Int J Syst Assur Eng Manag (July 2023) 14:S699–S721
https://doi.org/10.1007/s13198-021-01523-y

REVIEW PAPERS

Emerging technologies and design aspects of next generation cyber physical system with a smart city application perspective

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Received: 10 August 2021 / Revised: 18 October 2021 / Accepted: 9 November 2021 / Published online: 21 January 2022

Abstract The Cyber Physical System (CPS) is a disruptive technology that has combined the burgeoning technologies from various domains. The CPS is continuously evolving with the incorporation of next-generation technologies. A CPS capable of supporting next-generation applications is referred to as the Next Generation Cyber Physical System (NG-CPS). This paper comprehensively discusses the different emerging technologies such as Internet of Things, Machine to Machine communication, Machine Learning, Artificial Intelligence, Big-Data, etc. for the NG-CPS. Further, a generic NG-CPS framework is proposed covering all design aspects including physical design aspects, cyber design aspects and communication design aspects. Moreover, the smart city as a NG-CPS is designed using the proposed generic NG-CSP framework. To aid network designer in networking, the state-of-art protocols stack is also presented for smart city NG-CPS. Furthermore, to facilitate researchers in designing a smart city NG-CPS, the key technical specifications are comprehensively summarized, covering all domains of the NG-CPS.

Keywords Cyber physical system · Smart city · IoT · Machine learning · Protocols stack · Emerging technologies · 5G & 6G

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1 Introduction

Recent advancements in Internet technologies and embedded systems are the catalysts for the rapid growth of the Internet of Things (IoT) (Appasani et al. 2021a). Internet is one of the exponentially growing technologies of twenty-first century. It has an immense impact on the socio-economical strata of modern human civilization. The IoT has further revolutionized modern communication in the way we connect, communicate, interact, and control. State-of-the-art human–machine interaction known as User Interface-User Experience (UI/UX) techniques such as Augmented Reality (AR), Virtual Reality (VR), computer vision, holographic display etc., have added new perspectives in the field of IoT (Alonso-Rosa et al. 2020). High-speed data networks 5G and beyond, aided with technologies like IoT and Machine to Machine (M2M), etc., are game changers in achieving the future inter-connected intelligence ecosystem (Susanto et al. 2020). These inter-connected intelligent ecosystems, which can communicate with each other, are widely referred to as a Cyber-Physical System (CPS) (Jha et al. 2021a).

A CPS is an ecosystem with the physical realm connected to the cyber realm through the communication infrastructure. With the genesis of IoT and CPS, there has been an exponential growth in these fields contributed by state-of-the-art technologies. These emerging technologies have been promising in achieving greater functionalities and features in CPS-based next-generation applications. The Next Generation-CPS (NG-CPS) is different from the traditional CPS in the way they collect, process, compute, analyze and communicate the data for the next-generation applications.

The National Science Foundation (NSF) of the United States had coined the term CPS describing it as a complex, interdisciplinary, futuristic engineered application integrating recent cyber technologies (cyber system) and the physical world to realize a real-world application (Nsf.gov. 2021). The physical system of a CPS mainly consists of application-oriented infrastructural elements. In contrast, the cyber system is responsible for smart computation, algorithmic analysis, data analytics, and processing to monitor and control the physical system components effectively with little human interaction. Further, the cyber system is also responsible for analyzing, synthesizing, processing, and computing the data received from the physical world in an efficient manner. The cyber and physical systems are connected using communication infrastructure. Thus, the communication infrastructure bridges the gap between the cyber system and the physical system in a CPS. Such a CPS is shown in Fig. 1.

Research and development in material sciences and modern sensor technologies like micro-electromechanical sensors (MEMS) have given an enormous opportunity to deploy tiny embedded devices in a variety of application-specific CPS (Verma et al. 2017). Cloud-based technology plays a vital role in the communication of data among the different entities of a CPS. In this scenario, emerging software frameworks and network protocol stack support have been catalysts in provisioning cloud-based services to end-users. Further, implementations of various burgeoning technologies such as Machine Learning (ML), Artificial Intelligence (AI), etc., have been instrumental in achieving analytics and machine intelligence for the deployment of CPS (Monostori 2018).

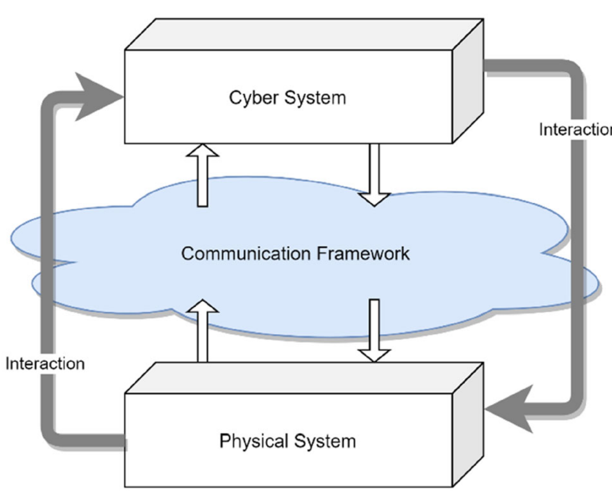

Fig. 1 An overview of CPS

1.1 A. Contribution of the paper

The NG-CPSs are highly complex systems with sophisticated cyber and physical systems. The complexity of the NG-CPS poses severe challenges from the design perspective, including the enabling technologies, architecture, protocol stack, etc. Also, these challenges depend on the application. This article presents a state-of-the-art overview of the emerging technologies. Also, a generic NG-CPS is proposed with a comprehensive overview of its design aspects.

The major contribution of the paper can be summarized as below.

- In today's era where technologies are evolving fast, the applications need to cope with the rapidly evolving technologies. Thus, many next-generation applications can be viewed to incorporate the ubiquitous CPS based technologies. Thus, the state-of-the-art review on emerging technologies from NG-CPS perspective is presented in this paper.
- A generic architecture of NG-CPS with a state-of-the-art technological overview is proposed in this paper.
- A smart city architecture is presented based on the proposed NG-CPS framework, covering different design aspects and challenges. The proposed smart city NG-CPS also covers the protocols stack, the implementation framework, enabling technologies, and challenges.
- The most comprehensive aspect of technological requirements, scope, and applications are presented in this paper to facilitate the researchers in designing the smart city based on NG-CPS framework.

In a nutshell, the paper provides the detailed technological aspect of the CPS for next-generation applications incorporating burgeoning technologies.

1.2 B. Structure of the paper

After presenting a brief introduction in Section 1, the state-of-art technological overview of NG-CPS from various aspects is presented in Section 2. The potential emerging technologies for ubiquitous NG-CPS is discussed with challenges in Section 3. A generic NG-CPS framework covering various technological aspects is proposed in Section 4. Based on the proposed NG-CPS framework, a smart city architecture is presented covering different design aspects and challenges in Section 5. To assist network designers, a protocols stack of smart city NG-CPS is also proposed in this section. Further, a comprehensive summary of the key design parameters covering all aspects of smart city NG-CPS is also discussed in Section 5.

Finally, the conclusion of the work has been discussed in Section 6.

2 State-of-the-art NG-CPS: a technical overview

A CPS is a conglomeration of *cyber-realm* with *physical-realm* with a communication framework. The physical realm is mostly the real-world entities like sensors, actuators, electro-mechanical machines, home appliances, vehicles, buildings, industrial equipment, energy systems, etc. (NIST 2021). To integrate physical systems with cyber systems, the physical systems must be equipped with embedded electronic modules powered by Micro-Processor Units (MPU) or Micro-Controller Units (MCUs) to convert the physical parameters into digital data vice-versa. The cyber system processes the physical systems' digital data to control the physical objects to achieve the goal. The communication infrastructure connects the cyber and physical systems using different communication and networking frameworks such as the Internet. The interaction between physical systems and the cyber systems can be modeled as a bi-directional communication since the real-world parameters can be sensed, processed, stored by the components of the physical system, which can be communicated to the cyber system using communication infrastructure whereas, the cyber system process, analyze, and command to the physical objects using communication infrastructure.

The footprint of CPS can be traced from IoT since the early 2000s. The IoT is quite fascinating as it has given an enormous opportunity for seamless interaction between physical systems over cyberspace. The NG-CPS would be the never smarter CPS as compared to today's conventional CPS without the help of emerging state-of-the-art enabling technologies. There are enormous opportunities and research scope in designing and developing such NG-CPS with some key technology enablers. In this section, a bird-eye view is presented with a broader perspective on the promising emerging technologies in the research and development of next-generation CPS.

2.1 A. A pragmatic design approach for NG-CPS

Designing state-of-the-art future NG-CPS would require functional modules (building blocks). The literature review of recent developments in IoT and CPS suggests some distinct functional layers for the NG-CPS (Mishra et al. 2020a). A generic layered architecture is proposed for designing a state-of-the-art NG-CPS that comprehensively analyzes several key enabling technologies. The proposed generic layered architecture with key enabling technologies is as shown in Fig. 2. As shown in Fig. 2, a four-layered architecture is proposed for NG-CPS. The layers are referred to as the bottom as, Layer-1 (Device Layer), Layer-2 (Communication Layer), Layer-3 (Data Layer), and Layer-4 (Application Layer). Any generic state-of-the-art NG-CPS may be modeled based on these four layers, which are fundamental building blocks for any CPS.

2.1.1 1) Device layer

The device layer primarily focused on the IoT-enabled devices or sensor/end nodes. The primary design aspect related to the device layer is a smarter and energy-efficient design of embedded systems, which is the platform on which their devices function. The NG-CPS would require the low-power MPU/MCU-based embedded platform to support smarter algorithms by providing the best-in-class computational resources with low-power consumption. The new-generation family of System-on-Chip (SoC), System-on-Module (SoM), and Network-on-Chip (NoC) would be more suitable for NG-CPS with low-power without trading-off with computational capabilities to support Edge Computing (EC). The EC is a key enabling technology to cater to the demand for efficient computing in distributed and decentralized networks. Many basic computational processes are done at the edge devices rather than the cloud to minimize the latency. This newer approach of computing is also referred to as Fog Computing (FC) in the literature. Since the device layer components are mostly battery operated, thus energy harvesting has enormous scope in the NG-CPS. As IoT and CPS are designed mainly for Machine-to-Machine (M2M) communication, the need for future large-scale deployment of interconnected smart devices and machines would require device-level support (network interface/adaptor) for Massive Machine Type Communication (mMTC) (Mishra et al. 2020a). The Device-to-Device (D2D) direct/ad-hoc communication between devices is a network feature provisioned in 3GPP standards, i.e., 5G and beyond. The devices of NG-CPS need support for such a modern communication framework.

Further, the sensors are essential components of the end device. The advances in cutting-edge sensor technologies are the need of the hour to develop modern NG-CPS applications. As sensing is the predominant aspect of physical-to-cyber interactions, similarly, the interaction from CPS, which is achieved using relay, drive, actuators, is also equally crucial for developing NG-CPS.

2.1.2 2) Communication layer

The communication layer of NG-CPS comprises the technologies for network framework and protocol support. The real-world deployment of NG-CPS would require a packet

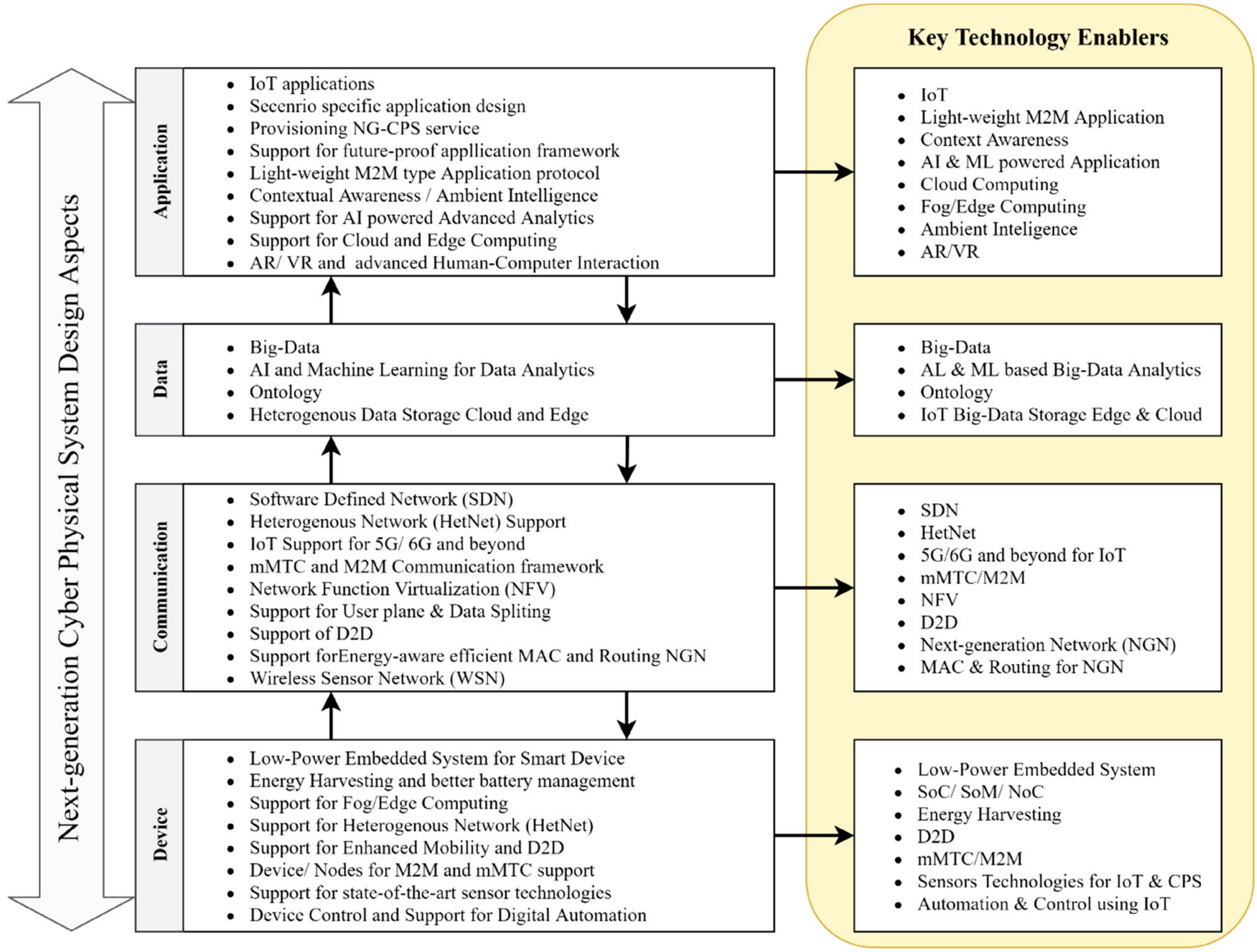

Fig. 2 Next-generation CPS design aspects with key technology enablers

switch data network framework supporting generic Transmission Control Protocol/Internet Protocol (TCP/IP) stack. Further, there is a viable requirement of wireless cellular network (5G/6G and beyond) as well as wireless sensor network (WSN) to support robust communication infrastructure. The NG-CPS would even take the technical advantages of many emerging communication technologies in the context of 3GPP standards i.e., 5G/6G and beyond. The technological advances in the field of 5G/6G such as Heterogenous Cloud Radio Access Network (HCRAN), Software Defined Radio (SDR) and Software Defined Network (SDN), Network Function Virtualization (NFV), mMTC, Enhanced Mobile Broad-Band (eMBB), Ultra-Reliable Low Latency Communication (URLLC) envisioned to revolutionized the communication infrastructure.

Consequently, the 5G/6G proposes a generic cloud hardware platform and software-based functional sub-systems for better resource allocation and management with traffic profiling. Moreover, the 5G/6G networks would have proper convergence among heterogeneous networks and protocols to support Heterogeneous Networks (HetNets). Some other network technologies which are prominent in the field of NG-CPS are M2M and D2D communications. Recently, many industries and standardization agencies have developed the OneM2M standard, which is quite promising in its generic architecture to support massive machine-type communications, which may be considered a stepping stone for efficient deployment and communication for NG-CPS. As far as the PSDN and TCP/IP stack are concerned, the underlying technologies like physical, Media Access Control (MAC), and the network layer are essential for packet delivery. Hence, energy-efficient MAC and Routing with support for IPv6 would be the most viable approach for designing the communication framework for Next-generation Network (NGN) infrastructure, which are imperative for NG-CPS.

2.1.3 3) Data layer

The predominant aspect of the data layer of NG-CPS is to handle the vast data generated from billions of connected, intelligent devices. A large amount of heterogeneous, unstructured data is being generated from the physical system by sensors. This vast amount of data can be referred to as the Big-data. The storing, processing, managing, and handling are some of the biggest hurdles in Big-Data. Further, it becomes even challenging to infer the meaning conveyed through the unstructured data. Such a problem needs a proper data analytics approach to coexist with Big-Data. Artificial Intelligence (AI) and Machine Learning (ML) algorithms are very commonly explored technology enablers towards data analytics which can be applied to the NG-CPS. The research trends suggest computational intelligence and soft-computing techniques like AI and ML algorithms have large potential for data analytics under the purview of NG-CPS. Another field of research in the data layer of NG-CPS would be Ontology and context-awareness of data. Recent research suggests a hybrid technique that uses both FC/EC and cloud-based big-data storage as per scenario-specific requirements.

2.1.4 4) Application layer

Now when it comes to the top-most layer of NG-CPS, the application layer, it can be inferred as the front-end (or user-end) to provide and provision end-to-end application support to scenario-specific demands of NG-CPS. The key technology enablers at this layer are lightweight application layer protocols to support machine type M2M communication framework. The Message Queue Telemetry and Transport (MQTT) and Constraint Application Protocol (CoAP) are NG-CPS's potential application layer protocols. The future applications framework and Application Process Interfacing (API) would require support from AI for NG-CPS. Further, the application layer protocols must be interoperable with the Big-Data, which is necessary for handling voluminous data in NG-CPS. Context-awareness and ambient intelligence are also the key technology enablers as far as the application layer of NG-CPS is considered. When it comes to human–machine interaction, and modern User Interface/User Experience (UI/UX) framework support the Augmented Reality (AR), and Virtual Reality (VR) technologies are promising from the perspective of User Interface (UI) or User Experience (UX).

The different enabling technologies can cater to the demands across several layers of the proposed generic NG-CPS, seen in Fig. 3 as a relational model of enabling technologies and proposed architecture.

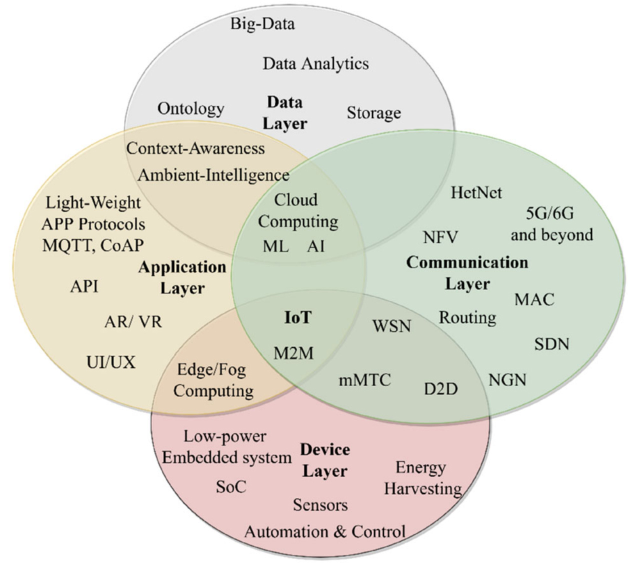

Fig. 3 NG-CPS Four-layer architecture relational model between key technology enablers

Having the availability of numerous technologies such as cloud computing, Big-Data, WSN, ML, IoT, SDN, M2M, AI, SoC, SoS, etc., its appropriateness for CPS is very challenging. Several factors such as Quality of Service (QoS), delay, throughput, security, integrity, etc., make a technology appropriate for CPS. Nevertheless, the technological requirements are even characterized based on application-specific requirements. This has motivated us to present a state-of-art review about various emerging technologies from the perspective of NG-CPS, which is discussed in the next section.

2.2 B. Some seminal work on enabling technologies for NG-CPS

Now we comprehensively survey some of the seminal works in the domain of the NG-CPS. An exemplary survey is conducted on Big-Data from the perspective of CPS by Wang et al. in (2016). Particularly, authors have considered an application-specific scenario, i.e., Industry 4.0 with CPS. With respect to the reliability enhancement in the manufacturing industries, the role of Big Data is discussed from the CPS perspective by Zhang et al. in (2020). Further, the issues of real-time monitoring and controlling of CPS-based processes are simplified through Big Data technology by Nica in (2020). The scope of CPS in Industrial applications and their improvement with Big Data, IoT, sensors, etc., burgeoning technologies have been thoroughly discussed by Popescu et al. in (2020). Nevertheless, the Big Data and CPS for health care applications have been discussed in Cabello et al. (2020). Furthermore, a detailed survey on Big Data can be found in Cui et al.

(2020), where authors discussed a comprehensive survey on Big Data from various perspectives, such as the application, requirements, challenges, and opportunities.

The most comprehensive work on cloud computing with CPS based Industrial applications have been presented by Villalonga in (2020) and Cao et al. in (2021). Haoxiang et al. in (2020) have proposed an intelligent scheduling scheme for CPS applications based on cloud computing. The seminal work by Noguchi et al. in (2020) proposed a unique CPS framework that utilizes cloud computing in an open IoT environment. The fog-assisted CPS framework with 5G infrastructure was reported in Singh and Sood (2020) by Singh et al. The cloud computing for CPS from other key perspectives such as privacy, security, QoS, etc., are reported in (Ghaffar et al. 2020); Singh and Sood 2021; Tripathy et al. 2020; Mishra et al. 2020b).

The SDN for the development of CPS architecture is proposed in Ulrich et al. (2020) by Ulrich et al. In this, authors proposed a resilient CPS architecture using SDN. Further, the modeling of SDN-based CPS with improved resiliency is reported by Moura in (2003). The security perspective of SDN, which can be seen in CPS, is most comprehensively reported by Singh et al. in (2020). Moreover, Alabadi et al. in (2020) had addressed different aspects of CPS with an excellent survey on security focusing M2M technologies. The design of an intelligent CPS using a hybrid neural network has been reported in Sokolov et al. (2020). The security issues in CPS with enhanced reliability are reported in Prasad and Rohokale (2020) by Prasad et al. using ubiquitous IoT and M2M technologies. Moreover, there are many works that use wireless sensor networks (WSNs) for designing CPS. Ravikumar et al. in (2020) reported the design of CPS-based smart grid applications where ZigBee is used as network infrastructure. Smart agriculture, which is a typical WSN-based application, is envisaged using CPS framework in Et-taibi et al. (2020) by Et-taibi et al. Yıldırım et al. in (2018), reported the interaction and interconnection of two WSN based infrastructure based on CPS frameworks. From the CPS perspective with ubiquitous WSN technologies, the other key issues such as threats, attacks, security, privacy, etc., are comprehensively reported by Sikder et al. in (2021).

Nevertheless, from the security perspective, the scope of emerging technologies such as AI and IoT in CPS-based applications have been discussed in Farivar et al. April (2020). The state-of-the-art review on security and threats is presented by Krishna et al. in Krishna et al. (2021). The risk assessment methodology for CPS testbeds using AI has been addressed in Matsuda (2019). An excellent survey for resilient CPS using a machine learning approach has been conducted by Olowononi et al. in (2020b). The prospect of ML in CPS with detailed taxonomy, issues, challenges, and opportunities are extensively surveyed by Rai et al. in (2020). The ML approach in CPS for improving securities and data integrity is reported in (Rouzbahani et al. 2020); Tertytchny et al. 2020). Yoo et al. in (2020) have reported reinforcement-based algorithms for CPS with optimal data generation. The seminal work by Möstl et al. in (2018) proposed enabling platform to make a CPS self-configurable and self-controllable.

The extensive survey on IoT for CPS perspective, including challenges and opportunities, is conducted by Zhou et al. in (2020). Numerous applications can be envisaged as CPS and IoT technologies. Hu et al. in (2020) had proposed a turbine assembly system using IoT based CPS framework. The prospect of emerging 5G technology with IoT enabled CPS is comprehensively reported in Li et al. (2018). The IoT enabled CPS from some other vital perspectives such as security, privacy, reliability, and data integrity have been reported in (Peng et al. 2020); Wolf and Serpanos Jan. 2018; Burg et al. Jan. 2018).

For a comprehensive and systematic review, some of the seminal works have been summarized in Table 1. The survey has been conducted to grab the development during the last 5 years to gain insight into the most recent work in CPS paradigm. For a comprehensive overview of different technologies and literature trends, the number of articles in the last 5 years that appeared in the Scopus database is analyzed. The year-wise appearance of the result is shown in Fig. 4. From the statistics, it can be inferred that some of the enabling technologies, such as ML, AI, Big-Data, IoT, etc., are heavily explored, whereas the technologies, such as M2M, IoT, and 5G, SDN, FC are sparsely explored in the literature. From literature, some of the seminal references covering different enabling technologies from the various perspective of NG-CPS have been summarized in Table 2.

3 Emerging technologies, issues and challenges for NG-CPS

3.1 A. Emerging technologies for CPS

The drastic changes have been observed in the cyber parts of the CPS, such as in the fields of information and communication technologies including Big-Data, cloud computing, SDN, M2M, WSN, AI, etc.; standardization of several communication protocols as seen in wireless sensor network (WSN), IoT, software-defined networking (SDN), and systems of systems (SoS) (Jha et al. 2021c). Some of the key technologies that contributed to the rapid advancement of CPS in recent years are shown in Fig. 5. All these unprecedented changes have paved the way for

Table 1 significant contribution on different emerging technologies from literature

Technology	Key aspects	Year	References
Big data	CPS use cases in Industrial applications and health sectors with Big Data analytics for handling voluminous data	2016–2020	Wang and Wang 2016; Zhang et al. 2020; Nica et al. 2020; Popescu et al. 2020; Cabello et al. 2020; Cui et al. 2020)
Cloud computing	Scope of Cloud computing for CPS based Industrial applications, and its use cases with other emerging technologies such as IoT, 5G, etc., to improve reliability, security, privacy, and QoS in CPS environment	2020–2021	Villalonga et al. 2020; Cao et al. 2021; Haoxiang and Smys 2020; Noguchi and Sugano 2020)
SDN	Resilient, reliable and secure CPS architecture using SDN technology	2020–2021	Ulrich et al. 2020; Moura and Hutchison 2003; Singh and Bhandari 2020)
M2M communications	Enhancing reliability, security, privacy, and data integrity in CPS framework with M2M	2020–2021	Alabadi et al. 2020; Sokolov et al. 2020; Prasad and Rohokale 2020)
WSN	WSN technologies for interconnections of cyber and physical entities of CPS based applications also addresses issues such as protocols stack and interactions of different layers of CPS architecture	2018–2021	Ravikumar et al. 2020; Et-taibi et al. 2020; Yıldırım and Tatar 2018; Sikder et al. 2021)
AI	AI techniques for improving real-time monitoring, controlling and decision in CPS applications such as Industry 4.0, smart grid, heathcare, smart city, etc	2019–2020	Farivar et al. April 2020; Krishna et al. 2021; Failed 2019)
ML	Appropriateness of ML for CPS based applications from the perspective of application framework, security, reliability, privacy, QoS including challenges and opportunities of ML in CPS paradigm	2018–2020	Olowononi et al. 2020b; Rai and Sahu 2020; Rouzbahani et al. 2020; Tertytchny et al. 2020; Yoo et al. 2020; Möstl et al. 2018)
IoT	The CPS framework using IoT for ensuring reliability, security, privacy in addition to effective real-time monitoring, and control of cyber and physical components of the CPS	2018–2021	Zhou et al. 2020; Hu et al. 2020; Li et al. 2018; Peng et al. 2020; Wolf and Serpanos 2018; Burg et al. 2018)

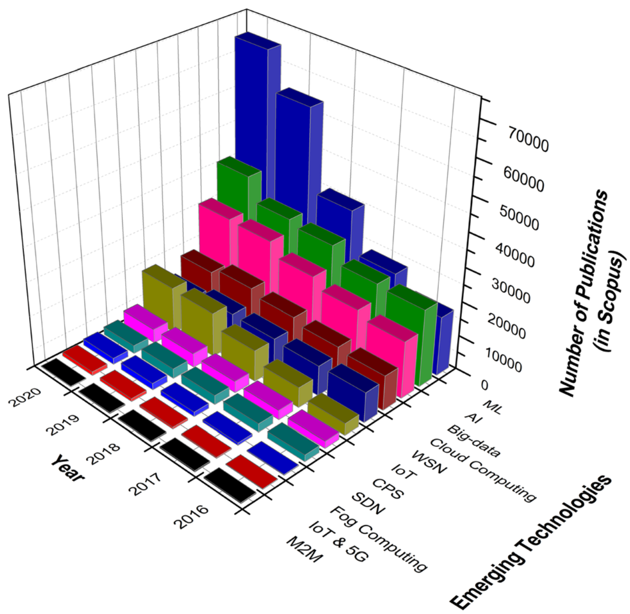

Fig. 4 Key enabling technologies research trend (Year: 2016–2020) as per Scopus Database

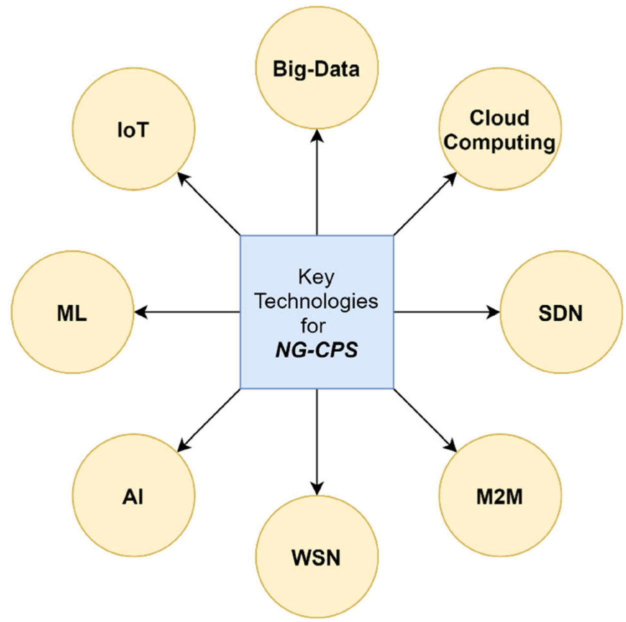

Fig. 5 Emerging technologies for CPS

Table 2 Emerging technologies, their significance and use cases in CPS

Technology	Its purpose	CPS based application domain	References
Big data	To handle voluminous and diverse data more efficiently	Industry automation, manufacturing industry, assembly and process industry, energy management, grid monitoring, healthcare-related applications of CPS	Bandura 1991)
Cloud computing	To provide distributed, transparent, scalable, fastest, and cost-effective computation solutions to voluminous and dynamic data generated during the operation of CPS	Enabling services such as platform as a service (PaaS), software as a service (SaaS), and infrastructure as a service (IaaS) for several applications of CPS such as Industry 4.0, smart grid, smart healthcare, etc.‘	Chen et al. 2020)
SDN	Ubiquitous integration, accessibility, dynamic management, high bandwidth, and efficient resource utilization of traditional Internet infrastructure using SDN	Applications such as adaptive routing, network virtualization, green networking, boundless mobility, consolidated security etc., in CPS networking infrastructure	Xia et al. 2015)
M2M Communications	Decision making based on real-time data gathered from several sensors and actuators of CPS by the use of the machine without or with minimum human interventions	Networking, resource allocation, monitoring related applications of CPS	Prasad and Rohokale 2020)
WSN	To enable cost-effective, affordable, and reliable communication infrastructure which integrates cyber and physical components of the CPS	Environmental monitoring, mining, underwater resource monitoring, military operation, agriculture, healthcare, etc., oriented CPS based applications	Jha et al. 2019)
AI	To provide intelligent capabilities in monitoring, controlling, and decision making in real-time	Industry 4.0, smart city, heathcare, smart grid	Failed 2019)
ML	Using computers as a human brain for controlling and monitoring behaviors of CPS based on machine-run algorithms and protocols	Intelligent cyber based patient monitoring, smart agriculture, telemedicines, e-health, power grid, industry 4.0, etc	Jha et al. 2021b)
IoT	To interconnect and integrate several components of CPS, including sensors, actuators, controllers, monitors, etc. for real-time communication	Industrial applications such as manufacturing, assemble, packing, etc., smart grid, smart city, smart healthcare, intelligent traffic monitoring etc., CPS based applications	Ding et al. 2020)

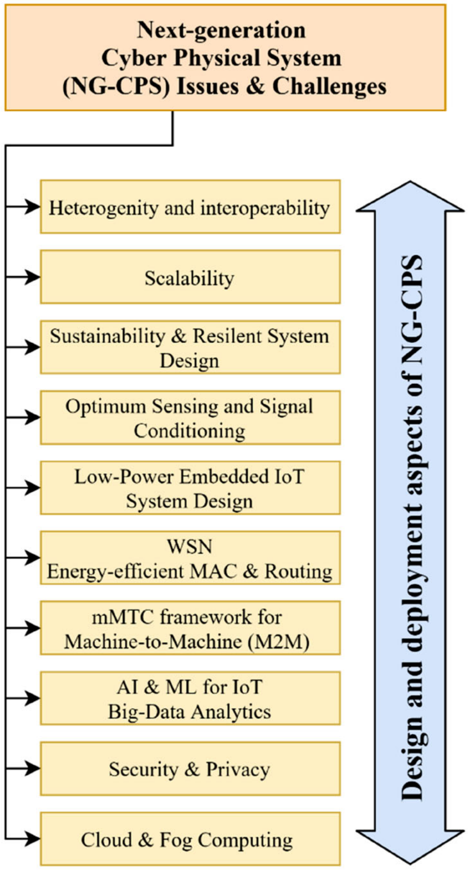

Fig. 6 Issues & Challenges in the design and deployment of NG-CPS

the implementation of next-generation applications using CPS technologies.

The recent research trend shows massive growth in AI and Machine Learning to enable smarter system implementation using computational intelligence (CI) and soft computing techniques. These CI techniques are not new, but the research on Embedded systems with low-power and higher computational capabilities of CPUs and GPUs, has given it a sudden boost. These advancements in the semiconductors and electronics industry have given the scope for AI and ML based algorithms to be implemented in a live real-time CPS to realize the truly connected intelligence. The lightweight advanced protocol stack deployment for M2M communication like OneM2M has further strengthened the communication framework much needed for realizing such NG-CPS.

The enormous scale of real-world deployment of such NG-CPS would generate huge data from the physical system with the aid of state-of-art sensors that would require massive storage and Big-Data support. Research in the domain of Big-Data, Analytics, and Data Mining has enhanced the scope of design and development for such future-proof NG-CPS services for large-scale real-world deployment and service provisioning. The recent advances in the computing technologies like cloud computing and fog computing have further strengthened the much-needed computing platform for more complex algorithms to be implemented in NG-CPS. The computing resources required for such large and complex NG-CPS would be staggering. Hence, various cloud computing approaches like Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS) are technology enablers for NG-CPS (Mishra et al. 2019).

From the genesis in 1999 by Kevin Aston, Auto-ID (MIT) IoT has emerged as the most sought after technology in recent times (Mishra and Mohapatro 2019). The potential of IoT is enormous, with many new allied technologies being added to the ecosystem every day. Researchers are exploring various aspects of IoT to further strengthen the technology ecosystem in various domains like state-of-the-art sensor and signal conditioning, embedded electronics, enhanced communication infrastructure, protocol framework, Big-data, AI/ML-based machine perception and analytics, etc. In the context of NG-CPS, the advances in IoT would be instrumental in realizing real-world deployment using an emerging smarter technology ecosystem. The key is to integrate the AI and ML-based advanced machine perception algorithms into the IoT-based system to truly achieve an NG-CPS. In order to enable the NG-CPS with advanced features like AI and ML, huge datasets are inevitable for the high-fidelity system. Hence, needless to say the Big-Data and analytics is the key technology enabler.

However, the AI & ML with Big-Data support would be enough to design and deploy such NG-CPS; rather, the proper computing platforms are essential for real-world implementation of such a system. However, in order to realize such a system, we should not forget that the key enabler is the advances in modern sensors and signal conditioning methods. Alone big-data or AL/ML is meaningless without a proper physical world data-acquisition system. Smart sensors and actuator control are the primary motivation behind the IoT ecosystem.

The recent advances in chip manufacturing technologies like Ultra-Large-Scale Integration (ULSI), even up to 5-nm fabrication technology from companies like Samsung, have enabled a much higher density of transistors for advanced SoC and SoM based micro-chips. End nodes and edge devices equipped with such a modern SoC/SoM chip-based Embedded system have higher computational capabilities than their predecessors. This advancement in chip technology has enabled a whole new era in the computing approach. Rather than depending on a centralized cloud computing infrastructure for all the computational requirements, recent research suggests a newer distributed computing approach on edge devices. In the context of NG-

CPS, it is inevitable to have massive deployments of edge devices and end nodes. Hence, the feasibility of the design and deployment of such an edge computing-based system has increased multi-fold. The major design advantages of such an edge/fog computing-based system are computing load distribution and low-latency API with a process-splitting computational framework. Research suggests a newer approach for computing called hybrid-computing with advantages of both cloud computing (centralized) and Fog/Edge computing (distributed) combined to give the optimized computing framework. The idea is to split all the processes as per their specific computational requirement. Some processes or parts of processes may perform better on a centralized cloud platform like big data and analytics, whereas some are more optimized for low-latency edge or distributed computing platforms. Hence, the amalgamation of Edge-Cloud computing is a promising research direction for the implantation of NG-CPS.

Apart from AI and ML-based techniques, the advancements in Next generation Network (NGN) technologies like 5G/6G and beyond have worked as a catalyst in the design and development of the NG-CPS. In addition to cellular communication, the support for heterogenous convergent network technologies like WSN (Zigbee, LoRaWAN, 6LRWPAN etc.) has created the much-needed communication infrastructure supporting large-scale energy and efficient spectral deployment of network clusters for NG-CPS applications (Appasani et al. 2021b). The modern communication framework with support for software-defined networks and H-CRAN have made the functional communication nodes more generic and flexible to handle large traffic flows and resource management required for massive machine-type communication for NG-CPS. Cloud has come near the edge devices to optimize the network latency for large-scale deployment of NG-CPS end-nodes.

Communication technologies like wireless network access of PAN, LAN, and WAN with support for NGN like 5G/6G wireless networks are emerging research fields to have proper communication and network infrastructure for NG-CPS. Many network access technologies for low-power large-scale sensor node deployments have been explored in recent times. In Wide-Area Network (WAN) segment, 5G/6G mMTC, LoRaWAN, and IEEE 802.16.1 Wi-MAX are more popular. However, as far as the WSN is concerned, more research suggests a personal area network segment is more suitable as the range and data rate of wireless networks are less so that the power requirement is less, making it the popular choice for the WSN ecosystem. The 6LRWPAN, ZigBee (IEEE 802.15.4), Bluetooth Low Energy (IEEE 802.15.1) are the most sought-after technologies in the WPAN segment of WSN implementation. Even the intermediate-range wireless access network technology like IEEE 802.11 family is popular for many medium-range applications.

Recent research in the cellular networks like 5G/6G and beyond has a Software Defined Radio (SDR) and H-CRAN based access network approach to deal with heterogeneous network architecture suitable for WSN type application support using mMTC framework. The 5G new-radio standard supports better resource management using SDN and NFV like advanced functions to accommodate the network features in NG-CPS.

3.2 B. Overview of NG-CPS and challenges

The NG-CPS envisages to revolutionize the modern world, is high in dimension and complex in nature. Consequently, the design and deployment of the NG-CPS is hindered by many technological issues and challenges. From the perspective of implementation of NG-CPS, a few challenges associated with enabling technologies discussed so far are presented in Fig. 6.

- ***Heterogeneity & Interoperability:*** It refers to the ability of a system to operate in co-existence with other systems in terms of communication technologies, standards, protocols, etc. A highly interoperable system should perform its services to the expected level and must be able to communicate among the several cyber physical components efficiently. Some of the key attributes of interoperability include scalability and heterogeneity, which needs to be addressed while designing a scalable CPS. Research issues in heterogenous CPS design is presented by Bhattacharyya et al. in (2020). The study includes interoperability, physical and computation modeling with features like self-awareness and adaptation, architecture, and scheduling. Papaefstathiou et al. in (2021) have presented heterogeneity and interoperability aspects of cyber physical systems with a Systems of Systems (SoS) approach. Dong et al. in (2021) have proposed modeling and vulnerability analysis of embedded heterogeneous CPS with functional dependencies.
- ***Scalability:*** It is the ability of the system to adapt to the dynamic changes in scenario-specific deployment. NG-CPS system must be highly scalable to accommodate large variables like size of sensor networks, support for multiple communication protocols, types and numbers of sensors and actuators, etc. Huang et al. in Huang et al. (2020) have presented a Scalable Uncertainty-Aware Truth Discovery in Big Data Social Sensing Applications for CPS. Designing a simulator for CPS is very useful to test and validate scalable CPS design. Garraghan et al. in (2016) have proposed SEED: a

scalable CPS simulator that can be useful for further research in this direction.

- ***Predictability:*** In addition to scalability, another aspect is the predictability of the system. It can be referred to as the ability to anticipate the system's performance, operation, and functionality qualitatively and quantitatively. The components of the CPS, such as sensors, actuators, etc., operate in real-time and exhibit their property based on the dynamic environment under which they operate. Under such a dynamically changing environment, the predictability of the system behavior becomes difficult, which needs to be addressed while designing CPS-based applications. Parto et al. in (2020) have proposed a novel architecture using IoT and machine learning for scalable and predictable ubiquitous CPS.
- ***Sustainability and Resilient System Design:*** It refers to the system's ability to perform its services to the expected level while renewing system's resources for the next generation applications. The characteristics, such as long-lasting, self-aware, self-configurability, etc., under a dynamic environment, are a few of the NG-CPS. Some of the key attributes that need to be systematically realized for sustained NG-CPS operation are adaptability, efficiency, configurability, and resilience. In the context of resilient system design, they have been categorized into key-functional abilities like 'dependability' and 'reliability'. Dependability defines the degree of trustworthiness of a system. Some of the key attributes of dependability include maintainability, availability, and safety. 'Reliability' defines the system's ability to perform consistently under different environmental circumstances. Robustness and maintainability are the key attributes that need to be considered to design a reliable CPS. Envisioned NG-CPS needs to be highly robust, sustainable, dependable, and reliable to function efficiently in a very complex real-world deployment scenario. Restrepo et al. in (2021) have presented a systematic mapping study on a sustainable-development approach for self-adaptive CPS life-cycle. Colabianchi et al. (2021) have presented a comprehensive review on issues, challenges, and recent research trends on resiliency aspects of a CPS. To improve adaptivity Jin et al. (2021) have proposed a self-aware distributed deep learning (DDL) framework for IoT applications for heterogeneous edge devices. The self-aware design enhances the system's reliability and resilience by dynamic self-organizing approach and the self-healing method.
- ***Optimum Sensing and Signal Conditioning:*** When it comes to NG-CPS, one of the foremost requirements is sensors and sensing techniques and its required signal conditioning. The major technical challenge in this aspect is to design state-of-art sensors with advances in material science. There is a huge research scope in the field of sensor design, and it's an allied field of research to have optimum sensing and signal conditioning for NG-CPS. The major challenge would be designing extremely complex CPS with multi-sensor data fusion and their appropriate signal conditioning. It is extremely difficult to practically implement such systems as each sensor uses its technique and working principle. Hence, developing a generic framework would be highly challenging. Belabbas et al. in (2019) have proposed optimal sensor design aspects of secure CPS. A study on the different types of smart sensors for IoT applications is presented by Sehrawat et al. in (2019). AlZubi et al. in (2021) have presented Multi-sensor information-fusion for vehicular IoT applications in a smart city. A recent research work by Lin et al. (2021) has proposed a multi-sensor data-fusion-based technique for mobile sinks in heterogeneous WSNs.
- ***Low-Power Embedded IoT system Design:*** The future-ready cyber-physical system would require many smart devices/ end nodes deployed for a real-world application. For large-scale deployment like NG-CPS, these sensor nodes need to be energy-efficient with a low-power design. The challenge is to design low-power SoC/SoM based embedded systems without compromising the computational capabilities. Modern RISC-based ARM architecture for mobile SoCs is extremely power efficient with significant computational capabilities, becoming a major catalyst in this field. Recent research trend suggests there is a lot of research scope in designing low-power energy-aware Embedded IoT systems. Energy-aware system design for battery-less LPWAN devices in IoT is proposed by Yuksel et al. in (2021). Hu et al. in (2021a) have presented Self-powered 5G NB-IoT system for remote monitoring applications. Radfar et al. in (2020) have proposed a battery management technique to reduce energy consumption in ultra-low power IoT and sensory applications.
- ***WSN- Energy-Efficient MAC & Routing:*** With many sensor nodes deployed, there is an inevitable requirement of a suitable MAC and routing protocol in the context of WSN. For NG-CPS, there would be the requirement of an energy-efficient MAC and routing/ protocols. Recent research work has suggested many energy-aware MAC and routing protocols that would be much suitable for NG-CPS. Deployment of large-scale energy-efficient clusters of sensor nodes is a technological challenge for NG-CPS. Zaraket et al. in (2021) have presented a review on low-energy MAC and routing protocol based on wake-up radio technology. Kaur et al. in (2021) has presented a survey on energy

efficient routing techniques in WSNs focusing on IoT applications and enhancing fog computing paradigm. Yadav et al. in (2021) have presented a review on energy-aware optimized clustering for hierarchical routing in WSN. Rawat et al. (Rawat and Chauhan 2021) have presented a detailed survey, issues with future research direction on clustering protocols in WSN.

- ***mMTC framework for Machine-to-machine(M2M) Communication:*** The communication framework for NG-CPS requires massive machine-type communication support for the legacy network infrastructure. Advanced in NGN technologies like 5G/6G and beyond has promising features to accommodate a large number of M2M communication with optimum resource management and network service provisioning. However, billions of devices communicate over a communication framework with low data rates and smaller payloads. It is challenging to manage the traffic, and resource allocation is extremely complex, posing a major design and deployment challenges for NG-CPS. Stojmenovic in (2014) proposes significant research in M2M communication for large-scale CPS. Issues, challenges, and recent research trend of M2M communication in 5G network framework are presented by Salem et al. in (2020).
- ***AI & ML for IoT & Big-Data Analytics:*** The IoT ecosystem is massive, with a huge amount of data being pushed towards the data centers or centralized cloud infrastructure for further processing and data analytics. There are many technical challenges in order to handle massive data using the Big-Data approach. However, data management and storage is not the challenge in this field. Rather, an effective technique to infer meaningful information for proper decision-making is the key to achieving future-ready applications in the context of NG-CPS. Machine perception algorithms like AI and ML are the key to achieve such an intelligent system. Recently, there has been a massive growth in AI and ML to address many applications. However, challenges and scope of research persist for such complex NG-CPS. The role of AI in CPS is presented by Radanliev et al. in (2020). IoT, smart devices, sustainable industrial Big-Data, and AI -based decision-making algorithms in CPS are presented by Shaw et al. in (2021).
- ***Security & Privacy:*** It is the ability of the system to provide genuine controlled access to the user and protect the system from unauthorized access to safeguard the system resources. The NG-CPS-based application must be connected to the Internet for data exchange. Thus, several security challenges such as malicious attacks, eavesdropping, denial of services, injecting fake sensor measurement or actuating data, etc., can attack the cyber or physical components of the NG-CPS. Some of the unsecured communication protocols, unreliable standards, heterogeneous networks, rapid adoption of open source communication technologies are other potential contributors that put the NG-CPS-based application at the forefront of the security challenges. In addition to a secured communication framework, the NG-CPS must ensure data and user privacy to have a resilient architecture. The massive sensor nodes generating huge data have to be private as per their user access requirements. This creates an implementation challenge as the scale of such a system is massive, with a lot of heterogenetic data rights and access constraints. State-of-the-art cyber security techniques like Blockchain would be promising in providing a secured data-exchange framework for future-ready NG-CPS. Neeli et al. in (2021) have presented a detailed review of the security paradigm for IoT with research trends. A comprehensive technical overview on foundations, principles, and applications of Security and privacy in CPS is given in Song et al. (2021) by Song et al.
- ***Cloud & Fog Computing:*** When it comes to computing, the most significant technical issues and challenges are associated with the hardware (CPU, RAM, Storage etc.) constraint and platform bottlenecks. IoT-based systems preferably use a centralized cloud computing approach for massive data storage and processing. However, newer research suggests the distributed Fog/Edge computing approach for a massive decentralized system like NG-CPS. The major challenge in the design and deployment of computing infrastructure for NG-CPS needs to deal with the real-world implementation complexities like optimum computational resource allocation and selection of Cloud, Fog, or hybrid computing approach as per the scenario-specific requirements of the application. Kuang et al. in (2020) has proposed a framework on cloud for CPS Big Data. Laroui et al. in (2021) have presented a comprehensive survey on current research activities and future directions on edge and fog computing for IoT. Cloud-Edge Computing for CPS is presented by Hu et al. in 2021b.

4 A proposed generic NG-CPS

The generic system model of the NG-CPS is proposed in this section. This NG-CPS would have some modern state-of-the-art emerging technologies amalgamated with the conventional CPS to provide a new paradigm for advanced and more intelligent features to the CPS. We envision that the future of CPS is quite promising in the era of '*Connected Intelligence*' with the help of AI-powered systems and modern telecommunication systems like 5G/6G and beyond NGNs. The proposed NG-CPS provides a road map on the design and development of future CPS enabled with some promising key technologies (Fig. 7).

4.1 A. physical system

The physical system consists of various physical objects such as sensors, actuators, relay, drive, etc. These physical objects are deployed in a wide range of smart cities, vehicular networks, industrial IoT, smart grid, assisted living, home automation, etc. For the past decade, we have witnessed skyrocketing growth in IoT and sensor technologies which have further augmented the spectrum of applications to be envisioned using NG-CPS.

In order to achieve a future-proof smarter NG-CPS, some key enabling technologies would become fundamental building blocks of NG-CPS. In particular, technologies on the hardware or embedded end devices can enhance the sustainability of battery-powered end devices. New research in wireless power transfer and energy

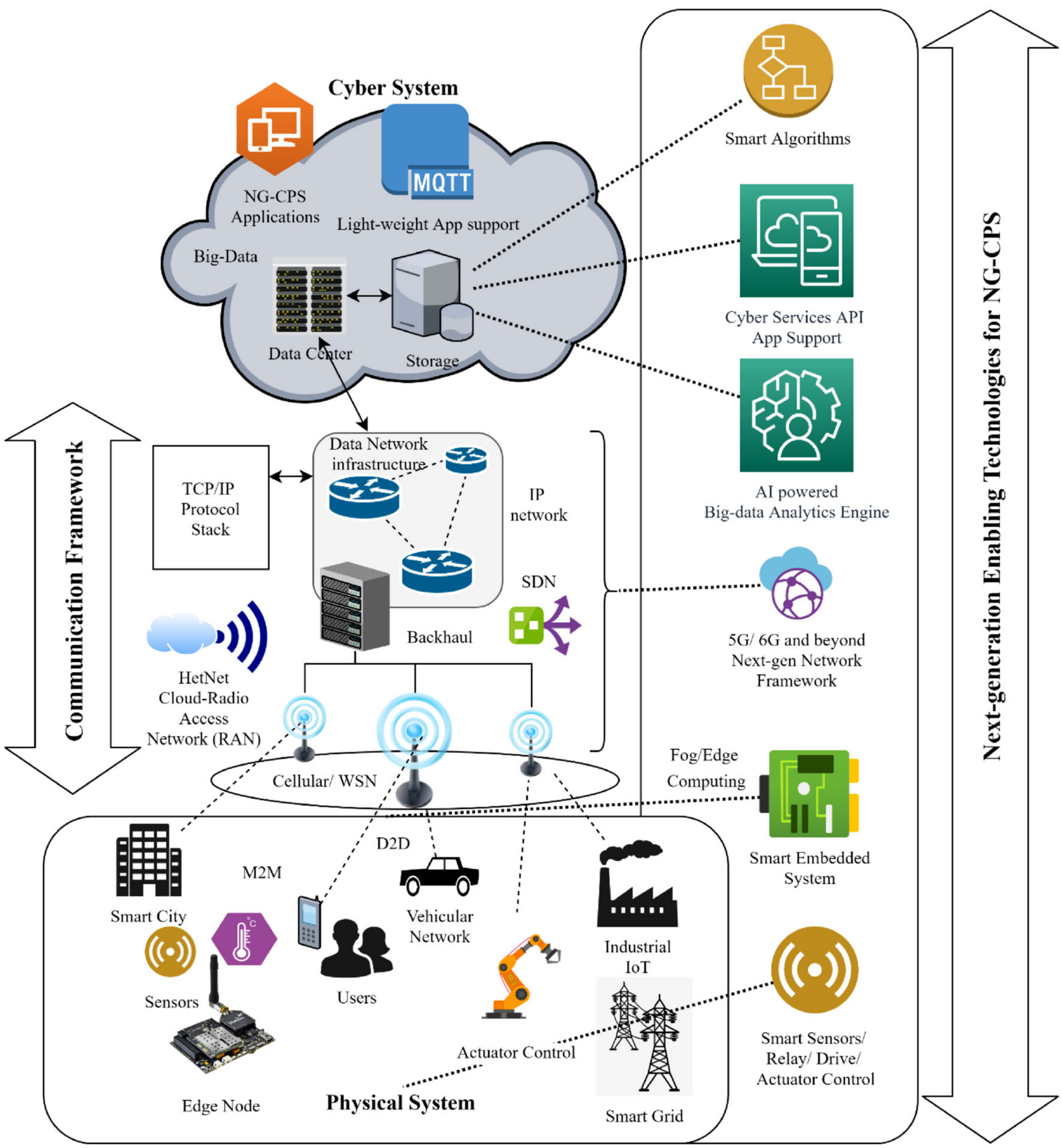

Fig. 7 NG-CPS: A bird-eye view

harvesting techniques for wireless sensor motes would be the pathfinder technologies for future self-sustainable physical systems in the context of NG-CPS. To be very specific, the research objective in this domain would be designing systems, techniques, and methodologies to make the physical systems like IoT-enabled embedded systems, sensors, signal processing, and conditioning modules and circuitry being energy-efficient with amalgamation to energy-harvesting techniques to make the physical system self-sustainable in-terms of energy requirements. Further, the recent research trend shows that Fog and Edge computing can be used on the end devices to enhance computing capability. The current research trend shows a substantial amount of research being carried out in the Mobile Edge Computing (MEC) domain using computing off-loading schemes. Sensors and actuators are important to interact with the physical world; hence, advances in modern sensor technologies would be the key to achieve a wide range of NG-CPS applications. Only sensing the physical world and generating digital data is not the requirement of NG-CPS. However, controlled actions in the physical world through the cyber world are a key requirement of NG-CPS. Hence, the technological advancements in actuator control through the more sophisticated relay, drives, and control systems are the need of the time for NG-CPS applications.

4.2 B. Communication framework

The NG-CPS needs state-of-the-art network technologies as a communication framework for NG-CPS, connecting cyber and physical systems. Recent advancements in telecommunication systems like NGN technologies like 5G/6G and beyond have promising contributions towards realizing an NG-CPS in a true sense. Recent 3GPP standard Release 14 onwards has support for features like Ultra-Reliable Low Latency Communication (URLLC), Enhanced Mobile Broad-Band (eMBB), Massive Machine Type Communication (mMTC), convergence, and even support for Heterogeneous Networks (HetNets). The NGN standards has some emerging technologies to achieve such modern communication functionalities, like Heterogenous Could Radio Access Network (H-CRAN), Software Defined Network (SDN), Network Function Virtualization (NFV), Machine-to-Machine (M2M), Device-to-Device (D2D) communication support, network splitting with separate user and control plane. Most of the network functional blocks of 5G/6G and beyond have become software implemented on generic cloud base computational platforms for all signal processing and networking functions rather than Application-specific Integrated Circuit (ASIC) type design of conventional telecommunication systems. Such cloud-based computing platforms can be achieved with the aid of Node-C (Cloud Node), gNodeB and Remote Radio Heads (RRH), and the Time wavelength division multiplexing (TWDM) based Passive Optical Networks (PON) based network backhaul. On the radio access network, unlike the orthogonal multiple access (OMA) techniques, the current research suggests that non-orthogonal multiple access (NOMA) would be more suitable for 5G/6G and beyond the next-generation network infrastructure the key to designing NG-CPS.

The NGN is mostly a packet-switched data network, making it more suitable for NG-CPS applications as it follows the generic TCP/IP stack. Since IPv6 has 2^{96} times more address space than IPv4, IPv6 protocol support for such NG-CPS is inevitable as it would be suitable for massive-scale deployment of end-nodes. NG-CPS's network and communication framework also need support for convergence with other network technologies like WSN and 6LRWPAN (IPv6 over Low -Power Wireless Personal Area Networks), Zigbee, and LoRaWAN (Long Range Wide Area Network) etc. Many real-world deployments of machine-type communication demand wireless PAN (Personal Area Network), LAN (Local Area Network), and WAN (Wide Area Network) support as per the range and scenario-specific to the NG-CPS applications.

4.3 C. Cyber system

Since the physical system and cyber system are digitally twined, thus, the efficacy of the physical system cannot be achieved without adequately enabled technologies for the cyber system. The key enabling technologies for cyber systems in NG-CPS are the cloud, big-data, AI, and ML-powered robust analytics support. Recent research suggests there is a substantial amount of research undergoing in cognitive CPS (CCPS). In a nutshell, the CCPS are systems with cognitive functional abilities with the help of computational intelligence techniques like AI and ML. The massive data acquired through billions of sensor nodes and smart devices must be structured, pre-processed, and analyzed properly to extract meaningful information. This is necessary to enhance user data visualization and effective decision-making in the physical world actionable events like user notification, on-demand actuation, machine control applications, etc. Last but not least, the application layer of NG-CPS would require a lightweight machine-type application protocol framework like MQTT and CoAP etc., for constraint battery powered edge devices. Smarter applications, algorithm and Internet API supports are inevitable to realize the NG-CPS for enormous next generation applications.

5 Smart city as an NG-CPS

This is worthy to recall that the NG-CPS has a wide range of applications, including the smart city. In this section, we design a smart city as a NG-CPS based on the proposed NG-CPS framework called smart city NG-CPS (Sc-NGCPS). The cyber and physical components of the Sc-NGCPS are interconnected using the proposed CPS protocol stack.

The potential use cases of smart city NG-CPS are generally diverse but exhibits similar cyber-physical characteristics as summarized follows.

- ***Integration:*** The integration of real and virtual world components of an Sc-NGCPS in a dynamic environment.
- ***Interaction:*** The interaction among the various units of the cyber system and physical systems is achieved through communication networks, which act as the backbone of the Sc-NGCPS.
- ***Real-time Computing:*** The data from the physical and cyber units of the Sc-NGCPS must be computed, analyzed, and processed in real-time.
- ***Self-adaptation:*** The Sc-NGCPS involves many wireless sensors network, which must be self-configurable, self-adaptable, self- organizing.

5.1 A. Architecture of smart city NG-CPS

A framework for a generic architecture of smart city NG-CPS (Sc-NGCPS) based on the proposed NG-CPS framework is as shown in Fig. 8. A Smart city CPS integrates the physical world (resources, utility infrastructure) with the cyber world (sensors, actuators, ICT, and other advanced computing technologies). A generic smart city encompasses many applications such as smart grid, utility management, smart hospitals, smart healthcare, smart business, industry, smart transportation, smart home, smart governance, etc. These domains constitute the physical components of the Sc-NGCPS. The sensors and actuators are deployed as physical objects across various applications in a smart city.

The physical system communicates its data to the control center used for monitoring the physical system. The control center acts as a cyber system in the Sc-NGCPS. The control center has a database, servers, processors, etc., to facilitate computing, processing, and analyzing the data. Moreover, the cyber components of the Sc-NGCPS constitute the burgeoning computing technologies such as BigData, ML, AI, etc., to enhance the capabilities of the cyber system.

Nevertheless, there exists a communication framework that is used to connect the cyber and physical systems. It is worthy to recall that the different physical objects also need communication support for communicating the data among themselves. On the one hand, the physical objects can use Bluetooth, ZigBee, etc., communication technologies for interacting within the physical system. On the other hand, the IoT, 5G, 6G, and other communication technologies are required to provide more comprehensive networking support between cyber and physical systems.

5.2 B. Smart city NG-CPS implementation framework

The IoT, ML, and M2M are the technology enablers for several next-generation applications (Kim et al. 2014). We now propose the potential applications of such technologies for a generic smart city next-generation cyber-physical system. The framework of Sc-NGCPS using ubiquitous IoT and ML technologies is as shown in Fig. 9. The components of the physical systems are designed with an embedded system aided with MCU or MPU (application-specific) at the core. In an industry with ARM® architecture, many players are operating in this segment. However, the prominent market shares in embedded IoT are by some leading brands like Microchip, Cypress, Intel, Raspberry Pi, Texas Instruments, Espressif Systems ESP-8266, NodeMCU, and Arduino. New generation embedded systems are optimized for low power with higher computational efficiency. These embedded systems are integrated with modern network technologies such as IEEE 802.11, BLE, M2M, LTE, 5G, and LoRaWAN, etc. (Kibria et al. 2018). These modern network technologies make the embedded system best suitable for Sc-NGCPS. The support for modern software tools, including scripting language such as python, is considered an accelerator for development, provisioning, and deployment of Sc-NGCPS with key enabling technologies like IoT, M2M, etc. (Jha et al. 2021d).

- In a nutshell, any IoT and ML-based solutions have the following building blocks (Xu et al. 2018):
- Embedded system and development board such as SoC, MCU/MPU with Integrated Network Adaptor
- Analog sensors, signal conditioning circuits, ADC with SPI or I2C interface to the MCU/MPU development board
- Digital sensors/ camera with GPIO interface to MPU/ MCU
- Relays and actuator control for the physical world and mechanical systems
- A power supply unit with battery for mobile and remote deployment scenario

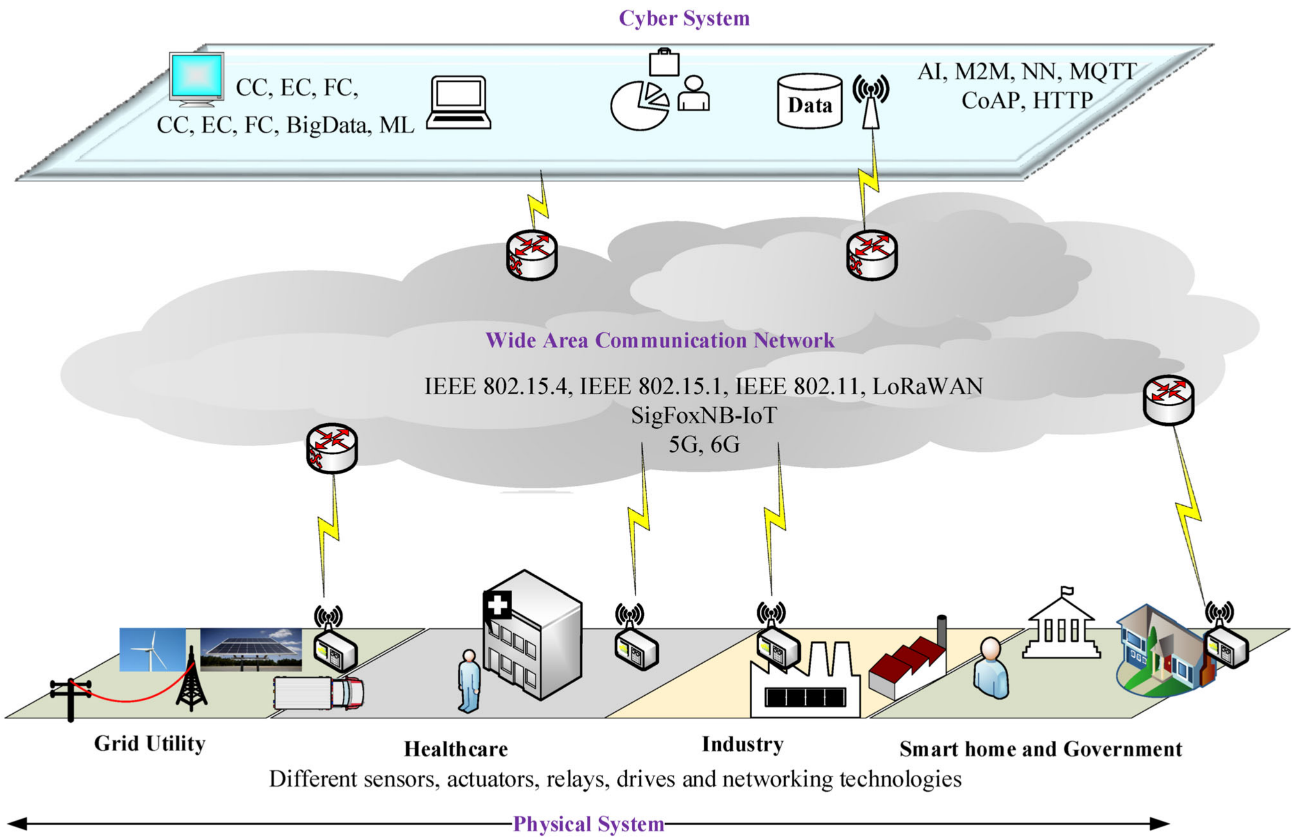

Fig. 8 Smart city CPS using proposed CPS framework

- Communication protocols and standards
- Cloud and sensor database integration (AWS, Microsoft Azure, IBM Bluemix, Google Firebase, MySQL, Thing Speak etc.)
- User Interface (UI/UX) for web-based data visualization, notifications, mobile app, etc.

The researcher and engineering communities are relentlessly trying to revolutionize the human–machine interaction. The advancement contributes the paradigm shift in technologies like AR and VR. AR and VR are fascinating fields where we get machine experience in the whole 3D rather than classical 2D (Aazam and Huh 2016; Munir et al. 2017). Multiple layers of interactivity and info panels can be added to these applications to make them more human-friendly. The ARM® System-on-Chip (SoC) based latest devices are powerful enough to handle many complex algorithms like image & speech processing, cryptography, sensor signal acquisition, signal conditioning, and even edge computing at the same time with optimized power consumption. These low-power devices are befitted for a battery-powered scenario like WSN and IoT. Developers and designers all across the globe are integrating these embedded smart devices into cyber infrastructure to realize efficient and scalable CPS.

5.3 C. Communication and protocol stack for smart city NG-CPS

Various research work proposes different network and protocol stack implementations for developing IoT and CPS (Ding et al. 2020; Jha et al. 2021c; Mishra et al. 2019; Mishra and Mohapatro 2019; Appasani et al. 2021b). The core of every protocol stack implementation is the TCP/IP. The layered architecture of TCP/IP is customized as per scenario-specific requirements of any NG-CPS. Figure 10 depicts the network protocol stack & implementation supporting generic smart-city NG-CPS. The bottom-most part is the physical system comprising various smart-city application-specific sensors and actuators connected to the physical world. An IoT system is nothing but seamlessly connecting sensors and actuators to the Internet as the network infrastructure (Cyber space).

This architecture of IoT makes it a multi realm system. Part of the system is in physical space and part in cyber space, making it a cyber-physical system. The physical system performs either data acquisition from connected sensors or controls relays, drives, and actuators to reflect actions in the physical space of the smart city. The sensors and actuators are interfaced with the embedded system to

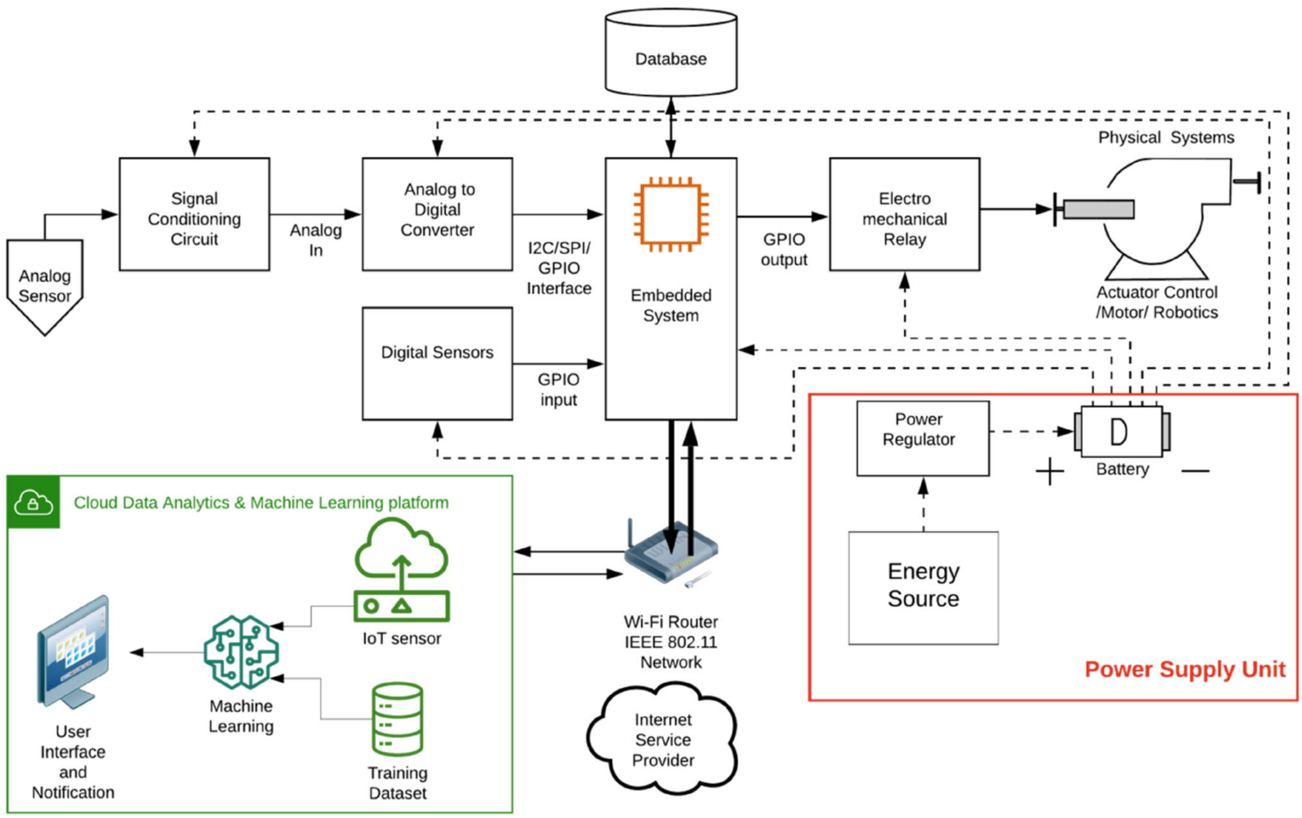

Fig. 9 A Proposed generic Smart City NG-CPS implementation framework using IoT and ML

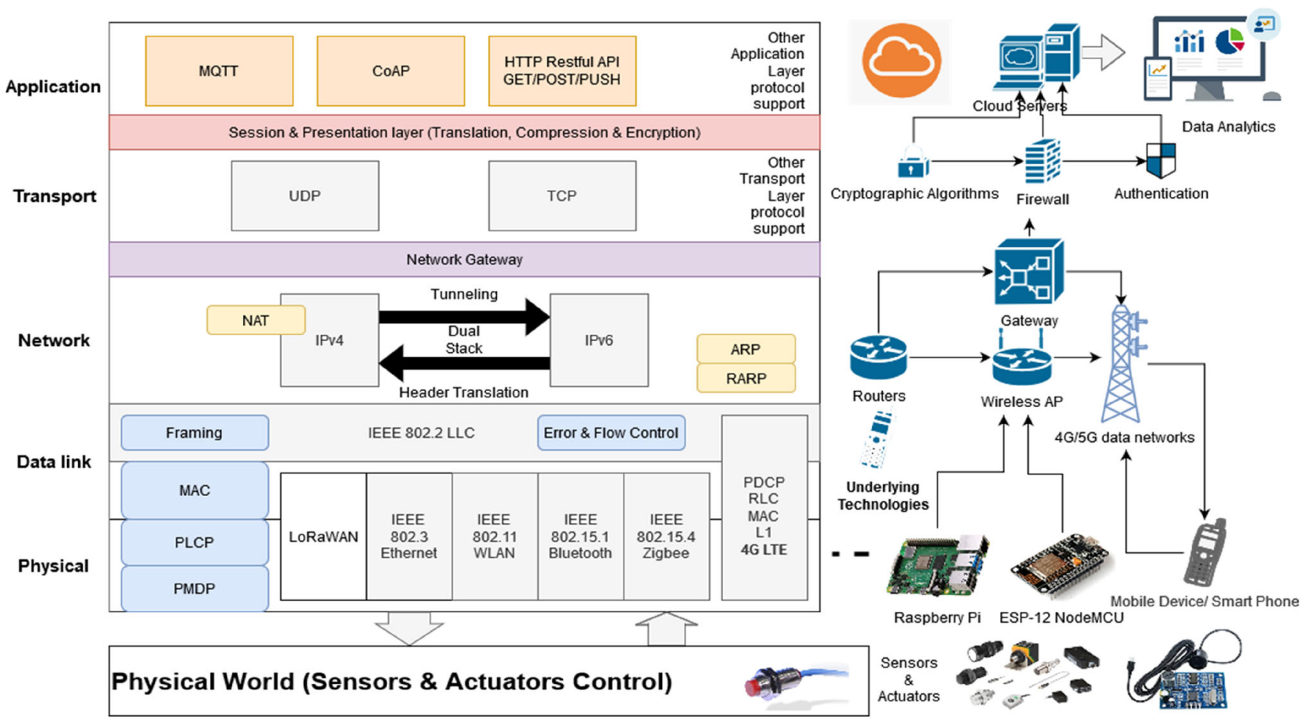

Fig. 10 A generic communication framework & protocol stack for Smart-city NG-CPS implementation

Table 3 Smart-city NG-CPS design & deployment aspects: A technical summary

Technology	Power consumption (Typical)	Computation resources (Typical)	Application
Processors/Embedded Platforms for Smart Nodes			
Micro-Controller Unit (MCU) based System	< 1 W	CPU Clock: < 10 MHz RAM: few KB	Suitable for WSN application with Long battery life
ARM RISC-based SoC	1–40 W	CPU Clock: 700 MHz–1.8 GHz, RAM: 1–4 GB	Suitable for battery powered constraint nodes/ Edge-device / End-node
Intel/ AMD CISC-based MPUs	100–200 W	CPU Clock: 3–5 GHz, RAM: up to 128 GB	Suitable for more computationally intensive cloud-based central nodes, Data-centres. Servers etc

Type	*Smart-city Applications*
Sensors and actuators	
Ultra-sonic sensor	Level sensing, Water-level, Object tracking, short-distance sensing
Piezoelectric sensor	Sound, vibrations
Magnetic/Hall effect sensor	Detection, localization of ferromagnetic objects
Optical sensor	Non-contact measurements, image, line-of-sight (LoS) communication
Infra-red sensor	Intrusion detection, Object tracking, counter, IR imagery, LoS control
Accelerometer	Movement, Acceleration, vibration, shock, direction, force
Gyroscope	Orientation, Localization
GNSS	Position, Localization
Opto-coupler/Relay/Drive	Actuator Control

Technology	Frequency Band	Range	Bandwidth	Data-rate	Latency	Application
Communication & network technologies						
Zigbee (IEEE 802.15.4)	2.4 GHz (ISM)-Worldwide 784 MHz (China), 868 MHz (Europe) and 915 MHz (US/ Australia)	10–100 m	2 MHz	250 Kbps	< 200 ms	Short-range WPAN, WSN
Bluetooth Low Energy (BT.5) (IEEE 802.15.1)	2.4 GHz (ISM)	100–400 m	1–2 MHz	2 Mbps	20–40 ms	Medical, Smart home/ peripheral device (WPAN)
Wi-Fi (IEEE 802.11n/ac)	2.4 GHz & 5 GHz (ISM)	35–70 m	20–80 MHz	100 Mbps–1 Gbps	36 ms	Gateway (WLAN)
LoRaWAN	433/470/780/868/ 915 MHz	2–7 k.m	125–500 kHz	< 50 Kbps	< 400 ms	Long-range sensor network (LRWAN)
SigFox	868–869/ 902–928 MHz	10–40 k.m	100–600 Hz	100–600 bps	20–25 s	Long-range sensor network (LRWAN)
NB-IoT	700 MHz–2.5 GHz	1–10 k.m	200 kHz	< 250 Kbps	1–10 s	Cellular-M2M

Table 3 continued

Technology	Computational Resource	Bandwidth requirement	Latency	Application
Computing				
Cloud computing	High	High	More	Data intensive Analytics
Edge/Fog Computing	Low	Low	Low	Edge, MEC, Latency optimized
Hybrid Edge-Cloud	Load-balancing	Moderate	Moderate	Hybrid Edge-Cloud (Combination)
Cognitive AI & ML techniques				

Technique	Application
Machine Learning (ML)	Prediction, Classification, Regression, Extraction etc
Neural Networks (NN)	Recognition, Semantic parsing, Translation, Classification, Extraction etc

Technique	Application
Storage and data management	
Cloud	Centralized data storage and management
Big-data	Data Science, Hadoop based tools etc
Edge-cloud	De-centralized data storage and management

Protocol	Application
Application protocols	
MQTT	Light-weight, Broker based Centralized Pub/Sub based architecture over TCP/IP
CoAP	Light-weight -One-to-One architecture for constraint devices over UDP/IP
HTTP	Connection-oriented, guaranteed, over TCP/IP

interface with the physical world. These embedded systems (edge devices) to the internet infrastructure make the system a typical NG-CPS. In the cyber system, the complete TCP/IP stack is implemented.

From a bottom to top perspective, the first layer is the physical layer having two sub-layers: Physical Media Dependent Protocol (PMDP) and Physical Layer Convergence Protocol (PLCP). The physical layer of the CPS supports several heterogeneous network standards such as BLE, ZigBee, Ethernet, LoRa, 4G-LTE, 5G-NR, and 6G networks, to integrate physical systems into the cyber system. Layer-2 is the data link layer consisting of media access control (MAC) and logical link control (LLC) sublayers. The third layer is the network layer, which is mostly implemented for integrating several networks. The fourth layer is the transport layer, which supports both connection-oriented transmission control protocol (TCP) and connection-less user datagram protocol (UDP) protocols. The fifth layer is the application layer which is solely application specific. Security features like encryption, authentication, etc., are implemented in this layer. Primarily, from the Sc-NGCPS perspective, message queue telemetry and transport (MQTT) and constraint application protocol (CoAP) protocols are implemented over UDP for service provisioning. Smart city NG-CPS applications even use HTTP restful APIs (GET, POST, PUSH methods) over the reliable TCP connection to guarantee service.

5.4 D. Smart city NG-CPS design aspects: a technical summary

We have discussed the various practical design and deployment aspects of smart city NG-CPS implementation. However, in order to summarize our proposal, we are now presenting a technical fact-sheet in Table 3, which is referred from the datasheet available at corresponding standardization organizations (Broy and Schmidt 2014; Serpanos March 2018; Cyber-Physical Systems—A Concept Map. 2021). These data are vital in the design of smart city NG-CPS as it covers technical aspects pertaining to the practical implementation of smart city NG-CPS. In this summary, the broad spectrum of the most relevant technologies along with their features is presented. The summary is envisioned to provide a complete technical depth to the researchers and scientists to implement a smart city as an NG-CPS.

6 Conclusion

The future is of intelligent machines having seamless integration of cyber-physical components for effective real-time interaction. The various technological enablers, such as IoT, M2M, etc., have immensely contributed to the CPS's advancement for several next-generation applications. Thus, the CPS has emerged as a burgeoning technology, which has a huge scope in terms of employability and market share in the coming days. This paper has presented the most comprehensive technical overview on several emerging technologies with their aim, scope, and use cases from the perspective of NG-CPS. Further, a generic architecture of the NG-CPS is proposed with in-depth architectural analysis, including different layers, physical system, cyber system, communication infrastructure, and protocol stack. Also, the scope of different emerging technologies with challenges and issues has been comprehensively reviewed in the paper. Moreover, the smart city is considered one of the next-generation applications envisioned using the proposed NG-CPS architecture. The different enabling technologies with challenges and issues have been comprehensively analyzed for its practical implementation, spanning cyber system, physical system, and communication infrastructure. The state-of-the-art requirements of the designed smart city NG-CPS is also summarized in the paper, which author believe to provide an extra edge to the researchers from the design aspects.

Funding These is no funding statement to declare. No funding has been received for this work. However, authors have used general resources like library and computing facilities from their Institute of affiliation (KIIT Deemed to be University, Bhubaneswar, India).

Declarations

Conflict of interest The author(s) declare(s) that there is no conflict of interest.

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