Advances and Emerging Challenges in Cognitive Internet-of-Things

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***Abstract*—The evolution of IoT devices and their adoption in new generation intelligent systems has generated a huge demand for wireless bandwidth. This bandwidth problem is further exacerbated by another characteristics of IoT applications, i.e. IoT devices are usually deployed in massive number, thus leading to an awkward scenario that many bandwidth-hungry devices are chasing after the very limited wireless bandwidth within a small geographic area. As such, cognitive radio has received much attention of the research community as an important means for addressing the bandwidth needs of IoT applications. When enabling IoT devices with cognitive functionalities including spectrum sensing, dynamic spectrum accessing, circumstantial perceiving and self-learning, one will also need to fully study other critical issues such as standardization, privacy protection and heterogeneous coexistence. In this paper, we investigate the structural frameworks and potential applications of cognitive IoT. We further discuss the spectrum-based functionalities and heterogeneity for cognitive IoT. Security and privacy issues involved in cognitive IoT are also investigated. Finally, we present the key challenges and future direction of research on cognitive-radio-based IoT networks .**

***Index Terms*—Internet of Things (IoT), dynamic spectrum access, spectrum allocation, optimization theory**

I. Introduction

THE pervasive adoption of Internet-of-Things (IoT) is made possible due to the rapid development of enabling technologies such as consumer electronics, cloud computing, big data analytics and wireless communications. In recent years, research advancement in cognitive radio network [1] also allowed the massive deployment of bandwidth-hungry IoT devices in remote and isolated areas.

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The world has witnessed an explosive growth in adoption of IoT in various sectors such as smart cities, smart manufacturing and many other kinds of cyber-physical systems [2]. Such IoT applications typically involve a massive number of IoT devices being deployed in field environment, which access some cloud platforms for big data analytics or intelligent decision making via a variety of wired and wireless networks. The most commonly used IoT devices include video cameras, environment sensors, motion sensors and actuators for mechanical control in the physical environment.

At the same time, the varieties and capabilities of IoT devices have also increased dramatically in recent years. Nowadays, it is very common to see high capacity IoT devices which capture high-precision data (or high resolution images) in very frequent intervals and upload the data to some cloud computing platform via wireless communication networks. In this regard, the evolution of IoT devices has generated huge demand for wireless bandwidth in order to meet the operational needs of new generation IoT applications. Hence, future IoT networks are required to support massive node access and big data transmission, which calls for more available communication bandwidth.

This bandwidth problem is further exacerbated by another characteristics of IoT applications, that is IoT devices are usually deployed in massive number, thus leading to an awkward situation that many bandwidth-hungry devices are chasing after the very limited wireless bandwidth within a small geographic area. At present, IoT can only use very limited authorized spectrum, which is likely to be occupied by WiFi, Bluetooth and ZigBee devices. Thus, the constraint of spectrum resource has become a significant bottleneck for IoT deployment. By enabling IoT devices with cognitive radio technology, IoT devices will be capable of sharing licensed spectrum resource of 4G and 5G, hence substantially expands the IoT's transmission capacity.

As such, cognitive radio has received much attention of the research community as an important means for addressing the bandwidth needs of IoT applications. Specifically, sensing and dynamic access of spectrum holes have received much research attention. When enabling IoT devices with cognitive functionalities, including spectrum sensing, dynamic spectrum accessing, circumstantial perceiving and self-learning, one will also need to fully study other critical issues such as standardization, privacy protection and heterogeneous coexistence. In [3], the authors investigated the use of distributed compressive sensing method to realize broadband spectrum sharing in cognitive-radio-based IoT. In [4], the authors proposed multi-

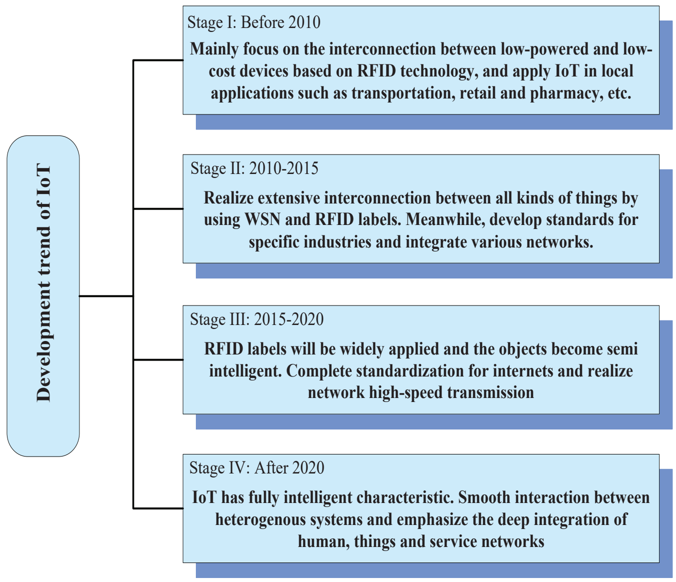

Fig. 1. IoT development trend

bands cooperative spectrum sensing which efficiently improves the access probability of IoT. [5] utilized genetic-algorithm-based dynamical spectrum allocation solution to increase the capacity of IoT. [6] adopted interference technology to combat the interference caused by IoT users to primary users. [7] investigated the co-allocation of time slot and transmit power. Besides, [8] presented an optimization method for spectrum sensing in cognitive IoT.

In addition, other critical issues such as the structural framework for designing IoT application, network topology and applications of cognitive IoT also need to be addressed. In [9], the authors discussed the need for cognitive-radio-based IoT and analyzed the desired cognitive radio functionalities of IoT, especially spectrum sensing and optimization. [10] investigated approaches for enhancing IoT by cognition functionality, and proposed an operational framework for cognitive-radio-based IoT systems. [11] investigated some applications of cognitive radio networks for IoT, and practical solutions for addressing some of the challenges of cognitive IoT. [12] discussed how to devise and model the cognitive process in cognitive IoT, where cognitive functionalities are designed to autonomously improve IoT network performance. [13] studied the structural framework for designing cognitive IoT, which featured minimally a perception layer, a network layer as well as an application layer. [14] proposed an IoT-based cognitive traffic management system.

At present, research on cognitive IoT mainly focuses on spectrum sensing, transmission resource allocation and interference mitigation, etc [15]. Yet, these research topics are being addressed in a relatively independent manner and there is a lack of a optimized approach to address sensing, transmission and interference at the same time [16]. Besides, with the rapid development of cognitive capability of IoT devices, there is an urging need to study mechanisms that integrate artificial intelligence, signal processing and other cutting edge features such as caching networks and flog computing into cognitive IoT.

In this paper, we present the rationale and recent development of cognitive radio technology in IoT. We focus on how cognitive-radio-based functionalities, especially spectrum-related functionalities, will be helpful for IoT. We also discussion standardization efforts, practical applications, security and cognitive capability of mobile terminals in IoT networks. We also consider the extension of traditional cognitive ability of spectrum sensing to more sophisticated features such as cognition of scenario and environment in IoT networks. Thus motivating further interests in social and cognitive mobility modeling, routing protocol, energy allocation, mobile computing, cognitive computing etc. in the IoT environment especially with stochastic layout shapes. Therefore, the fusion of cognitive IoT and other new technologies is also presented in this paper.

This paper is organized as follows. In Section II, we first discuss the motivation of using cognitive radio in IoT. Then, basic framework, standardization efforts and new applications for cognitive IoT are presented in Section III. We investigate techniques for spectrum-related functionalities in cognitive IoT in Section III. In Section IV, we present the issues of information fusion of cognitive IoT and other emerging technologies. Section V concludes the discussion of this paper.

II. Cognitive IoT Architecture and Application

International Telecommunication Union (ITU) documented a four-stage program for future IoT development [2], as shown in Fig. 1. Based on further in-depth research in this field, the desired functionalities and service characteristics of IoT have become clearer, and suggested that future IoT is expected to own key capabilities in service sensing, data sensing, environment sensing and even intelligent cognition ability in order to realize the vision of real smart IoT; thus, raising the target achievement of IoT from 'Perception' to 'Cognition' i.e. cognitive IoT.

A. Cognitive Capabilities

Current research on cognitive IoT's framework mainly concentrates on user's demand on IoT services with autonomous and intelligent characteristics by introducing cognitive elements. a three-layer cognitive cycle structure is integrated with information sharing mechanism and heterogeneous circumstantial sensing interaction to constitute the structure of autonomously cognitive IoT [17]. This research offers a basic framework and data provision for cognitive decision and optimal learning mechanism in IoT. As shown in Fig. 2, we give the architecture framework of cognitive IoT which is based on traditional IoT architecture. Wherein, four layers consisting of information sensing, network interconnecting, cognitive decision-making and intelligent service define the cognitive IoT.

From the perspective of functionality, cognitive IoT can be divided into object demand description layer, cognitive decision-making layer, ubiquitous access layer and physical networks layer. The definitions of the four layers do not

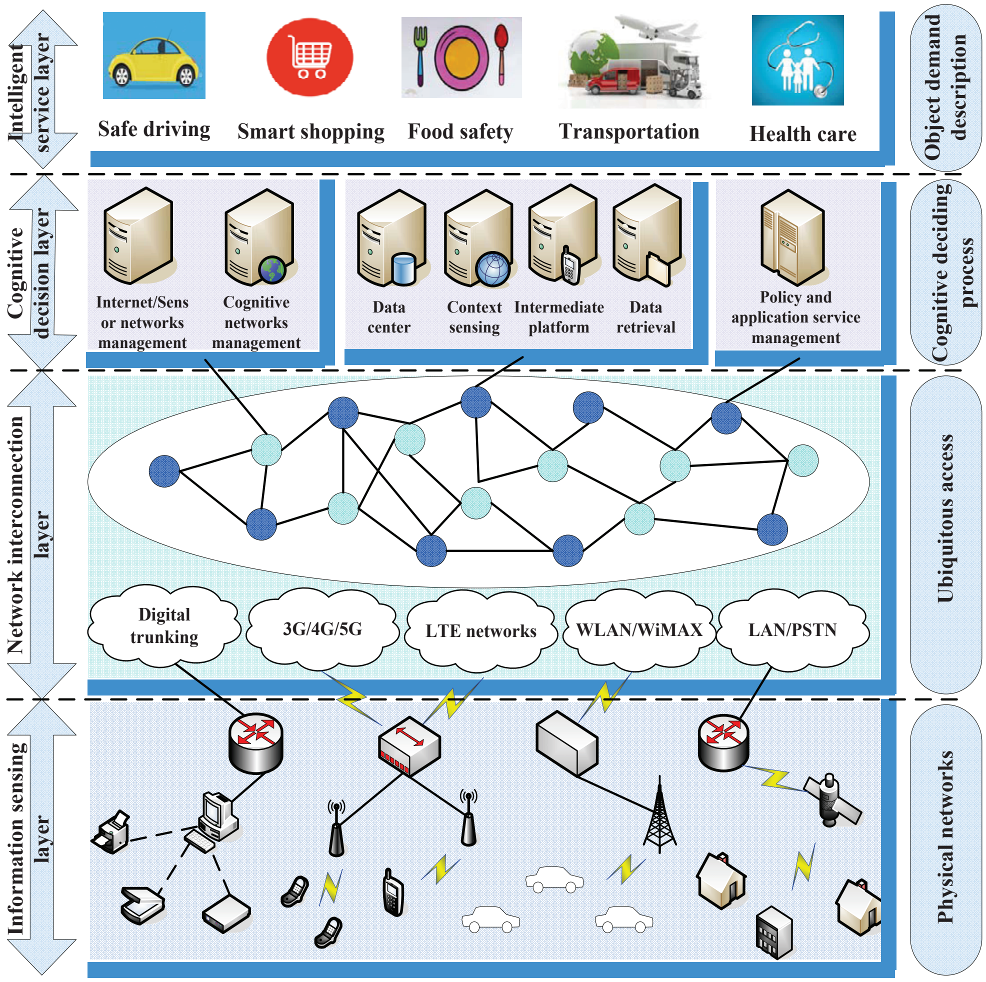

Fig. 2. Architecture framework of cognitive IoT

directly correspond to the layers of traditional network protocol. The framework presented in Fig. 2 should provide QoS guarantee for D2D users' various demands. The main functionality involved in this framework is to sense QoS requirement and network performance objective for users from various cells. Then, properly model the network behavior and make corresponding decision according to cognition, feedback and network status in self-learning. At the end, finally identifying the required behavior of cognitive IoT in future, while adjusting and allocating network resources of physical networks so as to meet user's real-time demand.

In cognitive IoT, it is essential to adopt the approach of a cognitive dynamic system as shown in Fig. 3, which is a goal-driven autonomous system with a cognitive controller as the core to sense and predict external environment. The cognitive dynamic system is mainly structured by probabilistic computing, perception and cognitive controller blocks, wherein interaction is performed in a closed loop, noted by perception-action cycle. In Fig. 3, the short interval or long interval is the time buffer preserved by the system in order to handle time delay caused by cognitive processing.

In addition, in the cognitive decision layer, the functionality of cognitive decision is one of the key factors that contribute to the intelligence of cognitive IoT. It is mainly based on the structure of the three-layer cognitive cycle [19]. The structure can be shown in Fig. 4. Through exploring internal framework structure, operation mechanism and cooperative relationship within the IoT, the structure aims to achieve massive heterogeneous sensing information with regard to network performance objective. It should be noted that the objective needs to be unfolded from the perspectives of detecting network environment and sensing surrounding information. Meanwhile, use the interconnection mechanism of various networks to release and share the sensing information. And, adopt data fusion method to perform information analyzing and integrating. The intelligent cognitive decision-making is completed on the basis of information fusion and decision knowledge base optimum improved by machine learning theory. At last, proper network adjustment will be carried out. Three-layers cognitive cycle structure provides strong theoretical support for the internal framework, relationship, cooperative mechanism of cognitive IoT.

B. Applications and Standardization Efforts for Cognitive IoT

With the capabilities of performing dynamic sensing and cognition of surrounding environment, many potential applica-

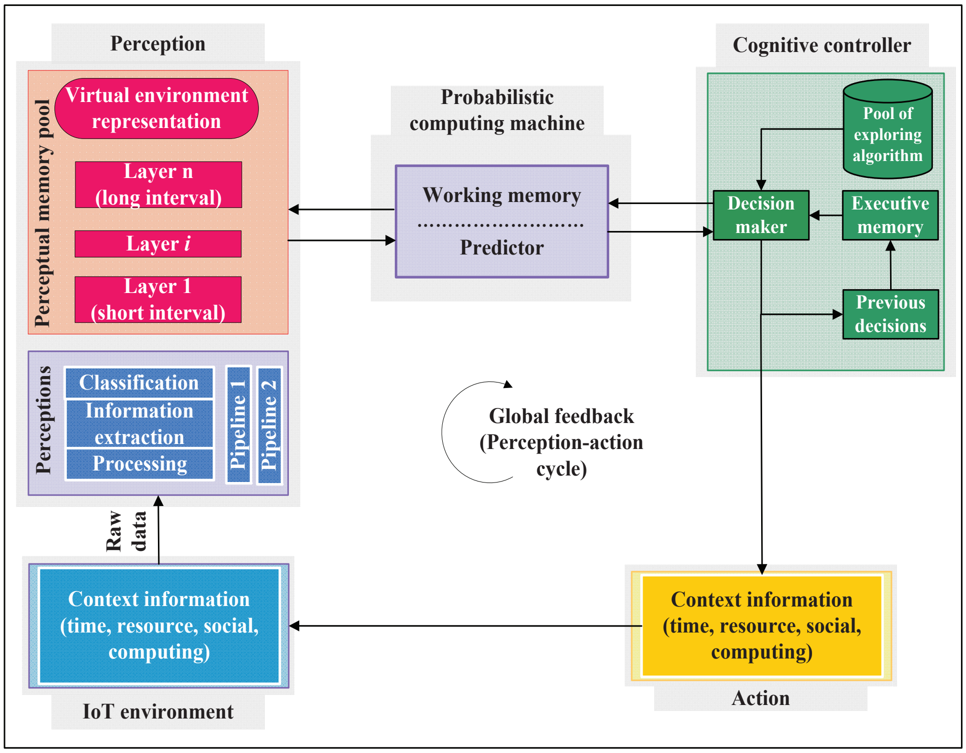

Fig. 3. Conceptual blocks of cognitive dynamic system and their interaction, adopted in [18]

tions and services can benefit from cognitive radio technology. In health care domain, cognitive IoT can assist in a smoother real-time monitoring in long ranges without any worry of spectrum availability [20]. In social activity domain, cognitive IoT has drawn attention recently as cognitive IoT objects for commercial purposes can improve smart traffic management [21]. For environment related applications, with cognitive radio technology, IoT can be a real potential solution for dealing with congested or spectrum scarce network areas [22]. For smart home applications, cognitive-radio-equipped sensors can handle potential heterogeneous network interference [23]. In smart grid domain, cognitive IoT can realize the goal of enabling consumers to know their energy consumption at any time and any place [24]. In smart cities, user data gathering and interaction are critical which can be supported by cognitive-radio-based IoT [25]. Besides, for internet of vehicles, a significant challenge is the availability of spectrum for mobile vehicles wherein cognitive radio networks will play a key role to solve the issue [26].

Enormous efforts have been conducted by academia and the industry to bring IoT and cognitive radio into real commercial deployment. Numbers of technical committees, working groups as well as standardization organizations are working to enhance or expand the applications of IoT and cognitive radio. For IoT standardization, communication protocols, interference control and data storage services are normalized by EPC Global and ITU SG 13, SG 16 technical committee. Information security, personal data privacy and other data protection issues are concerned by STF 396 and CEN TC 225 working group. The standardization of Spectrum usage

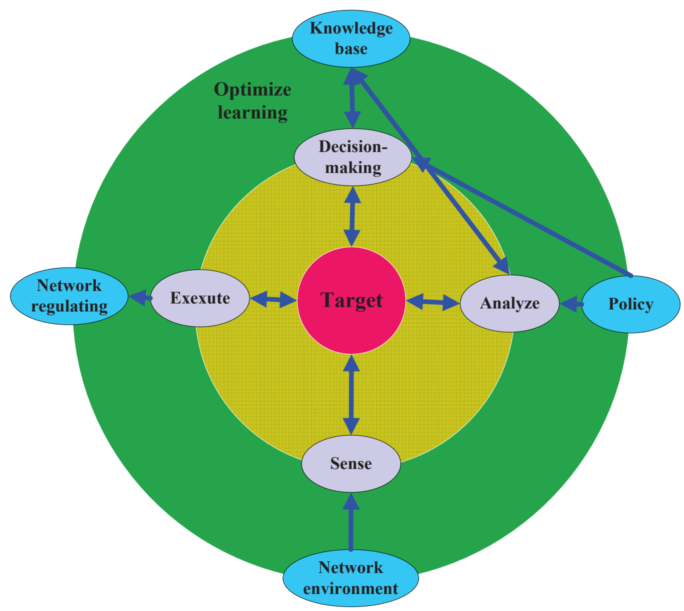

Fig. 4. Three-layers cognitive cycle structure of cognitive IoT

and RFID domain are performed by ISO and ECMA committees. Besides, IEEE, 3GPP, IPSO, NCF forum and ETSI etc. committees all participated in the related work.

Cognitive radio is regarded as a promising solution to solve the problem of scarce spectrum in the era of blooming wireless applications. Almost every kinds of wireless application or networks can benefit from cognitive radio to refine its spectrum availability and many international organizations or groups have involved in its standardization. Specifically, FCC is considering dynamic spectrum access over unlicensed VHF and UHF TV bands in the US. IEEE 802.11af technical committee is working on the modifications of physical and MAC layer during dynamic channel access and coexistence. 3GPP is considering the combination of new licensed bands consisting of higher frequencies and currently unlicensed bands. The spectrum operation of MAC and PHY layers in TVWS band is investigated by ECMA 392. Besides, IEEE institute is working on the standardization of dynamic spectrum access networks. ITU, ETSI and ANDSF working groups are also paying efforts on the standardization of cognitive radio.

At present, cognitive-radio-based IoT framework is still under-investigated and related summary of research works need to be forwarded. It is worthy of consideration that the long-range IoT applications can benefit from cognitive radio by introducing dynamic spectrum access to meet the spectrum demands of massive IoT devices. In addition, short-range or urban IoT applications can better their integration in the environment of heterogeneous spectrum by adopting cognitive radio.

III. Spectrum-Related Functionalities

Spectrum sensing is a fundamental and critical functionality for cognitive IoT. IoT objects equipped with cognitive radio module should sense spectrum hole in dynamic spectrum environment and detect the presence of authorized user. As the cognitive IoT users frequently work in distributed networks and heterogeneous spectrum scenario, joint sensing strategy appears significant to guarantee sensing accuracy. Besides, compared with other functionalities, the time and energy consumed by spectrum sensing block need to be concerned. Thus, in the energy-limited IoT objects, fast and efficient sensing solution is called for. Many promising spectrum sensing methods including alliance-based sensing, clustering-based sensing and self-learning-based sensing have been investigated in cognitive IoT.

Dynamic spectrum access is a key point in the process of spectrum sharing and optimization for cognitive IoT. Dynamic spectrum access allows IoT users to opportunistically access and utilize idle channels authorized to other primary users. In a distributed IoT network environment with imperfect sensing capability, techniques to decrease access collision and improve spectrum efficiency deserve full investigation. In fact, many critical cognitive functionalities including spectrum sensing, dynamic spectrum access etc, make use of deep learning methods to increase sensing or access probabilities. When IoT terminals dynamically access the idle spectrum especially in distributed mode, they should often record and judge the channel status. Deep learning methods can assist them to better identify the optimal channel to access. To combat the limited sensing capability, enforced self-learning method has been adopted to smooth the dynamic spectrum access [27]. From the perspective of whole networks, fully using spectrum reuse to enhance spectrum efficiency has drawn extensive attention [28]. Numbers of mathematical tools including graph theory, game theory and intelligent optimization algorithm have been utilized to optimize dynamic spectrum access and allocation [29]. In addition, due to the mobility of IoT terminals and the coexistence of various kinds of networks, heterogenous spectrum environment as shown in Fig. 5, is a main characteristic for the dynamic spectrum access in IoT. In the other specific IoT application circumstance, such as Internet of Vehicles as shown in Fig. 6, the strong characteristics of IoT terminals' movement will lead to a very complex spectrum circumstance to be addressed. It can be envisioned that traditional methods should be refined to better fit in the IoT scenario.

Besides, substantial research efforts have been spent in enhancing the efficiency of dynamic spectrum access for IoT devices. As dynamic spectrum access consists of several significant processes including spectrum sharing, spectrum allocation, power control along with spectrum switch, many techniques and mathematical tools are adopted to improve its efficiency. Due to space constraints, this paper will not give full account of the efficiency enhancement of dynamic spectrum access.

IV. Information Security and Fusion

To meet the stringent requirements of anytime, anywhere wireless services, the fusion of IoT, internet, communication networks, satellite networks becomes essential [30]. When the other wireless networks encounter massive IoT terminals' access, enhanced capabilities including information processing, security and privacy-preserving are called for wherein cognitive functionalities will be critical to smooth the information fusion and guarantee the transmission capacity for IoT nodes.

A. Information Security and Data Privacy

Cognitive IoT devices can sense spectrum 'holes' and dynamically access the holes to transmit information. During the course, sensing spectrum may become a detecting or monitoring behavior for other users in local networks. Then, when cognitive IoT devices complete the spectrum accessing, it may be considered as a 'intruder' and a potential safety flaw for authorized wireless networks. On the other side, for the overlay spectrum accessing mode in which the cognitive IoT users are authorized to use the idle spectrum temporarily, spectrum trading is always performed to efficiently share the band and improve the usage. To realize efficient spectrum trading, proper information sharing and a cognitive agent are essential. Frequent information exchanging and sharing may result in the potential issue in privacy preserving. It is envisioned that a full discussion and practical protocol on information security in cognitive-radio-based IoT should be conducted so as to constraint the unordered behaviors of cognitive IoT users and secure authorized users' security.

In the perspective of privacy-preserving, personal privacy is likely to be leaked by the behavior of embedded tagging. The data tracking with Radio frequency identification will lead to the damage of user privacy as well. Also, the information in the progress of sharing and broadcasting easily incurs attacking and leaking. Meanwhile, traditional wireless channels cannot

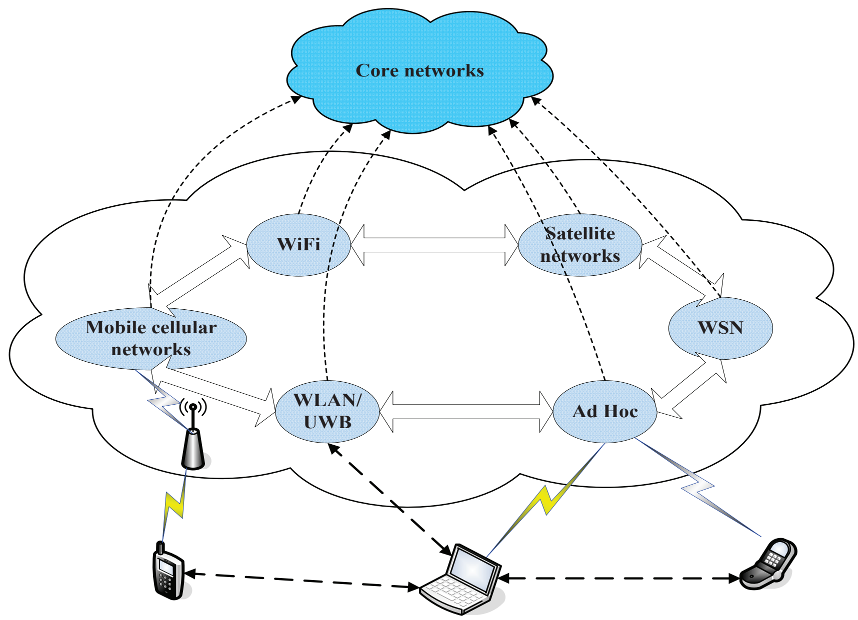

Fig. 5. Heterogeneous spectrum environment

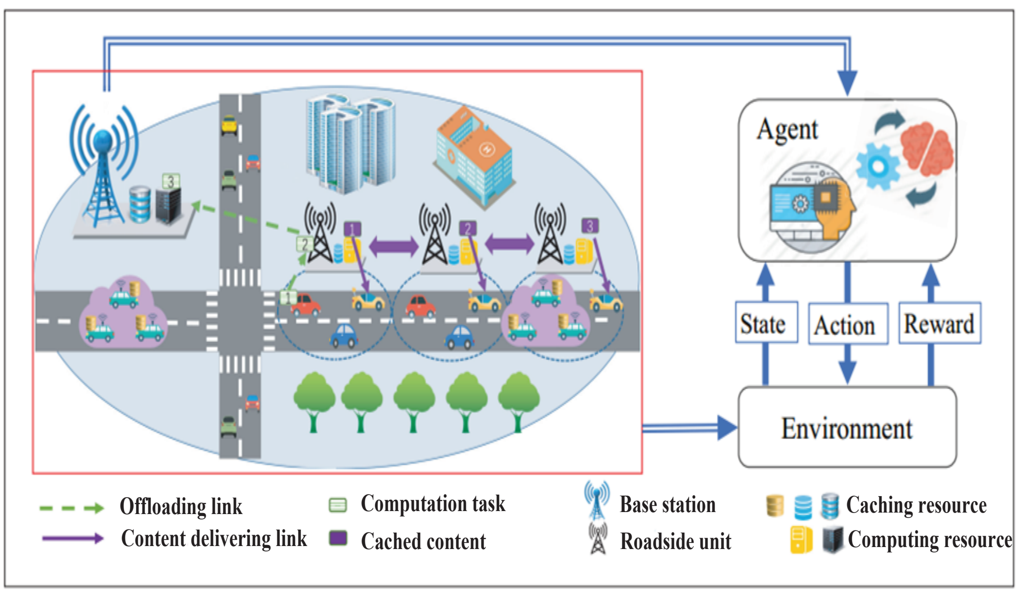

Fig. 6. Architecture of Internet of Vehicles

meet the user requirement of privacy protection and the stream data in IoT could be totally stolen if the invasion succeeds. In this condition, it is necessary to build a mechanism in IoT to secure a powerful privacy protection of IoT data. In cognitive-radio-equipped IoT, cognitive engine can automatically detect related system information and network behaviors, then perform self-learning process to adapt to the environment and identify malicious attack and invasion. It can be envisioned that blockchain technique, trust computation mechanism, enforced self-learning and big-data-mining, will be adopted to upgrade privacy protection level .

B. Fusion of Heterogeneous Networks

When IoT coexists with other wireless networks, it requires cognitive capability to sense surrounding spectrum circumstance, detect other networks' conditions. The more elements IoT user can perceive, the more suitable choice it can make. Current cognitive functionalities mainly focus on the spectrum sensing and forced self-learning, thus more extensive cognitive capabilities are needed to adapt to future complex heterogeneous networks. Many specific research works have been conducted to investigated the fusion of cognitive IoT and other wireless networks. In [30], the authors raised a novel parallel cooperative spectrum sensing solution in heterogeneous IoT environment in which the cognitive users' sensing abilities are always affected by heterogeneous channel condition. In [31], the authors proposed a method to enhance the spectrum efficiency based on the nonorthogonal multiple access technique for heterogeneous IoT. The imperfect interference cancelation and heterogeneous secondary users are mainly considered in this paper. In [32], a spatial and temporal idle spectrum sensing framework was proposed for heterogeneous spectrum IoT. In [33], the authors devised a asymmetric asynchronous spectrum selecting mechanism in heterogeneous IoT where various cognitive users have different available channels to choose.

When cognitive radio technology are applied in various IoT environments, it should support different kinds of sensing, sharing or access methods. In Ad hoc networks, the fast sensing or spectrum switching approaches need to be addressed. In traditional wireless sensor networks, distributed spectrum access solutions without any broadcasting information should be raised. In IoV, it can be envisioned that the efficient spectrum optimization method on the basis of mobility prediction will need to be addressed.

C. Information Fusion and Mobile Cognition

The cognitive and learning feature of cognitive IoT endow it some significant capabilities that traditional networks do not have. Cognitive IoT can merge various heterogeneous networks, shield details of underlaying networks and provide multi-service transparent transmission to users. On the other hand, in current network circumstance, it lacks reliable and effective information interaction among various terminals or networks. Inefficient communication and cooperation within different nodes will inevitably lead to the waste resource or irrational resource allocation in the whole networks, meanwhile decreasing network efficiency. The cognitive process not only senses surrounding network conditions, but also detects other networks' information, which can change the previous selfish and uncooperative behaviors caused by isolated status of traditional nodes. Through extensively recognizing the whole networks' environment and elements and building corresponding cooperative relationship, the wireless resource between nodes can be shared in an effective way.

IoT can be considered as an extension of pervasive computing, cyber-physical-systems and machine-to-machine communications from a macro perspective. With constant improvement of perception devices in IoT, the ability and approach of achieving sensor nodes' information can be obviously improved by using smart devices such as mobile phone and PDA, etc. The social-relation-based cognitive model and human-oriented mobile perception have been investigated and applied to strengthen the basis of mobile sensing services in IoT. Many researches have been conducted to reason and evaluate the complexity and uncertainty of social relation from various angles so as to summarize the social characteristics of mobile nodes [19]. The human-oriented mobile perception services can enhance the range of perception and reduce perception hole by introducing social computing or mobile computing theory and analyzing perception data. Rea et al. devised an embedded action-identified system on the basis of mobile perception mechanism, so as to further promote the applications of mobile perception in smart circumstance, monitoring, crisis response and military field [34].

In addition, the combination of cognitive radio and other cutting edges such as intelligent artificial and Blockchain has drawn growing attention from industria to academia [35]-[38]. Even the IoT has been involved into our real life from smart city to environment monitoring, the IoT without artificial intelligence and cognitive functionality will have limited capability. To achieve the actual and full benefits of IoT, it should be intelligent and automatic in various environments. Furthermore, in distributed IoT, the promising technology of Blockchain can take effect in terms of information security and decentralized computing.

V. Research Challenges and Open Issues

The full utilization of cognitive radio technology in IoT still calls for extensive research and development in hardware design, standardization, spectrum optimization, privacy protection and heterogeneous network fusion, etc. This section will summarize the potential research challenges and open issues involved in cognitive IoT.

A. Standardization Challenges

Standardization is a key step for the constant and extensive development of cognitive IoT networks while providing integral foundation for security-preserving, application extension, dynamic spectrum access and fusion of heterogeneous networks. Currently, many standardization efforts have been paid by academia and industria in direction of IoT and cognitive radio, respectively. How to integrate the related works from technical committees and working groups together efficiently to promote cognitive IoT deserves full intention. On the other hand, a more practical way to accelerate the standardization of cognitive IoT is to enrich or refine current IoT structure and protocol to enable and standardize the functionality of dynamic spectrum access for IoT nodes.

B. Spectrum Efficiency

Enhancing spectrum efficiency is the original intention of introducing cognitive radio to IoT which means spectrum sharing and dynamic spectrum access will be adopted to realize the dynamic utilization of idle spectrum. However, in the circumstance of distributed IoT networks, how to perform effective spectrum sharing without high overhead and energy consumption still needs more investigations. Besides, when the IoT is combined with other promising network technologies or modes such as caching networks, fog computing, satellite networks, how to refine current techniques of dynamic spectrum sharing for IoT to adaptively fit in the new circumstances lacks full studies until now.

C. Security and Privacy

The network heterogeneity accompanied by dynamic spectrum access for IoT nodes incurs security problem wherein we cannot apply traditional security mode to address the issue. Especially with the wider application fields of IoT, when the IoT nodes are equipped with cognitive functionalities to sense 'spectrum hole' and detect network elements, new security and privacy problems will emerge. More interactions within IoT networks will be performed to fully understand the circumstance.

VI. Conclusion

In this paper, we have presented the need for IoT to be equipped with cognitive radio functionality. Cognitive IoT is a new and promising paradigm to benefit IoT networks in enhancing spectrum efficiency and empowering more heterogeneous and intelligent networks. This article focus on the investigation and discussion of applications, standardization, spectrum-related functions as well as security-oriented issues of cognitive IoT. We also summarized the spectrum-function-related cognitive technology in IoT, including intelligent spectrum sensing, dynamic spectrum access as well as efficient spectrum sharing. Besides, the fusion of cognitive radio with other cutting edge techniques such as caching networks, flog computing and social networks are also discussed. Finally, the research challenges and potential applications for cognitive IoT are analyzed further. Currently research on cognitive IoT should put more emphasis on designing structure framework and standard protocol to realize the vision of large-scale IoT applications in important domains such as smart cities, smart manufacturing and cyber-physical systems.

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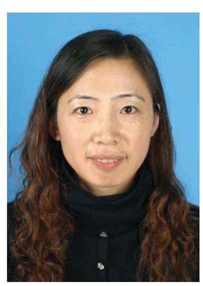

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