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A Comprehensive Study on Cognitive Radio Based Internet of Things

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ABSTRACT

The extension of Internet to the physical world realizes the Internet of Things (IoT). It increasingly connects heterogeneous devices wirelessly for remotely accessing and controlling them. IoT devices mostly use unlicensed wireless spectrum bands. Soon these bands will become congested creating collisions among users and thus resulting in spectrum scarcity problem. In order to support massive deployment of IoT systems, the radio spectrum must be used efficiently. Cognitive Radio (CR) is an emergent technology that overcomes this problem by efficient utilization of spectrum, ensuring reliability. CR is based on opportunistic use of licensed radio spectrum whenever it is sensed free. Thus CR based IoT is a promising research area, though posing challenges that must be tackled before its acceptance as a technology. In this paper, first IoT and CR are elaborated individually and then CR based IoT systems are discussed.

1. Introduction

Radio spectrum mostly lying within the frequencies 3 kHz to 300 GHz, is an important resource that should be managed efficiently for wireless communication. It can be reused over time and space. The groups of similar services are assigned radio frequencies statically for long term period [1]. The static allocation of spectrum results in wastage and underutilization [2-4]. To address these problems, a key enabling technology is Cognitive Radio (CR) [5-8]. CR increases the spectrum efficiency remarkably by enabling unlicensed users, also called secondary users (SUs) or CR users, to access over time and space the unused licensed bands opportunistically. Usage pattern of licensed users, also called primary users (PUs), create white spaces or spectrum holes (spectrum not used by PUs) during silent moments. SUs use these spectrum holes dynamically on non-interfering basis with the PUs.

The IEEE 802.22 working group was established in November 2004 to develop international standard based on CR for wireless regional area network (WRAN). The basic purpose of this development was to provide broad-band access in remote and rural areas. A WRAN cell consists of base station (BS) and one or more customer premise equipments (CPE). The cell having average coverage area of 33 Km^2 follows fixed-point to multi- point topology and can accommodate up to 512 CPEs. No CPE is allowed to transmit without receiving an appropriate authorization from a BS and the BS is responsible to control all the activities of its associated CPEs through medium access control (MAC).

The Internet of Things (IoT) is a new architecture that is catching up high growth (see Fig. 1). IoT connects different objects to facilitate many aspects of daily life of users and improve their behavior. It is immensely evolving by integrating through the Internet tiny objects such as Radio Frequency Identification (RFID) tags, mobile phones and sensors. RFIDs can be used in e-health, security and logistics. It also integrates technologies like wired and wireless actuator and sensor networks by enhancing and optimizing communication protocols. The IoT is liberating humans from dumb old devices and introducing novel devices. These new devices are low powered and low cost, which can operate autonomously. IoT is seen penetrating in daily life through significant applications like smart homes, smart grids, smart agriculture, smart cars, e-health, etc. [9].

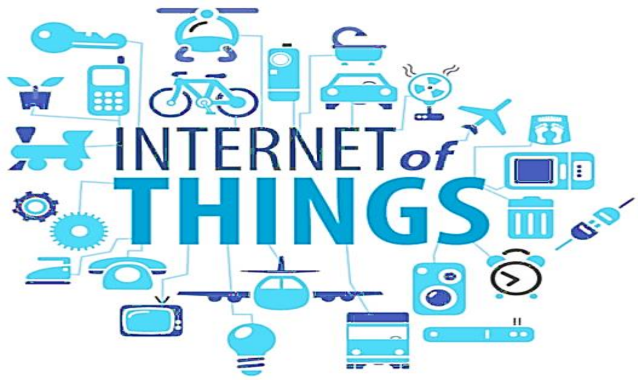

Fig. 1: A view of Internet of Things.

Most suitable spectrum band for the implementation of IoT services is the unlicensed industrial, scientific and medical (ISM) radio band due to its flexibility and low cost. It imposes no limitations on network topology used and wireless coverage [10, 11]. Most of the wireless technologies

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like WiFi, ZigBee, WiMAX, Bluetooth Low Energy (LE) and 6LoWPAN are key enablers for IoT services. These operate in ISM radio band. Consequently, the popularity of IoT has congested and overcrowded ISM radio bands. Other than these technologies, SigFox [11], LoRa [11] and Wi-SUN [12] using the unlicensed band within 800-900 MHz, also enable IoT services; this band is also overcrowded. To overcome this problem a shift is required from the conventional static spectrum allocation policy to dynamic allocation policy. It means that the advantages of CR techniques can be gained in IoT devices provided these devices fit well along with CRs. If equipped with CR capabilities, these devices can dynamically manage the radio spectrum. As CR improves network efficiency, increases spectrum utilization and enhances network life, it is the most promising technology for implementation of IoT systems. The aim of increasing the spectrum capacity of IoT systems can be fulfilled provided the safety of licensed spectrum users is ensured by non-interference with them. Cisco predicted that by 2020 about 50 billion objects will be linked through Internet (see Fig. 2) [13]. These objects may include domestic appliances especially for kitchen, televisions, smart cameras, cars, smart phones, thermostats and utility meters [14].

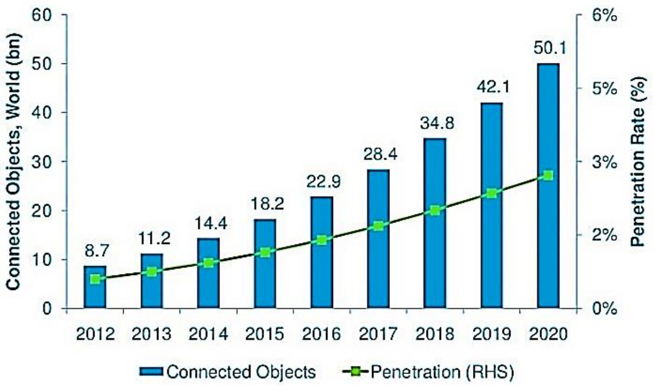

Fig. 2: Expected rise in the number of devices to be interlinked through the Internet by 2020 [13].

2. Suitable Technologies for IoT

The development of advanced technologies and tools has provided support for the implementation of IoT. In this section we discuss the basic technologies that enable the connectivity of machines/objects to the internet directly for the realization of IoT.

2.1 Radio Frequency Identification (RFID)

It allows wireless communication with IoT devices in the unlicensed bands and remains a low cost IoT solution. Physical objects are identified by RFID tags that are incorporated in them. These tags are actually barcodes used to identify objects, which are read by electromagnetic waves. They are microchips fitted to antennas and read by electromagnetic waves. RFID are currently used in many systems including transportation, medical, household, electronic passport, etc. As the number of RFID tags are increasing rapidly, the transmission collisions between tags data, reader to reader collisions and collisions between reader and tag are possible. To overcome this problem, collision avoidance protocols are developed that improve the communication of IoT objects.

2.2 Machine-to-Machine (M2M) Technologies

It is another enabler for IoT. M2M communication does not involve intermediate devices thus save bandwidth wastage. M2M does not require infrastructure. Smart homes, smart cities, smart transportation, smart grid, etc. are few possibilities due to M2M technology. It is estimated that by the year 2024, there will be 3.4 billion M2M connections worldwide [15].

2.3 Wireless Sensor Network (WSN)

Easy deployment and autonomous working make WSN a choice for the deployment of IoT. When WSNs work with RFIDs, it is easy to gather information about temperature, position, movement, location, etc. The improvement in WSNs has enabled collection of data from various environments, analysis and dissemination of information to IoT. Some of the limitations of WSN are routing and energy. For IoT, WSN should provide low cost route discovery and energy conservation. Some of the possible approaches to cope with these issues are reported previously [16-18].

3. Cognitive Radio Network Enabling IoT

CRN can potentially be the key technology supporting IoT. Joseph Mitola coined the concept of CR in 1999 [8, 19]. CRs are radios that can make decisions intelligently and autonomously by gathering information from surrounding RF environments. They learn from their past experiences to plan for future use of spectrum. In addition to this, CR as defined by Simon Haykin [20], is a wireless communication device that along with intelligently making decisions and learning from environment as being aware of it, can also change its operating parameters that may include modulation, carrier frequency and power dynamically (adaptively). They provide reliable communication everywhere and any time for using the radio spectrum efficiently. It can be established that CR has two main features, cognitive capability and re-configurability. The basis of CR is Software Defined Radio (SDR) that is the combination of Computer Software and digital radio [21, 22]. The concept of CRN has also evolved from CR. Fig. 3 shows the evolution from SDR to CR.

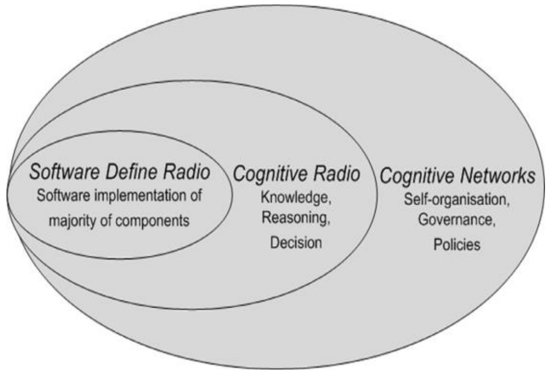

Fig. 3: The evolution from SDR to CR.

Now we discuss SDR as an IoT enabler. Communication in the conventional radios uses specific protocols. Some examples are mobile phones that have to communicate through cellular towers, GS signals, WiFi access points, etc. They use multiple radios, which are hardware based, hence, cross functionality in these devices is limited. Any required modification is carried out physically, thus increasing production cost and minimizing flexibility to support various signal standards. On the other hand, SDR is relatively inexpensive and efficient as compared to the hardware based conventional radios. The multimode, multi functionality and multiband wireless devices in SDR can be improved by upgrading software [21]. Most of the elements of SDR like filters, mixers and amplifiers are typically being developed in software instead of being implemented in hardware. Due to this, SDR has ability to tune itself to several diverse frequencies simultaneously. As in IoT, billions of devices require faster connectivity; there is a heavy reliance on existing and upcoming wireless and wired communication technologies with each one offering different bandwidth capabilities. In this context, SDR/CR is viable and feasible for the implementation of such communication technologies. It eliminates the need for hardware implemented upgrades. The devices equipped with CR are able to operate on multiple bands, adopt different protocols and modulation techniques.

The basic functionalities of CR that help this adoption are cognitive capability and re-configurability [23]. Main components that provide these capabilities in CR are radio, knowledge database, sensor, reasoning engine and learning engine. Based on these capabilities cognitive cycle is established for dynamic spectrum access (see Fig. 4). Dynamic spectrum access basically comprises of four main functions: spectrum sensing, spectrum decision, spectrum mobility and spectrum sharing. These functions make the cognitive cycle that includes detection of spectrum holes, selection of the best radio spectrum, coordination among multiple users for accessing spectrum and vacation of the spectrum band when a PU appears.

Among all functionalities, spectrum sensing is an important functionality of a CR based IoT as it plays a vital role in the detection of unused spectrum hole in CRN. Energy detection, matched filtering, covariance detection and cyclostationary detection are the most commonly used techniques for spectrum sensing. The performance of the spectrum sensing is greatly affected by shadowing, multi-path fading and receiver uncertainty problems. To mitigate these problems in order to meet quality of service (QoS) requirements for different applications, two basic sensing mechanisms have been employed: (i) collaborative sensing and (ii) autonomous sensing. At low signal to noise ratio (SNR) levels, collaborative sensing is preferred and it exploits location diversity to detect even a low strength signal [24]. On the other hand, at high SNR levels, autonomous sensing mechanism is adapted for CR user to make its own sensing decision.

3.1 *Formation of CRN*

There are two basic types of CRN that depend on the presence of central authority [25]. Centralized CRN is based on a central infrastructure that manages different functionalities of the network. Example of such network is IEEE 802.22 standard (Wireless Regional Area Network (WRAN)). The constant development in the field of IoT and CRN will emerge in future as CR based IoT architectures. Based on the cognitive cycle, the IoT devices learn, think and make decisions, thus bridging the gap between the physical entities and the social community [26]. Other functionalities may include making intelligent decision, providing services on demand and knowledge detection. As a result, a CR based IoT is an anticipated necessity in the near future. Some of the supporting reasons behind this anticipation are given below.

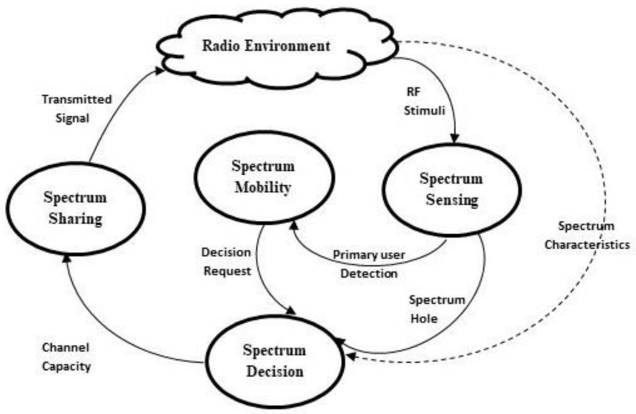

Fig. 4: Dynamic spectrum sharing.

3.2 *Bandwidth Allocation*

The key incentive for IoT devices is bandwidth availability. As the number of IoT devices are increasing rapidly, spectrum availability is getting difficult. Moreover, PUs are also increasing, thus worsening the spectrum shortage problem. As a result, unlicensed users will face problems to access the free channels. Fixed spectrum allocation policy is not suitable in this context as purchasing spectrum for massive IoT devices will generate unnecessary expenses by over provisioning. The solution to these problems is CRN. The spectrum sharing functionality of CRN is advantageous for increasing IoT devices. The dynamic decision making of CRN will provide services on demand.

3.3 *Range*

The cellular networks and some of the technologies which use unlicensed bands have limited range. CR based WRAN has long range of about 100 km, so it is suitable for short or long range communication required by IoT devices [27].

3.4 *Interference Elimination*

CR based connected devices can eliminate interference through the dynamic spectrum access capability of CRN by searching the interference free channels.

3.5 Seamless Connectivity

Mobility in IoT devices may interrupt the communication due to non-availability of channels at new location. CR can alleviate this problem by searching channels dynamically while on move, so providing seamless connectivity [26].

4. Standardization of IoT and CRN

Efforts for standardization of IoT and CRN are required for commercial and personal perspective. For IoT some of the working groups, standardization bodies or technical committees are Internet Engineering Task Force (IETF), IEEE, the European Telecommunications Standards Institute (ETSI), the Third Generation Partnership Project (3GPP) and the National Institute of Standards Technology (NIST).

CRN can benefit IoT from personal, commercial and industrial fields. Some organizations like the Office of Communication (OFCOM) located in United Kingdom, the Federal Communication Commission (FCC) of United States and the Electronic Communications Committee (ECC) of the Conference of European Post and Telecommunications (CEPT) in Europe are allowing the use of the TV bands for realization of CRN. IEEE 802.22 [28] is also first international standard that is based on CRN that works on TV white space (TVWS).

5. Standardization of CR based IoT

As the realization of CR based IoT structures is currently immature or in infancy, certain bodies that are working independently on IoT and CRN should globalize their task for the standardization of CR based IoT. Relevant work is in progress to allocate more frequencies for working of CRN. The standardization bodies should include IoT in their frameworks while working towards new standards.

6. Applications of CR based IoT

There are many applications of CR for IoT, few of them are public safety, disaster management, online gaming and femtocells [29]. Other applications like healthcare, smart homes, smart grids, environment related and medicine related are promising IoT areas where CR technology could be applied.

6.1 Medical and Healthcare Applications

Healthcare applications based on IoT already exist in society. Patients are deployed with smart sensors to monitor their data remotely. These include blood pressure, temperature, sugar level, oxygen, heart activity, etc. Smooth monitoring should be assured in many cases, e.g., in case of patient mobility. Thus, dynamic spectrum assignment policy of CR is promising. Medical Body Area Network (MBAN) is targeted to support medical applications (see Fig. 5). It consists of mini sensors and actuators that are connected wirelessly and placed around the human body [30].

6.2 Smart Home

Rapid growth of wireless technologies gave birth to the concept of smart homes, which consist of a large number of self-organizing wireless smart devices like smart phones, wireless cameras, laptops, HDTV, smart meters and smart domestic appliances (see Fig. 6). These smart devices are equipped with small radio devices for monitoring and remote controlling. Some of these devices use short range unlicensed bands like ISM band, which is overloaded. Also a large number of smart home devices tend to create interference while using these bands. The future smart homes will face spectrum shortage problem. The solution to these problems is CR. Additionally, switching from unlicensed ISM band to TVWS will reduce energy consumption [31].

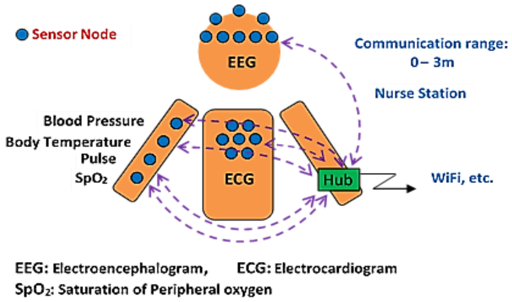

Fig. 5: IoT in healthcare.

Fig. 6: IoT for smart home.

6.3 Social Activities

CR based IoT for social activities include structures such as Intelligent Transportation Systems (ITS). ITS include multiple sensors based on road and vehicle for electronic tolling and traffic monitoring. ITS improve traffic safety, decrease air pollution and alleviate traffic congestion. Europe and United States are using 10 MHz bandwidth for short range communication within 5.8–5.9 GHz band and 30 MHz and 75 MHz bands, respectively. This limited bandwidth is used to deliver small data besides alarms during emergencies. Long range coverage can be provided through CRN [32]. Another social activity in the domain of CR based IoT are smart traffic lights. Currently, IEEE 802.11p standard comprising 5.9 GHz band is used for inter-vehicular wireless communication [33]. This band will be overcrowded soon due to the significant increase in vehicular applications like traffic monitoring systems in urban areas and in-car entertainment that use high bandwidth, e.g., video streaming. CR enabled vehicular networks (CRV) [34] and CR vehicular ad hoc networks CR-VANETs) are emerging technologies. The Internet of Vehicles (IoV) paradigm is the transformation of conventional VANET by the inclusion of IoT. By 2020, the IoV vehicles will occupy an important fraction among the 50 billion of things/objects linked through the Internet as predicted by Cisco Systems [13].

6.4 Smart Grids

Smart Grids are used for the reduction of energy consumption, hence minimizing costs. Now a day, consumers demand monitoring their energy consumption at any time and place. This calls for a need of smart grids everywhere in future. Smart grids make use of smart meters [35, 36], which are beneficial for both the consumers and suppliers of energy. For energy suppliers, it can forecast energy usage. While for consumers, both industrial and domestic, it is used to save carbon, reduce waste and observe energy consumption in real time. The transfer of huge volume of smart meters' data to long distances using limited bandwidth without creating interference is a significant limitation. The existing wired techniques and wireless cellular systems can eliminate this drawback but require huge investments for cable installation or purchase of spectrum. The solution again is CRN. A view of smart grid is shown in Fig. 7.

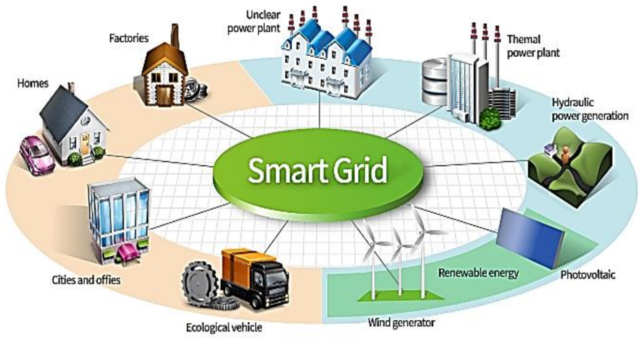

Fig. 7: A smart grid.

6.5 Emergency Networks and Public Safety

During emergency conditions such as accidents and natural disasters, the first thing to do is to identify and locate public safety agencies. Next reliable communication between these agencies and responders is established. In this situation, police, medical and fire services mostly rely on wireless communication devices to respond to emergency events. The emergency networks use wireless cameras and sensors to monitor emergency incidents for public safety. The spectrum bands used in these conditions are congested and overcrowded, so the survival is CRN.

6.6 Military Applications

Military require secure and reliable communication. Due to CR, military can protect their own devices and can identify the communication devices of enemies. The Joint Tactical Radio System (JTRS) and SPEAKeasy radio system used by United States Department of Defense (DoD) exploit CR for intelligent communication. The use of IoT in military applications has potential to empower battlefield. One example is the development of Military Internet of Things (MIoT) [37, 38].

6.7 Environmental Applications

Temperature and noise measurements, waste management, monitoring of CO_2 emissions and humidity estimations are some of key domains in this regard of IoT based applications. Dedicated vehicles and sensors are used for this purpose and a huge number of devices are installed at different locations to monitor environmental factors.CR based IoT objects are used to eliminate the spectrum scarcity problem, which is caused by communication of these devices.

7. Challenges

There may be the following main challenges faced by deploying CR based IoT.

- There may be some compatibility issues such as hardware design, antennas used, etc., related with CR based IoT. These components should be compatible with each other, because, in fact it is not ensured that the antennas used by one spectrum band (e.g., licensed band) will work for the other band (e.g., ISM band).
- Transmission power is another promising challenge to cope with. As it varies with location, therefore, for long distances to cover there should be more gateways to provide long term connectivity of CR based IoT devices to the network.
- Since the CR devices have proper permission to use licensed bands and the concerned agencies do not allow unlicensed users to access the licensed spectrum. So, for CR based IoT devices to function properly, these must have proper permission to use licensed band.
- The integration of these two technologies may raise some security issues. As IoT is combination of various heterogeneous networks and each network has its own security standard, therefore, the security standards should be uniform for the integrated network.
- Packet transmission efficiency is also a big challenge in the deployment of CR based IoT. Many transmission scheduling mechanisms have been proposed to achieve the appropriate system throughput [39].

8. Conclusions

IoT and CRN are promising technologies and growing rapidly to facilitate consumers. The near future is the era of CR based IoTs. Every field of society like, economics, industry and medicine will reap benefits from the strength of CR based IoT. In this paper we have presented the importance and need of CR, IoT and CR based IoT. We also discussed the challenges and issues faced by IoT due to lack of radio spectrum allocated for it. We also discussed the possibilities of how IoT can benefit from CRN. It is predicted that IoT without CR will just be a trouble for the existing infrastructures. Applications of CR based IoT will make the world effortless. There is a need to make this field more mature in the future for global IoT.

References

[1] S.S. Salwe and K.K. Naik, "Heterogeneous Wireless Network for IoT Applications", IETE Technical Review, vol. 36, no. 1, pp. 61-68, 2019.

[2] L. Csurgai-Horváth, I. Rieger and, J. Kertész, "A survey of the DVB-T spectrum: Opportunities for cognitive mobile users", Mobile Information Systems, 2016.

[3] S. Jayavalan, H. Mohamad, N.M. Aripin, A., Ismail, N. Ramli, A. Yaacob and M.A. Ng, "Measurements and analysis of spectrum occupancy in the cellular and TV bands", Lecture Notes on Software Engineering, vol. 2, no. 2, p. 133, 2014.

[4] B. Fatima and M.A. Shah, "Self organization based energy management techniques in mobile complex networks: a review", Complex Adaptive Systems Modeling, vol. 3, no. 1, p. 2, 2015.

[5] Y. Gao, Z. Qin, Z. Feng, Q. Zhang, O. Holland and M. Dohler, "Scalable and reliable IoT enabled by dynamic spectrum management for M2M in LTE-A", IEEE Internet of Things Journal, vol. 3, no. 6, pp. 1135-1145, 2016.

[6] A.A. Khan, M.H. Rehmani and A. Rachedi, "Cognitive-radio-based Internet of Things: Applications, architectures, spectrum related functionalities and future research directions", IEEE Wireless Communications, vol. 24, no. 3, pp. 17-25, 2017.

[7] P. Rawat, K.D. Singh and J.M. Bonnin, "Cognitive radio for M2M and Internet of Things: A survey", Computer Communications, vol. 94, pp. 1-29, 2016.

[8] J. Mitola and G.Q. Maguire, "Cognitive radio: making software radios more personal", IEEE Personal Communications, vol. 6, no. 4, pp. 13-18, 1999.

[9] M.R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel and L. Ladid, "Internet of things in the 5G era: Enablers, architecture, and business models", IEEE Journal on Selected Areas in Communications, vol. 34, no. 3, pp. 510-527, 2016.

[10] W. Ejaz, G.A. Shah, N.U. Hasan and H.S. Kim, "Energy and throughput efficient cooperative spectrum sensing in cognitive radio sensor networks", Transactions on Emerging Telecommunications Technologies, vol. 26, no. 7, pp. 1019-1030, 2015.

[11] K.E. Nolan, W. Guibene and M.Y. Kelly, "An evaluation of low power wide area network technologies for the Internet of Things", IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), pp. 439-444, 2016.

[12] K. Mochizuki, K. Obata, K. Mizutani and H. Harada, "Development and field experiment of wide area Wi-SUN system based on IEEE 802.15. 4g", IEEE 3rd World Forum on Internet of Things (WF-IoT), pp. 76-81, 2016.

[13] J. Dorrier, "Is Cisco's forecast of 50 billion internet-connected things by 2020 too conservative?", Online available: https://singularity hub.com/2013/07/30/is-ciscos-forecast-of-50-illion-internet-connected -things-by-2020-too-conservative/#sm.00007odqq3kivf25t582 bnxnotwtj.

[14] D. Evans, "The Internet of Things: How the next evolution of the internet is changing everything", CISCO White Paper 1, pp. 1-11, 2011.

[15] M2M device connections and revenue: worldwide trends and forecasts 2015–2025, online available from: http://www.analysysmason.com/ Research/Content/Reports/cellular-M2M-connections-Feb2016-RDME0/, 2016.

[16] Y. Shi, W. Wei, Z. He and H. Fan, "An ultra-lightweight white-box encryption scheme for securing resource-constrained IoT devices", Proc. of the 32nd Annual Conference on Computer Security Applications, pp. 16-29, December, 2016.

[17] H.Y. Lin and W.G. Tzeng, "A secure decentralized erasure code for distributed networked storage", IEEE Transactions on Parallel and Distributed Systems, vol. 21, no. 11, pp.1586-1594, 2010.

[18] B. Gong, P. Cheng, Z. Chen, N. Liu, L. Gui and F. de Hoog, "Spatiotemporal compressive network coding for energy-efficient distributed data storage in wireless sensor networks", IEEE Commun. Lett., vol. 19, no. 5, pp. 803-806, 2015.

[19] J. Mitola, "Cognitive radio for flexible mobile multimedia communications", Mobile Networks and Applications, vol. 6, no. 5, pp. 435-441, 2001.

[20] S. Haykin, "Cognitive radio: brain-empowered wireless communications", IEEE Journal on Selected Areas in Communications, vol. 23, no. 2, pp. 201-220, 2005.

[21] J. Mitola, "The software radio architecture", IEEE Commun. Mag., vol. 33, no. 5, pp. 26-38. 1995.

[22] O. León, J. Hernández-Serrano and M. Soriano, "Securing cognitive radio networks", Int. J. Commun. Syst., vol. 23, no.5, pp. 633-652, 2010.

[23] H. Afzal, M.R. Mufti, I. Awan and M. Yousaf, "Performance analysis of radio spectrum for cognitive radio wireless networks using discrete time Markov chain", J. Syst. Software, vol. 151, pp. 1-7, 2019.

[24] T. Li, J. Yuan and M. Torlak, "Network throughput optimization for random access Narrowband Cognitive Radio Internet of Things (NB-CR-IoT)", IEEE Internet of Things Journal, vol. 5, no. 3, pp. 1436-1448, 2018.

[25] I.F. Akyildiz, W.Y. Lee and K.R. Chowdhury, "CRAHNs: Cognitive radio ad hoc networks", Ad Hoc Netw., vol. 7, no. 5, pp. 810-836, 2009.

[26] A.A. Khan, M.H. Rehmani and A. Rachedi, "When cognitive radio meets the Internet of Things?", IEEE International Wireless Communications and Mobile Computing Conference, pp. 469-474, September, 2016.

[27] J. Wen, Q. Yang and S.J. Yoo, "Optimization of cognitive radio secondary information gathering station positioning and operating channel selection for IoT sensor networks", Mobile Information Systems, doi.org/10.1155/2018/4721956, 2018.

[28] IEEE 802.22 Working Group on Wireless Regional Area Networks, online available: http://www.ieee802.org/22/.

[29] M.A. Shah, S. Zhang and C. Maple, "Cognitive radio networks for Internet of Things: Applications, challenges and future", 19th IEEE International Conference on Automation and Computing, pp. 1-6, September, 2013.

[30] R. Cavallari, F. Martelli, R. Rosini, C. Buratti and R. Verdone, "A survey on wireless body area networks: Technologies and design challenges", IEEE Commun. Surv. Tut., vol. 16, no. 3, pp. 1635-1657, 2014.

[31] S. Kawade and M. Nekovee, "Can cognitive radio access to TV white spaces support future home networks?", IEEE Symp. on New Frontiers in Dynamic Spectrum, pp. 1-8, April, 2010.

[32] E.Z. Tragos and V. Angelakis, "Cognitive radio inspired M2M communications", 16th IEEE Int. Symp. on Wireless Personal Multimedia Communications, pp. 1-5, June, 2013.

[33] IEEE Standards Association, "802.11 p-2010-IEEE standard for information technology-local and metropolitan area networks-specific requirements-part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications amendment 6: Wireless access in vehicular environments", URL http://standards.ieee.org/findstds/ standard/802.11p-2010.html, 2010.

[34] M. Di Felice, R. Doost-Mohammady, K.R. Chowdhury and L. Bononi, "Smart radios for smart vehicles: Cognitive vehicular networks", IEEE Veh. Tech. Mag., vol. 7, no. 2, pp. 26-33, 2012.

[35] Y. Yan, Y. Qian, H. Sharif and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges", IEEE Commun. Surv. Tut., vol. 15, vol. 1, pp. 5-20, 2012.

[36] D. Niyato, X. Lu and P. Wang, "Adaptive power management for wireless base stations in a smart grid environment", IEEE Wirel. Commun., vol. 19, no. 6, pp.44-51, 2012.

[37] L. Yushi, J. Fei and Y. Hui, "Study on application modes of military Internet of Things (MIOT)", IEEE Int. Conf. on Computer Science and Automation Engineering (CSAE), vol. 3, pp. 630-634, 2012.

[38] C. Lever, "The Military Internet of Things", online Available: http://eecatalog.com/military/2014/05/09/the-military-internet-of-things /, 2014.

[39] J. Zhu, Y. Song, D. Jiang and H. Song, "A New Deep-Q-Learning-Based Transmission Scheduling Mechanism for the Cognitive Internet of Things", IEEE Internet of Things Journal, vol. 5, no. 4, pp. 2375-2385, 2018.