IEEE Access
The journal for rapid open access publishing

IEEE Xplore Digital Library
http://ieeexplore.ieee.org/Xplore

Overview of LTE Spectrum Sharing Technologies

Yun Ye, *Member, IEEE*, Dalei Wu, *Member, IEEE*, Zhihui Shu, *Member, IEEE*, Yi Qian, *Senior Member, IEEE*

***Abstract*—LTE communication systems feature advanced frequency reuse and interference coordination techniques providing faster and more secured mobile services. However, the network capacity in licensed spectrum is still behind market demands. Dynamic spectrum access, or spectrum sharing in other frequently vacant or unlicensed frequency bands is considered an effective means to boost system throughput. Different from operations in licensed spectrum with exclusive access, LTE deployment needs to take into account the distinct regulations on channel access to each shared frequency band, in order to avoid interference to incumbent users, and to maintain fair play with peer operators in heterogeneous networks. This article presents an overview on LTE spectrum sharing technologies on three popular spectrums, including the TV white-space channels, the frequently unused service-dedicated 3.5 GHz Citizens Broadband Radio Service spectrums, and the 5 GHz unlicensed bands. Existing spectrum usage in these frequency bands is analyzed, and the proposed methodologies on compliant operations are discussed for the reference of potential solutions to more efficient spectrum sharing mechanisms in the next generation mobile networks.**

***Index Terms*—LTE, spectrum sharing, carrier aggregation, cognitive access, licensed shared access, licensed assisted access, coexistence, interference management.**

I. INTRODUCTION

RECENT years have seen drastic increase in demand for bandwidth in mobile services. Despite the relentless march of radio access and networking technology revolution, from GSM to UMTS to LTE, the scarcity of spectrum resources in urban areas remains an aggravating problem as the number of smartphone and tablet users grows rapidly. According to Cisco Visual Networking Index forecast report, Wi-Fi and mobile devices will account for 81 percent of Internet traffic by 2019 [1], while the mobile network capacity gap keeps widening at an exponential rate [2]. LTE standards integrate a bundle of innovative solutions for spectral efficiency improvement, and prove to be the most advanced cellular technology. Nevertheless the system throughput still falls short of meeting the capacity demand. Therefore, the exclusive spectrum licensing in LTE is not sufficient to guarantee the quality of service (QoS) for mobile subscribers. Dynamic spectrum access (DSA), or spectrum sharing in other frequency bands, is suggested as an effective approach to maximize the spectrum utilization, with greater and more economic promise than other major spectral efficiency improvement measures like cell densification, and securing additional licensed spectrum [3]. Currently three types of spectrum resources are being considered for LTE data aggregation, namely the TV White Space (TVWS) channels, the frequently unused service-dedicated 3.5 GHz Citizens Broadband Radio Service (CBRS) spectrums, and the 5 GHz unlicensed bands [4].

Spectrum has long been shared via frequency, space, or time domain partitioning, or involving multiple dimensions, in order to improve the overall effective data throughput. The primary focus of most spectrum sharing mechanisms is on interference reduction, while priority and fairness among other policy and technology issues are accommodated in more complex wireless communications environment. For example, for different users within the same system, the frequency division multiple access (FDMA), and the time division duplexing (TDD) scheduled at the base station enable channel sharing in time and frequency domain; the cross polarization interference cancellation, and the directional MIMO (Multiple Input Multiple Output) antennas are representatives of spatial multiplexing [5-7]. For spectrum sharing among devices associated with heterogeneous systems, interference is controlled through software defined radio imposing restrictions on signal transmission and carrier sensing. The controllable system parameters include the transmit power level, the magnitude of out-of-band emissions, back-off time, energy detection threshold, transmission time interval, geo-location spectrum use restrictions, etc. [6, 8-10]. Various spectrum sharing models were developed for typical network arrangements, either it is based on cooperation or coexistence, sharing among equal devices or between primary and secondary devices [3, 11], as summarized in Table I.

The potential spectrums currently being implemented, or under consideration for sharing by the Federal Communications

---

Manuscript received September 26, 2016. This work was supported by National Science Foundation grants EARS-1547330 and ECCS-1307580.

Y. Ye is with the Department of Mathematics, Engineering and Computer Science at LaGuardia Community College of City University of New York, NY, USA (e-mail: yye@lagcc.cuny.edu).

D. Wu is with the Department of Computer Science and Engineering at the University of Tennessee at Chattanooga (UTC), Chattanooga, TN, USA (email: dalei-wu@utc.edu)

Z. Shu is with Intelligent Fusion Technology, Inc., Germantown, MD, USA (email: jxby002@gmail.com)

Y. Qian is with the Department of Electrical and Computer Engineering, University of Nebraska-Lincoln, NE, USA (email: yi.qian@unl.edu)

Digital Object Identifier: 10.1109/ACCESS.2016.2626719

TABLE I
SPECTRUM SHARING MODELS

Network Arrangement	System Coordination	Cooperation	Coexistence	Primary-secondary Sharing	Equal Primary/ Secondary Sharing
Sharing within the same system	System coordinated frequency, space, or time domain partitioning	Centralized spectrum allocation	Opportunistic access using common regulations	N/A	Access with a known communications protocol
Sharing among devices of disparate systems	Coordinated sharing based on a communications framework between the systems, a cooperation/coexistence infrastructure, and a database Uncoordinated access in unlicensed bands Cross-border coordination	Devices communicate and cooperate with each other to avoid interference, delay their own transmissions, or carry each other's traffic	Contention-based sharing with channel sensing	Secondary devices share spectrum when and where it is not used by primary users	Access to trunked spectrum after sensing its availability

TABLE II
THREE TYPES OF POTENTIAL RADIO RESOURCES FOR LTE SPECTRUM SHARING

Name	Primary Sharing Mechanism	Spectrum Bands	Shared Bandwidth	Incumbent Users	LTE Access	Regulations
TVWS	TV white spaces database	54-60, 76-88, 174-216, 470-698 MHz	Varies (average of 107 MHz)	TV broadcast	Unlicensed access to unused TV channels	FCC Third Memorandum Opinion and Order [13], IEEE 802.11af [14], IEEE 802.19.1 [15], IEEE DYSPAN-SC [16, 17], IETF PAWS [18].
CBRS	Spectrum Access System for 3-tiered access	3550-3650 MHz	100 MHz	Naval Radar	Reliable operation for Priority Access Licensees (PAL) and opportunistic access for General Authorized Access (GAA) users	FCC Report and Order and Second Further Notice of Proposed Rulemaking [19]
		3650-3700 MHz	50 MHz	Fixed Satellite Systems		
U-NII	Dynamic frequency selection	5150–5250 (U-NII-1)	100 MHz	Aeronautical Radio Navigation	Unlicensed access when the primary users are not present	3GPP LTE Release 13 [20]
		5250–5350 (U-NII-2A)	100 MHz	Earth Exploration and Space Research		
		5470–5725 (U-NII-2C)	255 MHz	Radiolocation		
		5725–5825 (U-NII-3)	100 MHz	Radiolocation		

Commission (FCC) and the National Telecommunications and Information Administration (NTIA), cover the higher end of the radio spectrum, from the TV white space initiative in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands, to the 60 GHz unlicensed, the 70-80-90 GHz millimeter wave, and the level probing radar initiatives in the Extremely High Frequency (EHF) band. Three frequency ranges are of particular interest for LTE spectrum aggregation due to the relatively wide bandwidth and high vacancy rate: the TV White Spaces, the3.5 GHz Citizens Broadband Radio Service, and the 5 GHz Unlicensed National Information Infrastructure (U-NII) spectrum bands. A summary on the features of these bands is listed in Table II [4, 10, 12].

Starting from 3rd Generation Partnership Project (3GPP) Release 10, the enhancement feature Carrier Aggregation supporting bandwidths wider than 20 MHz is included in LTE-Advanced as a preferred solution to meet the higher throughput and QoS requirements. This feature among other technical facilities enables LTE spectrum sharing in contiguous and non-contiguous secondary bands to opportunistically boost data rates, while a primary licensed band is used to deliver critical information and guaranteed QoS [21]. With the goal to mitigate interference and to improve overall throughput, LTE spectrum sharing utilizing other legacy radio resources has to accommodate these considerations: (1) protect the primary users; (2) ensure fairness among peers; (3) integrate with the small cell air interface; and (4) refine the operation policy regarding crucial transmission parameters or access mechanism [11, 22, 23]. To summarize the current LTE spectrum sharing technologies coping with these essential issues, so that it will be used for future development of more efficient solutions in the next generation mobile networks, this article provides an overview of LTE spectrum sharing in TVWS, CBRS, and U-NII bands. The challenges for practical deployment in these bands are also discussed based on analysis of existing infrastructure, regulations, and performance evaluation.

II. COGNITIVE ACCESS TO TV WHITE SPACE

TV White Space refers to the TV channels that are not used by any licensed services at a particular location and at a

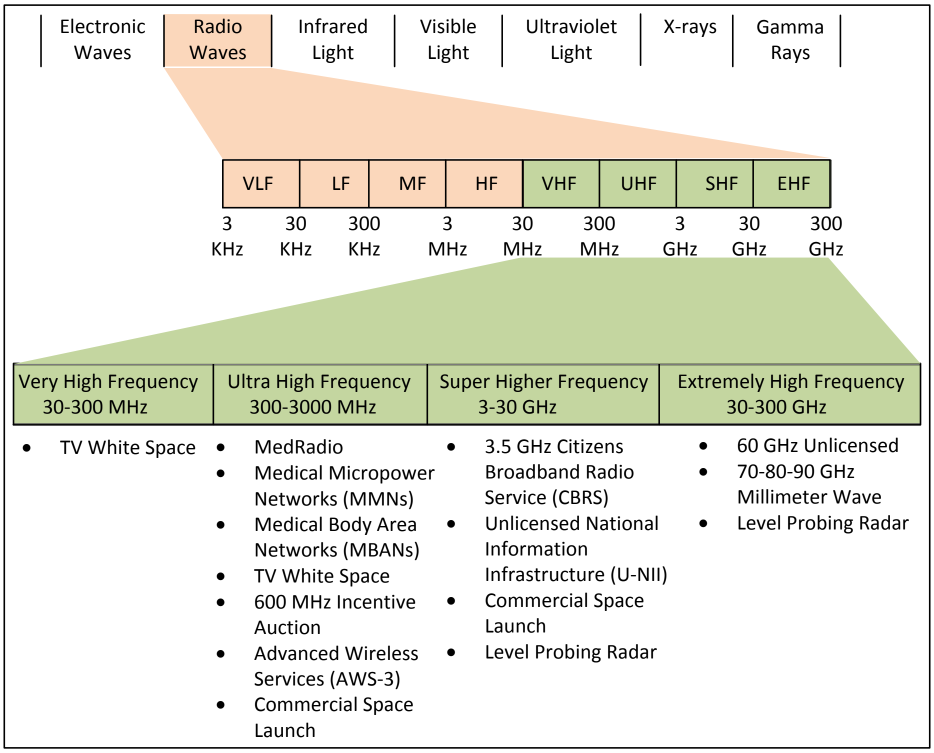

Fig 1. Spectrum sharing initiatives by radio frequency spectrum band [12].

particular time. This spectrum resource is attractive to LTE deployment due to the availability of many vacant analog channels resulting from the Digital Switchover (DSO) process that is taking place in many countries across the world [9]. This DSO process is to convert TV stations from analog to digital. With the development of the high efficient broadcasting technology for Digital TV in DSO, some previously occupied analog TV channels, including the radio spectrum used to avoid co-channel or adjacent channel interference between TV stations, and the unused broadcasting channels in a given geographic area or a given period of time indexed by the TVWS database, become vacant. Thus these frequency bands add to the existing portion of TVWS resources that have already been exploited for spectrum sharing by other wireless technologies.

A. Incumbent Users

The TVWS resides in the VHF and UHF bands below 900 MHz (470 to 698 MHz in US with 6 MHz wide channels, 470 to 790 MHz in UK with 8 MHz wide channels), as described in the FCC spectrum sharing initiatives illustrated in Fig. 1. Compared to the radio signals in higher frequency bands such as WiFi in 2.4 GHz/5 GHz, and 3G signals, the TV band signals have stronger penetration ability, and therefore could provide better coverage for a wide range of wireless communication services, especially with portable devices [24].

The availability of vacant TV channels for spectrum sharing by unlicensed devices varies with location, time, and usage characteristics specified in spectrum access management rules. An average of 107 MHz, with at least 96 MHz of spectrum resources in 6 MHz channels, is available in most areas in United States, and it is expected to be much better in under-developed countries [25].

Devices that operate in TVWS are commonly referred to as TV Band Devices (TVBD). Two types of TVBD are under constant discussion, the fixed TVBD which store their updated location information, and the portable TVBD able to self-geolocate when in motion. Due to the intensive requests, FCC began considering unlicensed TVBD operation in TVWS in the 2002 Spectrum Policy Task Force (SPTF). The main focus was to carry out regulations on the cognitive radio technology adopted by the unlicensed devices and the TV White Space Database Administrators (WSDBA), in order to avoid causing harmful interference to the incumbent users, mostly TV station licensees, including broadcast TV stations, broadcast auxiliary services, wireless microphones, multichannel video programming distributors, public safety, private land mobile operations, offshore radio telephone service, and specified radio astronomy sites. Public databases of licensed incumbent operations are maintained by regulatory agencies. These databases provide the identities, types and locations of protected systems, and serve as the standard reference for the WSDBA to restrict unlicensed operations in TVWS.

B. Cognitive Access Mechanism

Cognitive radio is advocated as the desirable means to manage unlicensed operations in TVWS. The successful implementation relies on the ability of cognitive devices to identify available TVWS without affecting primary services. Two major types of cognitive access mechanisms have been rigorously studied in the literature, namely the spectrum sensing based mechanism, and the geo-location &database based mechanism [3, 9, 11, 12, 22]. Table III shows some

TABLE III
COGNITIVE ACCESS MECHANISMS

Cognitive Radio Technology	Access Mechanism	Advantages	Disadvantages
Spectrum Sensing	TVBD autonomously detect the presence of TV signals with a power threshold, and only use non-occupied channels	Easy implementation, adaptive to indoor or high-speed situations	Hidden terminal problem, long integration time, low spectrum utilization efficiency, lack of standards
Geo-location &Database	TVBD send location and other device information to WSDBA, which apply protection criteria to determine available channels for TVBD	Reliable channel status information, centralized data distribution, fast response time, high spectrum utilization efficiency	Low geo-location accuracy for portable TVBD, out-of-band emission limit, WSDBA collaboration, regulatory uncertainty

characteristics of these two methods.

The spectrum sensing based mechanism incorporates a Listen-before-Talk (LBT) detector to check if a frequency is in use before an unlicensed device can access it. This direct signal detection is easy to implement, and is adaptive to complex situations such as in an indoor environment, or in high-speed status. An inherent issue with this method is the hidden terminal problem. When there is any obstacle in between the cognitive radio device and the TV station, the device may not detect the TV signal from the station, and decide to use the channel, causing interference to nearby primary users receiving the signal using the same channel.

To counteract this problem, the cognitive radio device has to sense the signal at a very low level. Based on the testing results with device prototypes from the industry, in 2008, FCC published the Second Report and Order and Memorandum Opinion and Order [26], and required spectrum sensing and database access control for TVBD operations in TVWS. Specifically, the signal detection threshold is -114 dBm for the 6 MHz channels, and -120 dBm for the 8 MHz channels -- 35 dB more sensitive than the typical consumer TV receiver with a sensitivity requirement of -85 dBm. Such high processing gain ensures reliable interference avoidance. However, the high sensitivity also leads to longer integration time and lower spectrum utilization efficiency. The device could detect TV signals hundreds of kilometers away, and thus preclude many usable TVWS. Another problem lies in detecting the existence of wireless microphone systems without standard modulation information, which renders the spectrum sensing mechanism impractical in typical environments clustered with other widely used wireless technologies. These disadvantages resulted in the cancellation of the LBT detection requirement for TVBD in the 2010 Second Memorandum Opinion and Order [27]. Instead the geo-location based spectrum sharing technique with database lookup became the mainstream cognitive access mechanism in TVWS.

The geo-location based technique is designed for the TVBD to contact TVWS databases of licensed incumbent users, and to obtain the information on unused channels at the time and area where the device is operating. In U.S. the databases are provided by third party WSDBA such as Spectrum Bridge, Telcordia, Neustar, Microsoft, and Google. These databases use the regulatory agency's public databases containing the information on the identities, types and locations of the protected systems. It is required that different databases collaborate and share data with each other. The TVBD synchronization could be achieved in near real-time using mature secure web service techniques like HTTP on top of the Secure Sockets Layer/Transport Layer Security (SSL/TLS) transport protocol.

To obtain updated spectrum information, the TVBD must periodically submit geo-location to WSDBA, and query available channels prior to use. TVBD queries typically provide device location, device information, antenna height, and additional identifying information. WSDBA process the queries and apply protection criteria to determine the channels allowed for TVBD access. Since the locations of the licensed receivers are generally unknown to WSDBA, the protection criteria are defined as exclusion zones established at specific radii around the TV stations with known geo-location details. For protecting primary services with more periodic uses such as the wireless microphone system, exclusion zones criteria with specified time of operation are adopted [3, 12].

The geo-location and database lookup method provides faster and more reliable channel occupation status for TVBD to avoid interfering with primary users, and hence higher spectrum utilization efficiency is achieved. Currently the technique is only applicable with fixed TVBD due to the incapability of portal devices to provide accurate geo-location when moving. Meanwhile, the stringent out-of-band emission mask requirement may prohibit TVBD from operating in adjacent channels. The requirement of WSDBA collaboration, and the regulatory uncertainty over auctioning repurposed TVWS for licensed mobile services, are also among the major challenges for implementing this mechanism.

C. TVWS Spectrum Sharing Standardization and LTE Small Cell Access

Several groups are working on the TVWS spectrum sharing standards, including the Institute of Electrical and Electronics Engineers (IEEE), the Internet Engineering Task Force (IETF), European Computer Manufacturers Association (ECMA), and FCC. The IEEE standards including IEEE 802.11af, IEEE 802.22, IEEE 802.15m-2014, IEEE 802.19.1, and IEEE DySPAN-SC (Dynamic Spectrum Access Networks Standards Committee), cover a wide range of regulations on TVBD

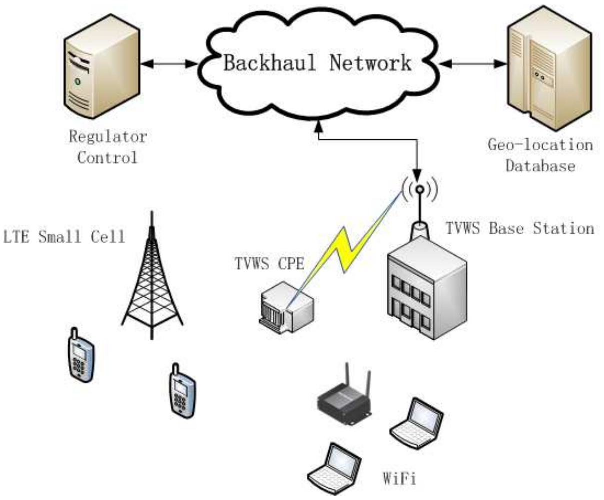

Fig. 2 LTE small cell access to TVWS.

operation and interaction with WSDBA. The IETF standard, IETF Protocol to Access White Space (PAWS) Databases, defines an Internet based protocol for WSDBA discovering and querying available channels. The Standard ECMA-392 specifies a physical layer and a medium access control layer for personal/portable cognitive wireless networks, including home electronics, computers, and high speed video streaming operating in TV spectrum bands [28]. Further, FCC proposed rules to create one unified set of rules for unlicensed white space operations in the TV bands and the 600 MHz band spectrum [29]. The rules specified the minimum distance the TVBD can operate in order to cause less interference to the licensed devices and services.

To enhance spectrum utilization efficiency, LTE deployment in TVWS could be implemented with small cell infrastructure, complying with existing spectrum sharing standards regarding power, bandwidth, out-of-band emissions, and other regulations. Small cell is a cost-effective network densification measure to meet capacity demands in high-traffic areas, through geographic reuse of spectrum [23]. Different from high-powered WiMAX-based cellular infrastructure, small cells are wireless Base Stations or Access Points operating at low power (20 to 100mW), limited range (≤100 m), and variable data rates. They are deployed by end users with self-provisioned broadband connections for backhaul to a point of interconnection with wide-area networks and the Internet. Fig. 2 demonstrates the potential network architecture for LTE small cell access to TVWS through TVWS Customer Premise Equipment (CPE).

Interference is one of the major concerns and challenges in LTE small cell access to TVWS. Since the transmission range among LTE small cell users is small, the interference between TVBDs is relatively strong. LTE small cells should be designed in full base station capability, with low cost and low power. It should also be fit for indoor scenarios with high transmission data rate and low packet loss rate [30, 31].

III. LICENSED SHARED ACCESS IN 3.5 GHZ CITIZENS BROADBAND RADIO SERVICE

The 3.5 GHz CBRS band refers to the 150 MHz radio resource in the 3550 -3700 MHz spectrum.

A. Incumbent Users

The CBRS band was initially allocated for authorized Federal users and grandfathered Fixed Satellite Service earth stations. Due to frequent vacancy, the 150 MHz radio resource is being considered for sharing with CBRS users via a three-tier spectrum access approach coordinated by a dynamic Spectrum Access System (SAS) [12]. In this approach, the incumbent users operate at the first tier with highest priority, while new CBRS users operate either at the second tier with licensed priority access, or at the third tier with general authorized access.

B. Spectrum Sharing Model

For spectrum sharing in the CBRS band, two models are constantly under discussion, namely the three-tier spectrum sharing model, and the two-tier ASA/LSA model.

1) Three-tier Spectrum Sharing Model

The three-tier sharing model was first proposed to explore sharing methods such as small cells for relatively low-power applications in 3550-3650 MHz. It was later extended to the 3650-3700 MHz band [32]. According to this model, incumbent users operating at the Federal Primary Access tier are granted the highest priority, and the CBRS users, including secondary access users operating at the Priority Access tier, and opportunistic users at the General Authorized Access (GAA) tier, are assigned different levels of priority based on their payment profiles or public interest benefits. SAS maintains a geo-location database with well-defined exclusion zones, and manages spectrum sharing in a way that incumbent operations are guaranteed interference protection according to the terms of their assignments whenever they are present in deployed areas. Meanwhile, secondary access users, also known as Priority Access Licensees (PALs), are granted short-term access in particular geographic area when no incumbent user registers to the database for the same frequency band in the same time slot and in the same geographic area. PALs are protected from interference by opportunistic GAA users that would be allowed to access unoccupied spectrum only if no incumbent user or PAL registers a conflicting deployment in the database [12].

In the proposed three-tier approach, SAS coordinates spectrum sharing among incumbent users and other CBRS users. To apply above-mentioned protection criteria, the core functions in SAS will need to access accurate geo-location information and operating parameters including antenna pointing angle and discrimination pattern of registered incumbent users, in order to specify exclusion zones in terms of distance from earth stations. All Citizen Band Service Devices (CBSDs), either PALs or GAAs, must register their location, and connect to an authorized database for the SAS to assign radio resources based on user profile and channel vacancy at the designated location. SAS also provided CBSDs with specific

TABLE IV
5 GHz UNLICENSED SPECTRUM USAGE REGULATED BY FCC PART 15 RULES [35]

Name	Frequency range (GHz)	Main Application scenarios	Power consumption
U-NII-1	5.15-5.25	Aeronautical Radionavigation Service	50 mW
U-NII-2A	5.25-5.35	Earth Exploration Satellite (active), Radiolocation, and Space Research (active) Services	250 mW
U-NII-2B	5.35-5.47	No technical rules	No technical rules
U-NII-2C	5.47-5.725	Radiolocation Service, Maritime Radionavigation Service, Earth Exploration-Satellite (active) and Space Research (active) Services, Meteorological Aids Service	250 mW
U-NII-3	5.725-5.825	Radiolocation Service, Amateur Radio Service	1 W
Part 15.247 Rules	5.725-5.85	Amateur radio and amateur satellite	1 W
U-NII-4	5.85-5.925	No technical rules	No technical rules

spectrum use instructions, such as allowed frequencies of operation, transmit power levels, out-of-band emissions, and durations. When the CBSDs are operating in a managed network, which means the transmission parameters are controllable, and the neighboring cell information could be obtained through network planning, SAS interacts at the network management function level to schedule network planning consistent with regulatory limits. For CBSDs operating in an unmanaged network, SAS interacts directly at the individual level to enforce the communications regulations, and this is usually considered in the opportunistic GAA scenario [3].

2) *Two-tier ASA/LSA Model*

Prior to the three-tier model, Qualcomm proposed a two-tier model in 2013 with a spectrum sharing scheme known as Authorized Shared Access/Licensed Shared Access [33]. In the ASA/LSA scheme, incumbent users operating at the first tier are guaranteed to access the radio resources, and the operations in the second tier are permitted only if the secondary users have been issued ASA/LSA licenses based on the agreement with the incumbents. The agreement with the incumbents specifies the geographical areas, the technical conditions for protection, and the procedures to vacate the occupied channel when the incumbents need to access the same frequency band in the same area. The ASA/LSA model is suitable for small cells since they could be deployed geographically closer to the incumbents, compared to the distance allowed for high power base stations, thus better local area coverage could be achieved. Once granted the access, secondary users have exclusive rights of spectrum use, and consequently are able to offer high QoS.

C. *LTE Deployment in 3.5 GHz Band*

Due to the exclusive protection policy, the ASA/LSA license model is considered capable of providing better QoS due to well managed network planning, though the three-tier model is generally recognized to offer higher throughput for the entire network. Since LTE services come with high QoS standards, PAL licensing using an ASA/LSA approach is envisioned as a desirable model for LTE deployment in the 3.5 GHz band, and it could be efficiently implemented through the Carrier Aggregation framework [34]. LTE deployment in 3.5 GHz Band is certainly in the nascent stage. Substantial testing and proof-of-concept efforts are required before it can be implemented. A number of seminal communications companies are already developing technologies for use in the 3.5 GHz band. The LTE-U Forum, whose members include Verizon, Ericsson, Alcatel-Lucent, Qualcomm, and Samsung, are working on protocol for unlicensed 3.5 GHz spectrum operations. Conventional device vendors are also appealed to launch handsets supporting 3.5GHz to enrich the variety of 3.5GHz portable devices. For example, Huawei released the world's first 3.5GHz LTE-A device at the 3.5GHz LTE TDD Roundtable at Mobile World Congress (MWC) 2015.

IV. LTE SPECTRUM SHARING IN 5 GHZ UNLICENSED BANDS

The 5 GHz Unlicensed National Information Infrastructure is a spectrum range from 5.150 GHz to 5.925 GHz, as listed in Table IV.

A. *Incumbent Users*

Since 2003, the 555 MHz of spectrum in 5 GHz bands, including U-NII-1, U-NII-2A, U-NII-2C, and U-NII-3, were used by U-NII devices complying with IEEE 802.a, 802.n, and 802.ac Wi-Fi standards. Dynamic Frequency Selection (DFS) is required in U-NII-2A and U-NII-2C to detect local radar signals, and to avoid selecting the same channel occupied by other users. In 2013, additional 195 MHz of U-NII-2B and U-NII-4 were proposed for sharing to support the growing needs of fixed and mobile broadband communications [12].

The U-NII bands are considered more ideal for LTE spectrum sharing than the already crowded unlicensed 2.4 GHz ISM (Industrial, Scientific and Medical) radio bands, since they have relatively large spectrum amount, global availability, and good channel propagation performance. For LTE deployment in 5 GHz U-NII bands, besides the traditional WLAN data offloading method, more sophisticated spectrum sharing mechanisms have been studied for achieving improved throughput, including LTE-WLAN aggregation (LWA), LTE Licensed Assisted Access (LAA), and other emerging multi-connectivity/aggregation options [36].

B. *LTE-WLAN Aggregation vs. LTE Licensed Assisted Access*

Data offloading to unlicensed spectrum in existing 802.11 WLAN infrastructure, e.g. WiFi, is the conventional method used by wireless network operators to increase system capacity for their subscribers. During WiFi offloading, licensed network interworks with WLAN, and shifts data bearer to WLAN when

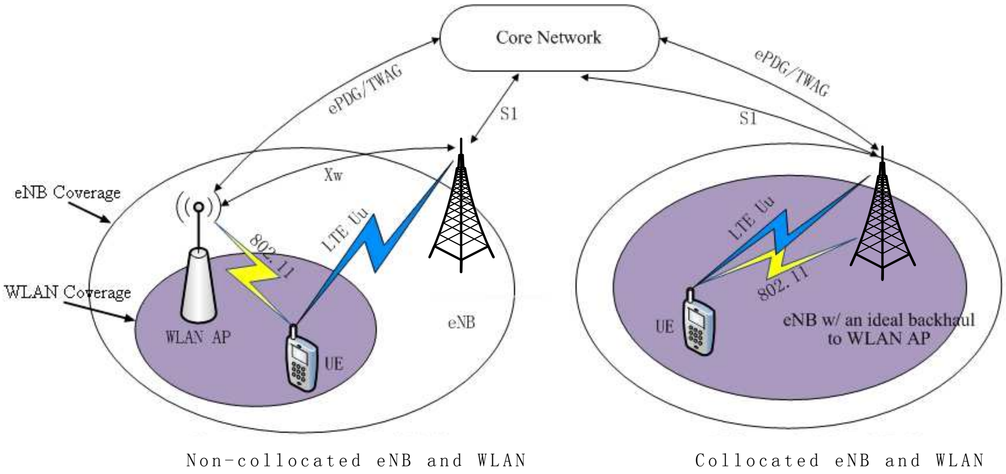

Fig. 3 LWA deployment and data aggregation.

the available unlicensed channels are detected using the contention resolution Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

To take advantage of the well-developed network management technologies in LTE, LTE-WLAN data aggregation(LWA) at the radio access network (RAN) is proposed as an alternative to WiFi offloading, and it has been included in a 3GPP Release 13 Work Item [37]. In LWA, depending on the real-time channel conditions and system utilization, an Evolved NodeB (eNB) schedules packet delivery using both LTE and WiFi radio links in the aggregation architecture similar to the Dual Connectivity split-bearer in 3GPP Release 12. In this way the scheduling decision can be made at a packet level by the core LTE network, leading to better control and utilization of the resources on both links. Two basic LWA deployment scenarios are illustrated in Fig. 3. The collocated scenario refers to the situation when the eNB is connected to a WLAN logical entity or an Access Point (AP) with an ideal backhaul; and the non-collocated scenario is when eNB is connected to a WLAN AP via the Xw standardized LTE-WLAN interface, or via the Xw through a WLAN Access Controller (AC).

Another spectrum sharing mechanism included in 3GPP Release 13 is Licensed Assisted Access (LAA). Under LAA, the unlicensed carrier can be used as a Secondary Component Carrier in the LTE Carrier Aggregation framework. Instead of switching packet transmission to WLAN as implemented in WiFi offloading, LAA deploys LTE itself in the unlicensed spectrum to provide enhanced QoS. While LWA integrates the WLAN radio link as part of the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) without imposing any modification request on the core network, LAA needs to adjust the channel contention scheme and the transmit power control accordingly. This kind of modification is applied to ensure fairness for other technologies in the worldwide usage of the 5 GHz unlicensed bands, in addition to the overall throughput enhancement in the network. Four possible LAA deployment scenarios of carrier aggregation among licensed macro cell, licensed small cell, and unlicensed small cell are described in [20].

C. *Coexistence and Interference Management*

A major challenge for LTE spectrum sharing in 5 GHz bands is to maintain efficiency and fairness at the same time. For instance, during data offloading, WLAN Clear Channel Assessment (CCA) cannot detect eNB if the packet size is below the RTS Threshold, resulting in LTE downlink (DL) performance degradation. On the other hand, continuous LTE downlink transmission degrades WLAN performance as well. Meanwhile, LAA implementation has to comply with existing regulations on U-NII device transmit power, and to comply with the DFS requirements for U-NII-2 devices. Based on these considerations, numerous studies have been dedicated to the coexistence and interference management schemes [5, 6, 38, 39].

Simulation results have shown that conventional LTE operation model in heterogeneous networks (HetNets) causes significant degradation to nearby WiFi systems, especially in densely deployment scenarios [6, 38, 39]. This is due to firstly the lack of sharing considerations in LTE operation which was initially targeted for exclusive licensed spectrum usage, and secondly the fact that WiFi users contend for channel access based on the Distributed Coordination Function (DCF) with a channel energy level threshold usually below the LTE interference levels. Another difference worth noting is that WLAN DL and UL (uplink) share the same band, while LTE DL and UL could have different bands. Existing research work on coexistence management schemes mainly focus on two aspects of the channel access mechanisms, namely the channel allocation methods, and the transmission duration/power control, as summarized in Table V.

Several proposed coexistence features, such as the Almost Blank Subframe/LTE muting [10], have been included in 3GPP Release 8/9 for enhanced inter-cell interference coordination (eICIC). Efforts outside 3GPP also seek applicable LTE deployment options in other spectrum sharing scenarios,

TABLE V COEXISTENCE MANAGEMENT SCHEMES

Category	Proposed Scheme	Simulation Settings		Performance Improvement
		Parameter	Value	
Channel allocation	Intra- and inter- system channel coordination schemes, Random Channel Assignment, Intra-RAT channel coordination, and Inter-RAT channel coordination [39].	Deployment scenario	Horizontally aligned WiFi/LTE nodes	In comparison with a single channel deployment, maximum absolute throughput gain of is ~3.5x for random channel assignment and ~4 to 5x for Intra and Inter RAT channel coordination schemes.
		Bandwidth	20 MHz	
		Center frequency	2.4 GHz	
		Transmission power	20 dBm	
		No. of Tx/Rx antennas	1/1	
		Traffic	Full-buffer	
		WiFi CCA threshold	-62 dBm	
	Simple CCA (LBT) mechanism for coexistence among multiple LAA operators. eNB is allowed to transmit if the detected energy level is below a threshold. The eNB will commence data transmission only after the channel is clear for the specified duration [10].	Deployment scenario	Indoor hotspot, indoor office, and outdoor small cell	Without LBT, a large percentage of users have zero throughput. In the indoor environment and with LBT implemented, LAA can provide downlink system throughput of up to 60 Mbps per 20 MHz channel in a 2Tx-2Rx configuration. At low loads, 50% of the users can receive throughput of at least 5 Mbps and 20% of the users can receive throughput of at least 20 Mbps.
		Bandwidth	20 MHz	
		Center frequency	5.8 GHz	
		Transmit power	Indoor 20 dBm, outdoor 30 dBm	
		No. of Tx/Rx antennas	2/2, TM4 (SU-MIMO)	
		Traffic	Bursty	
		CCA threshold	-85 dBm	
Transmission duration/power control	Modified almost blank subframe (ABS) Reuse the ABS feature in 3GPP Release 10 without reference signals, and different blank subframe patterns are tested to study the tradeoff between the time given up by LTE and the throughput gain in WiFi network [38].	Deployment scenario	Indoor single floor and indoor multi-floor, multiple LTE eNBs and UEs, WiFi APs	Improve the WiFi throughput per user from 2.46 up to 50 times in different deployment scenarios with multiple blank subframe patterns. The decrease on LTE throughput is proportional to the duration of blank subframes.
		Bandwidth	20 MHz	
		Center frequency	900 MHz	
		Transmission power	23 dBm	
		No. of Tx/Rx antennas	1/1	
		Traffic	Full-buffer	
		Channel vacancy detection threshold for WiFi transmission	-82 dBm	
		Threshold to detect LTE transmissions	-62 dBm	
	Uplink (UL) power control. Decrease LTE UL transmit powers according to interference measurements, giving opportunity to Wi-Fi transmissions [40].	Deployment scenario	Indoor office with 20 dual strip single floor rooms	High and intermediate penalization values produce small reduction of LTE UL mean user throughput and increase of Wi-Fi throughput, and low penalization values privilege Wi-Fi throughput at the cost of hard reductions of LTE UL throughput.
		Bandwidth	20 MHz	
		Center frequency	900 MHz	
		Maximum transmission power	20dBm	
		No. of Tx/Rx antennas	1/1	
		Traffic	Full-buffer	
		LTE power control	Closed loop, $\alpha = 1$	
	Simple fractional bandwidth sharing. Limit LTE presence on the bandwidth by allocating only a fraction of the time for it. LTE follows a muting pattern, which statically prevents its transmissions during part of its Transmission Time Intervals (TTI) [5].	Deployment scenario	Single floor indoor office rooms	LTE performance (served load per cell) decreases quite linearly along with increasing muting percentage. With 30-40 Mbps load each 20 % transmission time allowance steadily increases LTE served load by 5-7 Mbps. With high load, each 20 % allocated for LTE instead of WLAN does not drop WLAN performance as much as it increases LTE performance. The total combined throughput increases.
		Bandwidth	20 MHz	
		Transmission power	20 dBm	
		Traffic	File transfer	
		WLAN min. contention window	15	
		WLAN max. contention window	63	
		LTE muting percentage	[0, 20, 40, 60, 80, 100]	

including solutions for systems without LBT requirements, and network level multi-connectivity. Coexistence among different technologies is managed using methods compatible with Release 10/11 LTE standards, for example, the Channel Selection, the Carrier-Sensing Adaptive Transmission, and the Opportunistic Supplemental Downlink [41].

The transmission duration/power control in coexistence management falls into the category of interference coordination which is critical in all spectrum sharing solutions. New features described in LTE standards related to interference coordination include inter-cell interference coordination (ICIC)/eICIC, relay nodes, coordinated multipoint (CoMP) operation, spatial multiplexing (MIMO), etc. How to adjust the resource allocation and interference level adaptively according to the network condition, using a throughput ratio criteria acceptable to all users, and without incurring excessive communication overheads, remains an attractive topic for LTE spectrum sharing in 5 GHz bands.

V. CONCLUSION

The 4G LTE network is serving denser distributions of users with higher speeds than previous cellular technologies could offer. Spectrum sharing in non-LTE-licensed bands alleviates the throughput bottleneck experienced in conventional network infrastructure. LTE deployment utilizing those additional spectrum resources has to abide by the existing regulations on channel access to each frequency band, whether the sharing is via data offloading, or via data aggregation through the second component carrier in the Carrier Aggregation framework. In this procedure, multiple objectives have to be targeted simultaneously, i.e. accommodating the priority of incumbent users, managing the interference to other users in co-channel or adjacent channel operations, and achieving satisfactory spectrum efficiency in spatial/temporal/frequency domain. Study on advanced inter-node coordination techniques (small cell, massive MIMO, deployment in mm-wave frequencies above 6GHz, etc.) based on better understanding of signal propagation characteristics at various bands, and on finer interference modeling and prediction in different deployment scenarios, is included in the schedule of 3GPP and 3GPP2. New regulations on both sensing based and database based channel access to shared spectrums are expected to create a more cost efficient wireless communication ecosystem. The overview of LTE spectrum sharing technologies shows that in heterogeneous networks, adapting LTE cellular technologies into compliant mode of operation is feasible and crucial in improving system throughput and in coexistence management, as exemplified by formal LBT and ABS proposals which became part of LTE standards. Moving forward to the next generation mobile networks, 5G systems anticipate shortened distance between affordable data rate and Shannon's channel capacity, through developing more advanced spectrum sharing mechanisms, as envisioned in this survey.

ACKNOWLEDGMENT

This work was supported by National Science Foundation grants EARS-1547330 and ECCS-1307580.

REFERENCES

[1] "Cisco Visual Networking Index (VNI)," online available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/VNI_Hyperconnectivity_WP.html.

[2] A. Solheim, "Microwave Backhaul Radios Meet the Evolving Traffic Challenge," Mobile Dev Design, 2013.

[3] 4G Americas, "Spectrum Sharing," online available: http://www.4gamericas.org/files/2414/1323/5229/4G_Americas_Spectrum_Sharing_-_FINAL_Oct_2014.pdf, 2014.

[4] "Dynamic Spectrum Management," White Paper, InterDigital Inc., October 2012.

[5] Timo Nihtilä, Vitaliy Tykhomyrov, Olli Alanen, Mikko A. Uusitalo, Antti Sorri, Martti Moisio, Sassan Iraji, Rapeepat Ratasuk, Nitin Mangalvedhe, "System Performance of LTE and IEEE 802.11 Coexisting on a Shared Frequency Band," IEEE Wireless Communications and Networking Conference, 2013.

[6] Nadisanka Rupasinghe and İsmail Güvenç, "Licensed-Assisted Access for WiFi-LTE Coexistence in the Unlicensed Spectrum," IEEE Globecom Workshop, 2014.

[7] 4G Americas, "MIMO and Smart Antennas," online available: http://www.4gamericas.org/files/4614/0622/2152/MIMO_and_Smart_Antennas_July_2013_FINAL.pdf , 2013.

[8] "Unwanted Emissions in the Out-of-band Domain," Recommendation ITU-R SM.1541-1, 2001-2002.

[9] Fei Peng, Yue Gao, Yue Chen, K. K. Chai, and Laurie Cuthbert, "Using TV White Space for Interference Mitigation in LTE Femtocell Networks," Proceedings of IET International Conference on Communication Technology and Application (ICCTA), 2011.

[10] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, "LTE-Advanced: Next-Generation Wireless Broadband Technology," IEEE Wireless Communications, vol. 17, no. 3, pp. 10–22, 2010.

[11] Jon M Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, vol. 97, no. 4, pp. 708-719, 2009.

[12] Jonathan R. Agre and Karen D. Gordon, "A Summary of Recent Federal Government Activities to Promote Spectrum Sharing," 2015. Online available https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2015/p5186final.pdf

[13] FCC 12-36, "Third Memorandum Opinion and Order – Unlicensed Operation in the TV Broadcast Bands; Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band," online available, https://apps.fcc.gov/edocs_public/attachmatch/FCC-12-36A1.pdf, April, 2012.

[14] Adriana Flores, Ryan Guerra, Edward Knightly, Peter Ecclesine, and Santosh Pandey, "IEEE 802.11af: A Standard for TV White Space Spectrum Sharing," IEEE Communications Magazine (October): 92–100, 2013.

[15] Stanislav Filin, Tuncer Baykas, M. Azizur Rahman, Hiroshi Harada, "Performance Evaluation of IEEE 802.19.1 Coexistence System," IEEE International Conference on Communications (ICC) (June): 1–6. , 2011.

[16] Hiroshi Harada, Yohannes Alemseged, and Oliver Holland, "IEEE Dynamic Spectrum Access Networks (DYSPAN) Standards Committee," 2nd International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE) (March): 1–5, 2011.

[17] Maurizio Murroni, R. Venkatesha Prasad, Paulo Marques, Bernd Bochow, Dominique Noguet, Chen Sun, Klaus Moessner, and Hiroshi Harada, "IEEE 1900.6: Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and Other Advanced Radio Communication Systems Standard: Technical Aspects and Future Outlook," IEEE Communications Magazine (December), 2011.

[18] V. Chen, S. Das, L. Zhu, J. Malyar, and P. McCann, "Protocol to Access White-Space (PAWS) Databases," Internet Draft, Internet Engineering Task Force (IETF) (24 April). http://tools.ietf.org/html/draft-ietf-paws-protocol-12, 2014.

[19] FCC 15-47, "Report and Order and Second Further Notice of Proposed Rulemaking –Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band (21 April)," 2015.

[20] 3GPP RP-141646, "Study on Licensed-Assisted Access using LTE," RAN#65, September 2014.

[21] Jeannette Wannestrom, "Carrier Aggregation Explained," 3GPP. http://www.3gpp.org/technologies/keywords-acronyms/101-carrier-aggregationexplained, June 2013.

[22] Michael J. Marcus, "Spectrum Policy for Radio Spectrum Access." Proceedings of the IEEE, vol. 100, Special Centennial Issue, pp. 1685 – 1691, May 2012.

[23] William Lehr and Miquel Oliver, "Small Cells and the Mobile Broadband Ecosystem," 25th European Regional ITS Conference, Brussels, 2014.

[24] C. Cordeiro, K. Challapali, and D. Birru, "IEEE 802.22: An Introduction to the First Worldwide Wireless Standard Based on Cognitive Radios," Journal of Communications, vol. 1, no. 1, pp. 38-47, December 2006.

[25] Spectrum Bridge, Inc., "United States TV White Spaces: Usage &Availability Analysis," Second Quarte, online available:

http://udia.spectrumbridge.com/Libraries/White_Papers/TV_WhiteSpaces_Usage_Availability_Analysis.sflb.ashx, 2010.
[26] FCC 08-260, "Second Report and Order and Memorandum Opinion and Order –Unlicensed Operation in the TV Broadcast Bands; Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (14 November)," online available: https://apps.fcc.gov/edocs_public/attachmatch/FCC-08-260A1.pdf, 2008.
[27] FCC 10-174, "Second Memorandum Opinion and Order – Unlicensed Operation in the TV Broadcast Bands; Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (23 September)," 2010.
[28] ECMA, "MAC and PHY for Operation in TV White Space," standard ECMA-392, 2nd Edition, June 2012.
[29] FCC 15-99, "FCC Establishes Rules for Unlicensed Operations in the TV and the 600 MHz Bands," Aug. 2015.
[30] Abdelrahman Abdelkader, "Deployment of Indoor LTE Small Cells in TV White Spaces," Master Thesis, Universitat Politecnica de Catalunya, July 2015.
[31] A. Alsohaily and E. S. Sousa, "Spectrum sharing LTE-Advanced Small Cell Systems," IEEE 16th International Symposium on Wireless Personal Multimedia Communications (WPMC), June 2013.
[32] FCC 12-148, "Notice of Proposed Rulemaking and Order – Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550−3650 MHz Band (12 December)," 2012.
[33] Qualcomm, "1000x: More Spectrum – Especially for Small Cells," http://www.qualcomm.com/media/documents/files/1000x-more-spectrumespecially-for-small-cells.pdf. November 2013.
[34] Global TD-LTE Initiative, "Optimized Spectrum Use with LSA/ASA WHITE PAPER," 2014.
[35] FCC 14-30, "FIRST Report and order," April 1, 2014.
[36] 4G Americas, "LTE Aggregation &Unlicensed Spectrum," online available:http://www.4gamericas.org/files/1214/4648/2397/4G_Americas_LTE_Aggregation__Unlicensed_Spectrum_White_Paper_-_November_2015.pdf, 2015.
[37] 3GPP RP-151022, "LTE-WLAN Radio Level Integration and Interworking Enhancement," 2015.
[38] E. Almeida, A.M. Cavalcante, R.C.D. Paiva, F.S. Chaves, F.M. Abinader, R.D. Vieira, S. Choudhury, E. Tuomaala, and K. Doppler, "Enabling LTE/WiFi Coexistence by LTE Blank Subframe Allocation," IEEE International Conference on Communications (ICC), June 2013.
[39] Shweta Sagari, Ivan Seskar, and Dipankar Raychaudhuri, "Modeling the Coexistence of LTE and WiFi Heterogeneous Networks in Dense Deployment Scenarios," IEEE International Conference on Communication Workshop (ICCW), June 2015.
[40] Fabiano S. Chaves, Erika P. L. Almeida, Robson D. Vieira, Andre M. Cavalcante, Fuad M. Abinader Jr., Sayantan Choudhury, and Klaus Doppler, "LTE UL Power Control for the Improvement of LTE/Wi-Fi Coexistence," IEEE 78th Vehicular Technology Conference (VTC Fall), Sept. 2013.
[41] Qualcomm Technologies, Inc., "LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi," Qualcomm Research, 2014.

Yun Ye (M'15) received the B.S. degree in Electrical Engineering from Sun Yat-sen University, Guangzhou, China, in 2015, the M.Eng. degree in Telecommunications from Shanghai Jiaotong University, Shanghai, China, in 2008, and the Ph.D. degree in Computer Engineering from University of Nebraska-Lincoln, NE, USA, in 2013.

She is currently an Assistant Professor with the Department of Mathematics, Engineering and Computer Science at LaGuardia Community College of City University of New York, NY, USA. Her research interests include cross-layer design in wireless communications, video surveillance, and 3D multimedia signal processing.

Dalei Wu (M'11) received the B.S. and M.Eng. degrees in Electrical Engineering from Shandong University, Jinan, China, in 2001 and 2004, respectively, and the Ph.D. degree in Computer Engineering from the University of Nebraska-Lincoln, Lincoln, NE, USA, in 2010.

From 2011 to 2014, He was a Postdoctoral Research Associate with the Mechatronics Research Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. Since August 2014, he has been an Assistant Professor with the Department of Computer Science and Engineering at the University of Tennessee at Chattanooga (UTC). His research interests include wireless communications and networking, cyber-physical systems, and intelligent systems.

Zhihui Shu received a BE from Wuhan University, Wuhan, China, in 2006, and a ME from Shanghai Jiao Tong University, China, in 2010, respectively. In August 2014, he received a Ph.D. degree from the University of Nebraska-Lincoln.

He is currently a research scientist at Intelligent Fusion Technology, Inc., Germantown, MD, USA. His research interests include satellite communications, game theory, cognitive radio networks, wireless security, and smart grid communication systems, etc.

Yi Qian (M'95–SM'07) received the Ph.D. degree in electrical engineering from Clemson University, Clemson, SC, USA

He is currently a Professor with the Department of Electrical and Computer Engineering, University of Nebraska-Lincoln (UNL), Lincoln, NE, USA. Prior to joining UNL, he worked in the telecommunications industry, academia, and the government. Some of his previous professional positions include serving as a senior member of scientific staff and a technical advisor at Nortel Networks, a senior systems engineer and a technical advisor at several start-up companies, an assistant professor at University of Puerto Rico at Mayaguez, and a senior researcher at National Institute of Standards and Technology. His research interests include information assurance and network security, network design, network modeling, simulation and performance analysis for next generation wireless networks, wireless ad-hoc and sensor networks, vehicular networks, smart grid communication networks, broadband satellite networks, optical networks, high-speed networks and the Internet.

Dr. Qian is a member of ACM and a senior member of IEEE. He was the Chair of IEEE Communications Society Technical Committee for Communications and Information Security from January 1, 2014 to December 31, 2015. He is a Distinguished Lecturer for IEEE Vehicular Technology Society. He is serving on the editorial boards for several international journals and magazines, including serving as the Associate Editor-in-Chief for IEEE Wireless Communications Magazine. He is the Technical Program Chair for IEEE International Conference on Communications (ICC) 2018.