From IoT to Future Cyber-Enabled Internet of X and Its Fundamental Issues

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***Abstract*—As Internet of Things (IoT) is a fascinating paradigm in which all things and objects are connected together, it holds a significant position in fostering intelligent high-level services. However, the future IoT architecture is still under evolution profiting from the overwhelming development of cyberspace and cyber technologies. Based on the traditional physical-based IoT, social-inspired Internet of People (IoP) and brain-abstracted Internet of Thinking (IoTk), an intelligent embryo of cyber-enabled Internet of X (IoX) is being established where all things, entities, people and thinking are interacted seamlessly. In this article, we clearly introduce the cyber-enabled IoX from perspective of both ubiquitous connections and space convergence, and design an architecture with four pillars, namely, things, people, thinking and cyberentities in respective spaces. In addition, we analyze the fundamental issues in IoX development, such as information exploding, link exploding and application exploding from the view of ubiquitous connections, entity exploding and relationship exploding on the basis of space convergence, and service exploding from overall aspects, where potential solutions are discussed at the same time. The intelligent cyber-enabled IoX will be the cornerstone for future techniques and applications, and proves to be the solid foundation for upcoming intelligent and proactive era.**

***Index Terms*—Cyber–physical system, identity, Internet of Things (IoT), relationship, sensing, service, social computing.**

I. Introduction

SINCE the birth of Internet of Things (IoT) in 1999, it has become a ubiquitous network paradigm in which all sensors, objects and things are connected together. Particularly influenced by the substantial bloom of cyberspace and cyber technologies, IoT is truly continuously going up to expectations and delivering marvelous features across many sectors, ranging from energy, manufacturing, transportation to healthcare and financial services. It is publicly acknowledged that IoT provides a blueprint where all things could be connected and interacted at any time and place [1].

However, the continuous connected objects and things, such as the home appliances, smart sensors and devices with the large amount of access to the Internet keep going up straightly, which brings crucial challenges to existing resources and infrastructures. Since architecture is the foundation of IoT for supporting advanced applications and services, it is significant to construct an architecture with higher adaptability and practicability that complies with current development. In 2012, Dave Evans, Cisco's Chief Futurist described a framework of Internet of Everything (IoE), which empowers strong context awareness, enhanced processing power and better sensing capabilities with a network of billions or even trillions of connections [2]. The IoE has received high recognition, however, it mainly emphasizes the phenomenon of connecting the unconnected. In 2011, we once made a prospect of future IoT architecture from unit IoT to ubiquitous IoT, and the core analysis is based on mankind neural system and social organization framework [3]. Over the past few years, big data, 5G, artificial intelligence (AI) and cyber technologies have brought significant progress in which the ubiquitous IoT fail to handle such sudden load and pressure, and needs to be updated simultaneously.

In this article, we propose a novel concept of Internet of X (IoX) and illustrate the seamless interconnections from both view of ubiquitous connections and space convergence. Inspired from the research of smart world in 2015 [4], we regard traditional IoT as Physical-based, Internet of People (IoP) as social-inspired, Internet of Thinking (IoTk) as brain-abstracted, and finally, benefiting from cyber-physical-social-thinking (CPST) hyperspace [5], we come to the cyber-enabled IoX. The cyber-enabled IoX is expected to be an attractive paradigm in which all entities from multi spaces, such as things, people, thinking, and cyberentities, are interrelated and interacted with each other. It not only pays attention to the ubiquitous connections within respective space, but also the relationships across different spaces due to the overwhelming convergence. The main contributions of this article are as follows.

1) Overview and analyze the development status of physical-based IoT, social-inspired IoP and brain-abstracted IoTk, which has significant guidance for proposing the future cyber-enabled IoX.
2) Introduce the concept of cyber-enabled IoX from both space convergence and ubiquitous connections, and present an architecture with four pillars of things, people, thinking and cyberentities, which are active

Manuscript received August 9, 2020; revised September 28, 2020; accepted October 21, 2020. Date of publication October 26, 2020; date of current version March 24, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61872038; in part by Scientific and Technological Innovation Foundation of Shunde Graduate School, USTB under Grant BK19CF010; and in part by the U.K. Royal Society-Newton Mobility under Grant IEC\NSF\170067. *(Corresponding author: Huansheng Ning.)*

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Digital Object Identifier 10.1109/JIOT.2020.3033547

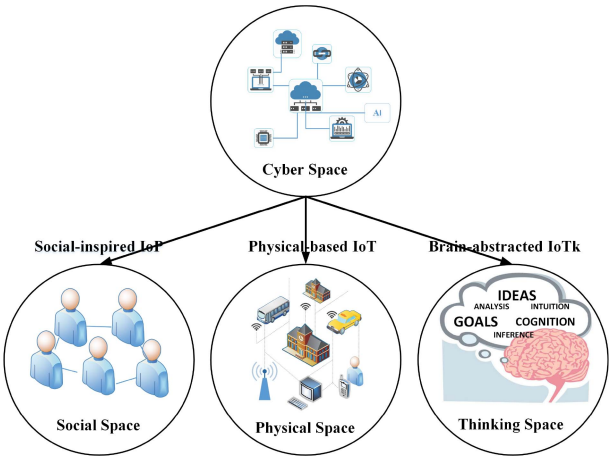

Fig. 1. Ubiquitous connections-based IoT, IoP, and IoTk.

elements in establishing complicated connections across different spaces.

3) Envision and illustrate fundamental issues in IoX, including information exploding, link exploding and application exploding from the view of ubiquitous connections, identity exploding and relationship exploding based on space convergence, and service exploding from overall aspects. Potential solutions are also discussed upon which we elaborate future research directions.

The remainder of this article is arranged as follows. Section II reviews the research status of physical-based IoT, social-inspired IoP and brain-abstracted IoTk. Section III represents the future paradigm of cyber-enabled IoX, including its general definition and the conceptual architecture. Section IV concludes the fundamental issues in IoX as well as potential solutions. Section V gives a conclusion.

II. Development Overview of IoT, IoP, and IoTk

In this section, we overview and analyze the development status of physical-based IoT, social-inspired IoP and brain-abstracted IoTk. It is inspired from the concept of smart world proposed by Ning [4] for which he defined physical-based coordination, social-inspired interactivity, brain-abstracted cooperativity, and cyber-enabled homogeneity as main characteristics. It is noteworthy that the smart world emphasizes more on each space, while these days has witnessed the inevitable space convergence and significant influence brought by cyberspace and cyber techniques. Hence, we focus on the interactions especially between cyberspace and traditional spaces, and discuss the interconnected paradigms of physical-based IoT, to social-inspired IoP and brain-abstracted IoTk impacted by Internet and cyberspace.

In order to better depict the physical-based IoT, social-inspired IoP and brain-abstracted IoTk, we draw a paradigm as shown in Fig. 1. This paradigm continues the concept of general cyberspace (GC) [6] proposed in 2018 that has already given simple definitions of IoT, IoP and IoTk. Here, we concentrate more on the driving force of seamless interconnections in physical, social and thinking space. Related research and works are also surveyed and analyzed.

A. Physical-Based IoT

Since the original birth of Internet in 1950s, things and objects existing in physical space have been connected together as building blocks and laid solid foundation for achieving ubiquitous connections in IoT. This is the so-called physical-based IoT, where intelligence can be embedded into devices and objects making them not only be able to collect information but also support smart data exchange and communication. In this section, we describe IoT as three main stages in accordance with the direction of data flow, from data collection, transmission to processing or computing.

First, the data collection usually takes place at sensing layer, where different sensors, devices and objects could achieve information collection with sensing abilities. For example, radio frequency identification (RFID) plays a significant role in helping identifying objects, collecting and storing data, transmitting information to other electronic devices by wireless communications [7]. Near-field communication (NFC) is another typical technique for data collection, which is most applied in scenarios of sharing personal information like ID card or bank card [8].

Second, data transmission is the inevitable stage transmitting collected data via the network, where heterogeneous communications have been developed, for instance, reliable Ethernet referring to standards of IEEE 802.3, flexible wireless communications, such as WiFi, Bluetooth, WiMax, Broadband techniques, etc., [9] makes an explicit comparison between 7 typical transmission techniques from the aspect of reference standard, transmission medium, frequency bands, data rates, maximum distance as well as limitations, which has provided with a solid guidance for further research.

Besides, data computing serves as an important part in IoT particularly in transforming dispersed data and information to advanced values. In 2018, we made a survey of data semantization in IoT [10], which concludes representative techniques in dealing with noisy and incomplete data. In addition, computing patterns, such as cloud, fog, edge, and dew computing also contribute a lot in handling data processing and computing.

B. Social-Inspired IoP

It is an intrinsic nature for social beings to establish relationships, whether based on the similarity of social attributes or influential environmental factors (e.g., geographic location, time-limited interactions etc). With the booming of cyberspace and Internet, this kind of social relationships transfers from physical space into the digital world, and the social-inspired IoP is formed.

Different from the physical-based IoT where physical things serve as the central role, IoP is a new wave accompanied with tighter relationships between users and intelligent devices, in which users become more important and centric. People are not merely end users but also significant elements in composing the interconnected networks [11]. In 2016, Ning [5] proposed a concept of Cybermatics in which he mentioned

that IoP was a kind of human oriented application where persons could communicate with each other regardless of physical limitations. For example, the online social networks could be regarded as microcosms of IoP consisting of social actors, such as individuals, communities and organizations, where people who have similar interests or are searching for the similar information could be linked together with no physical boundaries.

More in detail, smart devices also occupy essential positions in achieving intelligent IoP, since they serve as the main bridges connecting people to the Internet. For example, smart phones make people more connected, and even if in different places of the world they are not blocked by remote distance. Miranda *et al.* [12] proposed four principles for achieving the IoP manifest, that is being social, personalized, proactive and predictable. In addition, we regard the strong ability of supporting users establishing ubiquitous connections with personal devices, building broad communications with social individuals, getting access to massive data via Internet at any time also count a lot under the paradigm of social-inspired IoP.

C. Brain-Abstracted IoTk

The concept of IoTk was initially proposed at an open forum on "Top 10 Questions in Intelligent Informatics/Computing" for the Turing Year in 2012 [13]. At first, it is imagined whether it is possible for the thinking to be interconnected together in thinking space like what happens in IoT, especially as we deepen our knowledge in neuroscience and informatics. Until now, the brain-abstracted IoTk has been widely recognized and is gradually turning into reality. For example, Ning assigns IoTk with four labels that is collection, connection, coordination and creation [5]. In 2018, Accenture made a technology vision on the trend of IoTk, in which it points out the intelligence is everywhere and IoTk has become an overwhelming and new development tendency. In this section, we are going to discuss two types of IoTk.

The first representative IoTk could be regarded as embedding intelligent tools everywhere. For instance, with the popularization of AI, an increasing number of devices and sensors are becoming much more intelligent, even having their own ability of self-adapting and self-learning. They could own their own "thoughts" or "thinking modes," and support seamless communications with both machines and humans (e.g., understanding and exchanging the brain signals). Techniques enabling synergetic thinking and coordinative activities are needed to be improved further.

Another kind of IoTk is to "copy" physical thinking into a cyber brain, as an accurate mapping between physical space and cyberspace. This is much like the prospect of future AI, where human will have digital twins in cyberspace who own similar cognitions, emotions, memories as well as other brain activities. Following that, the thinking could be connected and exchanged in cyberspace with no limited boundaries, thereby virtual spiritual interconnections are established. In order to achieve the intelligent interconnections of IoTk, AI techniques must be introduced and aggregated. For example, it is vital to imitate the brain activities depending on the heuristic algorithms and bionic computing.

Generally speaking, physical-based IoT, social-inspired IoP and brain-abstracted IoTk all refer to paradigms formed by ubiquitous connections in single space to which they belong, for example, IoT mainly represents the paradigm where most objects and things in physical space are embedded with intelligence and connected with each other. In fact, these paradigms do encompass the possibilities enabling more active elements to be connected with tighter relationships. However, in the face of increasingly complicated and sophisticated tasks or problems, techniques in single space fail to answer as efficiently as expected. The CPST hyperspace appears at the right time with overwhelming space convergence and provides cross-space technologies for dealing with such predicaments, under which the traditional IoT framework needs to be improved and optimized simultaneously. Hence, we propose the concept of cyber-enabled IoX, which is driven and enabled by both ubiquitous connections and space convergence. It will make things, people, thinking, cyberentities, and all elements in different spaces integrate, interact, and interconnect with each other, and provide an intelligent paradigm on the basis of cross-space techniques.

III. Future Intelligent Cyber-Enabled IoX and Its Fundamental Architecture

The cyber-enabled IoX depicts a future intelligent paradigm, which overcomes the boundaries between traditional spaces and realizes seamless interconnections of everything based on space convergence and ubiquitous connections. In other words, IoX not only covers the traditional IoT, IoP and IoTk stemming from ubiquitous connections but has also been expanded to a large extent with the irresistible convergence between different spaces, equipped with strong abilities to resolve more sophisticated problems depending on cross-space techniques. In order to deepen and consolidate the understanding of IoX, we present a fundamental architecture of IoX with four pillars of things, people, thinking, and cyberentities, the representative elements in respective spaces. In addition, we also discuss involved communication techniques between different spaces, which are similarly fundamental for supporting IoX.

As shown in Fig. 2, the IoX architecture is depicted with four pillars of things, people, thinking and cyberentities, respectively, in accordance with physical, social, thinking and cyber spaces. Compared with traditional IoT, IoP and IoTk, the IoX emphasizes the significant impact of space convergence, in which various cross-space techniques could be combined and adopted for intractable problems. It is notable that the role of cyberspace has been slightly exaggerated as a centric force, since cyber techniques provide more possibilities for things, people and thinking to be interconnected. Without Internet and cyber technologies, objects are still scattered around the world, and people are still limited to traditional social relationships. As can be seen, the overlapping parts between physical, social, thinking spaces and cyberspace, which are defined as cyber-enabled X spaces, namely, cyber-enabled physical space (CePS), cyber-enabled social space (CeSS) and cyber-enabled

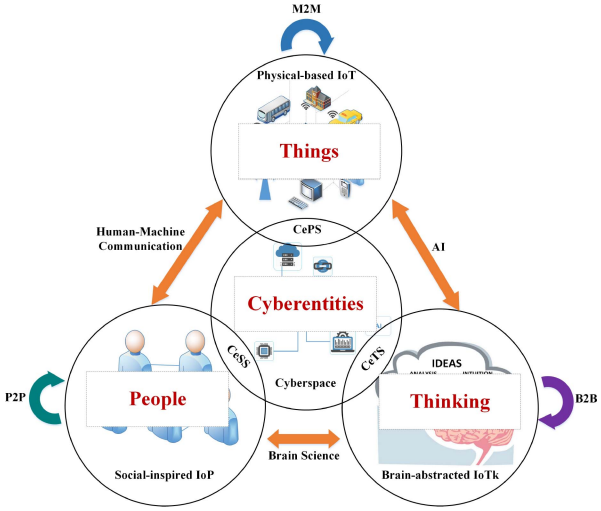

Fig. 2. Architecture of the cyber-enabled IoX.

thinking space (CeTS), are deeply reshaped and influenced by space convergence [6]. As a result, IoX could handle complex and dynamic cross-space tasks more efficiently.

On the other hand, Fig. 2 also analyzes the cyber-enabled IoX from the perspective of ubiquitous connections. In this architecture, things, people, thinking, and cyberentities are highlighted as representative elements in physical, social, thinking, and cyber spaces, and they are important bridges to establish seamless connections in IoX. In order to introduce it much clearer, we give a brief account of the four key concepts, as well as the communication techniques among them.

1) *Things:* As suggested by physical space, the most essential part in IoX should be physical things flooded around our surroundings, ranging from small sensors and devices to large furniture and infrastructures. They appear in both daily life and industrial manufacture for specific functions and services, and have become an indispensable portion up to now. Smart things owning the ability of sensing, collecting, transmitting and processing, indeed aid us a lot in better understanding the environment and achieving useful information.
2) *People:* Along with the trend that numerous smart devices are being connected with each other via Internet, people as the owners of smart devices are also jointed together. Generally speaking, the role of people could be classified as two types. On one hand, people serve as end users who are searching for various kinds of services, that is to say, the ultimate aims of almost all IoX behaviors or activities, from sensor events to large-scale data computing, are to satisfy users' requirements. On the other hand, people are also active participants in which each person could be an independent node connected with each other, on the basis of social attributes or relationships, and then the large connected paradigm is established by supporting various social activities.
3) *Thinking:* In the architecture of IoX, we specifically emphasize thinking as an important aspect due to the fact that thinking space is attracting an increasing attention in both academia and industry. Particularly along with the significant progress in robots and AI, it is urgent to learn more about the mystery of thinking space so as to imitate human intelligence as accurate as possible. The cognitions, ideas, thoughts, reasoning, analysis as well as other thinking activities need to be researched, as they will contribute a lot in achieving the full intelligent organizations and systems.
4) *Cyberentities:* Similar to traditional spaces, there also exist corresponding elements in cyberspace, namely, cyberentities. It refers to anything digitally existing in cyberspace, such as data, resources and any entity virtualized and synthesized with techniques [14]. Regarding the research about cyberentities, Ning proposed a secure cyberentity framework from three interaction phases (preactive, active and postactive) [15], and in 2020, he continues the research about cyberentity and its consistency in the CPST hyperspace [16].

Apart from the principal pillars, communication techniques regarding establishing ubiquitous connections in IoX are also discussed in detail. We classify the communications in IoX into two types, that is communications within the same space and across different spaces. First, for things in physical space, people in social space, and thinking in thinking space, they all have their own communication mechanisms. For example, things in physical space mainly depend on machine-to-machine (M2M) communications without any human intervention [17]. People in the social-enabled IoP would be connected with each other through person-to-person (P2P) communications, by which they could discover new attributes and relationships [18]. Similarly in thinking space, we define Brain-to-Brain (B2B) communications for thinking to be connected with each other. It not only includes the translation of real brain signals, but also the awareness and comprehension of cognition and ideas.

Most communications mentioned above are limited within independent spaces, while cross-space connections also count a lot in IoX. For example, the communication between people and things mainly adopts human–machine communication (HMC) [19]. Compared with M2M and P2P, HMC is faced with more serious obstacles as the communicators belong to different realms that humans and machines originally share no relevant knowledge bases at all. Back to 1980s, [20] put forward the concept of regarding humans and computers as a complete whole instead of independent compositions, which represents a novel view of HMC and co-operation. In 2018, Guzman pointed out that humans are better at interacting with machines due to their inherent nature of conceptualizations [21], which provides significant possibilities for communicating with machines. Continually, he made a research on ontological boundaries between humans and computers, and proposed the implications for HMC [22].

Besides, the communications and connections between things and thinking, mapping with the convergence between physical space and thinking space depend largely on AI, as AI enables things to imitate human intelligence. With the essential advancement of AI techniques like neural networks, deep learning as well as hybrid human-AI, smart devices and

machines which own AI chips could simulate human activities, even interpret and analyze data as how humans do.

Last but not least, communications between people and thinking benefit largely from brain science or the so-called neuroscience, which focus on structures in the molecular level and cellular level, intercellular changes in the nervous system, and the integration in the central function control system. In short, the relationship between people and thinking is determined by the structure of brain tissues and can be considered as a natural attribute, which could depend on P2P communications between humans.

Generally speaking, the concept of IoX benefits from both space convergence and ubiquitous connections, which enables it robust enough to handle more complicated cross-space problems or tasks. With the overwhelming development of CPST hyperspace, relationships and connections between entities become increasingly sophisticated, which makes traditional paradigms of IoT, IoP and IoTk limited within single space fail to support them. The IoX provides more possibilities for achieving a holistic intelligence by adopting and combining cross-space techniques. Due to the fact that entities in IoX comes from different domains, areas, and spaces, there are huge challenges in relationship establishment, data collection, information processing and knowledge extraction etc, while IoX has a relatively complete technical system. We take data computing in IoX as an example where IoX could allow computing techniques from cyber, physical, social, and thinking spaces to be effective simultaneously, such as context awareness, semantic interoperability, collective intelligence, crowdsourcing, emotional computing, cognitive science, etc, all of which would play important roles in processing raw data into higher-level cognitions and wisdoms. To sum up, by overcoming the boundaries between traditional spaces and realizing the deep convergence as well as ubiquitous connections between different spaces, IoX could serve as a strong and promising architecture to support the upcoming intelligent and proactive era.

IV. Fundamental Issues (Challenges) in IoX Development

Thanks to the great development of ubiquitous connections and space convergence, the cyber-enabled IoX will soon penetrate into daily life and foster better development in areas like home automation, mobile healthcare, traffic management and smart manufacture etc. However, the dramatic growth of connected objects, the continuous increase of information as well as the various applications and services cause severe challenges to limited infrastructures, thus the exploding of information, links, applications, identities, relationships as well as services have become fundamental issues in IoX development, which are urgent to be resolved.

In this section, we are going to discuss the fundamental issues from different dimensions. First, we classify information exploding, link exploding and application exploding from the view of ubiquitous connections. Following that, identity exploding and relationship exploding are illustrated from the perspective of space convergence. In addition, service exploding is analyzed as an overall issue which could be in any corner of IoX across all layers, domains and spaces. Potential solutions are also explored in detail.

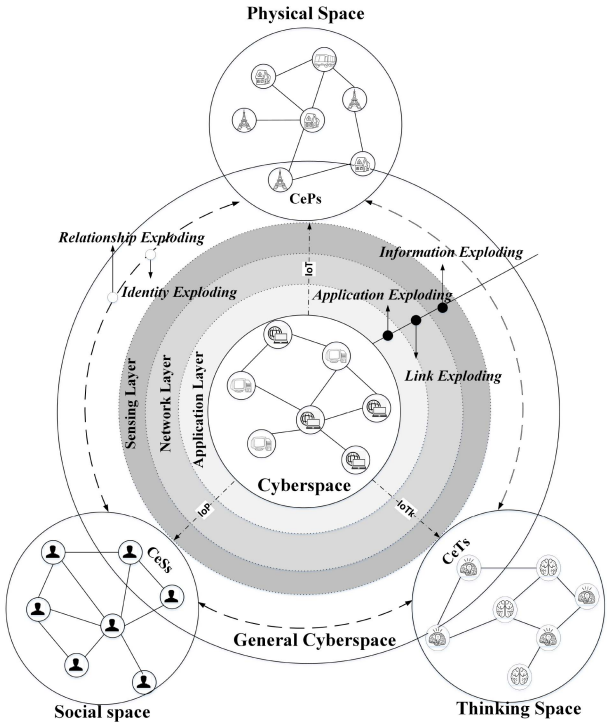

Fig. 3. Issues in IoX from the view of ubiquitous connections and space convergence.

A. Issues in IoX From the Perspective of Ubiquitous Connections

As an efficient extension of IoT, we regard the content covered by IoX, including IoP and IoTk shares the similar framework of sensing layer, network layer and application layer. As can be seen in Fig. 3, we have depicted the respective issues of information exploding, link exploding and application exploding according to the hierarchical layout, and analyze its main challenges and potential solutions.

1) Information Exploding in Sensing Layer: The information exploding refers to a rapid growth in the volumes of information, which almost reaches the saturation state. In particular with the rapid development of big data, AI and 5G, the number of sensors, machines and other embedded devices increases dramatically, followed by copious amount of information and data. As IDC predicts, there will be nearly 175 GB data worldwide until 2025, and the pace of data generation doubles almost every year [23]. The exploding information is worthy being a new kind of driving force especially in the era of digital economy, which will promote great innovation, release large dividends, drive high-technology industries and realize substantial transformation. In this section, we focus on the information exploding stemming from sensing layer as shown in Fig. 3, with explicitly analyzing the representative challenges and potential solutions.

Huge Amount of Information: Since the main contradiction facing with the information exploding in sensing layer

is between the huge amount of information and the limited sensing resources and abilities, the first fundamental challenge needed to be resolved is the significant amount of information generated and collected by various sensors, devices and humans in IoX. For example, the surroundings are equipped with various information, such as temperature, humidity and geographic location, while the sensing abilities of sensors are indeed restricted and fail to collect all these information. Therefore, both industries and acidemia are devoted to exploring potential solutions. In addition to achieve technological innovations of hardware, especially achieving breakthroughs in acquisition speed, memory capacity and transmission bandwidth, selective sensing is an efficient method which aims to select the data or information of most interest [24]. It could enable sensors concentrate more on specific information from the massive surroundings, for example, when abnormal case appears in the surroundings, sensors could adjust their attention and focus on the urgent data immediately, thus avoid a large amount of information inflaming into the system simultaneously.

Overwhelming Heterogeneity of Information: Another representative challenge of information exploding is the overwhelming heterogeneity resulting from both hardware and software aspects, such as the structural differences due to various operating systems, data formats and programming languages. It has made significant influences on information exchange and communication, and is needed to be resolved immediately. For example, the schematic heterogeneity refers to the problem that information of the same domain is described with various data formats and schematic schemes by independent resources, which has caused series of problems, such as a large redundancy in information storage, huge barriers in information exchange and sharing as well as the serious waste of limited resources. Kim *et al.* [25] analyzed schematic conflicts due to generalization, aggregation and methods, and meantime, it proposes potential solutions like homogenizing techniques which contribute a lot in dealing with the schematic heterogeneity. Besides, the heterogeneity regarding semantics is also one of the severe challenges in information exploding. It represents the scenarios when the same information is interpreted and analyzed by independent parties with various semantic understanding, so as to produce semantic ambiguity or contradictions. Kashyap and Sheth [26] proposed potential approaches with metadata, context and ontologies that could be employed for handling semantic heterogeneity and achieving semantic interoperability.

As information could be regarded as the most fundamental and valuable part in IoX, it is urgent to solve the contradictions between the huge amount of information and the limited resources and abilities. The massive volumes of information, the restricted sensing and processing capacities, the various schematic and semantic heterogeneity will continue to be main challenges, and pursuing technical breakthroughs in effectively sensing, collecting, processing and analyzing is still on the way in dealing with information exploding.

2) Link Exploding in Network Layer: Then, we come to the main issue of the so-called link exploding facing the network layer. Along with the continuous development of communication standards from the earliest 3G, 4G, and finally to the present 5G, more and more protocols, interfaces, network topologies are emerging and suffering with exploding growth. In addition, the huge amount of data flowing into the network layer challenges a lot over communication architectures with limited bandwidth, high latency and low throughput, which result in excessive network load and fail to establish efficient communication links. In this section, we will discuss the link exploding from the aspects of massive network protocols and heavy network load.

Massive Network Protocols: Since the network layer provides the function of transferring data frames between different adjacent endpoints, further managing the data communication via the network, its specific functions include addressing and routing, link establishment, maintenance and termination etc. However, the related protocols are experiencing with large number and high complexities, and it proposes high demands when selecting the most appropriate protocols. For example, taking routing protocols in wireless sensor networks as an example, data-centric, hierarchical and location-based protocols are representatives in helping achieving effective data routing. Rani and Sangam [27] provided a comprehensive survey of routing protocols in sensor networks, and it points out that protocols selection should take factors, such as sensors nodes, requirements of applications and architectures, as well as Quality-of-Service (QoS) awareness into considerations.

Contradictions Between the Heavy Network Load and Limited Communication Abilities: Besides, the contradiction between exploding network data and limited communication abilities is really severe and also needs to be resolved. Primarily, it is substantial to speed up the construction of 6G communications, as the innovation of communication technologies and infrastructures play fundamental roles in handling the contradictions [28]. Apart from this, there are also other ways that could help releasing the over burden in communication links. For example, considering the limited bandwidth and low computation power, it is possible to compress and fuse the exploding data by format transformation, where [29] provides a survey of practical data compression in wireless sensor networks. Optimizing network scheduling with generating a most appropriate resource allocation and schedule plan is also significant for achieving efficient communication. Techniques, such as machine learning and neural networks are of great importance during the resource optimization [30]. Furthermore, aimed at the heavy network load, cloud, fog, mist computing and mobile Internet technologies are really substantial in helping releasing the heavy burden [31], [32]. In 2020, Ning made a comprehensive survey on connection exploding from the perspective of network communications, and proposed detailed solutions for challenges related to heterogeneity, interoperability, computation power, connectivity and management, etc., [33].

Given the development status of massive network load and limited communication abilities in IoX, the link exploding will certainly maintain or even exceed the current growing speed for a long time. Hence, pursuing efficient communications would be the longstanding aim. For instance, exploring advanced algorithms for releasing heavy burden of links and

achieving efficient communications will be potential while super significant solutions in following research.

3) Application Exploding in Application Layer: Following that, the information and data generated and transmitted via network will finally be processed and analyzed in application layer. It is responsible for defining a variety of applications which could provide with various functions, ranging from the advanced smart cities, intelligent transportation and smart healthcare to various lightweight applications. However, the mushrooming increase of applications is proliferating at a faster rate which far exceeds our expectations, that has led to a phenomenon of application exploding and stirred up substantial challenges in high-level computation, analysis, discovery, recommendation and management. The application exploding has become another equally fundamental issue facing with application layer in IoX and is urgent to be resolved with potential and effective solutions.

Large Numbers of Applications Leading to Difficulties in Management: One of the primary features is the large numbers of applications that provide with various functions. The boom of diverse applications allows users to have more choices and stimulates the market development, however, due to the low threshold of program development and rapid technological innovation, its dramatic increase has led to huge difficulty in industrial management, in particular with issues of copyright, promotion, security and privacy. Therefore, it is substantial to standardize the development procedures, strengthen the market management and establish related laws and regulations in time. Gottschalk *et al.* [34] and Chu *et al.* [35] give introductions to various specifications for developing Web applications and services so as to make it much more standardized.

Contradictions Between Diversified Applications and Personalized Requirements: Although applications have significant potential in augmenting humans well beings and welfare, the varieties of applications ranging from hardware configuration to software designs are too complex to select the most appropriate one. On the other side, users' needs vary from person to person that leads to a high degree of personalization in requirements. For instance, someone prefers to ordering the same dishes in the usual restaurants while others like to try new cuisines in new places. Hence, achieving accurate recommendation by exact understanding users' stringent demands and providing with the most appropriate choice is really important in dealing with such massive applications. One of the potential solutions is optimizing user profiles with semantic modeling that could describe users' basic information, personality characteristics, hobbies and preferences in a more clear way [36]. With adopting users' personality traits, Ning once demonstrated a friend recommendation system that has shown better performance in terms of precision and recall [37].

Since users' experience has become one of the key factors in IoX, it is urgent to satisfy the personalized requirements and enhance users' satisfactions when dealing with the exploding applications. Therefore, providing with more efficient, accurate and active recommendations has become the overwhelming development trend which is worth further research.

According to the introduction mentioned above, we draw Table I explicitly listing the three fundamental issues in IoX from the perspective of ubiquitous connections, with analyzing the main challenges and potential solutions. It is significant to put research on solutions like selective sensing for information exploding, efficient communication for link exploding and satisfied recommendation for application exploding on the agenda as soon as possible.

B. Issues in IoX From the Perspective of Space Convergence

In addition to the ubiquitous connections, Fig. 3 also illustrates the fundamental issues in IoX from the aspect of space convergence. The paradigm of GC along with CePS, CeSS and CeTS fully demonstrates the overwhelming convergence between different spaces, and it is notable that the role of cyberspace has been slightly exaggerated as a centric force, since cyber techniques provide more possibilities for things, people, thinking and other entities to be interconnected. In this section, we focus on the exploding challenges of identities and relationships in IoX, which is significantly impacted by the overwhelming space convergence.

1) Identity Exploding: Along with the overwhelming trend of space convergence, establishing identities for entities is extremely significant as it could achieve the accurate mapping from physical, social, thinking spaces to cyberspace, further prompting the seamless interconnections in CPST hyperspace. Here, the entities include all elements in respective spaces, such as things, people, thinking and cyberentities. Identities could be regarded as remarkable and distinguishing symbols with attribute metadata and unique identifiers and it plays an important role in authenticating and authorizing entities getting access to the Internet, enabling accurate resource addressing and resolution, and achieving advanced information exchange and communication. Therefore, establishing safe and unique identities is an inevitable and overwhelming trend in IoX, for the sake of protecting sensitive information, supporting stable and safe services and maintaining security in cyberspace.

However, due to the enormous proliferation of connected entities in IoX, the identity modeling confronts with sudden and massive growth that so many identities are needed to be processed simultaneously, which severely challenges existing systems with limited capacity in identification, analysis and management. It also meets with severe redundancy, multimodality and complexity, coupled with the inherent nature of diversity and heterogeneity, which makes the accurate mapping even more tough with no unified standards. In addition, when it comes to information exchange across different domains, the barriers seem much more demanding to achieve seamless communications. Moreover, issues related to security and privacy in identity management are also urgent to be resolved under IoX paradigm. In order to provide with better descriptions, we analyze four typical characteristics faced with identity exploding, and point out potential solutions for each aspect.

Massive Volumes and Exploding Proliferation: The massive volumes of identities and its exploding proliferations are regarded as the most basic feature in identity exploding, since it proposes high requirements for computational capacity when dealing with the resolution and management of such

TABLE I
FUNDAMENTAL ISSUES AND POTENTIAL SOLUTIONS IN IOX FROM THE PERSPECTIVE OF UBIQUITOUS CONNECTIONS

Fundamental exploding	Main challenges	Potential solutions	References
Information exploding	The huge amount of information	Technical innovations from the aspect of hardware (Achieving breakthroughs in acquisition speed, memory capacity and transmission bandwidth); Selective sensing (Selecting the information of most interest from complicated environment).	[24]
	The overwhelming heterogeneity of information	Potential resolutions like homogenizing techniques which contribute a lot in dealing with the schematic heterogeneity; Approaches with metadata, context and ontologies for handling the semantic heterogeneity.	[25, 26]
Link exploding	The massive network protocols	Taking considerations of sensors nodes, requirements of applications and architectures, as well as quality of service (QoS) awareness when selecting protocols.	[27]
	The heavy network load; Insufficient communication resources; Limited communication abilities (restricted bandwidth, low computation power etc)	Continually speed up the innovative advances in communication techniques such as 5G, 6G; Data compression and fusion by format transformation; Optimizing network scheduling and resource allocation (Machine learning, neural networks etc).	[28–33]
Application exploding	Large numbers of applications leading to difficulties in management	It is substantial to standardize the development procedures, strengthen the market management and establish related laws and regulations in time.	[34, 35]
	Contradictions between diversified applications and personalized requirements	Accurate and satisfied recommendation (Establishing user profiles; Semantic modeling; Personalized recommendations).	[36, 37]

large-scale. In this section, we take the resolution as a typical aspect in dealing with massive identities and discuss potential techniques for efficient identity resolution.

It is acknowledged that pursuing technological revolution is the constant goal in dealing with massive identity resolution. In terms of hardware, it is substantial to improve the computational speed and power which will help ease the dilemma caused by a large number of identities. Besides, techniques from the aspect of software also counts a lot in response to identity exploding. For instance, a distributed identity resolution infrastructure can merge and allocate identities to be run parallel on multiple processors according to fluctuating requirements, which will achieve higher improvements in both resolution speed and scale [38]. Mathematical algorithms and AI-based techniques, such as machine learning, the advanced indexing and blocking could also help release the heavy burden of identity resolution associated with the overwhelming exploding [39]–[41].

Heterogeneity and Redundancy: Heterogeneity is also a fundamental characteristic along with the exploding identities, as there are diverse entities that need to be identified with considering multiple attributes, various applicable operating systems and programming languages etc. For example, the heterogeneity of sensors are significant barriers in achieving pervasive sensing since it generates large sets of issues with integrating and communicating among various descriptions. Approaches like middlewares are beneficial for such heterogeneity which provides with a unified interface making the heterogeneity invisible to applications or users [42].

In addition, another kind of heterogeneity of identities stems from the external factors that different organizations or users may have various knowledge about the same entity. For instance, some organizations may define name composed as first name and last name, while others prefer the forms of family name and given name. Even such a simple definition will produce obstacles in seamless communication as well as massive redundancy with duplicated identities. Therefore, the increasing heterogeneity and redundancy along with identity exploding are urgent to be resolved with potential solutions. Establishing the unified identity modeling is a substantial solution since it could provide a recognized identity modeling standard that reduces the possibility of heterogeneity and redundancy fundamentally [43]. Besides, effective techniques, such as deduplication, redundancy eliminating, merging and consolidation would also contribute a lot [44], [45].

Low Compatibility Between Different Domains: Another representative feature brought by identity exploding is the low compatibility between different domains, which leads to the substantial barriers when dealing with information sharing and exchange. This is due to the fact that each industry or domain has their own standards that needs to be followed, so that most organizations will define identities according to their requirements, instead of considering

too many external factors. Overtime, barriers between different domains are formed and there is low compatibility between different domains.

Therefore, it is really essential to find a balance between the various industrial norms and overwhelming barriers. One way is to establish unified identity modeling as mentioned above, which could provide a publicly recognized standard for all identity modeling. However, it confronts with series of challenges since the unified identity modeling must be compatible enough for supporting various domains. Another potential solutions is to establish a standard model for information exchange. The model serves as an intermediate platform in which it defines common vocabularies for information exchange and sharing, and it is possible for two distinct domains to communicate with each other regardless of low compatibility. The national information exchange model (NIEM) of USA is such a reference model [46]. By providing consistent, reusable, and repeatable data terms, definitions as well as processes, NIEM supports various and efficient information exchange across diverse public and private organizations. China and other countries are also devoted to developing such standard models of information exchange referring to own national policies and specific domains, which will largely overcome the problem of low compatibility in identity exploding.

Security and Privacy Issues: As the identity serves as an important symbol by which entities could get access to authorized resources, there is a demanding requirement of managing the security and privacy issues of identities in IoX, not only enabling the right authorization and authentication, but also avoiding any sensitive information leakage.

Since most traditional identity managements adopt centralized approaches where identity providers have absolute control over identity databases, it seriously infringes on identity owners' rights by possible identity disclosure, fraud, theft and other identity crisis. Compared with centralized approaches, the decentralized identity management is a more effective solution where identity owners could determine the way how to share their credentials. For example, distributed ledger technology (DLT) is such a paradigm where transaction details are recorded in multiple nodes, and if any information updates or tampering from any node, it will be synchronized simultaneously in all nodes [47]. Bouras has made a sound overview of DLT for eHealth identity privacy from state-of-the-art to future perspectives, and it is demonstrated that DLT shows potential performance in security, privacy, and scalability of identity management [48].

Considering the main challenges in identity exploding mentioned above, both industries and academia are actively taking measures for overcoming such massive and complicated identities. Although there is still no recognized standard for unified identity modeling, many organizations, nations and countries have developed specific applications. The development trend for further identity modeling should be unique, semantic, standardized and generalized, and it is extremely significant to achieve the unified identity modeling as well as efficient identity resolution and management, so as to ensure the security and stability of advanced services.

2) Relationship Exploding: As [52] once proposes, the social relationships are not only limited between humans that could be easily foreseen, but also among things or objects, such as parental relationship, co-location relationship, co-working relationship and so forth [53]. Since the IoX depicts a paradigm that almost everything could establish relationships with each other, the complicated varieties and large numbers of entities show tremendous influence on social relationships, and thus, the relationship exploding has become another fundamental issue in IoX development.

Difficulties in Massive Relationships Management: As for the massive relationships in IoX, it is significant to explore efficient ways for better management. We refer to knowledge graph (KG) as one of potential solutions, which contributes a lot in providing with interlinks between entities, objects, events as well as situations etc. By establishing KG, it could illustrate clearly the massive social relationships between heterogenous entities in IoX. Besides, KG owns the ability of reasoning and learning and it is also possible to discover hidden relationships with specific inference mechanisms. Nowadays, more and more researches focus on the establishment, mining, discovery and management of social relationships with KG, and it could be an efficient way for dealing with massive relationship management in IoX [49], [50].

Low Compatibility When Establishing Relationships Between Different Entities: Apart from the exploding amount of relationships, another significant challenge is the low compatibility when establishing social relationships between different entities. Especially when the entities are from different organizations or fields, they may follow different access standards and protocol specifications, which lead to great challenges for establishing relationships. A potential solution is to employ access gateways that could regulate protocol, timing and modulation between different devices. With the help of access gateways, most devices could achieve seamless interconnections with each other or with various networks, regardless of heterogenous protocols or standards. For example, Mauro discussed a system named WilmaGate that was designed for incompatible standards when establishing various user authentication and authorization between devices [51].

Since entities and relationships are main elements in IoX when it comes to space convergence, it is significant to deal with the exploding phenomenon of identities and relationships efficiently. Potential solutions, such as KG, unified gateways and specifications have shown great significance and will play huge guidance for further research.

In conclusion, Table II sums up the challenging issues and effective solutions of identity exploding and relationship exploding in IoX from the perspective of space convergence.

C. Service Exploding in IoX From Overall Aspects Across All Layers, Domains and Spaces

Apart from the five issues mentioned above, service exploding could be regarded as an overall issue that would happen across all layers, domains and spaces in IoX, and indeed covers the exploding of information, links, applications, identities

TABLE II
FUNDAMENTAL ISSUES AND POTENTIAL SOLUTIONS IN IOX FROM THE PERSPECTIVE OF SPACE CONVERGENCE

Fundamental exploding	Main challenges	Potential solutions	References
Identity exploding	Massive volumes and exploding proliferation	Efficient identity resolution (Improved massive computational speed and power; Distributed identity resolution architecture; Mathematical and machine learning based techniques; Advanced indexing and blocking etc).	[38–41]
	Heterogeneity and redundancy	Middlewares for overcoming the difficulties in seamless communicating among heterogenous sensors or devices; Unified identity modeling for resolving the massive heterogeneity of exploding identities; Preprocessing techniques of deduplicating, merging and consolidation for dealing with redundancy.	[42–45]
	Low compatibility between different domains	Standard model for information exchange (National Information Exchange Model).	[46]
	Security and privacy issues	Decentralized identity management (Distributed ledger technologies; Identity management with blockchains).	[47, 48]
Relationship exploding	Difficulties in massive relationships management	Employing Knowledge Graph to help establish, discover and manage social connections in IoX.	[49, 50]
	Low compatibility when establishing relationships between different entities	By adding access gateways that could provide with appropriate adjustments on protocols and modifications that keep seamless access and connections.	[51]

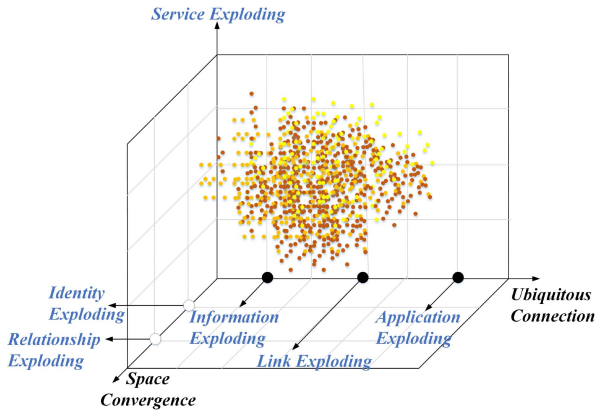

Fig. 4. Issues in IoX from the perspective of three dimensions.

TABLE III
REPRESENTATIVE EXAMPLES OF SERVICE EXPLODING IN IOX

		Examples of service exploding
Ubiquitous Connections	Information exploding	The services of information sensing, collecting, preprocessing and analyzing etc.
	Link exploding	The services of data packets addressing and routing, link establishment, maintenance and termination etc.
	Application exploding	The services provided by numerous applications such as information searching, mathematical analysis and language processing etc.
Space Convergence	Identity exploding	The services of identity identification, analysis, authentication, storage and management etc.
	Relationship exploding	The services of relationship establishment, maintenance, optimization, management and termination etc.

and relationships. As shown in Fig. 4, we explicitly describe all fundamental issues facing with IoX in three dimensions. The x-axis and y-axis, respectively, represent the fundamental issues in IoX from the perspective of ubiquitous connections and space convergence, while the z-axis refers to the service exploding which would cover each corner of IoX.

For better illustrating the relationships among different issues, we give representative examples of service exploding as shown in Table III. For example, the exploding services exist along with the information exploding, since there are numerous services regarding information sensing, collecting, preprocessing and analyzing etc. It is a publicly acknowledged fact that services are ultimate values for IoX, and by providing with high-quality services, IoX could attract more potential users so as to further promote its development scale.

In this section, we conclude six common and fundamental issues faced with IoX, that is information exploding, link exploding, application exploding from the perspective of ubiquitous connections, identity exploding, relationship exploding

from the view of space convergence, and service exploding from overall aspects. Main challenging features and potential solutions are discussed in detail. Honestly speaking, there do exist other emerging issues in IoX. Since the entities in IoX are from different spaces, domains, areas and even have no similarities at all, it will be interesting and promising to explore the issues related to entity identification, resource location, addressing and resolution etc. In addition, IoX presents a deep space convergence, which will foster new challenges in different spaces. For example, humans in social space are mainly connected to the Internet via various electric devices or software, and would be assigned with virtual identities according to respective requirements. How to manage the complex, redundant, and diverse identities? Could they be replaced by the unique identities in physical space, such as ID card, passport number, and if possible, how to ensure the security of user privacy data etc. Besides, as IoX emphasizes the IoE, does it mean that thinking will be seamlessly connected to the Internet automatically in thinking space, which represents that in the future, human and AI need to be conditionally integrated together, and should not be limited to the simple brain computer interfaces, under which humans could directly call or send messages by controlling their brains. All these new and specific challenging issues faced with IoX will be discussed deeply in our following works.

V. Conclusion

As IoT expands and develops with an overwhelming trend, the future fundamental architecture is always under evolution. In this article, we propose a novel concept of cyber-enabled IoX from the perspective of both ubiquitous connections and space convergence. First, we overview the development of physical-based IoT, social-inspired IoP and brain-abstracted IoTk, and then according to related works, we design the paradigm of cyber-enabled IoX, in which things, people, thinking and cyberentities are all connected together. In addition, we conclude fundamental issues of information exploding, link exploding, application exploding from the perspective of ubiquitous connections, identity exploding and relationship exploding from space convergence, and service exploding from overall aspects. Main features and potential solutions that would play significant guidance for further study are also discussed. The cyber-enabled IoX is really a prospective paradigm, and it will provide with much more intelligence in future.

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