertheless, many technological advancements can adapt and improve the lives of people in such situations. For instance, with the growing use of smart mobile devices, a simple carpooling mobile-based application might help to alleviate traffic congestion on inter-urban routes by offering an alternate form of transportation for those who rely on public transit for such trips [13]. While traffic system improvements remain
a top priority for many cities, the design of the proposed smart city solutions should consider the different possible contexts where their application could benefit, and improve the flexibility of their mechanism for the good of a wider audience.

In Table I, we present a relative comparison between smart city applications in different domains. We will explain the different characteristics for each domain in the following subsections.

In Table II, we give an overview of smart city technologies and possible security challenges.

In Table III and IV, we present an overview of some of the smart city developments grouped by domain, highlighting the major research interests in the respective sub-domains.

A. Smart Healthcare

Aging will soon be the top issue for many nations to tackle, especially in developed countries with high average life expectancy. The need for elder care increases significantly, while the establishment of an affordable, qualified, and responsive healthcare system remains of paramount importance to people’s quality of living. Fortunately, the recent development in technologies has paved the way for the transformation of the healthcare system into one that is data-driven, cost-effective, proactive, and personalized.

Since healthcare data is very sensitive and heavily regulated, applications that interact with it must provide extensive data protection. A successful attack on smart healthcare systems could result in life-threatening situations. Although the deployment size for these systems may not be as large as for smart utility systems, and the deployment environment is often in hospitals or residences with limited physical access, the hardware and software security of smart healthcare system components is crucial. Meanwhile, patient anonymity and data confidentiality would impose heavy privacy concerns on such systems. Thus, smart healthcare systems have high requirements for security and privacy.

The current smart healthcare system mainly revolves around two types of smart healthcare IoT devices: (1) clinical healthcare devices; (2) personal healthcare devices. Examples of clinical healthcare devices include smart continuous monitors for heart rate and glucose level. Personal healthcare devices, on the other hand, act as portable data collectors and aggregators to provide remote monitoring and health measurements for personal healthcare advice or care. They include devices such as smart wearable and self-monitoring activity trackers.

An overview of the developments in smart healthcare sensors can be found in the survey [74]. This survey also explores many smart healthcare applications that leverage emerging technologies for performing tasks such as activity recognition, stroke rehabilitation, medical adherence (e.g. monitoring adherence to medical guidance to patients with dementia). The authors in [75] went further by summarizing the current state-of-art technologies and standard protocols used for smart healthcare. Likewise, detail surveys about the challenges of smart healthcare implementations have been presented in [75] [76] [77] [78].

B. Smart Utility

Smart utility generally refers to the public gas, electricity, and water systems that utilize smart infrastructure for providing safer, more efficient, and reliable utility services.

IoT sensors are placed around critical infrastructures to constantly monitor the physical condition of the system and its components, providing important system measurements and feedback for performance analysis. For example, pressure sensors and temperature sensors are the common IoT sensors deployed to monitor the physical state of a system component in smart utility systems.

It is worth noting that smart sensors for utility systems have a higher requirement for battery life than in other applications. Many of these sensors will be placed in physically inaccessible locations, such as in the underground tunnel or bottomless water tanks constructed miles deep in the ground. Replenishing the batteries inside these sensors in such scenarios would be a challenging task. In other scenarios, system components may be placed in public spaces, where physical security cannot be guaranteed. Hence, the mechanism running in these sensors needs to satisfy a low power consumption requirement while maintaining adequate physical security.

Furthermore, due to the intrinsic scale of modern cities’ utility systems, which are continuously connected to a huge number of devices and systems, there is a large “attack surface” for the attackers to exploit on [44]. This “attack surface” includes smart IoT devices, central servers, user endpoint systems and all other possible entry points for the attacker to intrude the system. This problem is further exacerbated by the heavy reliance on communication and networking infrastructure for utility systems, posing system security and privacy risks via the communication channel. Among all, a successful attack on the electrical grid has the strongest instant negative ramification among all attacks on public infrastructure, as the majority of the city’s public systems will be paralyzed instantly.

In addition, some information flow in smart utility systems can be very sensitive, unauthorized modification of such data may indirectly lead to system failures. As a result, it’s critical to incorporate security and privacy considerations into the design of smart utility infrastructure, to protect the IoT devices and system components.

C. Smart Transportation

Intelligence transport systems (ITS) aims to improve the transport systems’ road safety, efficiency, reliability, and user experience for all road users, including pedestrians, train riders, motorcyclists, and everyone else who participates in the transportation network of the society. Hence, a proliferation of smart transportation applications emerges to enhance our transportation systems.

One of the popular research fields in smart transportation is the Internet of Vehicles (IoV), which is a combination of Vehicular Ad hoc Networks (VANET) and the Internet of Things (IoT). With recent developments in artificial intelligence and sensor technology, IoV has come to light as a promising direction to solve the rising demand for a safer, faster, and more comfortable transportation network in cities.
Overall Data Sensitivity
Moderate
Smart Healthcare
High
Small scale but highly critical
Relatively Restricted Access
Smart Utility
Moderate
Widespread
Some components in open environment
Smart Transportation
Moderate
Widespread
Open environment
Smart Homes
High
Small scale, can be critical
Relatively Restricted Access

| Domain | Roles In Smart City Applications | Security Challenges |
|--------|----------------------------------|---------------------|
| Cloud Computing | Cloud computing is a vital technology that enables massive data sharing in our smart cities. Cloud computing allows computation-intensive processes to be offloaded to the cloud, easing the resource constraints on a single device or network. With dynamic resource allocation, system can accommodate better to irregular network and improve their overall resource utilization rate. Cloud is also used for data storage, processing, and analysis. | The introduction of cloud computing has increased the attack surface. Due to the weaker computation power of the edge devices, they are more vulnerable to existing attacks which are ineffective on most advanced systems now, such as small-scale DDoS. Furthermore, if no user interface is provided, users are often unaware of the system states of sensors and panels, making attack incidence difficult to detect. Coupled with coarse-grained access control and heterogeneity between devices, edge computing creates numerous security challenges. |
| Edge Computing | Big data is characterized by the high volume, velocity, and variety of data which are too difficult for traditional systems to handle. Big data contains a combination of structured data (e.g., records, databases), unstructured data (e.g., images, videos), and semi-structured data (e.g., XML, JSON files). Thus, smart city applications dealing with big data will encounter a significant degree of heterogeneity in the data they collect. | Big data poses various security challenges, including the lack of representation, concerns deriving from its large scale, access control and key management, data encryption, privacy protection, and protection for quantum cryptography. |
| Big Data | 6G aims to provide more comfortable, intelligent and secure services to users and machines. The evolution of 6G core services from the 5G is based on the context-dependent performance requirements in implementation scenarios. In [19], the authors identified four types of core services for 6G: (1) mobile broad bandwidth and low latency (applicable to AR, VR holographic teleconferencing), (2) massive broad bandwidth machine type (applicable to tactile IoT), (3) massive low latency machine type (applicable to large scale industrial IoT), (4) 6G-Lite (applicable to intelligent driving). | A major enhancement from 5G to 6G is the level of security in the system. However, many physical layer security and network security concerns are still applicable to 6G and will need to be addressed. Furthermore, as our computers’ cryptographic capabilities develop, security issues for quantum-based communication arise, prompting new adaptations of existing protocols. |
| Artificial Intelligence | AI attempts to learn from experience and mimic human intelligence, it can assist in many smart city operations by learning from a massive amount of data in a short period of time. With constant data feedback from the environment, AI models could perform online learning and generate real-time insights with minimum human interaction. Thus, AI is one of the enabling technologies for our smart IoT systems to achieve the desired cognitive capability. | The security problems of AI are mostly focused on data protection, privacy preservation, communication security, and model ethnicity. Since AI is often coupled with other smart city components, secure interaction with system components is essential for system security. |
| Blockchain | Blockchain is a distributed ledger technology that provides decentralization, data integrity and system transparency to our smart city applications. There has been a proliferation of blockchain-based proposals for implementation in various smart city domains, and some of which are listed in Table III. | Due to the unmodifiability and transparency in blockchain, the concern for unauthorized modification will no longer exist. Samples of blockchain-based security proposals for smart city applications can be found in Section III of this paper. However, the preservation of privacy is a common concern for blockchain-based applications. |

TABLE I: A relative comparison between average smart city applications in different domains.

TABLE II: A relative comparison between average smart city applications in different domains.

VANET is a network formed by a group of vehicles and roadside units connected by a wireless network, and IoV can be seen as a superset for VANET, which has a considerable improvement upon VANET. An overview of the difference between VANET and IoV can be found in [79], where the authors conclude that the impediment for the commercialization of VANET is its unreliability and limited scalability in providing seamless connectivity. Likewise, the authors in [80] share a similar view on the relationship between VANET and IoV.

To further understand the transformation of vehicle-to-everything (V2X) technology towards the IoV, a survey on the challenges and opportunities arising from the evolution of V2X technology to IoV is presented in [81], where the authors also proposed a Mobile Edge Computing (MEC) enhanced cloud-IoV architecture as a vision of future IoV technologies.
TABLE III: Examples of smart city development group according to domain (smart healthcare and smart utility).

| Domain            | Sub-domain | Major Issue                                                                 | Literature Review                                                                 |
|-------------------|------------|----------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Smart Healthcare  | TMIS       | Security, patient anonymity, lightweight                                    | Telecare Medical Information System (TMIS) utilizes on-body or in-home IoT sensors to monitor users’ physiological signals, it allows patients to obtain medical consultations over the Internet with medical experts. TMIS system requires extensive security and privacy protection for the flow of sensitive healthcare data under the resource constraints of the devices. [30] [31] |
|                   | WMSN       | Security, patient anonymity                                                 | The Wireless Medical Sensor Network is a network that monitors health signals using wireless sensors placed on the human body. Such systems should meet regulatory requirements and be secure against cyber-attacks. Security proposals for WMSN includes anonymous user authentication, key agreement, etc. [23] [24] |
|                   | Authentication | Confidentiality, integrity         | Implementation of hardware-based authentication for smart healthcare systems include the use of Physical Unclonable Functions (PUFs) and Trusted Platform Module (TPM). While software-based authentication often includes multi-factor authentication [27] [28] [29] [30] [31] [32] [33], mutual authentication for cloud-assisted medical information system [34]. |
|                   | Blockchain | Privacy, computation overhead                                             | Aside from the general issues that the use of blockchain would bring about, blockchain-based healthcare systems will require extra effort to comply with regulations on sensitive medical data. Comparative analysis of the state-of-art blockchain-based approach for smart healthcare systems can be found in [35]. While smart contracts for secure automated remote patient monitoring [50] and integrity protection for outsourced electronic healthcare records [57] are also studied. |
|                    | Smart Utility | Smart gas system monitoring, leakage detection                                      | Smart gas management systems are mainly designed for system monitoring (load monitoring) and detection (gas or fire detection) [38] [39]. Other proposals explore on the accuracy of gas sensor reading [40] [41]. |
|                   | Smart water | System monitoring, resource utilization                                        | Smart water system enable cities to better manage and administer their water systems [42]. Examples of smart water systems can be found in [43] [44] [45] [46] [47]. The main issue here is the lack of consistent methodology and a unified data interpretation for developing a comprehensive water management infrastructure that encompasses all parts of a city’s water network, resulting in partial solutions that address specific problems in a given context. |
|                   | Smart grid  | Security, efficiency                                                         | Smart grid is a transformation of the electric power grid to allow interactive real-time connectivity between users and devices, enabling two-way high-speed communication across applications for smart system monitoring and control [48] [49] [50]. A successful attack on the electrical grid has the strongest instant negative ramification among all attacks on public infrastructure, security concerns like secure authentication and key management [51] [52] [53] [54] have been heavily researched upon. While the concept of Energy Internet (EI) emerges as an integrated solution combining the grid and the internet [55]. |
|                   | Blockchain | Privacy, computation overhead                                             | Blockchain can provide advanced metering infrastructure, which enables paves towards energy trading, microgrid, etc. [50] [57]. Blockchain can be combined with ECC and PBFT consensus mechanism to provide privacy-preserving authentication for energy transactions. |

The study of IoV spam covers a wide range of topics, from resource optimization for communication [82] to efficient charging systems utilizing the smart grid, to autonomous driving routing optimization. Nonetheless, the demand for a safer road environment and transportation infrastructure continues to be the main motivator for smart transportation. As a result, smart transportation applications must meet strict reliability criteria.

Furthermore, due to the dynamic and open environment that these applications operate in, secure communication with sufficient privacy protection and user anonymity becomes an important requirement. Since a successful attack on a smart transportation application might have far-reaching and life-threatening repercussions, system security is just as important.

Security from a design perspective is presented in [83], which provides a basis for designers to evaluate the appropriate level of security to be implemented for different system components and achieve the security of smart vehicular networks.

Other areas of interest in smart transportation include issues such as smart charging for UAVs and electric vehicles, smart traffic control and monitoring systems, smart transportation infrastructure, and examples of them can be found in Table III and IV.

D. Smart Homes

A smart home, also known as an automated home, is a home that is filled with the physical embodiment of an integrated and automated context-aware support system that improves our quality of life [84]. The intelligence of our interactive home system arises from its ability to be context-aware. It gains its perception via sensor readings obtained from IoT devices, which quantifies the physical phenomenon emerging from human activities, to convey the context around the inhabitant [85].

From the contextual data, our smart home systems could deduce the current status and provide adaptive services as defined by the user or its default algorithm. For example, a smart temperature sensor can deduce the presence of human activity by comparing records in its database and the sudden increase in temperature. These data are highly sensitive due to their ability to reveal user behavior patterns, thus strong data protection is needed.

A sample multi-level IoT framework for smart homes is proposed in the survey [86]. The smart home typically consists of smart IoT devices equipped with a wireless communication interface, which forms a wireless sensor network. A central
The recent developments in smart homes consider issues such as device-to-device communication between smart home device [69], interoperability [87], user authentication [88] [89], and the integration of smart grid with smart homes [50] etc.

III. CRYPTOGRAPHIC SOLUTIONS FOR SMART CITY

Cryptographic solutions and AI/ML-based solutions are the two leading security solutions for smart city applications. This section will focus on cryptographic solutions for IoT-enabled smart city and reserve AI/ML-based security solutions as future work.

A. Remote User Authentication Solutions

Authentication has always been a critical component of secure communication in systems, as it tries to prevent unauthorized access and tampering with the system and its components. As deployments grow and smart devices become increasingly connected, remote authentication is becoming more critical in systems.

Another impending stone for the wide adoption of smart city facilities such as the smart grid is the need for a trusted anchor to register the smart meter and service provider over a secure channel. This raises the issue of secure data storage at the trusted anchor; additionally, since most of the authentication schemes require users to register their identity, whether through biometrics, passwords, or a combination of both. It is difficult to guarantee the communication channel used for registration is always secured.

There have been many surveys that aim to summarize the different authentication schemes. For example, in [27], the authors present an overview of the different biometric-based authentication methods for smart healthcare. While the authors in [54] conducted a literature review on the different methods and techniques for authentication in smart grid. This
subsection will introduce recent authentication methods and their applications in various smart city domains.

1) Biometric-based Authentication: Biometric-based authentication relies on the biometric information that the user has, which is unique to the user. Possible biometric candidate includes fingerprint, voice, retina, iris, and face authentication.

A survey on the security and privacy of biometric authentication is presented in [90]. According to this study, biometric authentication systems are most vulnerable to replay attacks, impersonation attacks, and communication channel and server attacks. While many biometric-based authentication techniques presume that the biometric identity is universally usable and secure by nature, it is risky to rely solely on these inherent human characteristics for security.

A survey on spoofing attacks on facial recognition can be found in [91], iris presentation attacks in [92], audio-visual presentation attack in [93]. Furthermore, because of the sensitive nature of biometric identification, it is critical to ensure that the biometric identity is non-invertible, revocable, and unlinkable. Researchers and security professionals also have to consider how to re-establishing users’ credentials when their biometric identity is stolen.

2) Cryptographic Protocol Implementations: Many existing authentication schemes utilize cryptographic mechanisms such as hash function, AES, RSA, ECC, Message authentication codes, digital signature to provide security services.

Xia et al. [51] has proposed a simple and highly efficient secure key management system, with computation costs of 5ms and 4ms for a single authentication instance at the smart electricity meter and utility service provider respectively. However, [52] point out that the scheme fails to provide security features such as strong credential privacy and security for the session key.

\[ y^2 = x^3 + x + 1 \mod q \]

![Fig. 2: An illustration of the ECC curve.](image)

In the current context, elliptic curve cryptographic (ECC) is much stronger than the conventional AES and RSA keys with the same key sizes. It is thus a more efficient candidate if we choose to employ cryptographic algorithms. As shown in Fig. 2 we choose a non-singular elliptic curve \( E_q(u, v) \) of the form \( y^2 = x^3 + u^2 + v \mod q \) over a prime (finite) field \( Z_q = 0, 1, \ldots, q - 1 \) with a base point \( P \). A 256-bit ECC key over this ECC curve is as strong as a 3072-bit RSA key. Hence, ECC can be a more suitable candidate to keep up with the growing cryptographic capabilities of the attacker.

For example, [53] presented the AAS-IoTSG, a novel authentication scheme for the smart grid using ECC-based Schnorr’s signature mechanism, although it also comes with a considerable computation overhead.

Similarly, the work in [61] mainly was concerned with electric charging between the ground stations and vehicles. The authors conducted a thorough analysis of the literature concentrating on the security and privacy issues of EV-related applications, hence, proposing a security mechanism to optimize EV charging station allocation in a safe and privacy-preserving way via lattice cryptography and authentication. In the proposed scheme, EVs broadcast their charging requests to aggregators near charging stations, which then communicate the request to an operator who assigns EVs to the charging stations. Finally, when an EV arrives at its designated charging station, it exchanges data with the charging station and stores it. Lattice signcryption, which performs digital signature and encryption concurrently to decrease time consumption and withstand quantum attacks, protects the data exchange.

This scheme requires the initial registration of EV and the aggregator devices with the operator, where the operator is responsible for securely distributing the key pairs corresponding to their ID. However, because the system must keep separate pairs of public and private keys for each aggregator and EVs, the system cannot accomplish end-to-end security without considering key management and safe storage of the credentials utilized. Furthermore, the user’s current trajectory, road conditions, and ride destination are not considered in the allocation, which might result in an assignment that is off the track for users, reducing the scheme’s usefulness.

3) Hardware-based Authentication Protocols: Due to deployment in open environments, attacks deriving from unauthorized physical access to system components, such as physical capturing attacks and node replacement attacks, are concerning problems in smart city scenarios. Thus, hardware-based authentication mechanisms are proposed to address such security risks by implementing physical security components on smart devices.

For example, the authors in [25] proposed a lightweight two-way two-stage authentication scheme utilizing the Physical Unclonable Functions (PUFs). The PUF is physical security primitive that produces unclonable and inherently unique measurements of physical objects, which arises from the slight variation in sub-microscopic structures during the manufacturing process of the hardware. The use of PUFs allows computationally expensive cryptographic operations in the PUF chips, saving precious resources on the smart device.

While both logical and physical security during data exchange has been enhanced via the adoption of PUFs, the scheme requires the challenge and response pairs of every PUF to be stored in the cloud database before the deployment of these devices and be retrieved for each round of authentication. This will limit the scalability of the scheme because when the number of smart devices in the network increases, there will be increasingly significant storage demand and time delay due to cloud access.
Similarly, xTSeH [25] aims to build a trust chain from the hardware level to establish a network of trust for smart healthcare IoT devices. The scheme extends the security functions of the Trusted Platform Module (TPM) to Smart Embedded Devices (SED, which also refers to smart healthcare IoT devices here) that were not equipped with TPM, using TPM-chipped SEDs as the root of trust.

In xTSeH, non-TPM-chipped SEDs own a shadow copy of the remote hardware TPM, which collects system configuration information to generate current system metrics. Application-level proxies were designed as a communication bridge between the root of trust and non-TPM-chipped SEDs that requires authentication, verification, or trusted booting services. This scheme protects system integrity and ensures the authenticity of smart devices. However, these security services impose a significant delay on system performance, especially the validation of the non-TPM-chipped SEDs. This is a challenging bottleneck because TPM chip process in serial.

4) Multi-factor Authentication: Multi-factor authentication is a popular approach towards user authentication in smart city systems due to their multilayer protection. In [28], Awasthi and Srivastava proposed a three-factor authentication scheme for Telecare Medical Information System to enable secure data transfer between smart healthcare IoT devices and remote servers, as well as to provide medical personnel authorized access to patient data. This authentication scheme involves the authentication of the biometric identity of the patient (fingerprint), ID and password, and public-private key pairs for encryption. This scheme is found to be vulnerable towards offline password guessing attacks, reflection attacks and fails to provide patient anonymity [29] [30].

To overcome the drawback in Awasthi and Srivastava’s approach, both [29] and [31] suggested their version of three-factor authentication protocols using the smart card. Later, these schemes were found to be susceptible to offline password guessing attacks and lack patient anonymity as well [30]. From that point, Mishra et al. [30] proposed another three-factor authentication protocol using personalized smart card, which [32] [33] conclude to fail in protecting against server impersonation attacks, stolen smart card attacks, and being irresistible to MITM attack and replay attacks.

The authors in [34] reviewed authentication protocols for the secure smart healthcare system adopting smart healthcare IoT devices. Furthermore, they proposed a mutual authentication scheme for the cloud-assisted medical information system, allowing the secure exchange of electronic medical records (EMR) and patient data without data duplication. However, they did not address the issue of secure communication during remote registration of medical devices and patients with the healthcare center, nor the secure storage of medical records in the system.

Similarly, a three-factor user authentication for the smart grid was proposed by [32]. The scheme utilizes the user’s mobile device, password, biometric identity for authentication. The scheme also employs cryptographic operations. Furthermore, the system employs random nonces and timestamps to thwart replay attacks, assuming the network entities will be synced with their clocks.

However, with the increasing complexity in the proposed secure authentication mechanism, the computation overhead in terms of time and memory increases dramatically. Furthermore, multi-factor authentication based on biometric identities presents the issue of how to replace a stolen biometric identity securely.

5) Privacy-preserving Authentication: Privacy protection is an important component in protecting sensitive user data. For example, to protect users’ behavioral data, it is undesirable to authenticate IoT communications directly based on vehicle identity because an attacker can infer the vehicle’s location by collecting broadcasted IoV messages. Thus, patient anonymity in smart healthcare systems and vehicular identity protection in smart transport systems have been gaining popularity.

Due to the extensive connectivity and rapidly changing topology caused by high mobility, privacy-preserving authentication in the IoV has become challenging. To protect user privacy, assigning pseudonyms to IoVs and frequently updating them to ensure anonymity is common to establish conditional anonymous authentication. Such a method necessitates frequent changes to pseudonyms and is vulnerable to Sybil attacks, in which a single vehicle can impersonate several vehicles using multiple pseudonyms.

As a result, to reduce the risk of Sybil attacks, it is necessary to determine whether several signatures on the same message belong to the same vehicle, which leads to the concept of message linkable group signatures. However, this scheme has a key security flaw: it assumes that the group manager can be trusted.

For strict adherence to the ‘zero trust principle’ where no party should be trusted, the author in [62] proposed a novel Message Linkable Group Signature scheme with Decentralization Tracing (MLGSDT) for conditional anonymous authentication with abuse-resistant tracing in IoV. By combining the MLGSDT scheme and the decentralized group model, the proposed mechanism could achieve a distributed trust for IoV in smart transportation.

B. Blockchain-based Solutions

Blockchain is a promising technology that provides data integrity and system transparency to our smart city applications. Blockchain transactions are ideal for data exchange and storage due to their high transparency, security, and immutability. Healthcare institutions, for example, are incentivized to keep patients’ medical histories securely and efficiently. The legitimacy and quality of medical data can be easily verified by storing pointers to medical records on the blockchain, eliminating the need for further data management.

Currently, blockchain systems can be broadly classified into three categories [94]:

1) Public Blockchain: Public blockchain systems are generally permissionless blockchain systems in which anybody can join, perform transactions, and participate in the consensus process at any time. Many cryptocurrencies, such as Bitcoin and Ethereum, are examples of permissionless blockchain systems. Public permissioned blockchain systems, on the other hand, allow anybody
to read the transaction records in the ledger but only authorized users to make transactions and participate in the consensus process.

2) **Consortium Blockchain/Federated Blockchain:** Consortium blockchain systems are commonly used for cross-organizational transactions in which authorized members from different organizations participate. It is more secure and efficient than public blockchain, and it allows for access control.

3) **Private Blockchain:** Private blockchain networks are run by a single authority and typically function on small scales. As a result, private blockchain systems are permissioned networks in which only authorized entities can join, read transactions, perform transactions, and participate in the consensus process.

Despite its apparent benefits, the adoption of blockchain in our smart city landscape requires careful examination of the contextual background. In the domain of smart healthcare, due to the strict security and privacy requirements for protecting medical data, a blockchain-based approach for smart healthcare will require much more effort to satisfy the requirements of data anonymity and system reliability.

Given our constant need for utilities such as electricity to perform our daily routine, the transformation of the grid must be performed at a large scale to offer quality services to the public. Likewise, in the utility sector, the present physical infrastructure may need to undergo a major transformation to be compatible with blockchain’s operation. However, the performance of this blockchain-based system cannot be guaranteed as the implementation scales up since the schemes are evaluated under lab conditions with a limited number of nodes simulated. In contrast, the number of nodes dependent on the grid reaches millions in smart cities. In addition, many systems that use proof of work mechanisms to establish trust in the system incur a considerable computing burden on the nodes. When the number of nodes in the network becomes large, it could form a bottleneck in the system’s performance.

Another major issue with blockchain is privacy concerns since all transactions are visible to all participants in the blockchain system. Moreover, these transaction records list the sender, receiver, and transaction details. Even though pseudonyms can be used to replace user identities, attackers might infer user information from the combination of pseudonymous and contextual information obtained. Nonetheless, there have been many proposals to enhance the anonymity of the transactions. Methods such as homomorphic commitments, blind signature, and zero-knowledge proof have been suggested.

Recently, many novel blockchain approaches for smart city solutions have shown to be promising. A comparative analysis of the state-of-art blockchain-based approach for smart healthcare IoT devices can be found in [35]. This paper highlights various challenges towards the adoption of blockchain for smart healthcare.

Similarly, a review of the different use cases for blockchain in smart grids can be found in [56]. Likewise, another survey covering a broad aspect of the smart grid domain with respect to the state-of-the-art blockchain technology can be found in [57]. The authors conducted a thorough investigation into the new possibilities that blockchain technology has opened up for the smart grid.

In addition, an overview of the application of blockchain towards smart home security can be found in [73]. The authors highlight that public blockchain architecture does not fit with smart homes’ privacy and efficiency requirements due to its public nature and large overhead. Instead, private and consortium blockchain can be considered for this application.

Likewise, in the domain of smart transportation, the authors in [95] present a contemporary survey on the latest advancement in blockchain for IoV, highlighting the key challenges for the application of blockchain in IoV.

1) **Smart Contract:** Smart contracts are digital contracts placed on a blockchain that automatically execute the agreed transactions when conditions are met. The transaction is transparent to both parties involved without the involvement of a third party, contributing to more efficient and trustworthy transactions. Thus, smart contract-based smart city applications are gaining popularity.

One of the common applications for smart contract is data access control, in which access control policies can be set and handled automatically using smart contracts. For example, patients can use blockchain and smart contracts to define access control policies for their medical information, allowing only authorized users to access them.

The authors in [36] proposed a blockchain-based healthcare system for secure automated remote patient monitoring using the smart contract installed on various smart devices. This scheme had difficulty in key management when the number of transactions to be validated increased. In addition, it has a problem maintaining the integrity of the consensus mechanism when the number of devices in the network is small.

Another essential feature of the smart contract is the ability to automatically enforce the pre-agreed-upon rules in the transaction. This is critical for performing secure and effective energy trading and payments. For example, the authors in [60] investigated the problem of UAVs and offered an advanced blockchain (IOTA) and smart contract-based security solution to improve those limitations in UAVs. This article proposes a blockchain-based solution for UAV-to-UAV communication. Each UAV node has a pseudo-anonymous virtual wallet that stores tokens for conducting transactions with peers or charging stations.

In this proposal, the UAV node interacts with its peers to acquire updates on the energy availability at charging stations. It then travels to the optimum charging point and performs a transaction in which tokens are exchanged for electricity. To guarantee message integrity and non-repudiation, all messages sent during the data exchange are encrypted and digitally signed. A UAV node must first approve two prior transactions by solving cryptographic challenges to enter a new transaction. Only if the new transaction has been approved will the smart contract automate the exchange indicated in the transaction. DDoS attacks are unlikely to succeed since all nodes in the network must authorize new transactions in the block, either directly or indirectly. There will be no single point of failure that corrupts the entire network since there is no central
2) Authentication And Integrity Protection: The adoption of blockchain-based technologies is another alternative for providing safe mutual authentication in smart city systems. For example, a blockchain-based approach is proposed in [37], which aims to protect outsourced electronic healthcare records from unauthorized modification using blockchain technology.

Likewise, in [71], Dorri et al. presented a blockchain-based solution for IoT security and privacy in smart homes. In this approach, the local blockchain will store the block header referencing its previous block, its policy header, and a list of formatted transactions, providing traceability to the system. A central miner will distribute keys to authorized devices who request the privilege to perform transactions, and the user defines the key distribution policies. Miners also provide shared keys for devices to facilitate device-to-device communication based on user-defined policies. To revoke the permission, the miner can mark the key as invalid and inform devices about it to deny the granted permission.

Similarly, in [72], HomeChain was proposed for efficient authentication of smart home gateways, providing traceability on user’s access and anonymous authentication of group members. HomeChain can effectively withstand adversary attacks like MITM attacks, user impersonation attacks, and so on, thanks to the decentralization, verifiability, and immutability of blockchain combined with group signature and message authentication code. However, this mechanism relies on the PBFT consensus mechanism to approve a new block. When the number of nodes is small, this mechanism is vulnerable to Sybil attacks in which one adversary controls multiple identities. In addition, PBFT faces the issue of scalability. The time it takes to approve a block increases exponentially as the number of nodes grows, resulting in substantial communication overhead. Nonetheless, this is a promising way in which to meet our secrecy requirements.

C. Functional Encryption

Public key encryption has always been the choice to secure our data and communications. To retrieve the original data from the encrypted text, one has to get the associated decryption key which can be used to reveal all the encrypted information. This method incurs major privacy concerns, particularly when working with sensitive data. For example, suppose a job applicant has many medical records associated with him/her, rather than revealing only the necessary conditions for medical examination at job centers. In that case, the entire medical history can be revealed when the corresponding secret key to his/her encrypted medical data file is handed over to potential employers.

Thus, functional encryption (FE) emerges as a privacy-preserving cryptographic technique for encryption. This concept is advocated by Boneh et al., where “a decryption key enables a user to learn a specific function of the encrypted data and nothing else” [96]. A practical FE implementation using Intel’s Software Guard Extensions (SGX) is presented in [97].

In FE, a trusted authority holds the exclusive master secret key that encrypts the data. When the authority is provided a function description, it utilizes its master secret key to construct a derived secret key associated with the function. The authority uses the public key and the encryption function to generate the ciphertext $c$ to encrypt the plaintext $x$.

$$c = E(pk, x)$$

When the authority is provided with the function $f$, it generates a secret key $sk[f]$ associated with $f$ and gives it to the requester. The requester can now retrieve the requested output $f(x)$ from function $f$ without accessing the original data $x$.

$$f(x) = D(c, sk[f])$$

While both homomorphic encryption and FE would allow Bob to learn such a specific function, FE has the advantage of providing the plaintext output $f(x)$. In contrast, homomorphic encryption would produce an encrypted form of $f(x)$.

For example, Alice holds the value of the variables “age” and “gender”, where age = 50, gender = female. Furthermore, Bob is an insurance agent who wants to access Alice’s data in order to determine whether Alice falls into the category of “male over 30 years old.” Alice can compute a function $Sk[f]$ and pass to Bob, which will return the plaintext output $f(x)$, indicating that Alice does not fall under that category. Instead, Bob will receive an encrypted version of the text indicating that Alice does not fall into that group if homomorphic encryption is used.

Since FE is a new idea, its current application mainly focuses on privacy-preserving utility billing and trading for smart grids. The peer-to-peer (P2P) energy trading is an important component of smart grid technology, and it is frequently paired with blockchain technology to achieve decentralization and automation. However, while blockchain is better suited to providing matching and contracting services to perform logical transactions, physical transactions will have to rely on the existing utility lines [98]. In this way, the utility company/regulatory agency would serve as the middleman, acting as a distribution system operator (DSO) and a utility provider. Thus, smart grid implementations need to preserve user privacy and system security while providing an effective billing and accounting mechanism.

For example, the author [98] proposed a P2P energy trading system based on the private Ethereum blockchain, where all bids are encrypted. In this scheme, the functional encryption (FE)-based smart contract takes in the encrypted bids from users for peer matching. Thus, although transactions between peers are publicly verifiable through the smart contract, the encrypted information remains protected. This helps the users remain anonymous to each other, while the utility company can identify both parties of the transaction for accounting and billing purposes.

IV. SECURITY CHALLENGES FOR SMART CITY
APPLICATION

The interconnectedness between smart devices has a significant impact on how we live in cities, enabling a smarter,
cheaper, and more convenient alternative lifestyle. These IoT-enabled smart devices could perform tasks ranging from simple lighting control to complex traffic management in metropolitan cities.

Due to the vast capabilities of these smart systems and the magnitude of their impact on our lives, they require an unprecedented level of trust from their users. This trust stems from the technology’s reliability and security and the system’s commitment to protecting users’ private assets, such as private data and accounts. McKnight et al. mentioned in one of their studies that “one is more likely to explore and use more features of a technology if one trusts it” [89].

While numerous proposals for secure smart city applications have been made, most schemes that use contemporary innovations, such as blockchain, cloud, and edge servers, need to focus more on one or more security requirements. Furthermore, with growing connectivity between heterogeneous devices and systems in smart city applications, developers have to address a new set of security challenges in addition to the traditional security challenges.

In order to better illustrate the relationship between IoT systems and these security challenges, we adopt the ANT architecture from [11]. This security reference architecture is based on IoT systems’ device, internet, and semantic perspectives.

In this view, the activity-centric perspective facilitates understanding of system components’ context and identifies security challenges relating to the sensitive operations performed in the system. In comparison, the network-centric perspective focused on security challenges for communication between network components and the flow of sensitive data. The things-centric perspective aids in understanding the relationship between the security challenges of heterogeneous data acquisition via heterogeneous IoT devices.

This section will focus on a subset of IoT security challenges, diving deeper into specific IoT security challenges relating to the smart city application, which requires a specific set of security requirements to address their differences from the traditional scenarios (this is presented in the next section).

A. Activity-Centric Security Challenges

The activity-centric perspective facilitates understanding of the context of system components and identifies security challenges relating to the sensitive operations performed in the system. We have identified a few security challenges related to the usage of edge/cloud systems and challenges originating from big data and the use of big data in our operations, which are more relevant to IoT systems in smart cities in this subsection.

1) Assumption Of Trusted Cloud/Edge: The adoption of cloud infrastructure to improve the efficiency and performance of our systems is a key feature of the 5G network. In many smart city applications, the edge cloud is essential for bridging the central cloud and the local user to facilitate efficient data exchanges. Similarly, the adoption of edge servers for storage or computation offloading has become popular due to its relatively low latency and high computation capabilities.

However, a significant challenge for such applications is the assumption that the cloud/edge can always be trusted. Coppolino et al. [100] have identified the main security challenges in the cloud, including shared technologies vulnerability, data breach, account or service traffic hijacking, DDoS, and malicious insiders. To guard against data theft, system designers have to consider the major players, such as external attackers, malicious internal users, and even hostile employees from cloud providers. Furthermore, solutions employing hybrid cloud and edge cloud also have to consider intercloud interactions’ security to ensure consistent data protection throughout the backend process.

2) Accommodating Enormous Data Volume And Dynamic Traffic: With the deployment of smart IoT sensors in cities, large amounts of data are continuously generated, and this data forms the backbone of urban intelligence. This data load poses a significant challenge to the current technological infrastructure in processing, storing, and providing real-time insights. As a result, resource allocation and system performance optimization are critical for systems to meet their expectations in the face of large data volume.

In this context, any system attempting to address smart city issues needs to be prepared to handle a non-periodic, sudden burst of data gracefully. Depending on the application, this could entail efforts to maintain timely service delivery in a time-sensitive application or handle an unanticipated burst in data volume without compromising service quality.

Similarly, the security mechanism must accommodate an instantaneous surge in traffic without compromising security or performance, guaranteeing that the quality of security services promised to the user is delivered.

3) New Types Of Interactions: Different smart city systems could potentially interact due to the growing connectivity between them, leading to the frequent occurrence of cross-system or cross-platform interactions. Thus, a proliferation of new interaction types and styles can be expected. We will need to specify rules for handling such non-traditional interactions and incorporate resilience into our systems to protect against them. In addition, system designers have to consider the system’s openness and account for the security risk for possible interactions with external platforms or users.

Consider the case of D2D communication resource allocation in IoT applications, where there is a high density of smart devices per unit area that constantly demands communication resources. According to Hussain et al., [101], this leads to congestion, network overload, and degradation of the Signal Noise Ratio in the communication channel. While the traditional centralized approach deals with large but infrequent data transmission from traditional communication devices, IoT devices require a new approach for small and frequent data exchanges.

Additionally, while frequent packet transmission might be a sign of flooding in many traditional systems, many IoT device interactions are characterized by small and frequent data transmission; therefore, accessing such metrics the same way as conventional systems would be inappropriate.

Similarly, the temporal, once-only interaction with unknown smart devices can disturb system security in smart city sce-
narios. In the case of IoV, a user might travel to a neighboring country and share data with other IoV or smart transportation infrastructures there. The two transportation systems may not use a single platform and protocol due to different government regulations. However, to fully utilize the capabilities of IoV, the car must interface with other devices to gather traffic intelligence. While most of these interactions will be once-off, it is necessary to provide security protection to ensure the security of the device itself, i.e., not to be hijacked by others or attacked.

4) Lack Of Unified Representation: A unified representation of heterogeneous data types can support effective insight generation across devices and systems. It also allows systems to access the context and the security risk of the data exchange. Thereby, a more appropriate security setting can be established, avoiding unwanted interactions with sensitive data and preventing data loss.

The problem of defining a unified representation of heterogeneous data sources for cooperative tasks has been intensified by the introduction of big data. Prior to the emergence of big data, researchers have been focusing on knowledge discovery for structured data, attempting to unify representation among structured databases.

For instance, the authors in [102] have studied the problem of data integration for the structured data source. The types of semantic heterogeneity for structure data studied in the paper include name and structural heterogeneity, which can be further subdivided into type conflict, key conflicts, and domain conflicts.

Besides the heterogeneity mentioned above in structured data, the author in [103] has studied the heterogeneity in big data, which is likely to be a major characteristic for smart city applications. The heterogeneity in big data includes syntactic heterogeneity, conceptual heterogeneity, terminological heterogeneity, and pragmatic heterogeneity.

Although advanced processing and analysis techniques can achieve data integration between structured and machine data to a reasonable extent, providing a high-level data fusion between unstructured analog sensor data will remain a challenging task. However, due to the complexity of such tasks, it is tough to achieve a context-independent approach to present a unified representation of the heterogeneous data. As a result, appropriately handling heterogeneous data types may be a significant security challenge for smart city system designers.

5) Data Sensitivity: Different data types have different sensitivity levels, and even the input data in an application can have different levels of sensitivity. Pulse data, mobility tracker data, and a live video of the patient may all be fed into an in-home health monitoring system simultaneously. From a privacy-preserving perspective, the patient’s live video data deserves the most stringent security mechanism it could provide. From a healthcare product perspective, pulse data should remain top-secret to meet customers’ expectations on the security of their health data.

After defining the sensitivity of input data, how different data types should be protected comes the question. While we are familiar with how structured data could be stored and protected, the balance between protection for unstructured data and the ease in extracting knowledge from it for integrated information queries remains difficult. Thus, designing system security architecture with data of different sensitivity will be a challenging task.

B. Network-Centric Security Challenges

Secure communication is the foundation of a secure system. It safeguards the confidentiality, integrity, and availability of information exchanged in the network. Common attacks on communications channels include blackhole, wormhole, and pharming attacks that disrupt the delivery of data; Jamming channel, DDoS, and Syn Flooding attacks that disable the availability of services; eavesdropping and Traffic Analysis that leaks confidential data to unauthorized third parties. Thus, prevention and detection of attacks on communication channels are critical for all systems relying on wireless networks to perform data transmission to provide reliable and timely service delivery.

In addition, the survey in [104] has presented a few communication security challenges prevalent in IoT systems that deserve more attention:

- **Trust management:** Due to resource constraints in IoT devices, the size of cryptographic keys and certificates for trust management must be kept short, and the performance overhead for secure storage or code attestation must be within reasonable parameters to extend the battery life of devices that are not powered directly.
- **Heterogeneous network integration:** There are many wired/wireless communication systems, each with its security protocols, that can be involved in the communication with a single IoT system. Incompatibility and loopholes in integrating different networks can increase security risks in the overall system.
- **Secure routing protocol:** While the standardization of network protocols is extremely challenging due to different performance requirements between different system components, secure and efficient routing is vital to the overall security of the system. System designers should carefully evaluate the routing protocols to balance the trade-off between performance and security, depending on the nature of the application. If more than one routing protocol is adopted throughout the system, the compatibility between protocols should also be investigated.

1) Communication Protocols: A set of devices communicating with neighbors within its radio range can form a network, which can be arranged in different topologies. Simple network topology can achieve low latency in relaying messages, while complex network topology can offer better routing decisions and flexibility [104].

There are four main network topologies that are commonly implemented and they are illustrated in Fig. 3

1) **Star Topology:** In the star topology, all nodes are in the radio range of the central node and communicate directly with the central node. All network traffic in this network will pass through the central node. This is the most simple topology and works best for typical master-and-slave relationships between devices.
between heterogeneous devices. This becomes a major challenge in providing secure communication in the same system. Hence, interoperability between devices of different types and brands being deployed is a challenging task.

While there is no standardization for the protocols, data formats, and systems adopted by vendors, it is common to see smart devices of different types and brands being deployed in the same system. Hence, interoperability between devices becomes a major challenge in providing secure communication between heterogeneous devices.

2) **Security Protocols**: Various standard security protocols and solutions have been developed to ensure communication security, such as DTLS, CETIC-6LBR(6LoWPAN border router), IPsec, IKEv2, and Host Identity Protocol (HIP).

The authors in [104] present a summary of wireless communication principles about the connectivity requirements of IoT. Communication standards and the gap between their security features and actual IoT system vulnerabilities are also highlighted in the survey.

For example, traditional security protocols are built on OSI stacks, which may or may not be fully implemented in many IoT systems. Traditional security mechanisms are often employed in the Medium Access Control (MAC) or higher layers, assuming that the underlying physical link and data link layers will provide a reliable system link. However, the physical layer security follows the information-theoretic principle. The strength of the security mechanism depends on the assumption of varied channel conditions between the user and attacker. As a result, security guarantees are rarely 100 percent.

Furthermore, the system architecture of many IoT systems differs significantly from the traditional system architecture, where they introduce their layers, such as perception and actuation layers. These new layers often require new adaptations of current security protocols to ensure system security. Hence, it is wise to investigate the security requirements for every layer of the system and their context to evaluate the choice of security protocols used for system security.

3) **Distributed Communication**: The majority of current IoT communication solutions use a centralized approach, in which a central authority or server manages data sharing between devices. As the number of devices in the network grows, communication to and from the center server will quickly become a bottleneck, resulting in substantial network latency.

While others argue that edge servers should be used to offload centralized computing activities, a decentralization approach can best deal with the issue of scalability. One of the ways to establish a decentralized IoT network is via P2P networking technologies. Like any other widely adopted technology, when P2P technology is commonly deployed, we expect many adversarial attacks.

In [107], the authors highlight that besides adversarial attacks, there are other challenges in the architecture of a P2P network. One such issue is the selfish behavior of users. While many P2P applications are designed to serve a large number of users over a network, a “hotspot” issue may nevertheless arise, in which some nodes with popular content must service more peers than others. Some selfish users might want to reserve more resources for themselves, such as disk space, bandwidth, and power, by altering their system configurations to act in their interest. Although these users are not explicit attackers, their action degrades the overall system performance if no checks and balance are in place.

Another significant challenge in a peer-to-peer network is the concept of trust. Since there is no root of trust, the system must devise a way to assess the trustworthiness of external data transfers and respond appropriately to defend itself. Thus, providing a secure approach for distribution communication is a challenging task.

C. Things-Centric Security Challenges

Due to the growing connectivity between systems and applications’ dependence on big data, many smart city applications will be directly or indirectly dependent on a large scale of IoT devices for data collection. Unfortunately, while these
| Protocol | Security Features                                                                 | Security Challenges                                                                                                                                 |
|----------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Zigbee   | Zigbee Trust Center is responsible for key management and distribution in the network, and it provides cryptographic key establishment and frame protection. (AES 128-bit) | Zigbee is susceptible to jamming, traffic analysis attacks. Since different application layers on the same device trust each other, if one layer is compromised, it can jeopardize the security of the other layers. In addition, network keys can be extracted from the hardware, resulting in concerns for the physical capturing attack [105]. |
| Z-wave   | Z-wave network contains master and slave nodes. It provides authentication service, packet encryption, and integrity protection. (AES 128-bit, Message Authentication Code in Cipher Block Chaining mode) | Z-wave is susceptible to traffic analysis, spoofing, MITM attacks. Z-wave devices trust all MAC Protocol Data Unit, making them vulnerable to impersonation attacks [105]. |
| Bluetooth Low Energy (BLE) | BLE provides encryption, authentication, message integrity checks, and 12-byte signature to prevent relay attacks in mode 2. In addition, BLE changes the address of devices frequently to reduce the ability for attackers to track. (AES 128-bit, ECC) | BLE uses elliptic curve cryptography, which is not supported in legacy mode pairing. Thus, devices in legacy mode pairing are susceptible to MIMT and eavesdropping attacks [105]. |
| IEEE 802.15.4 | The security of IEEE 802.15.4 is implemented at the MAC layer. Security features such as encryption and authentication, access control, confidentiality protection are provided. (AES) | IEEE 802.15.4 is susceptible to active tampering, jamming, eavesdropping attacks. Many attacks aim at different layers of the protocol [106]. |
| 6LoWPAN | 6LoWPAN can operate over other platforms such as Ethernet, Wi-Fi, IEEE 802.15.4, and it has no security features. | 6LoWPAN does not provide any security feature and relies on other protocols or applications to complement its security requirement [106]. |
| Routing RPL | RPL provides message confidentiality and integrity. (AES, CCM, consistency check using challenge-response) | RPL is susceptible to internal attacks [106]. |
| CoAP    | CoAP requires other protocols to provide it with security features. E.g. CoAP can rely on Datagram Transport Layer Security (DTLS) for encryption. | Although DTLS is often implemented to provide security features for CoAP, DTLS is not fully compatible with CoAP (i.e., it does not suit CoAP proxy modes) [106]. |

TABLE V: Summary of the security features and the corresponding security challenges of popular communication protocols for smart city applications.

IoT devices are important data sources that support system operations, many of them have limited resources and capacity to implement comprehensive security measures, leaving them vulnerable to attack. More malicious attempts by attackers probing for the weakest link in the system are likely to occur due to the large-scale physical deployment, which increases the attack surface for attackers to interfere with system operations.

At the same time, due to the massive deployment scale, a successful intrusion into these end devices might cause a tidal effect, compromising the security of the system and even paralyzing it. Consequently, the effect of intrusion will be very significant and impacts many devices.

At the same time, dealing with the aftermath of an attack can be equally concerning. Traditionally, technicians could upgrade the sensor network on-site, either to install patches for updates or to address a loophole in these devices. Such a management approach is no longer feasible, especially for mass upgrades, due to a large number of devices deployed. Furthermore, many of these devices may be physically inaccessible to technicians or almost impossible to access. Hence, we shall direct our interest towards remote updating mechanisms, performing updates, and integrity attestation over the air. However, due to the wireless nature of such mechanisms, security concerns have become growingly prominent.

Smart city systems that have a large-scale physical deployment of devices in open environments will therefore contribute to a proliferation of security challenges, such as ensuring secure mass updates and performing large-scale system recovery.

V. SECURITY REQUIREMENTS FOR SMART CITY APPLICATION

With the growing connectivity among devices, security requirements for the future smart systems should also encompass protection for operational technologies such as industrial control systems and cyber-physical systems [4], which are traditionally assumed to be always secure in many security frameworks. Other emerging security concerns such as heterogeneous network integration and physical interface security further complicate smart city applications’ security requirements.

Many researchers have reviewed the security requirements for generic IoT applications, for example, in surveys such as [8], [9]. The security requirements that these surveys have considered range from basic security requirements for any data exchange, CIA (confidentiality, integrity, availability), to more IoT-specific challenges such as lightweight and interoperability of applications.

In this section, we would like to propose a set of specialized IoT security requirements that are more relevant towards future smart city IoT scenarios illustrated using the ANT architecture [11]. The security requirements that will be explored in this section are:

- **Activity-centric security requirements**: Security at the edge, secure storage, maintenance of Quality Of Security Service, secure integration.
- **Network-centric security requirements**: Authentication, identity management and access control, secure communication environment.
- **Things-centric security requirements**: Secure update, system resilience to attacks.

A. Activity-Centric Security Requirements: End-To-End Secure Data Flow And Storage

To provide comprehensive security protection towards a smart IoT system, we need to consider all security issues
related to different stages of the data life cycle. An end-to-end secure data life cycle should maintain an expected level of security from the generation of data to its collection, transmission, processing, and aggregation, until the final stage of storing and maintaining. In this section, we describe a specialized set of security requirements that focus on the applications’ operations, considering the flow of sensitive information throughout the system.

1) Security At The Edge: Edge computing provides computation and storage offloading for many smart city applications. It uses edge devices to operate as microservers, collecting data from end nodes, aggregating and filtering it, providing real-time feedback and completing any user requests it can, and only sending intensive processing and permanent storage to the central server.

Nevertheless, the adoption of edge computing raises many security challenges. Surveys studying security challenges for edge computing can be found in [16] [17] [15] [18]. While the authors in [18] build a security classification of multi-access edge computing, categorizing edge computing specific threat vectors according to conventional security challenges for easy comparison.

In [15], the authors believe that the introduction of edge computing has increased the attack surface due to:

- weaker computation power of the edge devices, which are more vulnerable to existing attacks which are ineffective on most advanced systems now, such as small scale DDoS;
- attack unawareness of the users, since users are generally unaware of the system states of sensors and panels if no user interface is provided;
- OS and protocol heterogeneity, since there is little standardization across different edge devices;
- coarse-grained access control, besides conventionally access permissions such as read and write, edge devices provide more capabilities that need to be regulated.

Furthermore, we have yet to establish a boundary for its responsibility. For example, in cases where devices are incapable of applying any security measures, we need to decide if the edge server should be responsible for encrypting the data. If the data is worth protecting, another challenge is how we, or the edge server, determine the security level that should be applied to it or treat all data equally. From the standpoint of data gathering, we must decide whether the edge server should listen to any device or only a restricted group of devices in the physical environment. As a result, maintaining security at the edge is a major requirement for systems with distributed edge devices that are not centrally protected. This is especially true in the case of edge computing, where edge devices can potentially disrupt the entire system’s operation.

Different combinations of technologies can be used to satisfy this requirement. System designers have to consider the different interactions with edge devices and employ appropriate security mechanisms. For example, multifactor authentication can prevent unauthorized access to edge devices. The complex cryptographic algorithm can secure communication between the cloud and the edge servers.

2) Secure Storage: The final stage of the data life cycle in a system will be its storage and management. Due to the increasing connectedness between data generated and the user in smart cities, the amount of sensitive data that requires sophisticated protection increases.

A vulnerability in one of the communication channels can expose a confined set of data exchanges to the attacker. When discovered early, its damage can be constrained within a relatively small range. On the other hand, a database vulnerability puts all information stored in the entire system at risk. As a result, in addition to improving data transmission security, ensuring data security at rest is also crucial.

While many of the recent developments utilizing emerging technologies can resolve challenging tasks in smart cities efficiently, the problem of secure storage needs to be more focused on. This paper classifies secure storage mechanisms into two types: (1) secure distributed storage (2) secure cloud storage.

Distributed storage refers to the use of storage space on distributed user nodes to provide storage services, avoiding a single point of failure. Kher and Kim [108] proposed a set of security services that a secure storage system should support. It includes authentication and authorization, to validate the identity of the party accessing the database; availability, to ensure that the data is readily accessible for authorized parties, where the system would have to perform backup and recovery services; confidentiality and integrity, so that users can trust the system in keeping their data; key sharing and key management, to facilitate efficient sharing and retrieving of data; auditing and intrusion detection, to monitor and detect unauthorized access; usability, manageability, and performance, to provide smooth data storage services to enhance user experience.

There has been an exploration on different technologies in achieving secure distributed storage, such as the combination of SHA-3 and Reed-Solomon (RS) erasure code [109], secure erasure codes [110], Redundant Residue Number System (RRNS) [111], blockchain [112].

Cloud has been a popular solution for hosting smart city applications due to its great scalability, stability, and efficiency in handling enormous data flows. The authors in [113] [114] have surveyed the security issues for cloud storage. Issues such as data confidentiality, atomicity, data access and data breaches have been presented in these surveys, coupled with different security mechanisms to resolve those issues, such as identity-based encryption, attribute-based encryption, homomorphic encryption and searchable encryption. Nonetheless, system designers will need to determine the optimal trade-off between computational complexity and storage and access security, ensuring that data of varying sensitivity is adequately protected.

3) Maintenance Of Quality Of Security Service: Similar to Quality of service (QoS), Quality of security service (QoSS) is the concept that quantifies the level of security in a system, where a variable level of security services and requirements exist. QoSS can enhance system performance and achieve higher user satisfaction to provide users or network tasks with a range of appropriate security choices [115].

Such as...
The level of security in a system would then refer to the degree of security factors considered. This is a critical metric for ensuring the safe deployment of large-scale IoT applications in smart cities. While users are becoming more aware of the importance of their privacy and data, common users cannot judge the level of security in an IoT system due to a lack of measurable security metrics. Even when a manufacturer gives assurances about the level of security that users can anticipate from their system, there is no way for users to verify that these promises are kept. As a result, there is minimal transparency for consumer checks and balances, making it difficult to build trust with the users in such situations.

The development of QoSS parameters not only can build trust between users and manufacturers, but it could also gain user involvement in monitoring the system status to provide more responsive feedback on possible attacks. Furthermore, it also allows users to regulate the trade-off between QoSS and other parameters like resource utilization and latency. The user could lower QoSS slightly for basic applications such as temperature monitoring in their garden in exchange for a longer battery life of their outside sensors. From the manufacturer’s perspective, the system only has to fulfill the user’s balanced security and performance expectations, thus achieving better resource utilization.

As a starting point, the authors in [116] have provided a quantitative Expert Opinion Survey (EOS) on the choice of quality criteria for the security metric, evaluating possible factors to consider for QoSS. Factors such as accuracy, time dependability of the system, are possible candidates for the security metric.

On the other hand, the method used in [83] can be adopted for a data-centric approach for the development of QoSS. In this paper, the appropriate level of security that the data deserves is determined by the path that the data has traversed in the system. In order to determine the final security level of the data, one has to refer to the security level given to all the physical components that it has visited, the various source data used in formulating it, the context where the source data is generated. By considering the sensitivity of all nodes and operations related to the data, we could determine the importance of the data and thus define a suitable level of security to enforce in our system to protect it. This approach can be used as a starting gear for system designers to evaluate the level of security their systems need.

In summary, maintaining QoSS through systems can help develop confidence between parties while also allowing for a thorough security evaluation for system designers to identify security risks early. Thus, this is an essential requirement that could benefit all parties.

4) Secure Integration: Integration for data collected from various sensors, applications, and processes is challenging. It is difficult to group multiple technologies into one for smooth data collection. The context and environment from which the data value is collected vary significantly. This contributes to barriers in providing consistent data interpretation, and additional contextual data need to be present to generate useful insights.

More importantly, we must consider the potential security risks associated with such integration. Since mandating a uniform set of protocols to be implemented by different manufacturers is currently challenging, the systems will try to connect resource-constrained devices securely using the methods that those devices support [117]. Some devices can support a basic mechanism, while others do not attempt to protect user information. Thus, these devices became the weakest link in the system, where attackers could easily breach in, and attacks can rapidly escalate to the rest of the system. Hence, efforts for secure integration would be necessary to enhance system security.

There are different ways in which this requirement can be satisfied. For example, the authors in [117] have provided a discussion on the recent effort towards secure integration. Similarly, a narrower integration perspective between IoT and cloud computing [118], blockchain [119] has also been studied. Likewise, an effort towards providing a generic IoT protocol to address the issue of communication protocol fragmentation, arising due to the inability of the current protocol to meet a wide range of QoS, is made in [120].

B. Network-Centric Security Requirements: Secure Communication

In this section, we describe a specialized set of security requirements that focus on securing the connectivity in the system.

1) Authentication: Authentication is the first line of defense for a secure communication channel. It verifies that the parties engaged in the information exchange are who they say they are. When combined with an authorization mechanism, the authentication protocol could ensure that only privileged users/devices with access are permitted to participate in the communication. Traditional authentication techniques are ineffective in IoT devices due to resource constraints.

Various IoT authentication schemes have been proposed to fulfill this requirement, each with its pros and cons. Nandy et al. [121] presented a summary of the recent authentication mechanisms in IoT.

Firstly, password-based authentication is the most basic form of authentication, where user registers their unique ID and password combination in a database or memory. After successful registration, when the user requests privileged actions, the protocol matches the supplied credential with the stored credential to validate user identity and access rights. However, applying password-based authentication to all smart devices for security protection is challenging. Furthermore, it places a burden on users to securely initiate and manage their passwords, particularly in a smart city scenario where there are many devices to handle.

Token-based authentication necessitates the usage of an authentication server, which is responsible for verifying the token information held by the user against its pre-registered information in its database. In a soft token-based authentication scenario, the server produces a one-time password (OTP) for the user’s request and sends it to the user and the device for authentication. At the same time, hard token-based authentication requires a physical device containing the
token, such as a smart card or RFID chip. Since physical hardware tokens are susceptible to physical capture attacks where adversaries gain physical access to these tokens, they are often combined with other authentication methods to provide enhanced security.

Examples of authentication mechanisms using biometric information, cryptographic algorithms, hardware-based authentication protocols, multi-factor schemes, and privacy-preserving authentication proposals for smart city applications can be found in Section II of this paper.

Due to the massive scale of IoT deployment and the heterogeneity of the devices involved, there can be different methods for various interactions and authentication with other smart devices. To communicate securely with various types of other devices, these multi-functional devices will need to support a variety of authentication mechanisms. When two such devices communicate, we must choose the most appropriate method when both parties in the information exchange have multiple authentication possibilities.

For example, for IoT devices driving in cities, how to authenticate unknown cars or roadside units in a foreign location encountered for the first time or a car which the current vehicle intelligence has no information about. Perhaps, the local government could set up a central transport intelligence authority to issue a standardized abstraction module to all foreign cars driving locally. This can ease the incompatibility between nations’ standards, protocols, and regulations.

Another approach would be to have a backup central authentication server. Both parties who wish to communicate securely have to prove something they observe concurrently to prove co-existence and be allowed to perform authentication via the central server instead. Given the many different combinations of secure authentication strategies, we have to evaluate the appropriateness of the method chosen and carefully weigh the trade-off in our application context.

**Identity Management And Access Control:** Identity management and access control refer to the technology that makes a set of rules to define who meets the requirements for accessing, using, or modifying certain resources or data in specific devices of a system. Identity management and access control can also be called identity and access management (IAM). IAM ensures the security and productivity of the system by allocating the right resources to the right objects.

It is a key technology to protect information security and avoid unauthorized data access by authorizing and revoking authorization based on delegation policies [122]. Unlike traditional Internet systems, identity management and access control in the IoT focus more on the digital management of devices that hardly require direct manual operation. Besides, IAM in the IoT system also involves the management and authentication of users and services. There are several challenges for IAM in IoT systems, including but not limited to credential abuse, default password risk, virtual eavesdropping, and some extreme environments on-site access control management.

- Credentials refer to the evidence of certification, status, and personality that the specified devices or users have the legal right to access or use corresponding resources or data in a system [123]. With the development of the IoT, the number of devices in IoT systems continues to increase. The credentials of these devices are at risk of being stolen by attackers. If there is no reliable identity and access management tool to verify the data users and change the user security verification policies regularly, the attacked users’ credentials will be abused. Some private information will be accessed or leaked by illegal users or devices. Credentials access management mechanisms like Lightweight Directory Access Protocol (LDAP), and Microsoft Active Directory (AD) technologies are popular techniques in the cloud-based environment [123]. Some systems use Secure Shell (SSH) keys to realize identity authentication by a special network protocol called public-key cryptography, except for DAP and AD. SSH keys can avoid brute force password attacks and execute commands remotely.
- Another challenge for identity and access management is that most IoT devices work with the default passwords or easily guessed passwords. These passwords are likely to be cracked by brute force, phishing, or spoofing attacks. Hence, an easy-to-operate and high-safety password generation mechanism should be devised for IoT devices and users, especially those who own privileged access rights.
- Virtual eavesdropping is intercepting or interfering with communication information through unauthorized methods on the network. Due to the outbreak of the covid-19, working from home and remote online meetings have become very important work and learning modes. Online calls and meetings relevant to individuals or enterprises’ privacy and paid training courses face the threat of eavesdropping. In addition, the number of devices with camera and phone functions in smart homes and smart medical care is also increasing. It becomes an emerging challenge to prevent virtual eavesdropping in IoT systems. Updating the access code regularly is one of the mitigation methods for eavesdropping attacks. Stronger encryption credentials can be used for important and private online communications. Advanced identification techniques like biometric authentication and 3D password objects can be utilized for the smart devices in smart city applications to reduce unauthorized access.
- For some special IoT devices and applications in extreme environments, such as deserts and volcanic craters, it is also challenging to realize effective identity management and access control. How can we safely provide on-site access control for the relevant devices if there is no internet?

To effectively cope with the increasing number of devices in the Internet of Things system and better adapt to the real-time communication functions in some smart city applications, the new IAM should consider more time-saving protocols and automatic authentication methods. To make the activities traceable, achieving system devices easily auditing and risk
assessment, the IAM can produce periodic reports or logs after most access actions have been taken. Nevertheless, how to best implement identity management and access control for a large number of resource-constrained sensors while still accommodating devices with higher capabilities, will be a key research area in the future for smart city development.

3) Secure Communication Environment: While secure communication between system components is critical, an end-to-end secure communication environment is also an essential requirement that we should consider. Since the security of a system is determined by how well the weakest link is protected, any parts of the system that are insecure can be the easiest target for attackers. For instance, suppose we construct a complicated cryptographic technique to protect communication between the edge server and the cloud, with the edge translating messages to the user’s end device. Suppose we did not establish a safe communication environment between the edge and the end device. In that case, an attacker could instead attack this connection and capture all important system data passed.

There have been many proposals that could provide valuable insights towards fulfilling this requirement. For example, in [124], [125], the authors aim to provide end-to-end security by enforcing the adoption of security protocols throughout the system. The work in [124] is a secure architecture built upon the DTLS protocol, called SEA. All parties communicating in the system mutually authenticate each other and establish secure sessions via a shared common key. Assuming that smart gateways have sufficient resources to perform security operations, smart gateways ease the computation burden on behalf of medical sensors by performing authentication and authorization of remote end-users. Furthermore, the architecture utilizes the DTLS session resumption without the serverside state to reduce the memory load for medical sensors to store session details by offloading the encrypted session states of sensors towards non-resource constrained user devices.

However, this application is designed for a smart healthcare IoT scenario and has a specific security context requirement - the application is implemented in smart homes/hospitals where authorized personnel cannot enter the physical premises, eliminating the need for authentication and authorization for remote healthcare centers or caregivers to those sensors. Thus, this design lacks genericity to be applied to another context.

Similarly, the work in [125] attempts to adapt the 6LoWPAN protocol to integrate lightweight end-to-end security to provide a secure communication environment, which they call 6LowPSec.

Although a universal security protocol could improve system security by providing consistency, such protocols will need to specify further their context and the minimum requirement on the hardware and software capabilities for their implementation to improve their feasibility. Alternatively, we could have a centralized agency that defines a set of security protocols for different types of devices or data. Thus, any device wanting to communicate with each other must support the common set of security protocols and pass specific security checks before proceeding with the communication.

C. Things-Centric Security Requirements: Secure System And Things

Due to the massive and distributed deployment of IoT devices in the open environment, issues such as secure updates and system resilience on attacks become particularly important to avoid the tidal effect of cyber attacks on these systems. This section describes a specialized set of security requirements that are highly relevant and specific to IoT devices, relating to the capabilities and data that these devices provide.

1) Secure Updates: Due to the enormous amount of devices deployed, on-site maintenance is no longer feasible, especially for mass updates. This has directed our interest towards remote updating mechanisms, performing updates and integrity attestation over the air. However, due to the wireless nature of such mechanisms, security concerns have become growingly prominent.

A combination of different security approaches can be adopted to satisfy this requirement. For example, in [126], SCUBA (Secure Code Update By Attestation) is presented for resource-constrained IoT sensor networks to perform detection and automatic recovery of compromised nodes via secure code updates. SCUBA identifies compromised regions using authentication and software-based attestation and transmits the code update to repair the infected region.

Similarly, in [127], the authors proposed a Proof of Secure Erasure (PoSE) scheme for the secure remote update. In PoSE, the prover first performs secure erasure of all writable memory contents to remove possible malicious code before retrieving and installing code updates. However, it is pointed out by [128] that SCUBA and PoSE have significant drawbacks that make them unrealistic for deployment. The assumption of strict local communication, or the lack of support for version roll-back if the current version fails, contributes to their unsuitability.

The authors in [128] then proposed ASSURED (architecture for a secure software update of realistic embedded devices) for secure remote updates, using GlobalPlatform TEE Management Framework (TMF) and extension on the TUF (The Update Framework).

Another recent direction for the secure update is the application of blockchain technology. Since the update package must maintain its integrity without compromising the code’s privacy, blockchain may be a viable option for implementing secure updates. Due to the unmodifiability and transparency of blockchain, the concern for unauthorized modification will no longer exist. Any node in the distributed network can verify the validity of the update package it receives. Due to the distributed nature of blockchain, no central agency will be needed to facilitate mass updates, and it would be possible to rely on peer nodes in relaying update packages. An example of blockchain-based secure update for IoT can be found in [129].

2) System Resilience On Attacks: Keeping resilience to deal with insider and outsider risks and attacks is crucial for smart city applications in the IoT system. As described in [130], resilience mainly focuses on the integration of runtime situational awareness and prior risk analysis, which means that a resilient system should have the ability to take proactive defense and mitigate countermeasures against attacks
to maintain system security and robustness. A resilient system can detect and resist most threats in the first place, but once it is attacked, it can also return to a normal and healthy operating state as soon as possible.

a) **Powerful Detection Capability Before Intrusion:**
As one of the most important security posture monitoring tools, intrusion detection systems (IDS) can identify suspicious activities and detect possible attacks to make the network run in more security and normal operating state. There exist many mature intrusion detection techniques for the traditional network system. However, these IDS techniques cannot be applied to IoT systems directly because of the many different characteristics between IoT and traditional network systems. Complex and high computational techniques are not suitable for IoT system as it is constrained, and there are many lightweight devices/sensors in smart city applications, which we should consider their memory capacity, battery life, and network bandwidth when designing security detection approaches [131].

According to the special characteristics of IoT systems, it is necessary and crucial to design a resilient system that applies powerful and efficient security monitoring techniques to build a safe, trust, and private environment for smart city applications [132]. This resilient system owns the ability to detect and identify most cyberattacks before possible damage occurs. IoT systems can be divided into three layers, including perception/physical layer, network/transport layer, and application layer [133]. The equipment complexity, architecture, and protocol stack of different layers differ greatly. Hence, the security detection techniques can be designed differently based on the characteristics of different IoT layers. The IoT security detection methods can also be devised to satisfy different requirements of different smart city applications. In summary, we can design the security monitoring mechanism in the Internet of Things from more perspectives, multiple levels, and a more flexible way.

b) **Strong Healing Ability After Being Attacked:** IoT systems and smart city applications cannot always prevent all attacks. As a result, another requirement for a resilient system is to recover to its normal status as soon as possible once a threat attacks it. Due to the limited memory capacity of the lightweight devices/sensors and limited bandwidth of the networks, IoT system is much easier to attack by the distributed denial of service (DDoS) attack. For smart transportation systems, it is very important to keep real-time communication.

If DDoS attacks occur on some communication devices, they may lead to a communication delay or mistake to cause a traffic accident. For smart grid systems, DDoS attacks may cause power interruption, which will affect the normal life of individual users and hinder the production work of enterprises. Besides, the basic components of an IoT system that generate data and make communications are small and simple devices/sensors instead of human or complex machines. It becomes more difficult to secure data privacy in different smart city applications than traditional internet applications. Private data of the users in smart healthcare systems and smart homes are in danger of being modified or leaked to cause unpredictable harm and cost. Since most of the smart city applications in today’s IoT systems are time-critical and safety-critical, security mitigation countermeasures should consider meeting the critical conditions while devices/sensors or applications are under attack. For some smart city applications that need to keep working in real-time, multiple security responses and recovery methods should be arranged to enhance the system’s resilience.

Due to the complexity of the IoT ecosystem, where a large amount of data traffic is exchanged constantly between heterogeneous devices, designing for system resilience on attacks can be a very challenging security requirement. Nevertheless, this is a vital step towards securing our IoT applications and thus, requires more research effort.

VI. **Future IoT and Future IoT Security**

Future IoT in smart cities is expected to be fully intelligent, with seamless cross-functional and cross-platform interactions. As IoT progresses from “perceptive” to “cognitive,” we expect these devices to learn from our actions and help pave the way for deeper integration of people, things, and infrastructure.

Cognitive IoT devices can sense their surrounding environment, gathering information about other participants nearby. The intelligence agent is fed with relevant data from users and the environment and a corresponding set of execution options and system/environmental feedback from the execution. The more information the cognitive IoT device can collect, the better it could formulate its decision path. By iteratively updating the best strategy under user-defined policies to achieve the best reward, the agent gains the ability to make intelligent decisions. Since the core model’s cognitive ability is based on the collection of behavioral insights from our actions and feedback, which serve as the model’s knowledge base, the quality of data can heavily impact the model’s performance.

However, since the cognitive IoT device can collect all forms of data and infer high-level interpretation, it is essential to construct a new set of regulations to limit the types of data collected. While devices can record high-precision photos and contribute to the formation of high-resolution road maps, they can also catch imagery of other persons and objects. With strong cognitive abilities and high computation capabilities, the device could run facial recognition models and search for the internet presence of the passerby. As neural networks become more powerful, they may one day reveal a great deal of personal information about strangers from the data collected.

As IoT applications become more intelligent, new security vulnerabilities emerge. To begin with, such a model’s training necessitates a large database, and the model could allow for online training, where new samples generated in real-time can be processed and fed into the model for training. The high volume and ever-expanding dataset put enormous strain on the system’s ability to store and analyze data securely. In addition, since more cross-functional interactions are anticipated, we can expect more frequent and massive data flows between systems, exposing more attack surfaces to external attackers. Future IoT security would require extensive protection towards sensitive data flow among system components and across systems.
Furthermore, as the number of IoT devices grows exponentially, more systems will be encountering large traffic flow from these devices due to the increasing connectivity between systems. The large growth in IoT devices further exacerbates the demand for wireless bandwidth. To achieve better efficiency with large data traffic, a popular approach is the adoption of cognitive radio, which provides appealing strategies such as spectrum sensing, self-learning, circumstantial perceiving, and spectrum access. However, they can also add to security and privacy risks [3].

Cognitive IoT devices can perform spectrum sensing to detect “holes” in the spectrum and monitor the behavior of network users. This can lead to two significant issues. Firstly, since cognitive IoT devices can monitor the behavior of network users, the usages patterns of these network users can be tracked, thus resulting in privacy concerns of the network user. Without a proper framework for secure and efficient spectrum trading, spectrum sensing by unauthorized devices might be considered a pre-event sign of intrusion in the wireless network.

On the other hand, the machine learning approach could also be applied in IoT security, providing systems with automated/semi-automated security defense. In [134], the author discusses how machine learning may be utilized for learning-based authentication, access control, IoT offloading for addressing attacks on the physical and MAC layers, and IoT malware detection. The proposed methods utilize machine learning techniques as the decision-making backbone, with large models and networks serving as the decision-making backbone. Although present IoT systems cannot handle such computing overhead and cannot provide sufficient state observation to train such models, future IoT security can aim to achieve a good balance of intelligence and performance with the help of machine learning.

Besides security and privacy challenges, the standardization of cognitive IoT networks remains a challenging task. While much research has been done in this area, most of the solutions address part of the issue. More research is needed to integrate these proposals and provide proper standardization.

VII. CONCLUSION

In conclusion, while emerging technologies have enormous potential for addressing difficulties in IoT-enabled smart cities, security must be considered throughout the data life cycle and any possible interactions with the outside world. Only then will the system withstand attacks on every component of the large network.

Aside from the usual security considerations, proposals for IoT-enabled smart city applications must carefully evaluate the application’s context and social expectations to ensure its feasibility. Other security issues such as secure updates for massive IoT networks, interoperability between different protocols, and maintenance of Quality of Security Services deserve more research attention. As our IoT systems gradually evolve from “perceptive” towards “cognitive”, autonomous or semi-autonomous complex systems capable of cognitive decision making will become commonplace. How best to implement security in such a sophisticated and intelligent system will be of great value towards the development of our smart city landscape.

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