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Cyber-Physical-Social Systems: A State-of-the-Art Survey, Challenges and Opportunities

Yuchen Zhou, F. Richard Yu, *Fellow, IEEE,* Jian Chen, *Member, IEEE,* and Yonghong Kuo

***Abstract*—It is the overriding trend of the present-day world that traditional systems and mobile devices are currently transforming into intelligent systems and smart devices. Against this backdrop, cyber-physical systems (CPSs) and Internet-of-Things (IoT) emerge as the times require. To achieve the parallel interactions between the human world and the computer network, IoT along with wireless mobile communication and computing open up some future opportunities as well as challenges for constructing a novel cyber-physical-social system (CPSS) that takes human factors into account during the system operation and management. In this article, a brief comprehensive survey is provided on some of the current research work that contributes to enabling CPSSs. Some crucial aspects of CPSSs are identified, including: the development from CPSs to CPSSs, architecture design, applications, standards, real-world case studies, enabling techniques and networks for CPSSs. To lay a foundation for the development of the upcoming smart world, we further propose a virtualization architecture and an integrated framework of caching, computing and networking for CPSSs. Simulations verify the performance improvement of the proposals. At last, some research issues with challenges and possible solutions are unearthed for researchers in the related research areas.**

***Index Terms*—Cyber-physical-social systems, Internet-of-Things, cyber-physical systems.**

I. Introduction

THE emerging technique innovations dramatically change people's lives in all aspects, such as industry, agriculture, transportation, medical treatment and other similar things. At the same time, they also bring new trials to the traditional physical devices. Taking the information systems as examples, it is easy to recognize that the traditional information systems are usually based on embedded devices with the closed characteristics. These systems are unable to satisfy the application requirements of the interaction, control and extension of physical devices. Therefore, with the development of information technology, *cyber-physical systems* (CPSs) have gradually become the mainstream of the current developing technique to replace the traditional information systems [1], [2].

CPSs are intelligent systems, where sensors, actuators and controllers are embedded to support the interaction between the physical world and the cyber world [3]. CPSs usually contain three layers, namely, the perception layer, the transport layer and the application layer [4]. The perception layer is used to acquire the perceptive information and to execute the feedback decisions. The transport layer, including the network layer, the medium access control and the physical layer, is used to transfer the information and decisions among different system elements. The application layer, which can also be viewed as the control layer, is mainly used to make decisions according to the analyzed results of the perceptive information. This architecture with the layered view is widely used in different kinds of CPSs. These CPSs can be explored in various application fields, such as transportation, factories, electric vehicles, smart grid and so on.

As the network applications in the traditional embedded information systems continue to deepen, researchers begin to emphasize the union of the network and the human society, thus realizing the interaction between the physical society and the network society [5]. In this context, *cyber-physical-social systems* (CPSSs) emerged, which are also known as the association systems that integrate the computing, physics and human resources [6], [7] and enable the coordination among the cyber, physical and social worlds [8]. CPSSs support self-synchronization, parallel execution and supervisory control in physical, information, cognitive and social domains [7], so that it is able to provide an ideal paradigm to achieve the design and construction of a smart environment with command and control organizations.

Compared with CPSs, CPSSs regard humans as a part of the system, and put humans in the loop. Through the intelligent human-computer interaction, CPSSs take human factors into account during the system operation, so that the element "people" can be accommodated in the supervision process of the system [7], [9]. Unlike the operation and management of traditional CPSs, humans in CPSSs can be viewed as not only the service consumers but also the service providers. CPSSs need to know the capability of a person before putting humans in the loop, which means in a given context, it is necessary to know what a person would choose to do and his ability to perform the task. The main challenges while further integrating the social space mainly come from the fact that the way people work is different from computers. People do not accomplish the task in the same way every time, and sometimes they may choose not to follow the instructions without notice. When compared with the computers, we may say that people are less reliable; however, people have a better ability to adapt to the dynamic environments, and can always come up with

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Y. Zhou, J. Chen and Y. Kuo are with the State Key Laboratory of Integrated Service Networks, Xidian University, Xian 710071, China (E-mail: ychenzhou@163.com, jianchen@mail.xidian.edu.cn, yhkuo@mail.xidian.edu.cn).

F. Richard Yu is with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S5B6, Canada (E-mail: Richard.Yu@carleton.ca).

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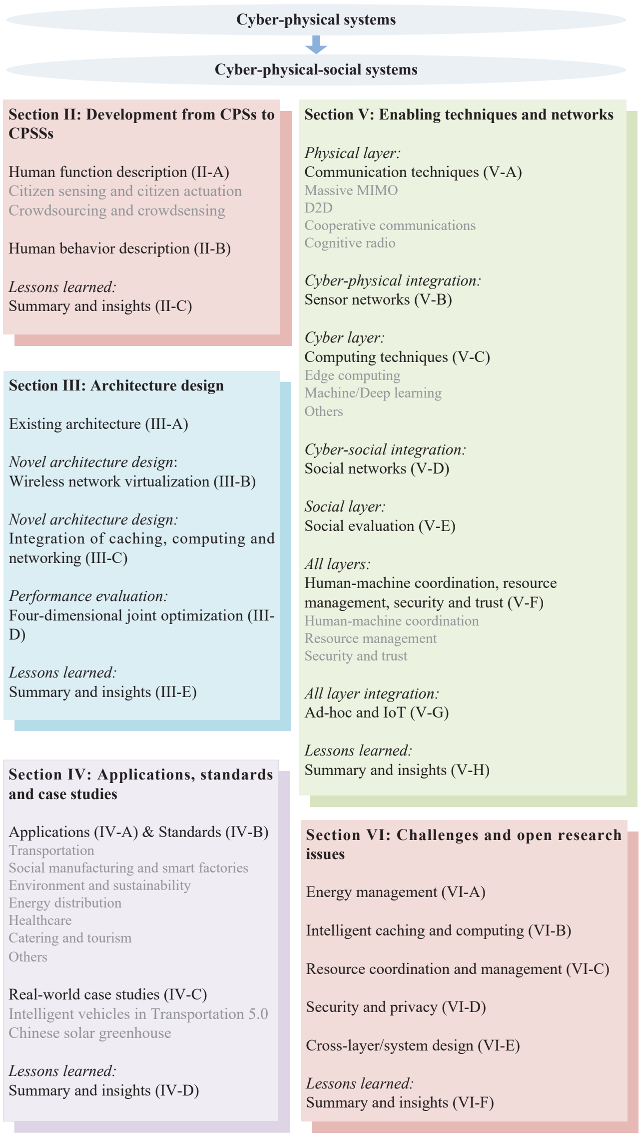

Fig. 1: Roadmap of this article.

innovative solutions. Therefore, CPSS designers need to take the human characteristics into consideration while designing and optimizing CPSSs, thus enabling the interaction among people, computers and other devices.

Against this background, this article aims at providing a comprehensive survey on the existing works related to CPSSs. Even though there exist some surveys about intelligent systems, most of them focus on CPSs. Among the existing research, some of them discuss the CPS application only in a certain field, such as the platoon-based vehicular CPS [10], industrial Internet [11], smart grid [12], [13], wind energy conversion systems [14] and healthcare [15], [16]. Others discuss a certain kind of research issues or techniques during the CPS applications, such as security [15], [17] and machine intelligence [16]. [18] and [19] respectively review the existing works about healthcare and smart cities in Internet-of-Things (IoT) instead of CPSs. However, the former has the limitation of application areas, while the latter only discusses from a data-centric perspective. The authors in [20]–[22] respectively highlight some recent advances in social manufacturing, smart grid and intelligent transportation. These surveys provide a brief investigation of CPSSs in a certain application field. Bedsides, [21] only aims at the research topics of deep learning and reinforcement learning, and [22] just has an emphasis on the significance of traffic data management in transportation.

Different from the existing surveys, this article shows a comprehensive discussion on CPSSs that integrate CPSs with social space. The discussion is not limited to a certain application field or a certain research topic. In addition, we focus on the function of humans in CPSSs, but the discussion is not restricted to the social part of CPSSs. Fig. 1 presents a taxonomy graph of our approach towards CPSSs. As shown in Fig. 1, we identify five aspects of CPSSs, on which we would like to focus: i) development from CPSs to CPSSs, ii) architecture design, iii) applications, standards and case studies, iv) enabling techniques and networks, and v) challenges and open research issues.

The rest of the article is organized as follows. In Section II, we explore the current technique development from CPSs to CPSSs. Section III mainly focuses on the discussion of the existing CPSS architecture and the proposals for promoting CPSS design and optimization. In Section IV, we discuss the existing research related to the CPSS applications, some common standards and real-world case studies to reveal how the different components, standards, frameworks or protocols orchestrate CPSS functions. Section V discusses some of the enabling technologies and networks to further promote CPSSs with hyper-connectivity, hyper-intelligence and hyper-automation. In section VI, some research issues with challenges and possible solutions are unearthed for researchers in the related research areas. Finally, we conclude this article in Section VII. This article is beneficial for future research on CPSSs, as it comprehensively investigates and surveys the current research status of CPSSs, and inspires readers to make more contributions to its developments.

II. Development From CPSs to CPSSs

Actually, a comprehensive introduction of CPSSs was first accomplished in 2010 [6]. The authors in [6] point out that the social and human dynamics should be considered as an integral part while designing CPSs, so that the cyber space, the physical world and the human resource can be effectively coordinated and integrated in CPSSs, which bring us an era of smart enterprises and industries. In recent years, with the research on CPSs leading to a number of astonishing technical solutions in various application domains, the topic of CPSSs is mentioned once again [23], [24]. Researchers focus on the individual human beings as an integral part of CPSs, and the paradigm shift from traditional CPSs to CPSSs [24], which is otherwise known as enhanced living environments (ELEs) [25]. In this section, we will discuss what roles humans can play and how to put humans in the loop of CPSSs.

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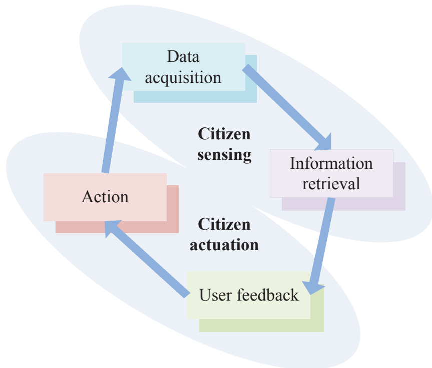

Fig. 2: Feedback loop of citizen sensing and citizen actuation.

A. *Human Function Description*

With the popularity of the concept of CPSSs, scholars begin to consider and discuss how humans play a part in the loop. The first thing we need to know is the purpose of humans in CPSSs. In fact, humans in CPSSs are similar to most users in existing systems, where they are regarded as consumers to access to services and information. However, humans in CPSSs can also be viewed as service providers to serve the system or other users.

1) Citizen Sensing and Citizen Actuation: The concepts of citizen sensing and social actuation are introduced to describe the function of humans in CPSSs when they work as service providers. Citizen sensing [26] focuses on collecting information and extracting useful ones, where citizen sensors are utilized to collect and report data. Citizen actuation [27] aims to produce the actionable items, and utilizes citizen actuators to affect surroundings.

Fig. 2 illustrates the feedback loop of citizen sensing and citizen actuation. The fist stage of the loop is data acquisition, in which the state information is collected and processed with a richer context. The second stage is information retrieval, where the information is acquired by users through visual representations, such as graphs, videos and warnings. The third stage is user feedback that returns the gain from what users report. The forth stage is action, in which users complete their actions or just make a choice. Afterwards, the action and choice will react on the system, and bring in a new feedback loop.

Consider that during the procedure of citizen sensing, a group of citizen sensors may report the surrounding physical environments with different degrees of uncertainty. The authors in [26] develop a confidence-aware truth finding scheme, which is formulated as a constraint optimization problem with the consideration of the different degrees of user confidence and uncertainty. The presented scheme is able to ascertain the source reliability and the claim correctness. The proposal is evaluated through extensive simulations, and the results validate the performance advantages when compared to other baselines.

A joint citizen sensing and actuation platform is first proposed by the authors in [28] for the energy management with Twitter integration. The authors indicate that the introduction of citizen actuation is beneficial for improving energy utilization, and the experiment shows the energy usage can be reduced by 24% averagely. Afterwards, the authors further present a citizen actuation framework in [27] and [29], where the tasks assigned by CPSSs can be sent to suitable occupants, and the authors outline the method for selecting the occupants to complete tasks according to social media profile features.

2) Crowdsourcing and Crowdsensing: Similar to the concepts of citizen sensing and citizen actuation, crowdsourcing and crowdsensing are known as two core building blocks, which can be viewed as the intersection point of things and human-based techniques [30].

Crowdsourcing acquires services and valuable ideas from a group of people. The solutions from crowdsourcing are mainly based on crowd wisdom, and most of the decisions made by crowd lead to the outstanding results when compared with the decisions made by individuals or computers. Crowdsensing adopts the similar principle to promote sensing area coverage and data quality through the inertial sensors of human mobile devices without the implicit cost of traditional sensor networks.

In order to support the social applications of crowdsourcing and crowdsensing, and to enable the distributed data analytic platform for CPSSs, [31] proposes CARDAP that is defined as a scalable, energy-efficient, generic, distributed and extensible component-based data analytic platform. The platform involves the on-the-move activity recognition and the data delivery strategies based on real-time data mining, and is designed for mobile crowdsensing applications to bring advantages in terms of energy, resource and processing efficiency.

Note that most of the existing smart environments often remove the users from the control loop, which may make people feel disengaged with environments. For example, heating systems and automated windows in smart buildings are always controlled centrally without any user input [27]. Contribution of humans is a key factor in CPSSs. The rise of these human-based technologies promotes the transformation from CPSs to CPSSs. Now, after figuring out the purpose of humans in CPSSs, we turn to the problem of human behavior description.

B. *Human Behavior Description*

Consider that most systems are designed to satisfy the users' requirements, since in these systems, users are regarded as service consumers. In CPSSs, it is also necessary to explore the dynamic behaviour of user participation when they are regarded as service providers. For example, when will a person participate in CPSSs, and when will he or she terminate? What is the identification of this person when he or she participates in? What kind of work that he or she can do? How do we motivate people to participate in the operation of the system in a good behavior?

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In CPSSs, humans will work together with other components, such as controllers, sensors, actuators, data stores and processing. They can perform or assist to complete various tasks according to their capabilities of sensing, storing and processing data. However, humans are different from computers. They may interrupt the tasks without bodement, and in different time periods, the capability of each person to accomplish the same task may be totally different, which brings about different results. All of these will bring great difficulties but need to be considered in the development of CPSSs.

It is of great importance to design the human behavior description model, and the key points of designing the model for the operation of CPSSs can be concluded as follows [5]: i) The access of a person, ii) The identity of the person from a system perspective; iii) The tasks that the person can handle; iv) The qualifications for the person to accomplish the tasks; v) The way to contact with the person; vi) The termination of the person to perform the tasks. Furthermore, the dynamic nature of humans, such as sudden interruptions and innovative solutions, also needs to be taken into consideration during the design of the behavior description model. With the help of the human behavior description model, people can be assigned various tasks according to their abilities, thus facilitating CPSSs to putting humans in the loop.

To motivate humans to join in the CPSS operation and management in a good behavior, it is necessary to analyze the user-related data generated in the behavior description model, such as the user access duration and the quality report. These data reflect the user indicators in terms of user credibility, influence, academic level or professional quality. Along this line, humans can be classified into different groups with different levels of the indicators. The group of users with higher levels can gain a higher reward or a higher quality of services; otherwise, they will be punished, thus encouraging the users to contribute to the operation and management of the system.

C. Lessons Learned: Summary and Insights

To create an intelligent environment depends on not only the modern techniques but also the natural resources of its inhabitants. Namely, "things" and "humans" are both necessary to enable smart environments to become smarter. Humans can enjoy intelligent services through the high technology, and meanwhile dedicate to promoting the business intelligence. As the development of CPSs, CPSSs can be viewed as a core approach to realize the smarter environment. It acquires information from humans, and serves people with user awareness.

In the following sections, we will discuss the developments of CPSSs at the present stage and reveal some possible future trends, where the discussion includes but is not limited to the social part of CPSSs.

III. Architecture Design

In this section, we will first introduce the existing architecture of CPSSs with detailed description. Afterwards, we will discuss the motivation and requirements for enabling CPSSs with wireless network virtualization, and then propose a virtualized CPSS architecture. Third, to promote the pervasive CPSS computation services and the scalable content retrieval and delivery, we will further present an integrated framework of caching, computing and networking for CPSSs. At last, the performance of the proposed architecture will be evaluated and analyzed, and a brief summary and insights will be provided at the end of this section.

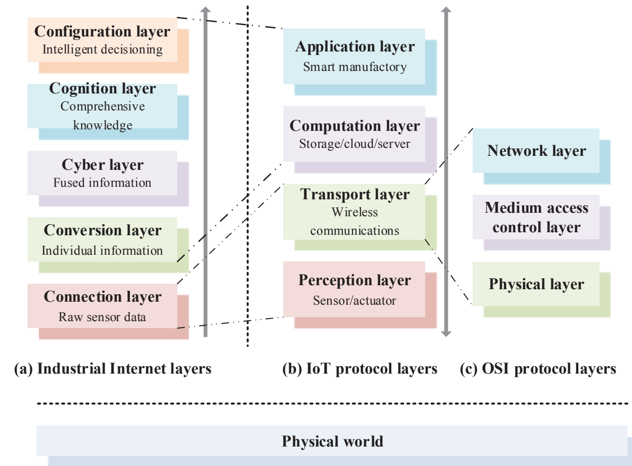

Fig. 3: Layered architecture of smart systems.

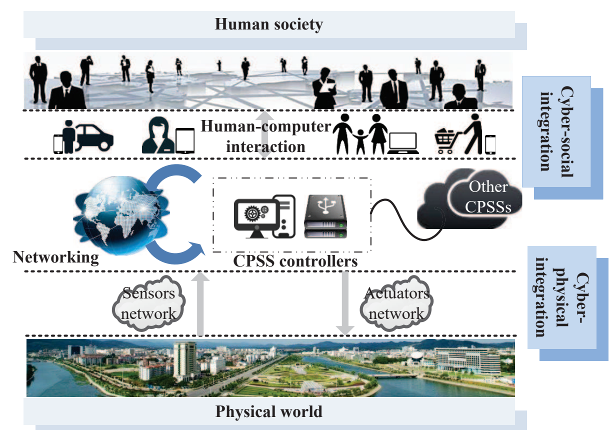

Fig. 4: Layered architecture of CPSS.

A. Existing Architecture

Fig. 3 illustrates two prevailing layered architectures of existing smart systems, where Fig. 3(a) and Fig. 3(b) respectively show the details of industrial Internet (also known as Industrie 4.0) and IoT protocols. Here, industrial Internet protocol can be viewed as the industry standard of a CPS-based application. As shown in Fig. 3(a), the architecture of industrial Internet consists of five different layers [11]: 1) The connection layer handles the accurate data acquisition from the direct sensor inputs, controllers or enterprise manufacturing systems in the physical environments; ii) The conversion layer converts the raw sensor data to the useful information, thus achieving

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self-awareness of physical components; iii) The cyber layer retrieves the useful information from the lower layer and provides data processing as a central information hub; iv) The cognition layer provides a comprehensive knowledge of the whole system through the gathered information from the lower layer, and achieves smart decision by big data analytics; v) The configuration layer offers the smart and adaptive control to the machine networks based on the smart decisions.

Due to the consistency of the design concepts, there exist some architecture similarities in Fig. 3(a) and Fig. 3(b). The connection layer in industrial Internet protocol could correspond to the perception layer and transport layer in IoT protocol. The layered architecture given in Fig. 3(a) dilutes the description of the wireless communications among various components, i.e., transport layer. Actually, this layer is equivalent to the physical layer, the medium access control layer and the network layer in the open system interconnect (OSI) protocol. The remaining four layers in industrial Internet protocol could correspond to the computer layer and application layer in IoT protocol, which are mainly used to achieve the data processing and smart decision.

The layered architecture of CPSS shown in Fig. 4 actually could be realized based on the existing protocols of CPSs and IoT. The cyber layer supports the intelligent data processing for smart decision making. Above this layer, there exists a social layer representing the human society, and below this layer, there exists a physical layer containing every component in the physical world. The physical layer and the cyber layer are connected by the sensor and actuator networks, and the humans in social layer participate in the CPSS system operation through novel social applications, such as citizen sensing, citizen actuation and so on. The details of these three layers will be discussed in the next subsection. In summary, CPSSs can be viewed as the development of CPSs. Even though CPSSs, CPSs and IoT all aim at realizing the intelligent monitoring of physical worlds, CPSSs prefer to emphasize the human effects on the system when compared with CPSs and IoT.

Actually, CPSS is an interdisciplinary subject still in its infancy stage. However, through investigating the existing research, we can find that the layered architecture of CPSS in Fig. 4 is approved by the academic circles, which is actually based on the existing academia and industry standards of CPSs. Actually, there exists a certain working basis for enabling the application practice of CPSSs. For example, intelligent transportation can be traced back to 2090s, where the University of California initiated the PATH project, i.e., Partners for Advanced Transportation Technology. The first CPS symposium was held in the United States in 2006. Industrie 4.0 high-technology strategy was put forward by Germany in 2013, and identified research towards industrial CPS as its backbone. The "Made-in-China 2025" ten-year strategy was launched by China in 2015, which aims at promoting the integration of industrialization and informatization. Actually, among the existing research, Industrie 4.0 is the only manageable protocol by using international standards. The reference architecture and the requirement specification for Industrie 4.0 are already available.

B. Novel Architecture Design: Wireless Network Virtualization

1) Motivation: IoT can be viewed as an effective medium to complete the interconnection of multiple distributed CPSSs [32], [33]. These CPSSs communicate over wired or wireless networks and generate massive amounts of data. To construct such an intelligent interconnection network, there are some design concerns that need to be taken into consideration during the deployment of the existing CPSS protocol.

- **Construction cost and scalability**: CPSSs contain abundant elements with a complex structure to support diversified functions in various application fields. To achieve such systems with the reduced construction and operation costs, the primary goals are to avoid redevelopment and redeployment of the same or similar infrastructures and resources, and take full advantage of the existed and limited ones. Meanwhile, the system should be developable to possess the scalability to other large systems or have the ability to extend to other innovative fields.
- **Business service and security**: Since CPSSs are widely used in all kinds of fields, the total number of covered facilities is growing rapidly. According to the survey, it is predicted up to 20.8 billion things that will be interconnected by IoT. This humongous number of devices will bring about the increasing amount of data traffic with diversified business services, which would bring a great burden to the limited network resources. In addition, since CPSSs deal with the physical world directly, it is expected to be highly secure, so that the users with security requirements can acquire a trusted and knowledge-based network environment.

Against this background, this article first proposes a virtualization architecture to overcome the above design concerns of CPSSs.

2) Architecture: Recent advances of wireless network virtualization (WNV) and software-defined networking (SDN) can be viewed as effective manners to realize the CPSS interconnection network and provide several benefits for its implementation.

- **Lower construction cost**: With the support of WNV, the utilization of generic hardware and advanced software contributes to reducing capital expenditures (CAPEX) and operating expenditures (OPEX) of network operators [34]. Through WNV, the infrastructures are decoupled from the services, and the devices with different service requirements can choose to access different virtual networks, while actually they share the same infrastructures, thereby promoting the system utility [35]. In this, WNV is able to achieve the reduction of the construction cost for the CPSS network.
- **High scalability**: Due to the abstraction and the standardization of the control plane by SDN, the evolution and the updating of networks and applications can be realized without upgrading network infrastructures [35]. Therefore, with the support of SDN, WNV is able to promote the scalability of CPSSs.
- **Service guarantee**: WNV is able to utilize not only the existing facilities but also the limited network resources

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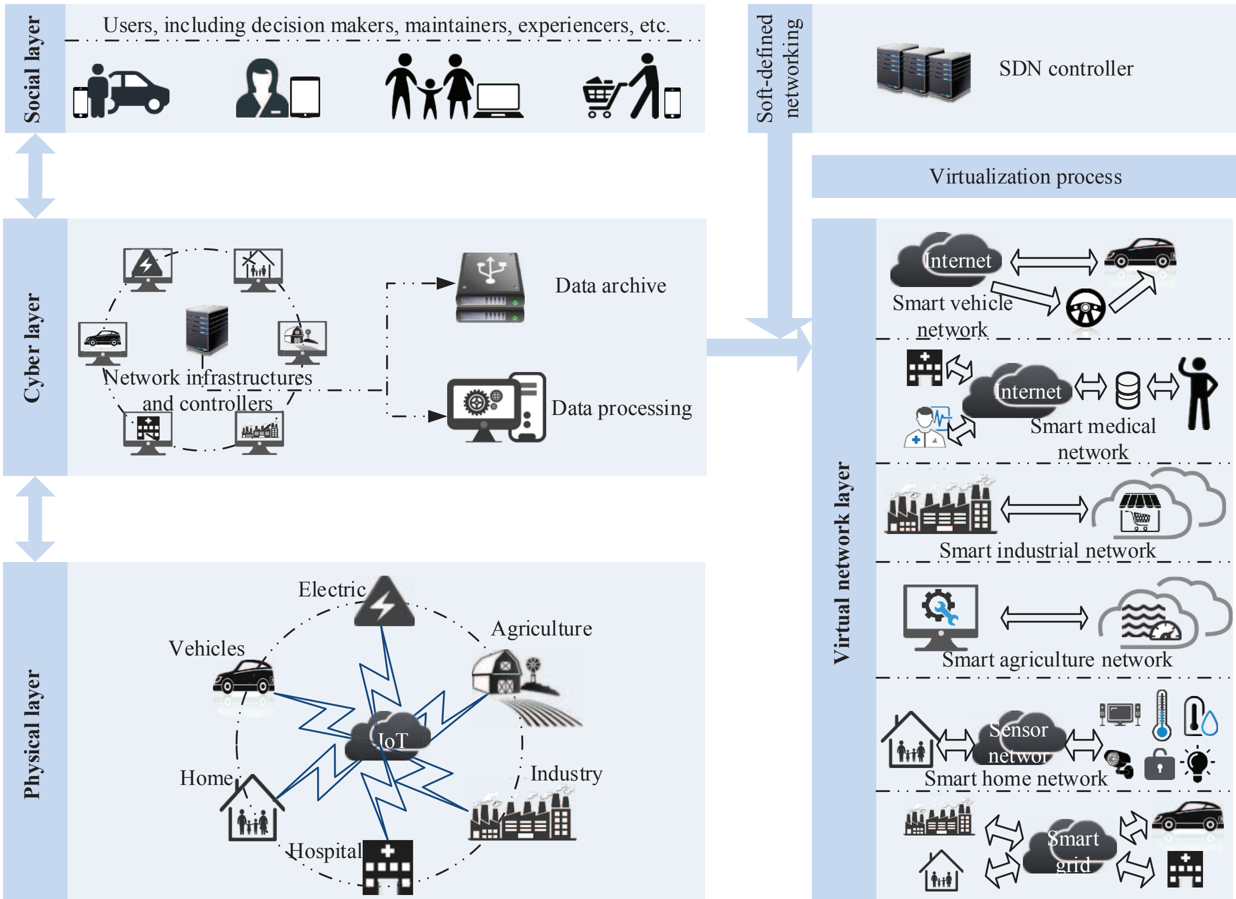

Fig. 5: A virtualized architecture for CPSSs.

to provide services for different business types, thereby improving the resource utilization [35]. In addition, through reasonable virtualized multi-resource deployment, the wireless communication requirements of the low-power consumption, the real-time performance and the transmission reliability can be better satisfied [36].

- **Security guarantee**: The devices requiring the services with different levels of secrecy can access to various virtual networks, and these virtual networks take various confidentiality measures, thus satisfying different levels of security requirements [36].

Fig. 5 illustrates the proposed virtualization architecture for CPSSs. The whole architecture can be divided into three layers:

- **Physical layer**: The physical layer covers widely distributed devices and infrastructures, and these facilities can be interconnected by IoT. They are involved in various fields, including home, electricity, traffic, hospital, industry and agriculture. Lots of sensors and actuators arranged in the physical layer could realize the intelligent monitor to the surroundings.
- **Cyber layer**: There exists a correspondence relationship between each of the computation modules in the cyber layer and each of the physical objects in the physical layer. The cyber layer can be regarded as a bridge to connect the physical layer and the social layer. The central controllers and the widespread distributed controllers in the cyber layer usually have the functions of the data archive and data processing. With the help of these controllers, the cyber layer supports the data collection, information collating and processing, decision making and assignment. Meanwhile, the cyber layer is able to provide some related services or tasks to users in the social layer, and also to distribute the authorities of browsing the collected information about the physical layer. The cyber layer can be further divided into two platforms as shown in Fig. 6.

1. Control platform: SDN is able to separate the control platform from the data platform. With the help of the SDN controller, the virtual network operator is able to realize the virtualization process, including the virtualization of the resources and the management of virtual resources among various virtualized networks in the data platform, through an efficient and low-cost manner.

2. Data plane: The virtualization process, including resource virtualization and virtualized resource management in the data platform, can help convert the physical networks into various virtualized networks. These virtu-

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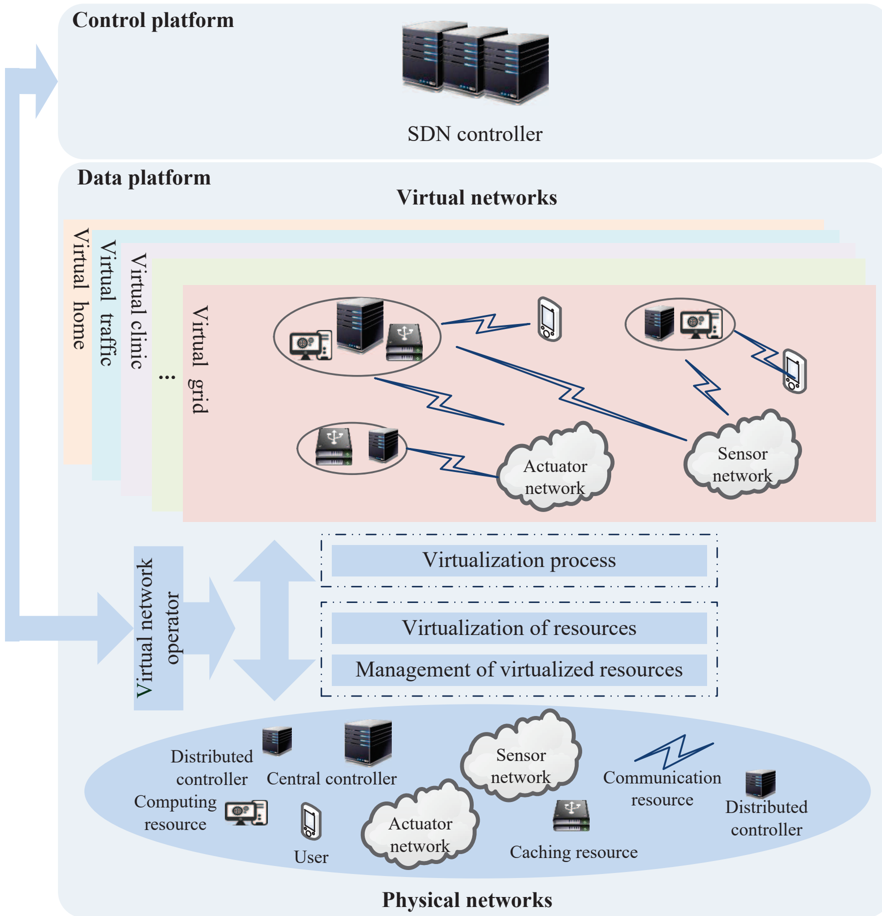

Fig. 6: Virtualization process for CPSSs.

alized networks can be targeted to different industries. For example, as shown in Fig. 5, smart vehicle network supports the intelligent interaction among vehicles as well as humans, including drivers, passengers and pedestrians, and helps to achieve semi-autonomous or autonomous driving. Smart medical network can help patients to be retrieved by doctors and hospitals even at a distance. Smart industrial network can accommodate the consumer behavior and the business model by dynamic configuration and production optimization. Smart agriculture network supports the real-time monitoring of various environment parameters to promote agricultural production. Smart home network can provide optimized living environments for humans through smart decision making, such as the control of heating, ventilation and air conditioning (HVAC). Smart grid realizes the intelligent energy distribution among different areas. These intelligent networks are all virtualized as shown in Fig. 6. For users in the social layer and sensors and actuators in the physical layer, each smart virtualized network in the cyber layer is mutually independent, while actually they have the right to share the same physical facilities (such as central controllers, distributed controllers, data processors and data storages) and physical resources (such as spectra, backhaul and so on).

- **Social layer**: For CPSSs, users in the social layer could have different social roles, such as doctors, customs, servers, workers, nurses and so on. According to these social roles, users can be treated as an experiencer, a maintainer, or even a decision maker. They can be viewed as service consumers to submit their experience information to the cyber layer for assisting the maintenance and the operation of the system, and they can also be viewed as service providers and authorized to participate in decision making to further promote the system development.

C. Novel Architecture Design: Integration of Caching, Computing and Networking

1) Motivation: Even though the virtualized CPSSs solve part of the scientific problems, there are still some challenges that need to be handled during the operation and management of virtualized CPSSs for further promoting its development.

- **Information retrieval**: The virtualized CPSSs contain a wealth of information. Either users as experiencers and

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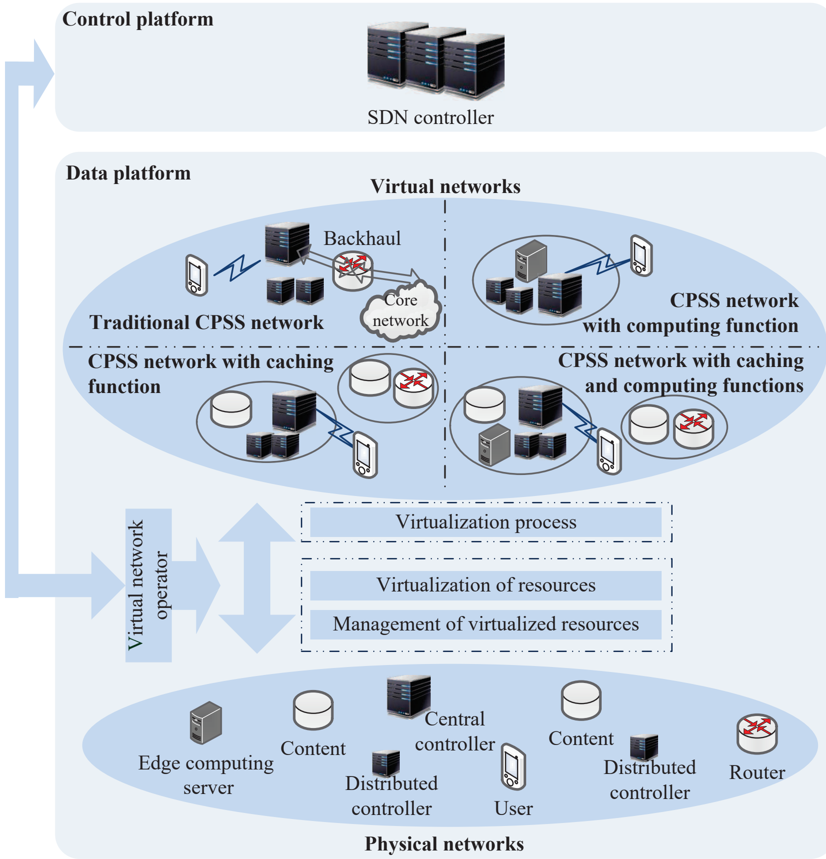

Fig. 7: The integrated framework of caching, computing and networking for CPSSs.

operators or CPSS controllers need to locate and extract the useful and required information at a high speed.

- **Data processing**: Most of the data in the virtualized CPSSs need to be analyzed in real time, especially for the data at the network edge, which have extremely high requirements for processing response and energy consumption.
- **Content delivery**: The virtualized CPSSs need to be designed to support the frequent and reciprocating delivery of large-scale information, including the service contents and the processing results, which will undoubtedly impose a greater burden on the limited bandwidth resources.

Against this background, this article further proposes an integration framework of caching, computing and networking for CPSSs based on the architecture proposed in Fig. 5 and Fig. 6.

2) Architecture: The integration of caching (i.e., information-centric networking (ICN)), computing (i.e., edge computing) and networking into CPSSs is beneficial to achieving the highly efficient and scalable content retrieval and delivery with the powerful capability of data processing [37].

- **Speedy information retrieval**: ICN is utilized to support the caching function of the CPSS interconnection network. The core of ICN is in-network caching [38]. With the support of ICN, the contents passing through the CPSS nodes can be named and stored within the networks, thus providing a highly speedy information retrieval.
- **Efficient data processing**: Installing edge computing servers at some CPSS nodes is beneficial for intensifying the processing capacity even at the edges. In addition, the joint design of caching and computing modules is conducive to achieving the mutual promotion between them. For example, edge computing servers can help transform the caching contents, so that fewer content versions need to be stored, thus improving the cache space utilization rate [34].
- **Efficient content delivery**: ICN adopts the receiver-driven information-level delivery principle instead of the sender-driven end-to-end delivery principle in the traditional networks [39], which means that the communication links can be directly set up by the receivers without the foreknowledge of the location information of the content holders. In addition, the joint optimization of caching, computing and communication resources is able to further promote the high-efficient delivery of required contents and analysis results among sensors, actuators, controllers and user devices.

Fig. 7 illustrates an integrated framework of caching, computing and networking for CPSSs. Through selectively

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installing edge computing servers or exploiting storage space at each CPSS controller, four kinds of virtual networks are created. These virtual networks can deal with different services according to the requirements of devices and users in CPSSs.

- **Traditional CPSS network**: Even though CPSSs have the advantage of wide application areas, these areas may have the same requirements for communication services. Due to the security and confidentiality features, some communication services, such as decision feedback, could be served by the traditional virtualized CPSS network without processing and storage.
- **CPSS network with caching function**: Some popular large files, such as photo collecting files, install packages, toolbooks and applications, can be delivered through the virtualized CPSS network with caching function, since these files may be called multiple times in the near future and have a certain degree of cache value.
- **CPSS network with computing function**: To provide the computation tasks with privacy, such as QR code recognition and face recognition, the virtualized CPSS network with computing function can be utilized with no need for storage.
- **CPSS network with caching and computing function**: The video acquisition services are provided by the virtualized CPSS network with caching and computing functions, where the collected video contents can be transcoded in real time to apply to the network conditions with the support of edge computing servers, and some popular ones can be stored to alleviate the backhaul bandwidth workloads. Actually, real-time navigation for virtual smart traffic can also be implemented at this kind of virtualized networks, where the edge computing servers provide the route guidance of the real-time navigation, and the global traffic map can be stored at various network nodes.

D. Performance Evaluation: Four-Dimensional Joint Optimization

The optimization of CPSSs can follow the architectural design philosophy in the previous subsections. Consider a virtualized CPSS network with U users and C controllers, where each controller has T_c tasks. Here, the controllers can also be viewed as the access points (APs). To promote the understanding of readers, we use three cases to show the performance advantages of the proposals.

In the traditional systems, including CPSs, users are always viewed as service consumers. The three-dimensional resource allocation scheme jointly optimizes the controller selection indicator $\{\alpha_{u,c} \in \{0,1\}\}$ with the allocation of the spectrum $\{b_u\}$, the computation capability $\{x_u\}$ and the caching space $\{y_u\}$, and the unit prices for each kind of resource are p_{cm}, p_{cp} and p_{cc}. Here, computation capability can be quantized by the total number of CPU cycles per second [36]. The resource optimization problem can be formulated to maximize the revenue of the virtual network operator, which can be regarded as the income from service consumers to rent resources. The details are shown as follows:

$$\max \sum \alpha_{u,c} f(\{p_{\mathrm{cm}}, p_{\mathrm{cp}}, p_{\mathrm{cc}}\}; \{b_u, x_u, y_u\}). \tag{1}$$

Here, $f(\{\cdot\};\{\cdot\})$ represents the profit function. The solutions to the three-dimensional resource optimization problem need to guarantee the user requirements of communication rate R_{cm}^{th}, computation rate R_{cp}^{th} and caching space R_{cc}^{th}.

In Case 1 of Fig. 8(a), we simply assume the user channel suffers from Rayleigh fading, and each user has the same requirements of R_{cm}^{th}, R_{cp}^{th} and R_{cc}^{th}. In addition, we set $U = 3$ and $C = 1$. The profit function is defined as $f(\{m,n\};\{v,w\}) = mn + vw$ [36]. The number of resources at each controller is normalized, and the unit prices of p_{cm}, p_{cp} and p_{cc} are all 10. Since we assume the allocated resource number is normalized, the thresholds for different user requirements and the final solutions of communication rate, computation rate and caching space are also normalized. As shown in Fig. 8(a), CPSSs sell all the resources almost evenly to users, and the income is 30. Numbers of communication and computation resources allocated to each user have some differences because the channel conditions and the offloading tasks of users are different. To guarantee the threshold of the communication and computation rates, some users need to be allocated more spectrum resource and computation capability.

In CPSSs, users can be viewed as not only service consumers but also service providers. CPSSs regard humans as a kind of network resources, and CPSS controllers can employ users to cooperatively accomplishment various tasks. The four-dimensional resource allocation scheme jointly optimizes the controller selection indicator $\{\alpha_{u,c} \in \{0,1\}\}$ along with the communication, computing, caching resources and the task allocation indicator $\{a_{u,t} \in \{0,1\}\}$, and the unit price for employing each user is p_u. The optimization problem can be reformulated to maximize the revenue of the virtual CPSN operator. The earnings can be regarded as the difference between the income from service consumers and the expenditure for employing service providers. The details are shown as follows:

$$\max \sum \alpha_{u,c} \left[f(\{p_{\mathrm{cm}}, p_{\mathrm{cp}}, p_{\mathrm{cc}}\}; \{b_u, x_u, y_u\}) - f(\{p_u\}; \{a_{u,t}\}) \right]. \tag{2}$$

Considering each user may have tasks that already exist for execution, the solutions to the four-dimensional resource allocation problem need to further guarantee the upper limit N_u of tasks allocated to each user.

In Case 2 of Fig. 8, we simply set $T_c = 10$, $N_u = 4$ and $p_u = 10$. As shown in Fig. 8(b), if we assume the users offer the same prices to compete the CPSS tasks, it is obvious that Case 2 almost assigns its resources and tasks uniformly, where the first 9 tasks are uniformly allocated to the three users, and the last task is randomly assigned due to its inseparability. In this case, CPSSs need to pay users 100 prices for employing users as service providers.

Considering the user behavior uncertainty of CPSSs, the user incentive mechanism could be installed for improving

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			User 1		User 2		User 3		
User number			1		2		3		*Case 1*
User evaluation value			\		\		\		
Service providers	Business volume		\		\		\		\
Service consumers	Number of communication resources	Normalized communication rate	26.77%[1] 18.57%[2]	0.1472[1] 0.1021[2]	46.49%[1] 69.36%[2]	0.0674[1] 0.1005[2]	26.74%[1] 12.07%[2]	0.2281[1] 0.1029[2]	**Earning:** **30.00**[1,2]
	Number of computation resources	Normalized computation rate	34.05%[1] 29.67%[2]	0.2118[1] 0.1846[2]	32.56%[1] 38.51%[2]	0.1142[1] 0.1351[2]	33.39%[1] 31.82%[2]	0.1714[1] 0.1633[2]	
	Number of computation resources	Normalized caching space	33.33%[1] 33.33%[2]	0.3333[1] 0.3333[2]	33.33%[1] 33.33%[2]	0.3333[1] 0.3333[2]	33.33%[1] 33.33%[2]	0.3333[1] 0.3333[2]	

(a)

			User 1		User 2		User 3		
User number			1		2		3		*Case 2*
User evaluation value			\		\		\		
Service providers	Business volume		40%		30%		30%		**Expense:** **100.00**[1,2]
Service consumers	Number of communication resources	Normalized communication rate	26.77%[1] 18.57%[2]	0.1472[1] 0.1021[2]	46.49%[1] 69.36%[2]	0.0674[1] 0.1005[2]	26.74%[1] 12.07%[2]	0.2281[1] 0.1029[2]	**Earning:** **30.00**[1,2]
	Number of computation resources	Normalized computation rate	34.05%[1] 29.67%[2]	0.2118[1] 0.1846[2]	32.56%[1] 38.51%[2]	0.1142[1] 0.1351[2]	33.39%[1] 31.82%[2]	0.1714[1] 0.1633[2]	
	Number of computation resources	Normalized caching space	33.33%[1] 33.33%[2]	0.3333[1] 0.3333[2]	33.33%[1] 33.33%[2]	0.3333[1] 0.3333[2]	33.33%[1] 33.33%[2]	0.3333[1] 0.3333[2]	

(b)

			User 1		User 2		User 3		
User number			1		2		3		*Case 3*
User evaluation value			5.0910		9.9692		1.4583		
Service providers	Business volume		40%[1] 40%[2]		40%[1] 40%[2]		20%[1] 20%[2]		**Revised expense:** **25.60**[1,2]
Service consumers	Number of communication resources	Normalized communication rate	9.09%[1] 18.19%[2]	0.05[1] 0.10[2]	85.05%[1] 70.09%[2]	0.1233[1] 0.1016[2]	5.86%[1] 11.72%[2]	0.05[1] 0.10[2]	**Revised earning:** **57.17**[1] **54.42**[2]
	Number of computation resources	Normalized computation rate	8.04%[1] 16.08%[2]	0.05[1] 0.10[2]	82.22%[1] 64.44%[2]	0.2886[1] 0.2262[2]	9.74%[1] 19.48%[2]	0.05[1] 0.10[2]	
	Number of computation resources	Normalized caching space	10%[1] 20%[2]	0.10[1] 0.20[2]	80%[1] 60%[2]	0.80[1] 0.60[2]	10%[1] 20%[2]	0.10[1] 0.20[2]	

(c)

Fig. 8: CPSS performance evaluation. (The corner mark 1 represents the relevant parameters during the simulations are $R_{cm}^{th} = 0.05$, $R_{cp}^{th} = 0.05$ and $R_{cc}^{th} = 0.1$. The corner mark 2 represents the relevant parameters during the simulations are $R_{cm}^{th} = 0.1$, $R_{cp}^{th} = 0.1$ and $R_{cc}^{th} = 0.2$.)

the system utility, thus promoting the four-dimensional resource optimization. An excellent incentive mechanism can take advantage of the users with higher evaluation value (such as reputation, influence and capacity) to assist in completing system tasks, and reward them according to their requirements as much as possible. Specifically, when users work as service providers, the CPSS controllers assign the tasks according to the users' evaluation values. A user with a higher evaluation value means that the user will efficiently complete the assigned task with honesty and punctuality, and the system prefers to assign the task to such a user. In return, users that complete their tasks can be served as the service consumers to gain some rewards to improve the service quality. The rewards can be the communication resources (e.g. the spectrum), the computing resources (e.g. the computing workload of CPSS controllers) and also the caching resources (e.g. the

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storage space in CPSSs). These resources can be utilized to provide communication and computing services and also the in-networking caching space for storing preferred large-sized files.

We take 5.0910, 9.9692 and 1.4583 as the evaluation values of the three users during the four-dimensional joint optimization of communication resources, computation resources, caching resources and human resources. To simulate such a process, we assume the expense and the earning of CPSSs can be modified according to the evaluation values of each user in real time. The modified unit prices can be calculated as $p'_{\{\cdot\}} = p_{\{\cdot\}} \pm \delta\text{EV}$, where EV represents the corresponding evaluation value and δ represents the correction factor. CPSS is more willing to sell the resources to the user with the higher buying rate and pay price for employing the user with the lower employing rate. Through revising the price in the right direction, users with higher evaluation values are motivated to participate in the operation and management of CPSSs. In practice, to ensure the interests of users, the actual transaction prices could be the prices before revision. The modification is only used to stimulate high quality users. The optimization problem can be reformulated as follows:

$$\max \sum \alpha_{u,c} \left[f(\{p'_{\text{cm}}, p'_{\text{cp}}, p'_{\text{cc}}\}; \{b_u, x_u, y_u\}) - f(\{p'_u\}; \{a_{u,t}\}) \right] \quad (3)$$

As shown in Fig. 8(c), Case 3 is inclined to assign its resources and tasks to the users with the higher evaluation values under the premise of satisfying the primary needs of users. One may say that the proposal seems to be unfair since strong users will monopolize the network. However, we can regulate the threshold values of R^{th}_{cm}, R^{th}_{cp} and R^{th}_{cc} to ensure fairness among users. For example, when compared with the first simulation with the corner mark of 1, the second simulation with the corner mark of 2 alleviates the unfairness of resource allocation among users. It's the same principle for task assignment. To ease the workload of the user with the higher evaluation value, we can simply reduce the task threshold N_u.

For the four-dimensional joint optimization with the incentive mechanism in real life environments, the situation is more complicated. For example, during the simulation, we assume the prices of employing each user are equal. In practice, the users with lower evaluation values can sell their labor at a lower price, thus winning the chance to participate in the system operation and management. Once they complete the tasks with higher efficiency and quality, the corresponding evaluation values will be promoted to increase opportunities to participate in the next round of system decision and also to promote their profits. That is to say, on one hand, we can utilize the high-quality users to make more contributions to the system, and on the other hand, the user behavior can be normalized by the rewards; otherwise, they need to pay more to get what they want.

Or to sum up:

- **Case 1** can be viewed as the optimization of CPSs, in which humans are only be viewed as service consumers and the system allocates the resources according to the users' requests. Besides, there is no closed loop between humans and systems. That is to say, humans cannot affect the system operation and management.
- **Case 2** can be viewed as one kind of optimization of CPSSs, in which humans can be viewed as both of service consumers and service providers. That is to say, humans can be regarded as consumers to enjoy the business services and can also work as service providers to execute the assigned CPSS tasks. After putting humans in the loop, some of the system functions, such as sensing and decision making, can be further optimized.
- **Case 3** can be viewed as the promotion of Case II, where the user incentive mechanism is introduced to make the loop between humans and systems more closer. A good incentive mechanism is able to regulate the human behaviors, motivate humans with higher reputation, influence or capacity to participate in the operation and management of CPSSs, and cooperate with the system to make better decisions, thus promoting the system benefits. In return, they can acquire better business services with richer resources. In this way, a virtuous circle is formed.

E. Lessons Learned: Summary and Insights

The contribution of this section is to present general architectures of CPSSs with its optimization, and the performance of the proposals is verified from the simulation. The results reveal some possible ways to design and optimize CPSSs. To put it in actual operation, there are still many issues that need to be handled, such as, how to integrate the proposed architecture with other existing protocols and standards, and how to evaluate users correctly and effectively. Besides, the optimizations in Section III-D are simplified, where we only focus on explaining the benefits of putting humans in the loop and how to take advantage of human resources. In practice, the total numbers of networks, devices, tasks and users are in increase sharply, which bring in great challenges in optimizations. Besides, how to determine the optimal thresholds to take into account of both the user evaluation values and the user fairness is still the typical issue. Only had reasonably solved these problems, could CPSS architectures be deployed with the installation of the human evaluation and incentive mechanisms and the four-dimensional joint optimization scheme in a real life environment. The authors hope this section can inspire readers to make more contributions to the development of CPSSs.

IV. Applications, Standards and Case Studies

Fig. 9 illustrates a vision of CPSSs. Actually, in the traditional design concepts, the human factor is removed from the system loop, which contradicts the prevailing design principle of the user-centered design. CPSSs aim at including humans throughout the loop to enhance the intelligence of surroundings through the novel social applications, such as citizen sensing and citizen actuation. The application areas that can be impacted involve all aspects of our daily life, including transportation, industry, agriculture, pro-environment, energy,

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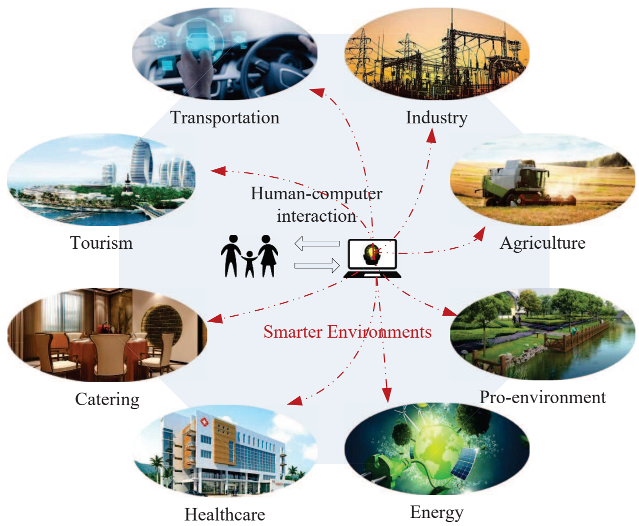

Fig. 9: Cyber physical social vision.

healthcare and so on. In this section, we will present the existing research related to the CPSS applications, some common standards and real-world case studies. The detailed discussion of the existing research status shows the huge market potential of CPSSs to promote intelligence in various application fields.

A. Applications

Table I summarizes the existing work of CPSSs, the motivation of which relies on the exploration of CPSS applications in different research directions. The details will be discussed in the following.

1) Transportation: CPSSs can be properly designed to achieve smart traffic. Vehicles are connected to the outside world, including infrastructures, other vehicles and pedestrians. These connections can assist in collecting and analyzing the status information of surroundings and help drivers to realize semi-autonomous or autonomous driving on the road.

The concept of intelligent transportation spaces is first proposed to integrate traffic management centers, vehicles, roadside infrastructures and pedestrians, thus promoting the safety and sustainability of vehicles, traffic and transportation efficiently [40]. In this context, the CPSS-based intelligent transportation systems (ITS) emerge to enable smart parking and vehicular communication-based traffic control [22], [41]. The authors in [22] discuss the architecture, applications and characteristics of traffic data, and the related operation and management techniques. In order to emphasize the impact of human factors on ITS, society should also be considered as an active entity in ITS, which participates in the processes of sensing, computing, communications, control and management [41]. This kind of ITS is also named as Transportation 5.0, the introduction of which is the inevitable course for the future ITS development [42].

The intelligent vehicle is the typical intelligent implementation in the field of transportation. Current vehicle automation has two levels: i) The driver needs to continuously monitor the driving situation; ii) The driver is fully disengaged from the driving task during a period of time. The challenges for fully autonomous driving mainly come from the complex dynamic driving environments that bring the difficulties in the realization of the reliable and robust operation. To promote the automated driving, the authors in [43] propose a cloud-based CPSS framework for parallel driving in order to realize the synergizing connected automated driving through safe and efficient interactions among vehicles, drivers and information. Within the framework, several parallel techniques, i.e., parallel testing, parallel learning, parallel reinforcement learning and parallel horizon, are reviewed and discussed. The proposal has the potential to be the feasible program for future road transportation systems.

For applications of CPSSs in the smart transportation, the road traffic signals also play an important role in adjusting road traffic. [44] proposes a road traffic signal control framework to realize self-configuration of traffic signals. The framework consists of a traffic signal configuration center and traffic signal controllers, and is expected to guide the drivers under the consideration of the social characteristics of the traffic. The experiments verify the feasibility and advancements of the proposal.

2) Social Manufacturing and Smart Factories: For social manufacturing and smart factory, CPSSs can acquire manufacturing data from the connected underlying facilities. Through analyzing the data and taking appropriate measures, dynamic configuration and production optimization can be achieved, so that the system can accommodate the consumer behavior and the business model.

Social manufacturing [20] is an emerging technique with personalization and socialization, and focuses on providing personalized products and individualized services for various prosumers. A literature review of social manufacturing is presented by the authors in [20], which is based on a constructive methodology in the aspects of the definition, business models, architecture, case studies, enabling techniques and future challenges.

Similar to social manufacturing, smart factories are also of particular interest to scholars. A CPSS architecture for smart factories is proposed in [45], where the authors associate the cyber control with the social network-based physical factory circumference through a NodeTrix-based visualization interface with triangle-shaped matrices, in order to display social networks for CPSSs within a smaller screen space. [46] investigates the current manufacturing modes with the operation management strategies for smart factories, where a CPSS-based high-end equipment manufacturing mode is presented to reach the win-win situation of enterprises and customers.

To overcome the difficulty of the high latency for data handling during manufacturing, the in-line data deduplication file system (LDFS) for cyber-physical-social computing and networking systems (CPSCN) in [47] can be applied to the social manufacturing and smart factories. Through writing the addresses of the data block to the corresponding fingerprint index, the LDFS system is able to decouple the unique data block and the fingerprint index, and thus the procedure of ac-

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TABLE I: Summary and Discussion of the Existing CPSS Applications.

Application fields	Reference number	Research direction	Key achievements (●) and results (⋆)
Transportation	Ref. [40]	Intelligent transportation spaces	●(⋆) Elaborate on some wireless communication technologies and standards
	Refs. [22][41]	Intelligent transportation systems	● Discuss the architecture and applications of CPS-ITS and CPSS-ITS ● Analyze the characteristics of traffic data ● Enumerate some data operation and management technologies ⋆ Reveal some advances in the coevolution of CPSs, CPSSs and ITS ⋆ Realize the stepwise control and management by parallel execution
	Ref. [42]	Transportation 5.0	● Discuss the parallel system methodology and some cornerstone technologies ⋆ Provide solutions to the architecture design of society-centered ITS
	Ref. [43]	Automated driving	● Propose an unified approach for synergizing connected automated driving ● Review parallel testing, learning, reinforcement learning and horizon ⋆ Realize an effective cooperation among vehicles with various levels of automation
	Ref. [44]	Road traffic signal control	● Propose and evaluate a road traffic signal control method ⋆ Verify the method feasibility and advancements to promote implementation
Social manufacturing and smart factories	Ref. [20]	Social manufacturing	●(⋆) Make a comprehensive literature review on social manufacturing ● Make an analysis on current research progress ● Point out the potential impact and future challenges
	Ref. [45]	Smart factories	● Propose a CPSS framework associating social factory with cyber control ⋆ Display social networks with fewer crossings within a smaller screen space
	Ref. [46]	Manufacturing modes	● Investigate the current manufacturing modes and operation management strategies ● Propose a CPSS-based manufacturing mode for smart factories ⋆ Reveal some results of ongoing research for high-end equipment manufacturing
	Ref. [47]	Data deduplication	● Present a low latency LDFS framework ⋆ Verify the enhanced read and write performance on the critical path ⋆ Achieve almost the same deduplication ratio as that of LessFS
Environment and sustainability	Refs. [48]-[49]	Smart agriculture	● Develop a hydroponic smart farming system ● Present an agricultural production management with a case of solar greenhouse ⋆ Realize the flexible hydroponic system monitoring ⋆ Achieve the decreased waste in labor and the sustainable agricultural production
	Ref. [50]	Water management	● Discuss the complexity and grand challenges of river basins ● Outline the prospect of a smart water grid ⋆ Address challenges of transparency, equity, devolution and variability in the basin
Energy distribution	Ref. [51]	Energy management	● Propose a concept called CCES ● Introduce some basic features of CCES ● Provide a CCES architecture for electric vehicles and the smart grid ● Propose a request-and-schedule energy management protocol ⋆ Achieve effective and intelligent energy coordination and scheduling
	Ref. [52]	Fuel supply	● Propose a CPSS implementation scheme as service innovation for public gas station ⋆ Fulfill the goal of excellent service and customer satisfaction
Healthcare	Ref. [53]	Disease control	● Propose and evaluate a green CPSS-based e-healthcare framework ⋆ Prove the efficiency of the proposal to prevent infectious diseases from being spread
	Refs. [54]-[55]	Smart recommender systems	● Propose a doctor recommendation algorithm ● Propose an integrated doctor recommender framework ⋆ Provide doctor recommendation lists
Catering and Tourism	Refs. [56]-[59]	Smart recommender systems	● Propose a group-centric recommender system in the CPSS domain ⋆ Provide restaurant recommendation lists ⋆ Provide the recommendation list of museums or tourism attractions
	Ref. [60]	Dynamic social structure	● Propose DSSoT as a smart CPSS service framework ● Provide an airport application to proof the concept of DSSoT ⋆ Reduce the situational awareness-based contextual complexity
	Ref. [61]	Geological information services	● Develop a modeling and computing method for geological information services ⋆ Reveal effective solutions to geological information service management
	Ref. [63]	Artificial evacuation	● Propose a CPSS framework for artificial evacuation systems ⋆ Achieve evacuation guidance in real time through data-driven parallel mechanisms

cessing the fingerprint index can be omitted. The experiments indicate that the proposal is able to enhance the read and write performance and achieve almost the same deduplication ratio as that of LessFS.

3) Environment and Sustainability: Along the same lines, CPSSs can also be utilized to maintain the environments and to realize the sustainable development. For example, in [48], a smart hydroponic farming system is developed to monitor important parameters, such as luminance, temperature and humidity via telegram messenger, and to realize the flexible hydroponic system monitoring. In [49], a CPSS-based agricultural production management system is presented to decrease the labor and fertilizer waste and to support the sustainable agricultural production.

Other than smart agriculture, it is also meaningful and noteworthy to refer to the environment protection. In [50], river basins are equipped with smart infrastructures to constitute a complex CPSS architecture, i.e., a smart water grid integrating data collection systems, decision support systems and automated responder units. The complexity of water management comes from the intricate interplay of physical elements and the human behavior at multiple levels, which result in the variability and uncertainties, such as population and climate changes. Against this background, the smart water grid can be taken as an Internet inspired and tightly connected cyber-physical-social network for promoting the water management and addressing the challenges of transparency, equity, devolution and variability in the basin by dynamic analyses and decision making.

4) Energy Distribution: As for smart energy distribution of our city, note that homes, offices and some other applications can be powered by smart grids with user awareness. The smart grid system collects and analyzes the information of a region, and some measures are taken to realize the reasonable

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distribution of energy according to the analysis results.

The consumer-centered energy system (CCES) [51] can be regarded as a kind of CPSSs, which aims at integrating the power grid (i.e., the physical world), the communications and computing (i.e., the cyber world) and the consumer interconnections (i.e., the social world). The authors in [51] propose a CCES architecture based on the smart grid and the electric vehicles, and a request-and-schedule energy management protocol is further presented by the authors to achieve the efficient and smart energy coordination and scheduling.

Besides the smart grids, the fuel distribution is another aspect to reflect the application of CPSSs in energy distribution. Superiority of inventory control [52] is beneficial to enhancing the sustainability of the fuel supply. The authors in [52] propose a CPSS implementation architecture for the inventory control system with the design purpose of fulfilling the service requirements and the customer satisfaction, which can be regarded as a service innovation for the public gas station.

5) Healthcare: CPSSs also enable smart personal healthcare. Sensors can be distributed on the body or even in the home or clinic/hospital to detect changing health conditions, potential diseases or health problems. The information of each patient can be retrieved by doctors, and then advice and medications can be fed back. The new generation of smart systems can even realize the robotic surgery and bionic limbs by personalized interoperable medical devices.

Even though the concepts of healthcare or health clinic/hospital spring up in the early days of smart systems, most of the existing work focus on the cyber-physical integration. To promote CPSSs in the field of healthcare, [53] focuses on the social network-based e-healthcare service, and proposes a green CPSS-based e-healthcare framework to control infectious diseases. The proposal devotes to monitoring the spread of infectious diseases and predicting the spreading range of infections based on the analyses of social features, thus preventing the infections diseases from being further spread.

CPSSs are the basic paradigm of the evolution for the information industry, where the smart recommender systems can be viewed as novel techniques to implement personalized intelligent computing, and have already been viewed as an important fundamental research topic. Today, most patients may be bothered by how to choose a proper doctor without relevant experience or professional knowledge. [54] proposes a doctor recommendation algorithm that can help patients select appropriate doctors according to the doctor performances and patient preferences. [55] further proposes an integrated doctor recommender framework that extends the patients' demand characteristics to not only the preference but also the illness symptoms. The proposed framework is able to find the similarities between the patient consultation and the doctor profiles, and an analytic hierarchy process is integrated for providing doctor recommendation and promoting the user experience by the accurate and efficient recommendation list.

Healthcare is one of the most typical examples of the CPSS applications, since humans in healthcare can be classified into two distinct but closely related categories: service consumers (i.e., patients) and service providers (i.e., nurses and doctors). Each nurse and doctor has different values of reputation, capacity and influence. The proposal in Section III-D can be viewed as an efficient manner to motivate nurses and doctors with higher evaluation values to retrieve the information of patients, thus feeding back superior advice and medications to medical CPSS centers, through which patients can acquire better services even in a distance.

6) Catering and Tourism: Smart recommendation systems can also be applied in the field of catering and tourism. To provide a firm foundation for the personalized smart computing in CPSSs, a group-centric recommender system is proposed by the authors in [56], which consists of the activity-oriented group discovery, the group preference modeling and the revision of rating data. Smart culinary [57], [58] is an implementation of CPSSs incorporating global positioning system (GPS), cloud computing and social media. The system is able to present a restaurant recommendation list to show tourists the locations and addresses of restaurants [57]. In addition, the authors in [58] further strengthen the location accuracy of the users and the streets under the usability testing and evaluation. The smart recommender systems can also be applied to the field of cultural heritage space [59]. Similar to the smart culinary, the recommender systems in cultural heritage spaces are integrated with recommending engines that present the recommendation list of museums or tourist attractions.

The authors in [60] propose the dynamic social structure of things (DSSoT) to reduce the situational awareness-based contextual complexity of computing and networking, which can help people who lost in the unfamiliar places during the journey. DSSoT can be viewed as a smart CPSS service framework supporting the sociality extension. The reasoners are used in DSSoT to ascertain the short-term goals of users in a temporal social structure. After ascertaining the goals, DSSoT is able to classify the social objects and the provided smart services according to direct service provisioning and interactions, and the short-term goals can be reached through incorporating some available social objects and smart services. To demonstrate the efficiency of the DSSoT, the authors further present an application scenario, i.e., airport dynamic social, to realize the interactions among physical things in DSSoT.

To promote the geological information services during the journey, the authors in [61] present a novel modeling and computing method, in order to discuss and evaluate the geological hazards and to satisfy the requirements of complex data processing of geological services under the dynamic environments. The model is based on cyber-physical-social-thinking (CPST) [62], which can be viewed as a broader vision of IoT. The authors add a new module of thinking space in CPSSs, in order to simultaneously support the cyber interactions, physical perceptions, social correlations and human thinking [61].

Since there are always crowded areas during the journey, the smart evacuation systems are necessary especially in the buildings, such as restaurants. [63] considers the uncertainty, diversity and complexity of human behavior during evacuation processes, and it proposes a framework of artificial evacuation

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systems to simulate the physical evacuation process by determining the evacuation options. The proposed framework is based on the strength of the CPSS methodology with computational experiments and parallel execution, where the computational experiments are utilized to test and evaluate the prearranged emergency plans, and then the designed data-driven parallel mechanisms are used to achieve evacuation guidance in real time.

B. Standards

In this subsection, we will list some common standards frequently utilized in the smart systems.

1) Transportation: To enable vehicular networks, many vehicular communication standardizations have already been released, such as European Committee for Standardization (CEN) TC278, Institute of Electrical and Electronics Engineers (IEEE) 1609, Internet Engineering Task Force (IETF) and International Organization for Standardization (ISO) TC204. As for ITS as one leading effort toward CPSSs, Intelligent Transportation Society of America (ITSA) is granted a bandwidth of 75MHz from 5.65GHz to 5.925GHz for dedicated short-range communications (DSRC) [40]. The ITSA proposes a single standard based on IEEE 802.11 for the physical layer and the media access control sublayer, where IEEE 802.11p amends the IEEE 802.11a standard and defines the physical layer and the media access control sublayer to accommodate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. IEEE 1609.x covers the protocols in other layers, and together with IEEE 802.11p, they compose the wireless access standards in vehicular environments [40]. It is envisioned that ITS needs to adopt multiple communication technologies and standards to fit different applications.

2) Industry: Innovation in manufacturing environments is mainly guided by the reference architecture model for Industrie 4.0 (RAMI4.0), where the machine-to-machine (M2M) standards are necessary to realize the cost-effective manufacturing and smart factory. OneM2M standards aim at integrating isolated M2M standard activities and minimizing fragmentation [64]. In addition, to further promote the low-level controlling and the functionality reconfiguration in manufacturing environments, the IEC 61499 standard is also introduced for machine controlling and functionality modeling [65].

3) Agriculture: The International Electrotechnical Commission (IEC) 61400-25 standard supports the unified information exchange during the monitoring and control of wind power industry [14]. It can adapt well to the communication network architecture for smart wind farms [66]. Through extending the IEC 61400-25 standard, the offshore wind farms can be integrated into smart grids. In addition, the transport layer security (TLS) protocol [67] mainly focuses on the communication security problems and develops agent mechanism model with the consideration of security requirements in IEC 61400-25-3 and the combination of the international safety standards IEC 62351.

4) Smart Grid: The communication standards and protocols for smart grids include Distributed Network Protocol (DNP3.0), IEEE Std. C37.118, IEC 61850 and MODBUS [12], where the IEEE Std. C37.118 standard and IEC 61850 standard are the core protocols. The former involves synchrophasor measurements from the data information model and power systems, and the latter is a new international communication standard integrating all substation functions, such as the measurement, monitoring, control and protection.

5) Healthcare: The ISO/IEEE 11073 standard is released to define the communication protocols for exchanging healthcare information in medical and wellness devices [68]. Note that the ISO/IEEE 11073 standard does not support the Internet Protoco (IP) protocol, which limits the application area of healthcare services. Fortunately, it can be extended through using 6LoWPAN (i.e., IPv6 over low-power personal area networks) and BLE (i.e., Bluetooth Low Energy), and the extended standard is well equipped to various environments, even in the IoT environments.

6) Others: When discussing the common standards in the fields of CPSSs, worthy of note is that in all types of information flows among the cyber, physical and social spaces, "video big data" become the majority of traffic. The IEEE 1857 standard (i.e., the Standard for Advanced Audio and Video Coding) is released in June 2013 [69]. Different from other standards, such as High Efficiency Video Coding (HEVC)/H.265, the IEEE 1857 surveillance groups focus more on the fact that most of surveillance videos are captured by s-tationary cameras with the same scenes; hence, the IEEE 1857 standards double the coding efficiency through removing the "scenic redundancy" in several consecutive pictures. Against this background, the IEEE 1857 standards can be used to boost the various video applications in CPSSs [69].

C. Real-World Case Studies

The existing research of CPSSs lacks probe into the real-world case studies. Here, we will give two typical real-world examples of CPSSs. These examples can be the foundation to promote CPSSs in various practical applications.

1) Intelligent Vehicles in Transportation 5.0: Similar to Industrie 4.0 as CPS-based applications, Transportation 5.0 or ITS 5.0 can be viewed as the CPSS-based transportation applications [41]. Urban transportation is a typical real-world application of CPSSs, since it relates to both of the environment elements and social elements. Here, the environment elements include transportation infrastructures, i.e., roads, bridges and parks. The social elements include passengers, drivers and pedestrians. Considering the complexity of urban transportation, ITS needs to be upgraded to ITS 5.0 or Transportation 5.0.

Intelligent vehicle is taken as a typical case study in the next generation ITS 5.0 in [41]. In this case study, three major agents are installed, driver agents in the controlled vehicles, personal agents of pedestrians and traffic manager agents on the roadside or intersection. The driver agents and the personal agents first call and attempt to reserve a space-time block before meeting. The traffic manager agents determine whether to grant the request according to the analysis results of the control centre in cyber layer of CPSSs. Once the request is granted, travel guidance will be sent to the driver agents

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from the traffic manager agents. Otherwise, the negotiation is necessary to avoid pedestrian collisions. This case study is based on the cloud-based system and V2V/V2I protocols, where the former is used to collect and analyze the most recently updated road information, and the latter is used to support surrounding information gathering and travel guidance acquiring.

In ITS, humans such as drivers and pedestrians are viewed as service consumers with the service guarantee of collision avoidance by acquiring the travel guidance. The dynamic behaviors of humans may influence the data analysis and service results. Therefore, at the present stage, human assistance is still needed in automatic driving. ITS 5.0 is still in its initial stage, and the case study in [41] only provides an application hypothesis without actual test. Extensive investigations, investments and tests are needed for its implementation and development.

2) Chinese Solar Greenhouse: The main horticultural facility in China is the traditional solar greenhouse, the profit of which may be influenced by not only the environmental control and the plantation scheduling but also the social conditions, such as price fluctuation and knowledge of growers [49]. Due to the difficulty in environmental controllability of the solar greenhouse, the cropping plan needs to be designed based on the analyses of social and physical information. Against this background, CPSSs are beneficial for the effective greenhouse management, thus avoiding the low production and unsalable products.

Similar to the layered architecture of CPSSs in Fig. 4, CPSSs first need to collect the information from the physical worlds and social worlds. Sensing information includes social information and physical information, where the former can be the vegetable prices that are directly required from the wholesale markets. As a real-world case study, the price data of tomato from 2014 to 2017 in Xinfadi market of Beijing, PudongXinqu market of Shanghai and Baiyunshan market of Guangzhou is chosen as the typical data. The physical information consists of the environmental data and the crop data. The environmental data includes the air temperature, air humidity and light intensity of the solar greenhouse, and the crop data includes the weight of internodes, leaves and fruit. Agricultural CPSSs have the ability of predicting the plant development and growth with the support of artificial system, computational experiment and parallel execution-based method. It needs to analyze the sensing information of social data, environmental data and crop data, thus determining the timing of fertilization, the timing of spaying and the timing of marketing. In addition, agricultural CPSSs can estimate the fertilizer quantity and the economic profit according to the analyses of the crop data and the prediction of the crop growth. This real-world case study verifies that the agriculture CPSSs are able to achieve the stable supply and the maximized gross profit [49].

In agriculture CPSSs, the historical market prices of plants are analyzed with the prediction of the plant growth and the environments. Service providers, including price makers and growers, assist the system to determine the planting strategy and the marketing plan according to the analyzed results. Thereout, a win-win situation is achieved for service providers and consumers, where the former can obtain a maximized planting profits, and the latter can get a better product quality.

D. Lessons Learned: Summary and Insights

To further promote CPSSs and simplify its implementation, the different parts of the system (i.e., the physical part, the cyber part, the social part, the physical-cyber part, the cyber-social part, etc.) can be designed separated such that the existing standards and proposals can be well applied in a straightforward manner. However, when we think of it as a whole, the standards and proposals need to be operated in a joint manner. Actually, even though there exist some real-world case studies of CPSSs, they are confined to one research area and may have some limitations in other application fields because of the diversified application and business requirements. It is also not clear how to change the main parts of the standards to implement an efficient interface among the existing proposals, which determines whether the theoretical studies of CPSSs can be commercialized.

However, from the theoretical developments of CPSSs at the present stage, we can still see that CPSSs have the potential and value to be constructed in various markets for civil, mechanical and industrial engineering, such as transportation, industry, agriculture, pro-environment, energy, healthcare, catering and tourism. The market size of CPSSs will continue to be expanded under the general trend of IoT. As the technology matures, CPSSs will keep a good momentum of development, and provide new impetus for sustained and steady growth of the global economy. The future trend of CPSSs is to design a comprehensive platform and business model with the integration of the relevant technologies and human behavior patterns, and enable the long-term development of CPSSs by achieving multi-win of hardware or software manufacturers, network operators, system integrators and application service providers.

This section commits to providing a vision of CPSSs, where the detailed discussion of the existing research status shows the huge market potential of CPSSs in various application fields. The common standards as discussed above provide the foundation for the applications of CPSSs in extensive fields. Advances in CPSSs will jointly enable the adaptability, capability, resiliency, scalability, safety, security and usability, which are superior to the today's simple embedded systems. The mature work foundation of CPSs provides an effective channel to implement CPSSs, and the applications of CPSSs have a great advantage when compared with CPSs. It takes humans as a part of the system and forms a closed loop, thus enabling the smart environments to become smarter.

V. Enabling Techniques and Networks

The realization of CPSSs heavily relies on multiple enabling techniques and existing networks, the understanding of which helps readers to gain insights on the functionalities of CPSSs. In this section, we will discuss the enabling technologies and network applications in CPSSs, which are classified according to the hierarchical structure of CPSSs. Fig. 10 illustrates an overview of enabling techniques in each layer of CPSSs and

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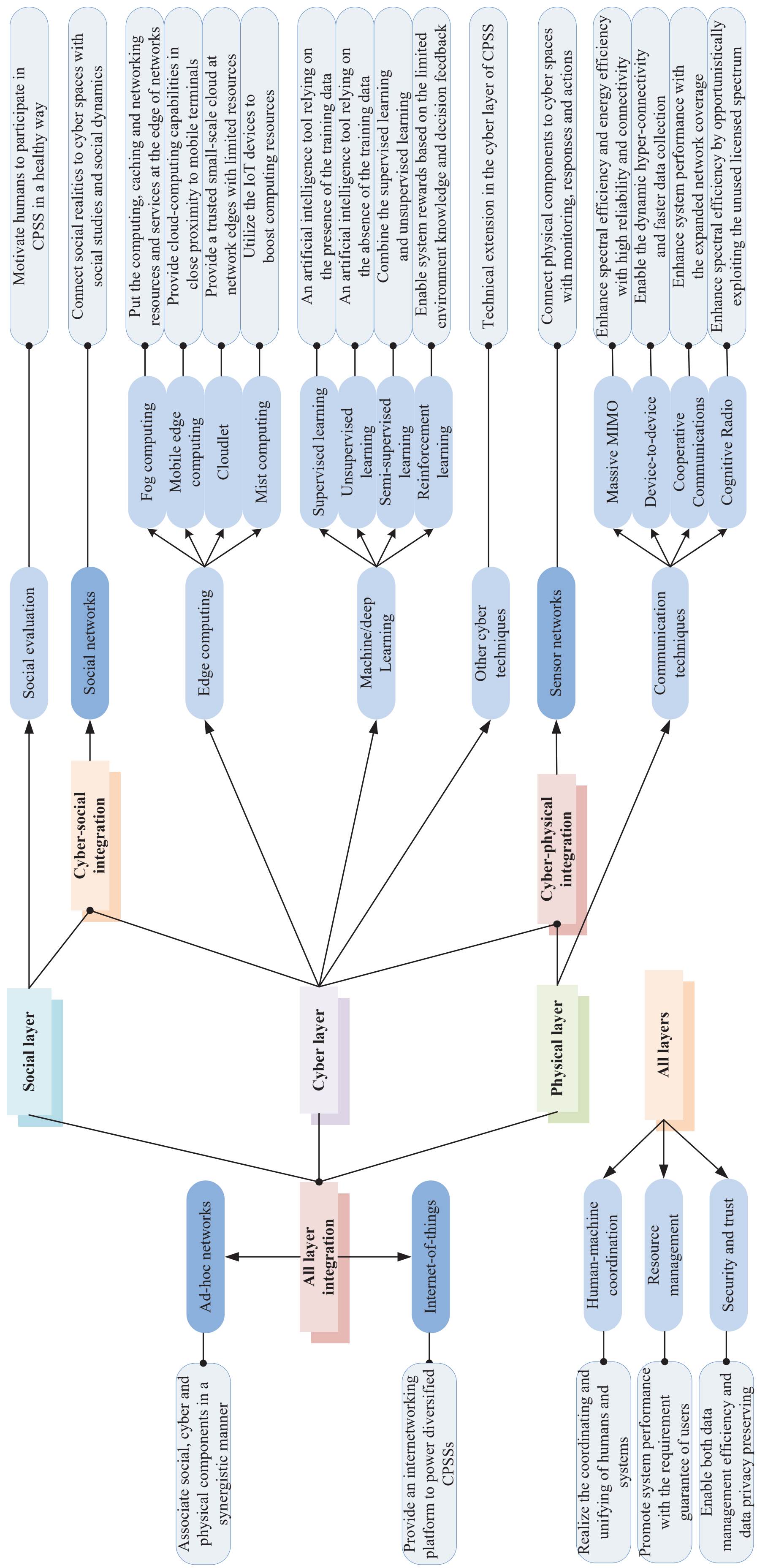

Fig. 10: An Overview of Enabling Techniques and Networks in CPSSs.

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enabling networks for the layer integration, where the items in mazarine represent some potential network applications and architecture. The discussion of the enabling techniques and networks by the category as shown in Fig. 10 is beneficial to helping readers to understand the function of each kind of techniques and networks in CPSSs, and it is also conductive to making out how these techniques and networks support the various parts of CPSSs. This category also indicates the relationship among different techniques and networks, and at the end of this section, we will further give a deeper insight of introducing these techniques and networks.

A. Physical Layer: Communication Techniques

Communication techniques are the basic techniques to connect each component in CPSS physical layer and guarantee the characteristic of hyper-connectivity. Before exploring the possible communication techniques, we first need to focus on the challenges of incorporating CPSSs in the existing communication networks.

Note that CPSSs mainly contain two different types of communications, i.e., human-type communications and machine-type communications. Human-type communications are the common communication services in existing communication networks, while machine-type communications are viewed as one of the emerging services to support the connection of CPSS and IoT devices in the upcoming 5G [70]. Machine-type communications can be defined as the sensing and actuation data transmission among machines to perform data processing and decision making without any human supervision during the communications. This function conforms to the design principle of CPSSs, and enables a variety of novel smart systems, such as ITS, smart grid and healthcare [71].

For the human-type communications, we take cellular as an example to discuss the challenges of incorporating CPSSs in the existing communication networks. Human-type devices in cellular follow the control of eNodeB in Long-Term Evolution for spectrum access. As for CPSSs, human-type devices may generate a large volume of traffic with the requirements of high data rates. However, the spectrum in cellular is limited for traditional communications, let alone to CPSS communications. The anticipated massive human-type devices bring in the packet scheduling problems along with the degraded network capacity and spectral efficiency.

For the machine-type communications, the challenges are different. When compared with human-type devices, the number of machine-type devices is usually numerous, even though they generate small amounts of data and have little or no mobility. Considering the massive access requests with the low-latency requirements, the existing contention-based transmission protocols are only applicable for human-type communications, and may cause frequent network congestion in machine-type communications. Furthermore, compared with the human-type communications, machine-type communications need to be designed to support the specific attributes, such as the high connection density, the extra-long battery life, and so on.

However, to the authors' knowledge, the optimization of machine-type communications or the joint optimization of machine-type communications and human-type communications is still unexplored in the field of CPSSs. Fortunately, there exist some studies of machine-type communications in CPSs, which can be the foundation work for enabling it in CPSSs. These current works mainly cover three aspects: the network congestion and system overload [71], delay of radio access process [72] and physical layer security [73], [74].

The authors in [71] focus on the problems of network congestion and system overload for CPSs, and propose a recursive operation-based analytical model to evaluate the network performance and the congestion control effectiveness. The accuracy of the analysis results is demonstrated by numerical results, and the authors further indicate that the proposal is appropriate for any machine-type communication traffic. The authors in [72] focus on the delay problem of machine-type devices in CPSs. The authors investigate a dynamic backoff indicator assignment algorithm, which has the ability to accelerate the delayed devices and finish the radio access process within an expected period of time. The proposal is verified to be feasible in CPSs with the reduced collision probability in large-scale machine-type communication scenarios. [73] and [74] focus on the problem of cyber active attacks in CPSs. The authors in [73] propose a physical layer security mechanism to guarantee the integrity and authenticity of exchanged messages among machine-type devices. The authors in [74] further introduce a new method based on a Gaussian Mixture Model for clustering the channel estimates of various transmitters, and the results show that the proposal is able to promote the goal of the defense of active attacks in CPSSs.

To further incorporate CPSSs in the existing communication networks, such as cellular, four different wireless communication technologies can be applied in CPSSs. The comparison of these communication techniques is shown in Table II. In the following, we will discuss these four communication technologies with their technique advantages in detail.

1) Massive MIMO: For CPSSs, both of the stationary devices (i.e., machine-type devices) and the moving devices (i.e., human-type devices) need to connect the data centers. To satisfy the hyper-connectivity of such a connection in CPSSs, a powerful wireless technique needs to be installed to support the fast information exchanging. Massive multiple input multiple output (MIMO) is different from traditional MIMO in nature. The total numbers of transmitter antennas and receiver antennas are almost the same in the traditional MIMO system to achieve the maximized channel capacity. Increasing one side of transmitter and receiver antennas is of little help for promoting the channel capacity. For CPSSs, it is with great difficulty to install the same number of antennas at human-type devices as the number of antennas at data centers because the space of data centers is much bigger than that of human-type devices. However, massive MIMO supports inequality of antenna numbers at different terminals, which means the data centers can be installed several times the antennas to serve multiple human-type devices with single antenna at the same time. Therefore, massive MIMO can be regarded as a great manner to enhance spectral efficiency and network capacity [75], [76], and also a core technique to support human-type communications in CPSSs.

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TABLE II: Comparison of Potential Wireless Communication Techniques.

	Solutions to the challenges of human-type communications	Solutions to the challenges of machine-type communications	Advantages for CPSSs	Current research focuses in CPSSs
Massive MIMO	It provides the spatial freedom on the same time-frequency resource to enhance spectrum efficiency.	A narrower beam can be formed to focus on a smaller space area, thus promoting energy efficiency.	Enhanced spectrum efficiency; Enhanced energy efficiency; High reliability	Power control; Energy harvesting; Equipment scheduling; Signal processing
D2D	It supports frequency reuse for enhancing spectrum efficiency.	1. Frequency reuse is used to avoid contention; 2. Nearby devices can be directly interconnected with each other to enhance connection density.	Dynamic connectivity; Faster data collection; Enhanced spectrum efficiency	Spectrum sensing; Spectrum access; Spectrum jamming; Eavesdropping
Cooperative communication	/	/	High reliability; Reduced transmission power; Improved system capacity; Expanded network coverage	Signal estimation; Signal forwarding; Optimization complexity
Cognitive radio	Unlicensed users are allowed to opportunistically exploit the unused licensed spectrum, thus improving spectrum utilization.	/	Enhanced spectrum efficiency; Improved robustness	Blind rendezvous

In practice, with the consideration of the user mobility of human-type devices, massive MIMO has the ability to adaptively adjust its diversity gain and multiplexing gain. When human-type devices move closer to the data center, the signal-to-noise ratios become relatively large; thus the multiplexing gains can be increased with the reduced diversity gains. When human-type devices move far away from the data center, the diversity gains need to be increased with the reduced multiplexing gains, thus guaranteeing the reliable transmission and better quality of services. However, the channel estimation of massive MIMO under high mobility scenarios is still the main challenge because of the Doppler frequency shift and the two-dimensional time-frequency varying channel. One of the possible solutions to the challenge is to acquire the moving device velocity instead of the accurate instantaneous channel state information [77], [78], since the velocity is not hard to estimated.

When using massive MIMO to support the human-type communications in CPSSs, it brings both of the benefits (i.e., high spectral efficiency and network capacity) and challenges (i.e., the difficulty in accurate channel estimation due to human mobility). However, it is still noteworthy that the human-type devices are just one of the device types in CPSSs. Since massive MIMO is capable of forming a narrower beam to focus on a smaller space area, it can be regarded as an efficient manner to enhance the energy efficiency for machine-type devices with little or no mobility in CPSSs. For promoting massive MIMO in CPSSs, the authors in [33] evaluate the performance of utilizing the massive MIMO base station installed at the data center to support the massive hyper-connectivity to a large amount of terminals, and discuss some research issues of deploying massive MIMO in the smart systems, such as energy efficiency design under energy harvesting, equipment scheduling, power control, signaling techniques and applications.

2) D2D communications: D2D communications can also be viewed as a great manner to facilitate the machine-type communications and the human-communications among CPSS devices over existing network infrastructures. In D2D communications, it is allowed that the nearby CPSS devices can be directly interconnected with each other without the assistance of the base stations or center points, thus enabling the dynamic hyper-connectivity and faster data collection in CPSSs. D2D can be incorporated into CPSSs to avoid the collision and guarantee the high connection density in machine-type communications [79], [80], and also to enhance spectral efficiency and network capacity for human-type communications.

The current works lack in the utilization of D2D in CPSSs. However, there exist some works about D2D in CPSs and IoT, which can be the basics to extend its application to CPSSs. The authors in [81] discuss the main challenges that the massive amount of CPS devices compete to access the limited spectrum, and study the utilization of D2D communications with the spatial spectrum sensing to mitigate the spectrum access of the devices. The authors also discuss the security problem to protect the D2D links in CPSs from eavesdropping.

D2D communications can also be applied to IoT for the information exchange among different IoT devices without human control [82]. The authors in [82] investigate some research issues of D2D communications for IoT, such as the spectrum jamming and eavesdropping. Afterwards, the blind rendezvous is introduced as an advanced technology to support secure spectrum access for the D2D users. The results validate that the proposal is able to provide a new experience on spectrum access for communication pairs in IoT by helping each other to be invisible and hiding from attackers.

3) Cooperative Communications: Cooperative communications can enhance CPSS system performance through repeating or retransmitting the signal from one transmitter to one destination with the assistance of intermediate nodes [83], thus achieving the lower error transmission rate, reduced transmission power, improved system capacity, and expanded network coverage. Even though cooperative communications may reduce the spectrum efficiency, the combination of cooperative communications and D2D communications, i.e., relay-assisted D2D communications [84], is helpful for further extending the limited communication range among different CPSS components.

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The authors in [85] propose a CPSS-based forwarding strategy for full-duplex cooperative vehicular networks. The focus of the proposed strategy is to forward a soft estimation of the received signals from the relay nodes to the destination nodes, where the forwarded signals are estimated based on the historic social data. The authors demonstrate that the proposed strategy is able to promote the reliability for cooperative vehicular networks when compared with the traditional amplify-and-forward method and the traditional decode-and-forward method, and it can realize a trade-off between system performance and computation complexity.

4) Cognitive Radio: Cognitive radio technology can also be viewed as an efficient manner to overcome the problem of the spectrum utilization in human-type communications. In cognitive radio networks, the secondary users (i.e., unlicensed users) are allowed to opportunistically exploit the unused spectrum of the primary users (i.e., licensed users). The reutilization has a premise that the performance of primary users should be guaranteed; thus the secondary users need to periodically sense the signals of the primary users when using the corresponding spectrum.

When a secondary user intends to communicate with another node, it needs to be allocated a common channel in order to establish the communication link, the process of which is called as "rendezvous" [86]. The blind rendezvous as an advanced technique can liberate the common control channel and work without the available channel information of the target user. Authors in [87] propose a Sender-Jump Receiver-Wait blind rendezvous algorithm that contributes to enabling CPSSs in existing networks with improved spectrum utilization and robustness.

B. Cyber-Physical Integration: Sensor Networks

Wireless sensor networks (WSNs) consisting of energy-sensitive and wireless-communication sensors have been applied to several practical fields, including industrial IoT, in order to achieve the ubiquitous monitoring [88]. It can be viewed as a great manner to achieve the closely connection between the cyber space and the physical world. The responsibilities of WSNs are the data collection in the physical layer through sensing nodes and the information delivery to the cyber layer with the operation and scheduling [89]–[91]. Compared with the traditional monitoring and control systems, the advantages of WSNs are the flexibility, inherently intelligent processing capability, rapid deployment and self-organization. Therefore, WSNs are necessary for CPSSs to support the highly reliable cyber-physical integration with rapid responses and appropriate actions [92], [93].

Sensor scheduling is one of the key technologies in WSNs. It supports the sensing resource allocation with the optimization objective of maximizing the scheduler performance over a future time horizon. Sensor resource management is a process of determining which sensors are better to be activated at each time epoch, the problem of which can be formulated as a constrained discrete optimization problem and solved by enumerative method, greedy method or approximate dynamic programming technique. At the present stage, few studies of CPSSs are related to the sensor resource management. However, most of the existing work for WSNs can be well used in CPSSs. The difficulty mainly lies in the joint optimization of sensing resources with other resources and the performance tradeoff.

The parameter estimation is the key for understanding the physical situation according to the distributed information captured in WSNs. Considering that most of the existing work on WSNs is assumed with homogeneous nodes, the relay-assisted WSN is explored in [88] for enabling the distributed estimation in the field of industrial automation, where the emulated network is mainly comprised of two kinds of nodes, i.e., the sensing nodes and the relay nodes. The authors propose a tree-based broadcasting strategy based on a Kalman filtering approach for the distributed sensor fusion, and design consensus-based estimation algorithms for both the sensing nodes and the relay nodes. To illustrate the advantages of the proposed methods, they are estimated in a hot rolling process monitoring system that is also a typical smart industrial system, and the results show the estimation efficiency and accuracy of the proposed methods.

CPSSs have the functionalities of detection and regulation; thus the WSNs can be extended to wireless sensor-actuator networks (WSANs) for processing control applications. Compared with the traditional control systems, wireless control systems in WSANs face the following challenges: i) The difficulty to satisfy the stringent latency requirements of feedback control; ii) The dynamic characteristic of channel conditions caused by external interference. [94] provides a brief survey of real-time WSANs for smart industrial systems to review a series of recent advances to solve the above challenges.

C. Cyber Layer: Computing Techniques

Edge computing and machine/deep learning are two valuable techniques that enable the hyper-intelligence in the cyber layer of CPSSs and achieve efficient data processing and smart decision making.

1) Edge Computing: No matter for CPSSs or for IoT, an increasing amount of data will be produced even at the network edge. Although this torrent of data can be delivered to the cloud center and efficiently processed at the cloud-based computing paradigm with a fast processor speed, the issues of the data transportation delay, transmission reliability and scarce bandwidth should also be concerned. Against this background, edge computing emerges as a novel computational paradigm to replace the cloud computing at the network edge [95]. The benefits of edge computing can be summarized as follows, when compared with the cloud computing: i) It can provide a faster response time and release the bandwidth; ii) It can provide a safer manner for processing the user data [96]; iii) It can provide the lower-energy radio access for terminals, especially for cell edge users.

The existing main representative paradigms of edge computing can be summarized as follows:

1.1) Fog Computing: Fog computing is an alternative to cloud computing. Instead of establishing channels between the central cloud and the network edge, fog computing makes

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TABLE III: Comparison of Different Edge Computing Techniques.

	Fog computing	MEC	Cloudlets	Mist computing
Locations of the computing nodes	Any point between the cloud and the edge, such as gateways, routers, switches and APs.	Servers at various base stations.	Data centers at cellular base stations or WiFi APs.	IoT devices, such as sensors, controllers, cell phones, home appliance devices and probes.
Whether or not to use dedicated devices	No	Yes	Yes	No
Computing and caching capacities at the computing nodes	Low	High	High	Medium
Proximity to devices	One or multiple hops	One hop	One hop	One or multiple hops
Range of service objects	Wider	Limited	Limited	Wider
Context awareness	Medium	High	Low	High
Whether or not to connect to central clouds	Yes	No	Yes	No
Privacy and security	High	Low	High	High
Architecture	The deeper hierarchy with the storage and deep packet networking.	A computation-oriented single layer of the nodes.	A three-layer framework of components, nodes and cloudlets.	No uniform specification.

it possible to put the computing, caching and networking resources and services at the edge of networks [97]. In fog computing, the decentralized computing infrastructures, i.e., fog computing nodes, are placed at any point between the central cloud and the terminals, and the computed contents and the processed data can be receding from the network centralized points, thereby reducing the communication latency and enabling the location awareness for CPSS services and applications. In order to solve the high transportation latency problems, the concept of fog computing can also be applied to the field of mobile cloud computing (MCC) [98], thereby introducing mobile edge computing (MEC).

1.2) MEC: The European Telecommunications Standards Institute (ETSI) announced a new standardized platform called as MEC in 2014, which is another representative paradigm of edge computing [99]. MEC is able to provide cloud-computing capabilities and information technology in close proximity to mobile terminals within the radio access network; thus CPSS devices can acquire a low-latency and high-rate access. With the development of MEC, experts find that not only the mobile terminals but also the APs are a part of the network edge. In order not to be limited to mobile networks, MEC was changed as multi-access edge computing by the ETSI Industry Specification Group (ISG) in 2017 [100]. Therefore, the term "MEC" is also used to represent multi-access edge computing now.

1.3) Cloudlet: Cloudlet is a concept associated with fog computing. Compared with cloud computing possessing unlimited resources, cloudlet can be viewed as a trusted small-scale cloud at the network edges with limited resources and private services. It can be composed by a cluster of Internet-connected computers with available resources and services for nearby devices [101]. The architecture of cloud computing can be extended to a three-layer architecture such as "devices-cloudlets-cloud" [102], where the cloudlets provide the caching and computing resources for the devices at the network edge.

1.4) Mist Computing: Due to the contradiction of the limited computational resources at the fog computing nodes (such as APs, routers, switches and gateways) with the ever-increasing amount of the data traffic, researchers put forward the concept of mist computing that utilizes the IoT devices (such as sensors, controllers, small servers, cell phones, home appliance devices and probes) to boost computing resources [103]. Most of the edge devices only utilize some of their processing resources, including power, storage and network connectivity. The unutilized resources are taken full advantages by mist computing to further promote the development of edge computing. Mist computing can be viewed as a lightweight and rudimentary form of fog computing. It can also utilize microcontrollers and microcomputers to feed into the fog computing nodes and to provide the resources and services at the extreme edge of the networks.

Table III illustrates the comparison of different edge computing techniques, where the detailed instructions are as follows:

- **Locations of the computing nodes**: The computing nodes in fog computing can be any point between the cloud and the edge. These points are restricted to the network infrastructures, but mist computing extends them to be IoT devices. In MEC and cloudlets, the computing modules are always integrated in servers or data centers.
- **Whether or not to use dedicated devices**: The specialized computing modules integrated in servers and data centers mean that MEC and cloudlets need to use the dedicated devices to realize the computation function, while fog computing and mist computing do not.
- **Computing and caching capacities at the computing nodes**: Fog computing leverages legacy network infrastructures by installing storage and processing modules, so that its computing and caching capacities are usually lower than those of MEC and cloudlets. However, since there are more devices that can be utilized as the computing nodes in mist computing, the computing and caching capacities are usually higher when compared with fog computing. Even so, its computing and caching capacities may be still less than those of MEC and cloudlets because MEC and cloudlets exploit the special space at base stations and APs for storage and processing.
- **Proximity to devices**: In fog computing and mist com-

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puting, the first hop connected to the edge devices may not be resourceful enough. Therefore, the suitable computing node may be present one or multiple hops away. However, resources in MEC servers and cloudlets are abundant, so that one hop is enough to provide services for nearby users.

- **Range of service objects**: Fog computing and mist computing support multiple hops to edge devices, and fog computing utilizes things (such as routers and gateways) as the computing nodes supporting non-IP based protocols. Therefore, they have a wider range of service objects when compared with MEC and cloudlets.
- **Context awareness**: MEC has fine grained information on the locations of edge devices and the network load in order to promote content awareness [104]. The computing nodes in mist computing can analyze and learn the dynamic behavior of IoT devices, operate under fuzzy environments, cooperate with the neighboring nodes, and achieve the advanced autonomous behavior by means of self- and context-awareness [105].
- **Whether or not to connect to central clouds**: The architecture of fog computing and cloudlets includes the central cloud, while the level of mist computing usually connects to the level of fog computing.
- **Privacy and security**: Fog computing, cloudlets and mist computing focus more on privacy and security when compared with MEC. Therefore, it is necessary to specifically discuss the privacy and security issues while designing the resource management strategies based on MEC [36].
- **Architecture**: Fog computing has a deeper hierarchy with storage and deep packet networking when compared with MEC, while the structure of MEC features a computation-oriented single layer of the nodes or base stations. Cloudlets have a three-layer architecture consisting of the component layer, node layer and cloudlet layer [106].

The current reported studies are still lacking in edge/cloud computing-enabled CPSS systems, and further research is very necessary. Table IV summarizes the existing work integrating smart systems with various computing techniques.

To accommodate the ever increasing and the wide variety of in CPSSs, [107] presents an integration cloud framework for CPSS big data, which is mainly comprised of five functional processes, including data representation, dimensionality reduction, relation establishment, rank and retrieval. The authors show that the proposed framework has great advantages for integrating the CPSS big data on the cloud.

To replace the cloud computing at the network edge, the authors in [108] point out that the features and advantages of fog computing are desirable for most IoT applications, especially for the latency-sensitive and mission-intensive services. [108] focuses on the definition and architecture of fog computing. The authors discuss the issues of the latency reduction, fault tolerance, security and privacy concerns in fog computing, and further investigate an example scenario on the fog to reveal some insights on the scalability of the edge computing-enabled systems. Different from [108], [109] considers MEC as an advanced computing model for supporting the computing ability of mobile users in CPSs. The authors in [109] propose a joint optimization model to minimize the system energy and the packet congestion, and the results show that the proposal has great advantages of energy consumption and execution delay while transmitting packets to MEC.

With the popularity of the concept of CPSSs, scholars begin to explore edge computing in CPSSs. A novel data processing pattern for CPSSs is designed by the authors in [110], which is based on the stream processing technology and focuses on distributing the workload to edge devices, sharing personal computational resources to provide collaborative data processing, and supporting cluster computing at the network edge. The results demonstrate the feasibility of the proposed pattern through evaluating an intelligent surveillance system with an edge device cluster.

An application platform for CPSCN with all the fog-based characteristics is presented based on a distributed dataflow programming model by the authors in [111]. The contributions of [111] are the establishment of an exogenous coordination model that supports the separation of the computation activity and the communication activity, and the solutions to the challenges brought about by the large-scale distribution of computing resources and the dynamic characteristic of mobile hosts in CPSCN systems.

Furthermore, [112] and [113] mainly focus on presenting the cloud-edge computing CPSS framework for CPSS services. In [112], the presented framework consists of the cloud and the edge planes, where the former is utilized to make decisions through processing the long-term, large-scale and global data, and the latter is utilized to reflect the real-time situation through processing the short-term, small-scale and local data. Based on the presented framework, a tensor-based service model is further developed to satisfy the local CPSS devices' requirements, and an application case of proactive and personalized services is evaluated to verify the application features of the presented framework. The authors in [113] present an edge cloud-assisted CPSS framework to promote the development of smart cities. The framework aims at shifting some of the computation tasks from the central cloud to the network edge devices, so that the services and resources could be closer to mobile users, thus supporting lower-latency and proactive services for residents and policymakers.

2) Machine/Deep Learning: Even though the mass data can be efficiently processed even at the network edge with the support of edge computing, some advanced techniques are still necessary to be installed on the computing servers for supporting hyper-intelligent data processing or hyper-automatic decisions [43].

In 2010s, a smart manufacturing era of IoT, cloud computing and edge computing is coming along with the emergence of big data. It is necessary to explore artificial intelligence techniques to analyze and process the big data [114]. The research interest for artificial intelligence is mainly promoted by the following factors [115]: i) The source sides of big data, such as social media, research community, the government and organization; ii) The machine leaning methodologies or algorithms for promoting the analyses and processing of the

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TABLE IV: Summary and Discussion of Existing Contribution Works Integrating Smart Systems with Edge/Clould Computing.

Reference number	Specific areas					Motivation (○), key achievements (●) and results (⋆)
	CPSS	CPS	IoT	Edge computing	Cloud computing	
Ref. [107]	✓				✓	○ To integrate the massive data generated from multiple sources ● Propose an integration cloud framework for CPSS big data ⋆ Verify the feasibility and competition of integrating CPSS big data on cloud
Ref. [108]			✓	Fog computing		○ To reduce the latency and cost of delivering data to a remote cloud ● Design a fog computing-enabled system framework for IoT ⋆ Reveal some important insights on the scalability of fog computing systems
Ref. [109]		✓		MEC		○ To answer limited executing capabilities and energy of mobile devices ● Present a joint resource optimization for MEC-enabled CPSs ⋆ Perform efficiently in terms of the execution delay and energy consumption
Ref. [110]	✓			✓		○ To facilitate the computationally-intensive processing of large CPSS datasets ● Propose a data processing pattern deployed on CPSS edge device clusters ⋆ Demonstrate the feasibility of the proposal
Ref. [111]	✓			Fog computing		○ To build CPSCN systems that embraces all the fog-based characteristics ● Propose an application platform for CPSCN systems ⋆ Resolve some challenges from the dynamic and large-scale CPSCN systems
Ref. [112]	✓			✓	✓	○ To provide the high-quality, proactive and personalized services for humans ● Propose a tensor-based cloud-edge computing CPSS framework ⋆ Verify the application features of the proposed framework
Ref. [113]	✓			✓	✓	○ To promote the development of smart cities ● Propose an edge cloud-assisted CPSS framework for smart cities ⋆ Provide more effective and proactive services for residents and policymakers

big data; iii) The powerful computing servers for providing the computation services of big data. The authors in [115] summarize the evolution of artificial intelligence, compare and discuss artificial intelligence with smart manufacturing, and further propose a smart manufacturing for Industrie 4.0. Compared with the traditional symbolic artificial intelligence with the centralized control and structured contents, the next generation of artificial intelligence supports the decentralized control, unstructured contents, machine learning and deep learning.

Machine learning is regarded as the core of the artificial intelligence, with which the computing servers can learn from experience without being explicitly programmed [19]. Generally, machine learning can be classified into four categories: reinforcement learning, supervised, unsupervised and semi-supervised learning [19]:

2.1) Supervised learning: Supervised learning relies on the presence of the training data, where the input data and the corresponding label are given. Based on the supervised learning, the machine can find the relation between the label and the features of data, which means the future input data can be identified even though the data are only with features and without labels.

2.2) Unsupervised learning: Unsupervised learning relies on the absence of training data, which means the data label is unnecessary and it has to discover the hidden patterns in the data. Based on the unsupervised learning, the machine can divide the input data into several categories according to the intrinsic relation and similarity among the data.

2.3) Semi-supervised learning: The semi-supervised learning uses a small amount of labelled data and a large amount of unlabelled data for learning. Compared with supervised learning, semi-supervised learning can reduce the learning cost and improve the learning accuracy.

2.4) Reinforcement learning: The objective of reinforcement learning is to enable the system rewards based on the limited environment knowledge and the limited decision feedback. It takes a series of actions in response to a dynamic environment, and the rewards reflect whether or not each action approaches the right solution.

Deep learning can be viewed as a branch of machine learning, which realizes the artificial intelligence through establishing an artificial neural network with a hierarchical structure. Since the hierarchical neural network can extract and screen the input information layer by layer, the deep learning has the ability of representation learning, and can realize the end-to-end supervised learning and unsupervised learning. With the development of artificial intelligence, deep learning can also be incorporated into the construction of reinforcement learning system, namely, deep reinforcement learning, which integrates the perception of deep learning and the decision making of reinforcement learning [116].

Authors in [70] point out the main advantages and disadvantages of different learning techniques in IoT. Here, we focus on the discussion of the above learning techniques in the existing CPSS research. The current research about learning techniques in CPSSs mainly contains four aspects: neural network, classification, clustering and reinforcement learning. Table V illustrates the comparison of these different learning techniques in the existing CPSS research, where the Input/Datasets and the Output/Results list the data or the datasets entering the learning techniques and the corresponding learning results.

Neural network is a type of supervised machine learning to enable detection, annotation and prediction through large-scale data analyzing and processing, where deep learning can be viewed as the extension of the neural network. The neural network-based intelligent algorithms can be applied in the field of the optimization. For example, [117] accomplishes several numerical optimizations and computations to verify the performance of the neural network model based on the glowworm swarm optimization back-propagation for optimiz-

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TABLE V: Summary and Comparison of Different Learning Techniques in the Existing CPSS Research.

Learning techniques	Reference number	Deep learning	Application fields	Motivation	Input/Datasets	Output/Results	Convergence	Achievements
Neural network (Supervised learning)	Ref. [117]	✗	Elliptical treadmill	Vibration optimization	Excitation forces	Fitness value	Verified	An elliptical treadmill with the minimum mass and vibration
	Ref. [118]	✓	Industrial applications	RUL Prediction	Spectrum-Principal -Energy-Vector	Bearing RUL	–	Improve the prediction accuracy of bearing RUL
	Ref. [119]	✗	CPSS applications	Blind signal detection	Blind signals	Expected signals	Verified	Improve the detection precision and reduce the omission rate
	Ref. [120]	✗	CPSS applications	Image annotation	Corel-5K; IAPR TC-12	Deep image features	–	Show the effectiveness of the proposal for image tagging
Classification (Supervised learning)	Ref. [121]	✗	Video conference	Data prediction	24865 video conference call instances	Bandwidth and destination	–	Improve prediction accuracy
Clustering (Unsupervised learning)	Ref. [122]	✓	CPSS applications	Multi-modal data clustering	NUS-WIDE; CUAVE	Feature learning; Tensor clustering	–	Improve the accuracy of clustering results
	Refs. [123]-[124]	✗	CPSS applications	Dynamic data clustering	Multiple features dataset; Reuters multilingual dataset; NUS-WIDE dataset; Benchmark dataset	Distance matrix; Cluster center; Cluster result; Difference parameter; Contribution parameter	–	Improve effectiveness and efficiency in clustering dynamic multi-modal data
	Refs. [125]-[126]	✗	Automation industries	Multiple clustering	Bike and Meteorology; Electronic commerce	Multiple clustering results	–	Improve the clustering quality with the lower redundancies; Provide enhanced knowledge extractions and services
	Ref. [127]	✗	Human fishing	Behavior recognition	Fishing vessel datasets	Behavior clustering	–	Judge the human behavior of the vessel
	Ref. [128]	✗	Human sentiment	Sentiment classification	Datasets of book, digital versatile disc (DVD), electronics, kitchen, movie in Amazon	Sentiment clustering	–	Improve classification accuracy
Reinforcement learning	Ref. [43]	✗	Transportation	Parallel driving	Destination state	Control actions and trajectory	–	An automated vehicle design
	Ref. [21]	✓	Smart grid	Survey	–	–	–	An overview of the existing work on the applications of reinforcement learning, deep learning and deep reinforcement learning in smart grids

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ing the vibrations of the elliptical treadmill.

Other than the optimization problem, the neutral network can also be applied to various example applications. To accurately predict the remaining useful life (RUL) in CPSSs for industrial IoT, the authors in [118] propose a novel data-driven method along with a smoothing approach based on the deep convolution neural network. To enable the blind communication signal detection for CPSSs, the authors in [119] explore a novel method based on the back-propagation neural network for promoting the signal detection's precision and reducing the omission rate. To enable image annotation in CPSSs, the authors in [120] focus on the internal relevance of the image labels and the imbalanced distribution of the image classes, and design a novel learning model for extracting the deep features of images based on the convolution neural network approach. The results show the effectiveness of the proposals.

Data classification is also a type of supervised machine learning, which includes but is not limited to support vector machine, binary decision tree, Naive Baysian classifier and so on. Considering the video contents become the majority of Internet traffic, the authors in [121] study the multimedia transportation over IP networks, and perform a multivariate analysis of video call data in CPSSs over a period of time through a learning-based prediction. The authors train the classifiers by four kinds of learning algorithms, including support vector machine, decision tree, Naive Baysian and k-nearest neighbors. The results report an enhanced accuracy of 60% for destination prediction and 81% for bandwidth prediction during the video conference connection.

Mining large data is another important research subject in CPSS developments, which contributes to promoting the quality of service for CPSS devices. Clustering, as a well-known data mining technology and a type of unsupervised machine learning [19], has the ability to discern the underlying pattern that hides in the data. There exist some studies related to data clustering-based models and algorithms in the field of CPSSs:

The authors in [122] indicate that CPSSs may collect a large amount of heterogeneous data with multi-modalities, such as image, text and audio, thus proposing a high-order k-means heterogeneous-data clustering algorithm to cluster the heterogeneous objects through learning and revealing the features of the objects. The algorithm is based on the deep learning model and aims at promoting the accuracy of the clustering results for CPSSs.

The authors in [123] and [124] point out that most of the existing clustering algorithms mainly deal with the static data, and these algorithms may be infeasible to process the multi-modal data, especially in dynamic CPSS environments. Therefore, a parameter-free incremental co-clustering method is proposed by the authors in [123] to cluster the dynamic multi-modal data. Afterwards, in order to well handle the large-scale dynamic data, the authors in [124] further present an incremental clustering method through extending clustering with the ideas of the fast search and find of density peaks approach. The experiments verify the improved effectiveness and efficiency in clustering dynamic multi-modal data.

The authors in [125] and [126] focus on constructing a flexible clustering framework for CPSS big data, and consider the heterogeneity, diversity and high-dimensionality of the CPSS big data. The authors first present an analytic and service framework for flexible multiple clustering with a novel tensor-based multiple clustering method, which aims at enhancing the quality of the clustering results with lower redundancies while satisfying the application requirements for CPSSs [125]. The contribution of this work is beneficial for promoting the hyper-automation in CPSS industries through discovering the latent data patterns in big data from multiple views. Afterwards, the authors present two kinds of multiple clustering methods, each of which produces different clustering results based on the arbitrarily selection of the feature combinations, and design a multiple clustering method based on the tensor decomposition and the multi-relational attribute ranking method to efficiently handle the high-dimensional data [126]. The simulation results verify that the presented method is able to effectively cluster the CPSS big data and to support the enhanced information extractions and services.

The authors in [127] focus on a more specific data processing problem, i.e., learning and exploring human fishing behaviors. A multi-step clustering algorithm is presented to support the studying of the human fishing activities, the monitoring of illegal fishing and the protecting of the fishing resources at sea. The authors in [128] also focus on a specific problem, i.e., sentiment classification of online reviews, and propose a word embedding clustering-based deep hypergraph model to promote the classification accuracy among different reviews.

There also exist some studies exploring reinforcement learning in CPSSs. For example, the authors in [43] concisely review the techniques of parallel testing, learning and reinforcement learning for enabling parallel driving, i.e., a cloud-based CPSS system framework with the function of the connected automated driving. Reinforcement learning, deep learning and deep reinforcement learning are the representative learning techniques in artificial intelligence 2.0. The authors in [21] introduce the concepts and current status of the three techniques, and also provide an overview of the existing research work on the applications of these techniques in smart grids.

3) Other Computing techniques: To operationalize big service, also known as service computing that aims at providing predictive services, a multi-order distributed high-order singular value decomposition (HOSVD) method is proposed by the authors in [129] with an incremental computational algorithm. The proposed method supports the high-efficient analyses of the large-scale heterogeneous data. The authors show that the method is able to improve the extensibility and adaptability of the data diversity, and also to convert the low-level data into actionable knowledge. To avoid redundant computations on the historical data while handling the incoming periodic data, the authors in [130] propose a columnwise HOSVD algorithm and a similar columnwise incremental method for promoting the scalability of the existing big data processing methods. The proposed algorithm aims at enabling the reduction of the dimensionality and noise for the tensor-based big data, and

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supporting the online computation for the incremental data streaming.

Three-dimensional scanning technology that is based on reconstruction algorithms and shape extraction algorithms with regularized points becomes the mainstream technology in CPSSs. It is one of the effective data processing skills to treat data as point clouds. The authors in [131] propose a slicing-based regularization method, which can well apply to the scenario of huge raw point clouds, and is able to produce the regularized point clouds.

D. Cyber-Social Integration: Social Networks

Social networks, such as Facebook and Twitter [132], [133], are the key part of CPSSs. It is mainly comprised of social realities, such as individuals, organizations and corporations, and can connect these social realities to the cyber space. In the cyber layer of CPSSs, the social realities can be considered as interconnected nodes with some specific types of interdependency, such as friendship, beliefs, financial exchanges and common interests.

With the increasing popularity of social networking sites or services, the total number of users joining in social networks continues to rise in recent years. Due to this status quo, the social network is of great difficulty to be analyzed and improved with the large amount of entities. Besides, social entities have the dynamic characteristics, which further increase the difficulty of analysis and processing. In this context, social computing emerges and focuses on the promotion of the social studies and the social dynamics through handling the large-scale social context with the information techniques.

In addition, we also need to focus on the problems of how to improve the information propagation in the social networks, so that the data can be propagated in fewer hubs, thus improving the communication efficiency. The authors in [134] investigate the way to enhance the information propagation for social networks. Through adding the new linkages to the social networks and meanwhile decreasing the total number of communication hubs, the communication effectiveness can be improved, which contributes to the development of the practical social network communications and the cyber-physical-social interaction and computing.

In most of the discussion before this subsection, humans are always viewed as individuals with different levels of credibility, influence, or professional quality. The incorporation of social networks regards human society as a whole that can be arbitrarily divided. Under different divisions, there exist relationships among people in terms of friendship, beliefs, financial exchanges and common interests. That is to say, social networks emphasize the human dependency. When we utilize the collective wisdom to serve the system instead of the individual wisdom, it will produce even more outstanding results.

E. Social Layer: Social Evaluation

Humans in CPSSs could be not only the service consumers but also the service providers. An efficient social evaluation mechanism is conducive to putting humans as both of service consumers and service providers in the CPSS loop. However, the current status of CPSSs is still lacking in the research field of social evaluation. Here, the authors will give some possible evaluation directions that can be used in CPSSs.

On one hand, when the role of users is the service consumer, the social evaluation could be the satisfaction evaluation, which is used to estimate the satisfaction degree of users after acquiring the required services. This kind of evaluation is very common on most existing systems or networks, and it can be an index to guide the direction of service improvement. The satisfaction degree can also be predicted before business supplying, thus promoting the service quality [135]. Specifically, in CPSSs, the satisfaction evaluation mechanism can be performed for the smart recommendation systems in real target environments as discussed in Section IV-A, since the recommendation lists should be not only accurate and helpful but also pleasure for users.

On the other hand, when the role of users is the service providers, the social evaluation mechanism covers more possibilities, such as influence evaluation, capability evaluation, reputation evaluation and so on. The influence evaluation measures the social influence of a person [136], [137]. For example, in CPSSs, it could be used to determine the influence of a person in an industry, thus taking full advantages of the high-value human resources at the right time. In addition, the capability and the reputation also need to be evaluated when the users work as service providers in CPSSs. The capability means the completion quality of a user to fulfill the assigned task. The reputation signifies whether a user honestly completes the assigned task within the task's time-to-live (TTL).

A reasonable mechanism can adequately inspect every aspect of each user, thus making better use of human resources and serving people better. In addition, the social evaluation mechanism can be incorporated with the human incentive mechanism as discussed in Section III-D, thus motivating the humans with the higher ability and credit to participate in the operation and management of CPSSs.

F. All Layers: Human-Machine Coordination, Resource Management, and Security and Trust

The current research status related to all layers in CPSSs mainly lies in the human-machine coordination, resource management, and security and trust. Besides, after putting humans in the loop of CPSSs, some research contents have their unique characteristics or have additional considerations when compared with the techniques applied to CPSs. Table VI summarizes the existing research related to the human-machine coordination, resource management, and security and trust in CPSSs, the details of which are shown in the following subsections.

1) Human-Machine Coordination: Since humans are regarded as an organic part of CPSSs rather than being placed outside the system boundary, the system needs to be designed to realize the coordinating and unifying of humans and systems. However, in CPSSs, humans and systems usually coexist in distributed environments, and thus the coordination

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TABLE VI: Existing Works About Human-Machine Coordination, Resource Management, and Security and Trust.

Research orientation		Reference number	Motivation (○), key achievements (●) and results (⋆)	Performance parameters
Human-machine coordination	Coordination	Ref. [138]	○ To realize the coordinating and unifying of humans and systems ● Propose a coordination theory-based modeling method for CPSSs ⋆ Reveal the applications of the proposal through a case of air attack	–
		Ref. [139]	○ To investigate the reliability of CPSSs and to coordinate mixed compute units ● Present some basic coordination patterns ⋆ Test and verify the reliability among different coordination patterns	Reliability
		Ref. [140]	○ To realize the monitoring of the centralized coordinated CPSSs ● Develop a monitoring framework to capture and analyze the runtime metrics ⋆ Verify monitoring features through a monitoring framework	–
	Self-organization	Ref. [141]	○ To provide a shared understanding of some domain across multiple CPSS resources ● Propose an upper level context ontology for CPSSs ⋆ Apply the ontology in the self-organising resource network	–
	Self-synchronization	Ref. [7]	○ To construct command and control organizations ●(⋆) Propose a CPSS framework for command and control self-synchronization	–
Resource management	Computation resources	Ref. [142]	○ To optimize CPSS computation from multiple perspectives ● Propose a general model for tensor computation to optimize multiple indicators ● Measure a case from different aspects of user requirements through HOSVD method ⋆ Verify the applicability and generality of the proposal	Execution time; Energy consumption; Economic cost; Security; Reliability
		Ref. [143]	○ To allocate the CPSS tasks by crowdsensing with high-confidence ● Present a game theoretic method for assigning tasks with trust and incentives ⋆ Demonstrate the performance improvement of the proposal	System revenue
		Ref. [144]	○ To provide efficient crowdsourcing in CPPS ● Propose an incentive scheme for CPSS social users ⋆ Reduce the data collection cost and promote the data accuracy	System revenue
	Communication resources	Ref. [145]	○ To model the social interaction among smart devices in the autonomous WiFi scenario ● Propose an active interference measurement methodology ● Present a Nash bargaining-based coordinated power control method ⋆ Reduce the interference of APs with hidden terminal interference	Interference
		Ref. [146]	○ To guarantee the communication requirements of social components ● Propose a joint resource optimization and access control scheme ⋆ Demonstrate the performance improvement of the proposal	Bandwidth connectivity; Quality of service
		Ref. [147]	○ To support the interconnection of various machines ● Propose an energy-efficient resource optimization scheme ⋆ Demonstrate the efficiency of the proposed scheme	Energy efficiency; Quality of service
		Ref. [148]	○ To guarantee the communication requirements of various CPSS components ● Propose a robust energy-efficient resource optimization scheme ⋆ Verify the algorithm convergency and the scheme performance	Energy efficiency; Robustness
	Power resources	Ref. [149]	○ To reduce the variability of renewable generation and peak demand ● Propose a centralized demand side management approach ⋆ Reduce the robust bounds on the anarchy price	Power loads
		Ref. [150]	○ To optimize the power loads with the consideration of human behaviors ● Formulate a convex optimization problem to incentivize human decisions ⋆ Verify the accurate prediction of the reducible power	Power loads
		Ref. [151]	○ To rapidly obtain a higher quality of energy distribution ● Design a distributed energy management scheme for a microgrid with parallel learning ⋆ Obtain a higher quality optimum of distributed energy management	Operation energy cost
		Ref. [152]	○ To promote the job processing with mobile devices ● A job allocation mechanism for minimizing the battery consumption ⋆ Demonstrate the increment in the job processing speed of the proposal	Battery consumption
		Ref. [153]	○ To extend the service life of mobile devices ● Propose a minimized energy consumption scheme for IoT device charging ● Propose moving-path planning algorithms for point-to-multi-point charging ⋆ Demonstrate the near optimal performance of the proposal	Energy consumption
Security and trust	Security threats	Ref. [154]	○ To explore the problems of CPSS attackers ● Present different leakage models and design inference methods ⋆ Demonstrate the effectiveness of the proposed inference scheme	–
		Ref. [155]	○ To further investigate associated risks in CPSSs ● Propose a hybrid Bayesian risk graph model ⋆ Demonstrate that the proposal can evaluate risks of user activity patterns	–
	Security guarantees	Ref. [156]	○ To enable both data management efficiency and data privacy preserving ● Propose a convergent key management scheme and a convergent key sharing scheme ⋆ Achieve computation and communication efficiency	Communication overhead; Computation overhead
		Ref. [157]	○ To further promote the data management efficiency ● Propose a secure certificateless public integrity verification scheme ⋆ Provide stronger security guarantees	Communication overhead; Verification Overhead
		Ref. [8]	○ To explore the problems of privacy concerns ● Propose a novel privacy preservation framework and a data publishing mechanism ⋆ Achieve a local maximized performance on the published data size	–
	Social trust	Ref. [158]	○ To explore the problem of social trust ● Propose an approach for analyzing trust ⋆ Verify the utility and the feasibility of the approach in telemedicine domain	–
		Ref. [159]	● (○⋆) Address the needs of trust and explore the approaches of trust formalisms	–
		Ref. [160]	○ To explore the trust problems among the artificial agents ● Propose a robot-virtual human bilateral trust model ⋆ Realize the satisfying collaboration among agents	–

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theory is viewed as an efficient manner to model CPSSs and meanwhile overcome the difficulties of complex structures and dynamic processes in CPSSs. Against this background, the authors in [138] propose a multi-dimensions meta-model based on the coordination theory, where the coordination meta-model is constructed in the coordination view, the human view and the system view. The coordination view defines the interdependency and the actions of CPSS components, the human view explains how humans integrate and interact with the CPSS components, and the system view presents the co-organizing relationship and the structural relationship among the components. The authors further reveal and verify the applications of the proposal through a case of air attack.

Note that CPSSs are able to utilize both of machines and humans as active compute units, which mean that CPSSs allow humans to participate as the service consumers and also the service providers. In this context, the machine-based compute units and the human-based compute units become a collective to execute computation tasks. During the task implementation, the coordination patterns need to be designed to enable the collective of the different compute units. Against this background, the authors in [139] present several typical coordination patterns of the human-based compute unit and the machine-based compute unit, and investigate the reliability among different patterns through a proposed reliability analysis framework. To further promote the coordinated CPSSs, the authors explore the monitoring issues in [140], and present the metric models with the associated quality of data to support the elastically monitoring of the execution metrics. The authors implement a monitoring framework to capture and analyze the runtime metrics from different compute units, such as sensors, actuators, human-based compute unit, software services and gateways in the coordinated CPSSs.

Self-organization is a main self-control function in CPSSs, which contributes to achieving the hyper-automation characteristic of CPSSs. Since CPSSs contain numerous resources from the physical, cyber and social worlds, it is difficult but also essential to achieve the efficient interaction of these resources for CPSS operation. Self-organization is one of the efficient solutions to organize the interaction and communications among the various resources. The authors in [141] propose an upper-level ontology for CPSSs with the multi-level self-organization of CPSS resources. The design goal of the proposed self-organization mechanism is to support human decisions, activities and task solutions in their daily life, where humans are viewed as participants during the resource self-organization process. The introduction of the upper ontology indicates that the physical resources are merged into the human resources in the application domain. Humans can act as the role of resources in providing knowledge and services, and they can also be consumers of CPSSs to acquire knowledge and services.

According to the coordination theory, self-synchronization of CPSSs is also a self-organization and self-adapting process [138]. To enable self-synchronization mechanisms of the command and control organizations for CPSSs, the main challenge mainly comes from the organic combination of different domains, i.e., the social domain with social networks, the cognitive domain with the mental elements, the information domain with cyber networks, and the physical domain with physical systems. The self-synchronization mechanisms in CPSSs include the vertical self-synchronization throughout different domains and the horizontal self-synchronization in each domain. In [7], a CPSS framework is proposed to support the dynamic operational mechanism of self-synchronization for the entire command and control organization, where the essential components of the operational mechanism in the four domains are considered while connecting the social network, the mental space, the cyber space and the physical network. Since the presented CPSS framework couples humans and physical systems in the loop, it is constructed to emphasize the human-system interaction during the command and control. Specifically, the observation, orientation, decision and action of humans are supported by the physical systems, and meanwhile the physical systems make supplementary decisions or implement routine work based on the organizational intelligence of humans.

2) Resource Management: To promote the system performance, we then focus on the discussion of resource management in CPSSs, which includes the management of computing resources, communication resources and power resources. The computing resources have two types, i.e., system-type computing resources and human-type computing resources. The reasonable deployment of CPSS computing resources is conducive to promoting the data processing and decision making. The reasonable deployment of CPSS communication resources is the basis to support the interconnection of each components in different layers of CPSSs. Since the energy optimization is not restricted to the communication field and computation field, the discussion of power resource management is separated from communication resources and computation resources. The power resources also need to be managed with consideration of human behavior effects, and the reasonable deployment of CPSS power resources is beneficial to extending service life.

2.1) Computation Resources: CPSSs contain abundant computation resources to support real-time analytics and business intelligence. It is of great importance to effectively plan and utilize these resources. Considering the issues of the economic cost, energy consumption, execution time, reliability and security during computation processing in CPSSs, the authors in [142] design a general model for tensor computation to jointly optimize the above indicators, investigate a case from different aspects of user requirements through the tree-based distributed HOSVD method, and verify the applicability and generality of the proposal.

For CPSSs, the social users can also be viewed as a portion of computation resources. For example, the incentive scheme can be regarded as an alternative method to encourage social users to participate in the task computing in CPSSs. Aiming at the task allocation in the high-confidence CPSSs with the vast amount of sensing data and the limited resources, a novel bargaining game theoretic approach is proposed in [143] to assign tasks with trust and incentives. The trust evaluation mechanism is designed to evaluate the user reputation, and the incentive mechanism based on the virtual currency is presented

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to encourage users to handle the computation tasks. The authors present a game theoretic method for assigning tasks, and the experiments indicate the performance improvement of the proposal when compared with other schemes. Furthermore, [144] designs a novel user reputation-based incentive scheme. After dividing social users into different types as malicious users, speculative users and honest users, the designed incentive scheme is able to encourage social users with a higher degree of reputation to contribute to sourcing data for promoting crowdsourcing services, such as Wikipedia, YouTube and Facebook. The optimal social users can be selected through the presented auction game model, which have the right to access the tasks, thus enhancing the accuracy of the sourcing data when compared with conventional methods.

2.2) Communication Resources: The communication network is an important part of CPSSs to provide a medium for exchanging information among different components, and thus the rational deployment of communication resources is also of great importance.

The authors in [145] aim at designing and investigating the social interaction model for self-managed smart CPSS devices in the WiFi scenarios. The authors propose an active interference measurement methodology for detecting the in-range and the hidden terminal interference, and present a Nash bargaining-based coordinated power control method that can significantly reduce the interference when compared with the non-cooperative power control method.

Spectrum management is investigated in [146] to guarantee the communication requirements of social components in CPSSs. The authors design a joint resource optimization and access control scheme based on the parallel network architecture, where the social users are classified according to their social properties, i.e., priorities and bandwidth requirements, and then the high-bandwidth connectivity and the quality of services can be guaranteed through the bandwidth allocation and the access control. For practical implementation, the authors apply the Q-Learning to realize the automated network configuration, management and optimization.

Besides the interference and spectrum management issues, the transmission energy efficiency and robustness are also the key problems in CPSS communication networks. A resource allocation problem is formulated in [147] to maximize the communication energy efficiency of cyber-physical IoT systems (CPIoTS). The optimization problem is decomposed into power allocation and channel allocation to reduce the computational complexity. The simulation results demonstrate the efficiency of the proposed scheme in terms of energy efficiency and quality of services. Furthermore, [148] proposes an energy efficient resource allocation scheme under the assumption of imperfect channel state information. The presented scheme is able to significantly promote the system energy efficiency and jointly guarantee the transmission outage requirements of CPSS controllers and actuators, and the authors also verify the algorithm convergency of the proposal.

2.3) Power Resources: The power optimization is not restricted to the communication field and computation field. For example, considering the increased variability in renewable power generation, such as wind and solar power, [149] indicates that the electric power load management of consumers can be viewed as a promising approach to solve this issue. The authors propose a centralized demand side management approach for the cyber-physical-social electric grid with sensing, communication and computation technologies. Flexible power loads of consumers are modeled to maximize the total utility while minimizing the overall power consumption of legible loads subject to several operational constraints, and the power loads can also be controlled through a decentralized approach based on the non-cooperative game. The results show the property of a valid monotone utility game in the proposed decentralized approach, which brings in a robust lower bounds on the anarchy price. The authors in [150] focus more on human interactions while managing the power loads of CPSSs, where it is assumed that the input of the system is induced by human behavior. The convex optimization problem is formulated to minimize the power loads and the price compensations for user participants, and the solution is able to stimulate human decision to construct a system-wide optimization model. The authors further verify the accurate prediction of the proposal in terms of the reducible power through experiments.

For CPSSs, both the energy suppliers and the energy demanders can be humans in the social space. They cooperate with each other and make decisions with different preference behaviors. In order to effectively realize the collaboration among humans and computers and also to rapidly obtain a higher quality of energy distribution, [151] focuses on the design of the distributed energy management scheme for a microgrid based on CPSSs with parallel learning. The proposed scheme is able to minimize the total operating energy cost while guaranteeing the constraints of energy balance, capacity limits, operating regions and minimum demands, and verified to be effectiveness in improving the quality optimum of the distributed energy management.

In addition, job splitting and allocation are the critical factors for processing CPSS big data. A job allocation mechanism for minimizing the battery consumption is proposed in [152] to continuously reflect the battery consumption rate of mobile devices to handle the jobs, and to minimize the job reallocation problem according to the periodic measurement results of the battery consumption and the surplus resource. The mechanism is beneficial for avoiding the job reallocation because of the battery rundown, and the results show the proposal is able to increase the job processing speed.

To extend service life of CPSS devices, especially for the human-type devices, the authors in [153] study the emerging technique of wireless power charging based on the radio frequency with mobile chargers. An optimization problem is formulated to minimize the energy consumption during the IoT device charging through planning the motion trail of the mobile charger and determining the efficient charging points. The results show that the performance of the proposal is near optimal in terms of charging efficiency.

3) Security and trust: The security and trust issues are the common issues for both of the human society and systems. Security threats, including information leakage, inference attacks and some other associated risks, are insurmountable obstacles in CPSSs. [154] points out that the attackers may seek the

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chance to acquire sensitive information and data in the system. Therefore, the authors identify different leakage models with inference methods, and indicate that some of the information leakage models can tolerate a powerful attack on the premise of little prior knowledge. Afterwards, the authors propose novel inference attacks only based on a partial knowledge of the target documents, which are shown to be more scalable and effective without the optimization overheads. In addition, [155] investigates some CPSS-associated risks, and proposes a hybrid Bayesian risk graph model to estimate and evaluate the risk propagation for a layered risk architecture, and to analyze the temporal attack activity patterns in dynamic CPSS environments.

Secure deduplication [156] and secure verification [157] are advanced techniques to enable both data management efficiency and data privacy preserving for CPSSs. The authors in [156] propose a convergent key management scheme based on the session key, which is able to guarantee the security of the dynamic update for data deduplication. The authors further present a convergent key sharing scheme in order to support the group combination and to remove the gateway aid, thus achieving computation and communication efficiency for key management. A secure certificateless public integrity verification scheme is proposed by the authors in [157], which is able to support the certificateless public verification and the resistance against malicious auditors at the same time, thus providing stronger security guarantees. In addition, a novel privacy preservation framework is proposed based on the real-world knowledge in [8] for CPSSs. The framework is constructed with the formulation of user expectations and privacy concerns. A data publishing mechanism is further designed to conceal the sensitive user profiles and meanwhile guarantee the comprehensive social profiles. The results indicate that the proposed scheme is able to achieve a local maximized performance on the published data size.

Trust realized by analyzing the expectations of social interactions and dependencies among humans and other components is a key subject for the development, operation and management of CPSSs. In [158], the structured assurance cases are utilized to analyze trust in CPSSs, and the authors demonstrate the utility and the feasibility of the proposed trust analyzing method by a telemedicine domain example. In [159], smart and connected senior caring systems are explored to discuss the necessity of trust in CPSS design and trust formalism approaches for CPSSs. In addition, [160] refers the trust problems among the artificial agents of both the humanoid robot and the virtual human, where the different artificial agents posses the similar autonomy, functionalities, intelligence and modalities, and can be integrated as a CPSS with a shared communication platform. To support such a system with trust guarantee, a robot-virtual human bilateral trust model is proposed by the authors in [160], where a real-time trust measurement method is presented in order to realize the satisfying collaboration of the virtual human and the robot, and also to support the assistance of various human tasks.

G. All Layer Integration: Ad-Hoc and IoT

1) Ad-Hoc Networks: Each of the social, cyber and physical components in CPSSs can be promoted in a synergistic manner through associating the components with each other, namely, the ad-hoc connection among the devices in CPSS networks. To construct an ad-hoc CPSS network, it is necessary to realize an efficient connectivity among various components [161]. There are some challenges while realizing the hyper-connectivity for ad-hoc CPSS network: i) The difficulty to simultaneously associate all the concerned nodes due to the limited network resources, such as power consumption and spectrum; ii) The difficulty to keep the fixed network state due to the devices mobility, which may result in the network performance degradation.

To overcome the above challenges, the authors in [162] present a novel mobility-aware method with a reliable local tree-based topology for constructing an ad-hoc based mobile smart system. The presented method aims at achieving adequate network connectivity and reducing the level of power consumption. Furthermore, the authors in [163] focus on a more concrete scenario of dynamic transportation systems, i.e., vehicular ad-hoc network (VANET), and investigate an analytical approach for evaluating the network performance by dynamically adjusting the transmit power and the contention window of vehicular communications. The Monte Carlo simulations indicate the proposal is able to achieve well dynamic adaptation when compared with the existing works.

2) IoT: The concept of IoT origins at the 1990s. It is an ambitious plan and also an ultimate goal [164]. It has a lot of similarities with CPSSs, which can be summarized as follows [32]:

- The interaction among the social world, the physical world and the cyber world.
- The detection of the physical components in the real world through information sensing equipment.
- The transmission and sharing of the measured data information over the communication network.
- The computing process of the measured data through central controllers and distributed controllers to achieve safe, effective and intelligent monitoring.
- The wide range of application fields, such as smart traffic, smart home, smart hospital, smart grid, smart industry, smart agriculture, etc.

However, IoT differs from CPSSs in its emphasis on the architecture design [32].

- CPSSs: The focus of CPSSs is “system”. It has the vertical system architecture, and it can be used to realize the different intelligent applications.
- IoT: The focus of IoT is “network”. It has a horizontal system architecture, which aims at interconnecting all the physical components in the network through the transport layer. The result of IoT can also be viewed as the integration of information technologies and physical objects or systems [164].

As mentioned above, different from CPSSs, IoT emphasizes the internetworking of every element, and it possesses a horizontal architecture. Along this line, IoT can be viewed

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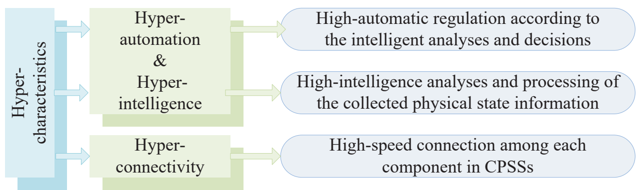

Fig. 11: The hyper-characteristics of CPSSs.

as an efficient way to achieve the interconnection of all the CPSS devices through the transport layers by extending to almost everything [33]. [148] and [159] explore the resource optimization and trust problems for CPSSs powered by IoT.

H. Lessons Learned: Summary and Insights

CPSSs pursue real-time and comprehensive fusion of the cyber world, physical world and social world with the characteristics of hyper-connectivity, hyper-intelligence and hyper-automation, as shown in Fig. 11. The techniques and networks discussed above are able to guarantee these basic hyper-characteristics in CPSSs.

- **Hyper-connectivity**: The communication techniques in the physical layer are the powerful means to support the ultra-high speed connection among various components in physical worlds. These techniques can also be applied to sensor networks and social networks, in order to promote the physical-cyber and cyber-social integrations. Besides, the networks of ad-hoc and IoT also provide efficient and effective connectivity among each of the social, cyber and physical components in CPSSs.
- **Hyper-intelligence**: This kind of hyper-characteristic is guaranteed by most of the techniques in cyber space, such as edge computing and machine/deep learning. These techniques make sure that the system can produce the valuable decisions, thus driving it in a way that is more conducive to improving human lives.
- **Hyper-automation**: On one hand, the learning techniques are used for providing intelligent services to service consumers. One the other hand, it can be regarded as an effective approach for the high-automatic regulation based on the intelligent analyses and decisions; therefore it is also used to enable hyper-automatic control in CPSSs [43], [125], [146]. In addition, the self-control functions and the coordination mechanisms of CPSSs discussed in Section V-F can also realize the hyper-automatic management.

Automation and intelligence achieve some expected goals of humans in the absence of human intervention or based on little human intervention, which seems to be contradictory to the principle of CPSSs that puts humans in the loop. It is noteworthy that CPSSs make full use of ideas that humans can come up with innovative solutions and have crowd wisdom, which means that most of the decisions made by crowd leads to the outstanding results. The techniques can realize the high-intelligent and high-automatic control or management, but it may not always show you innovations. Besides, neither automation nor intelligence is in the service of humans, and putting humans in the loop can better ensure the service effectiveness. However, as for CPSSs, we still need to further explore the intelligent automatic control and management, especially for the harmonious coexistence of automatic smart systems and humans.

Moreover, the current research status in various technical fields shows that it is still unclear how to apply social networks along with social evaluation in CPSSs. Sections V-D and V-E only discuss the advantages of incorporation of social networks and social evaluation. However, the application still has great challenges, such as how to select social groups according to the evaluation values, and how to evaluate each individual in the social group after task completion. Besides, when we use the collective wisdom to serve the system, the situation is more complicated. For example, how does the system harmonize each individual in the social group if their opinions are contrary to each other? The system needs to determine the dominance of each person in the group, which complicates the system design and optimization.

VI. Challenges and Open Research Issues

In this section, we will reveal some future directions with the discussion of the challenges and some potential solutions.

A. Energy Management

CPSSs have a wide range of applications, and connect almost everything in our daily life. Most of the connected devices are energy-limited, such as sensors, actuators and user devices. Therefore, the energy consumption problem is a major challenge in CPSSs, the solutions of which are conducive to the realization of the overall system optimization goal, sustainability.

The challenge of energy management for CPSSs mainly lies in the difficulty to balance the energy consumption with other performance indicators. For example, communication power can be attenuated with a reduced transmission rates. The computation power can also be saved with a lower computational efficiency. Therefore, it is necessary to tackle the problem of energy consumption with the guarantees of other index requirements.

Here, we will provide some potential solutions for energy management of CPSSs, all of which are beneficial to solve the above challenge. i) Energy efficient design: The novel energy optimization protocol can be designed to balance the performance of energy and other indicators. This is the most common energy management strategy in various network applications. ii) Utilization of renewable energy: CPSSs can be designed to take full advantages of renewable energy sources, such as wind, hydropower and solar. However, it needs to be equipped with the special conversion equipment, which increases the construction cost and the floor space. iii) Harvesting of radio energy [165]: Besides the renewable energy sources, the energy can also be harvested from the radio frequency sources, such as interference signals. This kind of energy harvesting does not need to take up excessive

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equipment space, but suffers from random variations in radio frequency energy.

B. Intelligent caching and computing

As we discussed in Section III-C, caching and computing are two areas worthy of further exploration to promote the content delivery and data processing in CPSSs.

1) Intelligent Caching: The optimization of caching in CPSSs mainly considers two aspects: cache decision and content delivery. Cached contents are usually frequently requested by adjacent users, thus promoting the content delivery in CPSSs. However, CPSSs contain massive dynamic data and various contents. Moreover, some of them have different versions with different bitrates, formats or resolutions. Besides, different users have different preference for the same content, and the degree of the preference is dynamic. All of these increase the difficulty of caching optimization. Intelligent caching can be a great manner to solve the above challenges. Through analyzing the information and data within the system with the support of machine learning techniques, dynamic behaviors and preference characteristics of users can be learned and predicted, thus enabling intelligent cache decisions based on the predicted future content popularity and user mobility.

2) Intelligent Computing: CPSSs are required to have the capabilities of real-time data analysis and processing of massive data generated by sensors or user devices. To improve the efficiency of data analysis and processing, it is necessary but also difficult to separate the useful data (such as big data) from noisy data. Intelligent computing can be a great manner to solve the above challenge. With the support of machine learning, intelligent computing can remove the data impurities, and also support the process analysis and prediction of the future trends. Furthermore, collaborative computing can be jointly designed with the intelligent computing, where the collaborative computing focuses on utilizing the computing servers in close vicinity as a collaboration unit to perform the computation tasks. Intelligent collaborative computing is beneficial to promoting the big data analyses in CPSSs.

C. Resource Coordination and Management

As what we mentioned in Section III-D, the multi-resource deployment can be viewed as a great manner to bring some technique advantages to meet some challenges, but further progress is still needed.

1) Distributed multi-resource deployment: CPSSs develop a new digital space with ubiquitous interconnections and interactions of social, cyber, physical, mental and other s-paces, which contain almost everything in this world. The large scale will continuously bring more and more significant challenges. As for the multi-resource deployment, the most obvious challenge is the optimization computation complexity. The distributed algorithm is beneficial for its application, such as alternating direction method of multipliers (ADMM) [36]. It can reduce the signaling overhead and the computation complexity through decoupling the optimization problem into several subproblem executed on different virtual CPSS controllers.

2) Context-aware reliable crowdsoursing: The current research statue still lacks in how to take full advantages of human resources. The context-aware technique is able to use the user information of locations, times, environments, adjacent member, equipments and activates to infer events [166], thus promoting the application of crowdsoursing in CPSSs. Context-aware reliable crowdsoursing may be a good solution to the task assignment and execution among social groups with high efficiency. The reliability of results depends on the reputations of not only the leader but also the contextual work. Therefore, the user evaluation and incentive mechanisms are particularly important here.

D. Security and Privacy

On one hand, CPSSs connect the physical system with the computer system, so that it creates a larger attack surface to the whole system when compared with a pure computer system. Specifically, side channels in the physical system make it possible to observe and manipulate the computer system through the captured information as power consumption, timing, electromagnetic emissions and even disk drive sound in the physical world. Therefore, CPSSs need to be designed for guaranteeing the stringent security requirements.

On the other hand, the multiple CPSSs enabled by IoT connect almost everything in our daily life, so that it is of great importance to support the protection of privacy among devices interacting with each other. Furthermore, CPSSs associate the social worlds with CPSs, and the network needs to be designed to often admit new participants. Hence, CPSSs also need to be designed for establishing secure communication channels, and meanwhile protecting users' information, including data and locations.

1) Security: The existing security measures are usually applied at the upper layers as what we discussed in Section V-F, in which the standard cryptographic principles are adopted with the assumption of reliable physical links. This kind of measure takes no account of received wireless signal and does not react upon the physical layer. To compensate for this point, the technique of physical layer security emerges as the times require [167], which focuses on the physical layer and adopts the information-theoretic principles. The security can be ensured and promoted through the analysis of the mutual information among senders, receivers and eavesdroppers, so that the side channel attacks can be prevented under various assumptions of the channel conditions. However, in real scenarios, the information-theoretic principles cannot guarantee the absolute security, instead of which, it can increase the difficulty of eavesdropping the useful information. Moreover, performance specifications and environmental interactions of CPSSs are dynamic, and the information loss may exist when associating with the upper layers, thus increasing the difficulty of information-theoretic idea propagation. To strengthen the security of CPSSs, the technique of physical layer security could be jointly designed with some reasonable protection strategies at the upper layers.

2) Privacy: The traditional privacy method, such as the anonymity and fuzzification technology, may be infeasible to

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support the data and location privacy protection for CPSSs, since CPSSs need multiple data fusion by big data. Besides, traditional cryptography technology produces no significant effects on the timely analyses of big data. In this context, differential privacy model [168] can be viewed as an advanced concept to protect the privacy of the user's location and meanwhile to keep enough useful information for data analyses. Differential privacy model is independent of the attacker's background knowledge and computing ability, and the main advantages are as follows: i) The assumed maximum background knowledge of the attackers; ii) A solid mathematical foundation utilizing a reliable quantitative evaluation method with a strict definition of privacy protection.

E. Cross-Layer/System Design

The word 'system' in CPSSs can be interpreted as different intelligent systems, such as smart factory, smart grid and so forth, and it can also be understood as different systems with different functions, such as communications, caching and computing. The heterogeneous nature of the connected infrastructures and wireless resources requires CPSSs to be compatible with different intelligent systems and different functional systems. However, for each kind of systems, the requirements may be different. It is of great difficulty to design a standardized protocol and strategy to satisfy each system, since the concomitant different standards respectively for different systems will consume a large part of the design space.

Furthermore, CPSSs do not necessarily adopt the OSI model [4]. It directly interacts with physical worlds, and has its own layers, i.e., the physical layer, the cyber layer, including the control platform and the data platform, and the social layer. Existing protocols and strategies need to be updated to adapt to the system architecture for CPSSs with virtualization. Besides, the enhanced features and functionality of CPSSs require multiple applications coexisted in each layer. The different design and optimization objectives of applications may conflict even for a single layer in CPSSs.

The traditional works, including multi-resource deployment schemes and security measures, may not be applicable, since CPSSs utilize a different architecture from the OSI model, and could involve a wide range of virtual intelligent and functional systems, which may interact but have quite different characteristics and requirements. To the authors' knowledge, the existing works have failed to exploit the cross-layer design or the cross-system design for CPSSs. Multi-resource deployment schemes and security measures need to be extended towards different layers and different systems, thus promoting the overall system performance. In addition, in the cross-layer/system design, the performance tradeoff is necessary for CPSSs to balance the different indicators from both of the system aspect and the user aspect.

F. Lessons Learned: Summary and Insights

In this section, we offer some possible future research directions to inspire the researchers in the related research area. Actually, CPSSs involve the fusion of all the knowledge and the cross of multi-disciplinary. The utilization of the multi-disciplinary knowledge to do the research alternately is beneficial to promoting the CPSS construction.

VII. Conclusion

This article addressed CPSSs associating CPSs with the social world, which is becoming an important research topic that contributes to the construction of the future smart world. First, we explored the current technique development from CPSs to CPSSs. Afterwards, we introduced the existing CPSS architecture. Based on the existing architecture, we discussed the motivation and requirements for enabling CPSSs with WNV, and then proposed a virtualized CPSS architecture. To promote the pervasive CPSS computation services and the scalable content retrieval and delivery, we further presented an integrated framework of caching, computing and networking for CPSSs. A four-dimensional joint optimization was put forward to verify the performance improvement of the proposals through the simulation. Third, we summarized the existing research related to the CPSS applications with the discussion of some common standards and real-world case studies. This part of work can help readers understand how the different components, standards, frameworks or protocols orchestrate CPSS functions. Forth, some enabling techniques and networks for CPSSs were discussed to further promote CPSSs with hyper-connectivity, hyper-intelligence and hyper-automation, including the potential techniques in different layers and the network applications for layer integration. At last, some research issues with challenges and possible solutions were unearthed for researchers in the related research areas.

In summary, even though the research on CPSSs is quite broad and a number of challenges lay ahead, it is necessary for the wireless community to swiftly handle these challenges and go forward. This article briefly explored the architecture, applications and techniques related to CPSSs at a very preliminary level, and further discussed future research issues that are beneficial for the pursuit of this vision. We hope that our exploration and discussion in this article will open a new avenue for the development of the future smart world.

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Yuchen Zhou received the B.Eng and Ph.D. degrees from Xidian University, Xian, China, in 2013 and 2018, respectively. She was a joint Ph.D. Student with Carleton University, Ottawa, ON, Canada, from 2016 to 2018. In 2018, she joined the School of Telecommunications Engineering, Xidian University, where she is currently a Lecturer. Her current research interests include Internet-of-Things, cyber-physical systems, and wireless network virtualization.

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F. Richard Yu (S'00-M'04-SM'08-F18) received the Ph.D. degree in electrical engineering from the University of British Columbia (UBC) in 2003. From 2002 to 2006, he was with Ericsson (in Lund, Sweden) and a start-up in California, USA. He joined Carleton University in 2007, where he is currently a Professor. He received the IEEE Outstanding Service Award in 2016, IEEE Outstanding Leadership Award in 2013, Carleton Research Achievement Award in 2012, the Ontario Early Researcher Award (formerly Premiers Research Excellence Award) in 2011, the Excellent Contribution Award at IEEE/IFIP TrustCom 2010, the Leadership Opportunity Fund Award from Canada Foundation of Innovation in 2009 and the Best Paper Awards at IEEE ICNC 2018, VTC 2017 Spring, ICC 2014, Globecom 2012, IEEE/IFIP TrustCom 2009 and Int'l Conference on Networking 2005. His research interests include wireless cyber-physical systems, connected/autonomous vehicles, security, distributed ledger technology, and deep learning.

He serves on the editorial boards of several journals, including Co-Editor-in-Chief for Ad Hoc & Sensor Wireless Networks, Lead Series Editor for IEEE Transactions on Vehicular Technology, IEEE Transactions on Green Communications and Networking, and IEEE Communications Surveys & Tutorials. He has served as the Technical Program Committee (TPC) Co-Chair of numerous conferences. Dr. Yu is a registered Professional Engineer in the province of Ontario, Canada, a Fellow of the Institution of Engineering and Technology (IET), and a Fellow of the IEEE. He is a Distinguished Lecturer, the Vice President (Membership), and an elected member of the Board of Governors (BoG) of the IEEE Vehicular Technology Society.

Jian Chen (M'14) received the B.Eng degree from Xian Jiaotong University, Xian, China, in 1989, the M.Eng degree from Xian Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xian, China, in 1992, and the Ph.D. degree in Telecommunications Engineering from Xidian University, Xian, China, in 2005. From 2007 to 2008, he was a Visiting Scholar with the University of Manchester, UK. He is currently a Full Professor at the School of Telecommunications Engineering, Xidian University, Xian, China. His research interests are cognitive radio, physical layer security, wireless sensor networks, compress sensing and signal processing.

Yonghong Kuo received the B.Eng and M.Eng degrees from Xian Jiaotong University, Xian, China, in 1989 and 1992, respectively, and the Ph.D. degree from Peking Union Medical University, Beijing, China, in 1998. She is a Professor at the school of Telecommunications Engineering, Xidian University, Xian, China. Her research interests include OFDM systems, cognitive radio and wireless sensor networks.

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