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LTE IN UNLICENSED SPECTRUM AND IN-DEVICE COEXISTENCE WITH WI-FI

SHREYANJIT GUPTA[*], SAPTARSHI ROY[*], ANKIT KUMAR CHARAN[*], KOUSTAV MAJUMDER[*], KOUSHIK SARKAR[**]

ABSTRACT

The rising traffic in the licensed band now used for LTE is concreting the way for LTE in unlicensed spectrum, which has been planned to permit cellular network operators to divest some of their data traffic by accessing the unlicensed 5 GHz frequency band. In this paper we supply an introduction to the current methods which can put into practice LTE in the unlicensed spectrum, namely LTE-U, LAA, MulteFire and LWA and we furnish a relative study about them. We also reveal about 'in-device coexistence' and how it can solve the interference between Wi-Fi receiver and LTE RF receiver concurrently.

KEYWORDS: LTE-U, LAA, CSAT, LBT, MulteFire, LWA.

INTRODUCTION

As the number of mobile devices in use which include mobile phones, tablets and IOT devices keeps on increasing day by day, the requirement of mobile data also increases rapidly and according to [1], by 2020, there will be 11.6 billion mobile-connected devices, the including machine-to-machine [M2M] modules, exceeding the world's projected population at that time (7.8 billion), meaning 1.5 mobile devices per capita. Also, 4G connections will have the highest share (40.5 percent) of total mobile connections by 2020.

However, due to the limited nature of licensed spectrum, it is impossible to allocate exclusively new spectrum to fulfil demand. The current technologies that are there to solve this issue of rapidly increasing traffic demand in the sector of mobile communications are MIMO, OFDM, Carrier Aggregation (introduced in the LTE-A or LTE-Advanced standards of 3GPP) etc. All these methods aim to utilize the LTE channel, currently in use, in some specific way to meet this ever-increasing demand in the LTE spectrum [2,3,4]. LTE in Unlicensed or license exempt spectrum is a completely new aspect which aims to utilize the 5GHz band which is currently used by IEEE 802.11a and 802.11ac compliant Wi-Fi equipment[5], to transmit data and thus opening up a whole new opportunity for serving more mobile device users and providing a better experience in terms of data

[*]Fourth Year Student, Department of Electronics and Communication, Future Institute of Engineering and Management, Kolkata, India.
[**]Assistant Professor, Department of Electronics and Communication, Future Institute of Engineering and Management, Kolkata, India.
Correspondence E-mail Id: editor@eurekajournals.com

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rate by extending techniques like Carrier Aggregation, from licensed spectrum only, to both licensed and unlicensed spectrum[6] which is possible as the unlicensed band is not over-crowded .This will be discussed in details later in this article. Hence there has been a recent push by many major companies suc has Qualcomm, Huawei, Nokia, Ericsson, T-Mobile, and NTT, to deploy LTE devicesin5GHz [7, 8].

The deployment of LTE in the 5GHz band comprising the frequency range between 5150 MHz and 5925 MHz, will mean that it has to coexist with the Wi-Fi and hence comes the different techniques in which the LTE technology can be implemented in the unlicensed band in such a way that there is efficient channel allocation for both Wi-Fi and LTE to achieve the coexistence and collaborations between multiple Wi-Fi access points and LTE eNodeBs. The techniques that exist are namely LTE-U (LTE-Unlicensed), LAA (License Assisted Access), MulteFire, LWA (LTE-WLAN Aggregation). The two main methods for usage of LTE in unlicensed band are LTE-U and LAA. LTE-U is a relatively simple mechanism in the early deployment, proposed by Qualcomm, which does not require changes to the LTE air interface protocol [9]. Moreover, the LTE-U does not utilize the Listen Before Talk or LBT regulation and hence can be deployed in the countries like US, South Korea, India and China. On the other hand, LAA proposed by 3GPP or 3rd Generation Partnership Project uses the LBT which is mandatory in Japan and Europe. These two methods could achieve the coexistence of LTE and Wi-Fi devices when they share the same spectrum. However, in both LTE-U and LAA the Wi-Fi and LTE signals must use the same spectrum alternatively i.e. they are time division multipleaccess methods.

LITERATURE SURVEY

The survey done in [1] by Cisco, gives the fact the 4G LTE traffic has accounted for 72% of mobile traffic in 2017 alone. Cellular network connection speed grew 1.3 folds in 2017 from its previous year. Also mentioned in [1] is that the average Smartphone usage grew by 49% in 2017. All these indicate the rapid growth in LTE network usage and ever-increasing number of mobile device users. In order to tackle these requirements [2] mentions about Multiple-input multiple-output (MIMO) systems, which aim to improve spectral efficiency, energy efficiency, and processing complexity of next generation cellular system. [3] mentions about Orthogonal frequency-division multiplexing (OFDM) effectively mitigates inter symbol interference (ISI) caused by the delay spread of wireless channels. In [4] we find the concept of Carrier Aggregation as another method to fulfil the high demands of LTE transmission, wherein multiple eNodeBs (eNBs) serve the same user to achieve faster data rates. We encounter a whole new approach in [5,7] with Qualcomm's introduction of LTE-U and [6] discusses about the LTE and Wi-Fi coexistence challenges analyses the performance degradation of the Wi-Fi networks at the presence of LTE. We see gradually how other carriers like T-Mobile, Ericsson take interest in LTE-U and aim to deploy LTE services in the 5GHz bandin [8].However, the methods which can be applied for implementing LTE in unlicensed band are talked about in[9,10].[11] establishes the minimum RF characteristics and minimum performance requirements for E-UTRA User Equipment (UE), whereas the physical channels for evolved Universal Terrestrial Radio Access (E-UTRA) are mentioned in [12]. Mina Labib et al. explored the different mechanisms for LTE operation in the unlicensed band. They have done a great comparative study of those mechanisms namely, LTE-U, LAA and MulteFire in [13]. In this article [14], the future scopes of cellular network industry have been discussed. Implementation of convergence of Wi-Fi and cellular networks by using techniques such as LAA, LWA etc. are the main content of this

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article. R. Burbidge in [15] talks about the integration of LTE and Wi-Fi signals [16] contains evaluation methodology and possible scenarios for LTE deployment in the 5 GHz bands. It mainly focuses on the LAA service and the co-existence of LAA with Wi-Fi. In article [17] we find how LTE and Wi-Fi antennas already available on smartphones transmit together and successfully decode the interfered signals. This gives the way for LWA which has been thoroughly discussed in [18]. The MulteFire, another emerging method for LTE transmission in unlicensed band, has been cited in the article [19]. [20] talks about Carrier Sense Adaptive Transmission (CSAT) procedure, which is basically a time division multiplexing technique that enables transmission of LTE and Wi-Fi signals at different chunks of time over the same frequency band. [21] mentions the architecture of LBT or Listen Before Talk utilized in LAA. Z. Jiang and S. Mao in [22] talk about the 'in device co-existence' as the further evolution of Unlicensed band LTE, which will pave way for the further development of this technology which is relatively new and has a lot of scopes to be researched on.

LTE-U VS. LAA

LTE-U would permit cell phone carriers to enhance exposure in their cellular networks, by using the unlicensed 5 GHz band already occupied by Wi-Fi devices. To develop the user skill, a amalgamated LTE network can lengthen LTE carrier aggregation from licensed bands to unlicensed bands, to get better data capacity, user data rates, and coverage [6]. LTE-U specification were planned principally for the case when a single e-Node-B has access to licensed spectrum (called Primary Cell or PC) and a number of other e-Node-Bs which have access unlicensed spectrum (called Secondary Cell or SC). Now by aggregating carriers from these multiple e-Node-Bs a quicker data rate can be provided to exacting user [4].LAA also has to co-exist with Wi-Fi without making any kind of interference with Wi-Fi channels being used by other users and in order to implement that it uses Listen-Before-Talk (LBT) regulation. LBT dynamically latches on to channels that are not being used by Wi-Fi users. In case there is no clear channel available, LAA shares a channel equally with others.

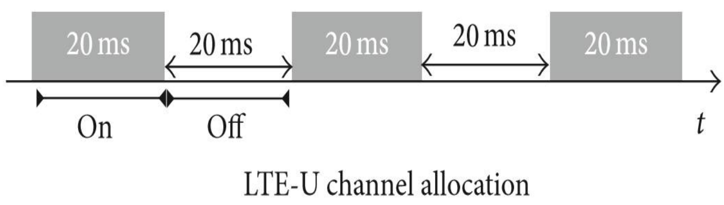

Figure 1.LTE-U channel allocation [23]

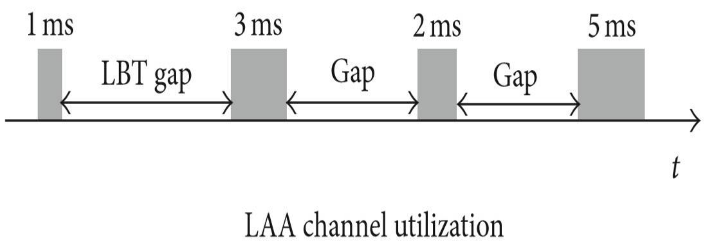

Figure 2.LAA channel allocation [23]

LTE-U	LAA
LTE-U supports supplemental downlink (SDL) only within the frequency bands 5150-5250 MHz and 5725-5850 MHZ, whereas the frequency bands 5250-5725 MHz has been reserved for future use[10].	Licensed Assisted Access (LAA), was standardized in 3GPP Rel-13, which define LAA for downlink only. The operating frequency band for LAA spans the frequency range 5150 MHz - 5925 MHz (channel numbers 46 and 47 in the 3GPP specifications). The current allowable bandwidths for LAA operation in unlicensed spectrum are 10 and 20 MHz [11]. The 3GPP Rel-14 has the introduction of enhanced-Licensed Assisted Access (eLAA), which includes uplink (UL) operation for LAA [12].
Does not use Listen Before Talk (LBT) regulation.	Uses the Listen Before Talk (LBT) regulation.
The different methods for coexistence with Wi-Fi include on-off switching, Channel Selection, CSAT and Opportunistic SDL.	LBT is the integrated process itself that ensures efficient coexistence of LTE and Wi-Fi in the same band.

ON-OFF SWITCHING

When the traffic order is low, the small cell e-Node-B can stop transmitting in the unlicensed spectrum and relies only on the licensed spectrum. Doing this will reduce the amount of nosiness to Wi-Fiusers [20].

CHANNEL SELECTION

LTE-U uses a scanning practice to look for apparent channels for SDL carrier broadcast, which is based on LTE and Wi-Fi measurements performed in the initialization phase and occasionally during the SDL operation stages. Scanning can be passive or active, carried out every few seconds, and channel assortment can be made at any time, during 10s of seconds.

If several obvious channels in unlicensed bands are identified by the system, LTE-U generally chooses the clear channel, thus potentially avoiding main channels of Wi-Fi and the channels of other LTE-U operators. If LTE-U detects nosiness in the operating channel and catches some other available channels in unlicensed bands, it will control to another clear channel that has less interference.

CSAT

When the scanning procedure cannot identify a clear channel in unlicensed band, LTE-U desires to contribute to the channel with adjoining Wi-Fi access APs or other LTE-U systems by executing the CSAT algorithm. In addition, no clear channels can be established in the thick consumption of LTE-Us and Wi-Fi APs. In general, the coexistence methods in unlicensed band are by using LBT or CSMA for Wi-Fi, which uses contention-based access. For CSMA or LBT, the medium should be sensed, and accessed if it is sensed apparent. The key idea of these techniques is to implement TDM for coexistence. In fact, CSAT also leverages TDM coexistence for medium sensing. However, it senses the medium about 10s of milliseconds to 200 milliseconds, which is longer than LBT or CSMA techniques. Moreover, based on the measured medium activities, CSAT can turn off LTE transmission proportionally. In particular, CSAT uses a duty cycle, so that LTE-U can fiddle with the on/off ratio and transmission control. The duty cycle can be a few hundreds of mili seconds. The opening/ closing actions can be adaptively accustomed for calculating the transmission delay.

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During the CSAT on period, LTE-U can transmit in high power. During the CSAT off period, LTE-U can operate in low power or even turn off to keep away from interference to neighboring Wi-Fi users. Furthermore, Wi-Fi can resume normal transmission during the CSAT off periods. To put into practice, CSAT algorithm in LTE, the Almost Blank Sub-frame (ABS) feature can be used [6]. In summing up, CSAT can make sure compatibility with Rel. 10/11 UE PHY/MAC standards. Also, CSAT can attain sound and efficient channel sharing between LTE-U and Wi-Fi.

OPPORTUNISTIC SDL

SDL carrier can be used in an opportunistic way, usually; the is based on load requirement. If the downlink load of the little cell is high and there are energetic users using the unlicensed band, SDL transmissions should be turned on for spiraling data offloading in the unlicensed bands. If the downlink load of small cell is low, or there are no active users using the unlicensed band, the SDL transmission should be turned off to reduce the interference to neighboring Wi-Fi APs and other LTE-U operators.

LBT

With LBT, each equipments act Clear Channel Assessment (CCA) based on energy revealing, which can decide the occurrence or absence of other occupants in the channel. The equipment cannot right to use the channel when the energy level is over the CCA threshold. Besides the regulatory requirements, LBT is the technique for fair sharing of the unlicensed spectrum. It is measured for an important feature of LTELAA in a single global solution framework.

Based on European Telecommunications Standards Institute (ETSI) regulatory rules, two LBT mechanisms are mainly used in LTE-LAA. One mechanism is Frame based Equipment (FBE) and the other is Load based Equipment (LBE) [16,21].

MULTEFIRE

MulteFire is an LTE-based technology that operates standalone in unlicensed and shared spectrum, as well as the global 5 GHz band. Nokia, Qualcomm, Intel and Ericsson formed MulteFire alliance in 2015 and since then many other organizations have joined it. MulteFire will offer the benefits of advanced LTE technology along with the simplicity of Wi-Fi deployment [10]. This technology supports Listen-Before-Talk (LBT) for correct co-existence with Wi-Fi and other technologies operating in the same spectrum. It supports confidential LTE and neutral host deployment models as well [13].

There are two different ways by which we can deploy MulteFire: i) by traditional mobile operators, ii) by neutral hosts

I. Public Land Mobile Network (PLMN) access mode, which permits mobile network operators to broaden their coverage into the unlicensed band, especially for certain locations where licensed band is not available.
II. Neutral Host Network (NHN) access mode, which is alike to Wi-Fi, a self-contained network deployment that provides right of entry to the Internet.

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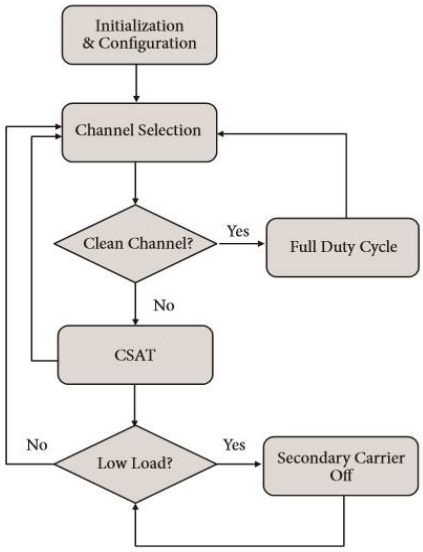

Figure 3.Flow diagram of Opportunistic SDL [9]

a) DOWNLINK OPERATION

A MulteFire eNodeB will need to carry out LBT before transmitting any signal. The LBT method is similar to the one of LAA and has the same four channel access precedence classes. The eNodeB can broadcast a DRS that contains critical data for synchronization and acquiring the system information. DRS for MulteFire is also 12 OFDM symbols long, but its structure is different when compared to LAA.

b) DYNAMIC DL/UL CONFIGURATION

In order to become accustomed energetically to the DL and UL traffic loads MulteFire adopts a very flexible frame structure. Therefore, the ratio between DL and UL transmission can differ from one frame to the next. The eNodeB will broadcast whether a sub frame is DL or UL through the Common Physical Downlink Control Channel (C-PDCCH) [13].

c) UPLINK OPERATION

MulteFire uses Block Interleaved FDMA (B-IFDMA) as the UL transmission scheme, where the bandwidth is separated into N interlaces, each interlace consists of 10 equally spaced physical resource blocks. MulteFire uses two dissimilar formats for the Physical Uplink Control Channel (PUCCH): Short-PUCCH (MF-sPUCCH) and Extended PUCCH (MFePUCCH). MF-sPUCCH is transmitted by the UE during the last four OFDM symbols of a DL subframe. In other words, the UE is allowed to transmit the MF-sPUCCH immediately on the gap between DL and UL transmission, and, therefore, does not need to perform LBT [13].

LWA

LTE WLAN aggregation (LWA) is a technology defined by the 3GPP.For a user, LWA supports both LTE and Wi-Fi networks and offers increased presentation. LWA simplifies Wi-Fi deployment improves system utilization and reduces network operation and management costs. LWA can be brought into accomplishment in two ways, collocated manner, where the eNB and Wi-Fi AP integrated into the same physical device and Non-collocated manner, where the eNB and the wi-Fi AP are connected via a standardized interface referred to as Xw.LWA becomes another likely option of using LTE in unlicensed spectrum which shows great possibilities for wireless and mobile industry development [14-15].

LWA uses unlicensed band in 5GHz like LTE-U and LTE-LAA for transmission. But unlike previous versions in LWA LTE data payload can be transmitted by both LTE and Wi-Fi, which means that some data is sent by LTE in unlicensed bands and rest is channeled by Wi-Fi in unlicensed bands, the data payload is allocated at the LTE eNB and aggregated at the used device, while Wi-Fi APs are connected to LWA base stations and can be brought into action by LTE core network functions. Unlike LTE-U, LWA needs only software alterations for device and networks with relatively lower cost where as in LTE-U modifications in hardware are required to do so. By using bearer split LWA improves the average as well as the cell edge user perceived throughout across all small cell users in the system when compared to the Rel-12/Rel-13 radio networking schemes .AS LWA uses only Wi-Fi transmissions in unlicensed bands hence fair-access problem is solved. LWA eNB sends Packet Data Convergence Protocol(PDCP) packets on PDCP layer in which some are organized by LTE and rest by Wi-Fi APs after encapsulating them in Wi-Fi frames .Once all the packets are received by Wi-Fi and LTE ,PDCP re-ordering and aggregation are performed to recover the DL data eNB is responsible for LWA activation – deactivation .After LWA has been activated ,the eNB figures the LWA user with a list of WLAN identifiers within which without notifying UE movement becomes possible , Wi-Fi As linked with LWA eNBs can report channel state information (CSI) to LWA eNB . System performance as well as effective traffic scheduling can beoptimized and enhanced by resource management based on traffic and CSI conditions between LTE and Wi-Fi.

Unlike LAA, LWA does not require extra antennas or RF components to transmit in unlicensed bands. This is as it uses the accessible WLAN MAC, PHY and RF. The best thing about LWA is that LWA not only is most excellent implemented on mobile devices with a enormous system solution in which LTE and Wi-Fi modems are unswervingly interconnected, but can also be supported on existing hardware such as WLAN, LTE with just some software manipulation. As LWA uses the WLAN device in order to utilize the unlicensed spectrum, its RF resource sharing, spectrum sharing with non-LWA WLAN and Bluetooth are implemented and optimized within the WLAN device. Unlike LAA, it does not require complex inter-device coexistence interfaces and protocols [18].

IN-DEVICE CO-EXISTENCE

When two radio technologies having neighboring bands operate simultaneously in the same device, the out of band (OOB) radiations of the transmitting radio leak on the band of the receiving radio due to the filters non-idealities. These OOB radiations are commonly referred to as in-device coexistence (IDC) interference, which is marked as the main difficulty for obtaining high wireless capacity [22]. The interference from LTE and Wi-Fi affects Wi-Fi receiver and LTE RF receiver simultaneously. But fortunately, 3GPP Release 11 provides solutions to handle IDC interference on adjacent frequencies or sub-harmonic frequencies for multiple radio transceivers.

We should design the LTE-U in such way that it will be able to support other types of radio modems which are used to detect Wi-Fi network during LTE-U transmission but it does not mean that LTE-U and Wi-Fi having concurrent transmission. The solution to avoid IDC interference in Release 11 is discussed in the following.

First, the UE detects and tries to deal with the interference on its own by TDM model (multiplexing the use of the transceivers in time). If the interference cannot be solved, the

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UE requires assistance from the LTE eNB by sending an indication as a bit-map or Discontinuous Reception (DRX) cycles. If the LTE eNB obtains the indication, the interference problem can be solved by getting rid of the problematic cell or configuring the UE by a DRX configuration, or by implementing a handover of the UE to other carriers.

To support Wi-Fi background scanning during LTE-U operations the solution to IDC interference can be used. Detach and attach procedures for UE to enable Wi-Fi transmission should be used when LTE eNB is unable to enable IDC.

However, IDC interference becomes a serious issue when it comes to LTE-U and Wi-Fi are for concurrent DL transmissions at the same unlicensed band. Fortunately, the mobile devices are equipped with both LTE and Wi-Fi antennas, which can theoretically decode LTE and Wi-Fi transmissions [17]. The solution is to perform LTE and Wi-Fi channel estimation without clear reference symbol and to decode two interfering cross-technology OFDM signals.

CONCLUSION

This paper has discussed the LTE in unlicensed spectrum as the next big milestone in the evolution of LTE. We have mentioned different methods and techniques that are there to implement it and also given a comparison of those techniques. This paper has highlighted the differences and uniqueness of each variant of LTE operating in unlicensed spectrum. LAA is the most unified solution and will be operable worldwide. LTE-U is less regulated and thus expected to be introduced first. MulteFire is most flexible and will be as simple to deploy as Wi-Fi and LWA simplifies Wi-Fi deployment improves system utilization and reduces network operation and management costs. It is expected that LTE in unlicensed bands will become more important and the technology be leveraged for LTE moving into additional unlicensed bands. This can be expected with the ongoing spectrum relocation in the US and worldwide.

REFERENCES

[1]. "Cisco Visual Networking Index: Global Mobile Data TrafficForecastUpdate,2015–2020", 2016, pp.1--39., url: https://www.cisco.com/c/dam/m/en_in/innovation/enterprise/assets/mobile-white-paper-c11-520862.pdf, visited:03/03/19.

[2]. Hyoungju Ji et al., "Overview of Full-Dimension MIMO inLTE-Advanced Pro", IEEE,2016,Volume: 55 , Issue: 2, pp:176 - 184, DOI: 10.1109/MCOM.2016.1500743RP.

[3]. Victor C. M. Leung et al., "OFDMA Architectures, Protocols, and Applications", Hindawi Publishing Corporation, 2009, Volume 2009, pp.1-4,DOI:10.1155/2009/703083.

[4]. Ekta Gujral et al.,"LTE Evolution towards Carrier Aggregation (LTE-advanced)", Journal of Telecommunications System & Management, 2016, Vol 5(1): 124, ISSN: 2167-0919, DOI: 10.4172/2167-0919.1000124.

[5]. Joey Jackson, "CES 2015: Qualcomm takes on Wi-Fi with LTE-U", RCR Wireless News, 2015, url: https://www. Rcrwireless.com/20150106/network-infrastructure/ces-2015-qualcomm-demonst rates-lte-u-tag20.

[6]. A. Babaei et al.,"On the impact of LTE-U on Wi-Fi performance", IEEE PIMRC'14, 2014, pp.1621—1625, DOI: 10.1109/PIMRC.2014.7136427.

[7]. "Qualcomm wants LTE deployed on unlicensed spectrum," 2015, url: https://www.fiercewireless.com/wireless/qualcomm-wants-lte-deployed-unlicensed-spectrum, visited :03.03.19.

 ISSN: 2581-5113

[8]. Mike Dano, "T-Mobile push unlicensed LTE into limelight a s'4.5G' technology for IoT", 2015, url: https://www.fiercewireless.com/wireless/ericsson-t-mobile-push-unlicensed-lte-into-limelight-as-4-5g-technology-for-iot, visited:03.03.19.

[9]. Qualcomm, "LTE in unlicensed spectrum: Harmonious coexistence with Wi-Fi," White Paper, 2012.

[10]. LTE-U Forum, "LTE-U SDL Coexistence Specifications V1.3", 2015, url: https://www.scribd.com/document/334388169/Lte-u-Forum-Lte-u-Sdl-Coexistence-Specifications-v1-3, visited:03/03/19.

[11]. "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 14)," 3rd Generation Partnership Project (3GPP), TS 36.101, 2017, url: https://www.etsi.org/deliver/etsi_ts/136100_136199/136101/14.03.00_60/ts_136101v140300p.pdf, visited:03/03/19.

[12]. "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (Release 14)", 3rd Generation Partnership Project (3GPP), TS 36.211, 2017, url: https://www.etsi.org/deliver/etsi_ts/136200_136299/136211/10.00.00_60/ts_136211v100000p.pdf, visited: 03/03/19.

[13]. Mina Labib et al., "Extending LTE into the Unlicensed Spectrum: Technical Analysis of the Proposed Variants", Research Gate, 2017, DOI: 10.1109/MCOMSTD.2017.1700040.

[14]. Ruckus, "Making sense of convergence: LTE-U, LAA-LTE, and LWA," Whitepaper, 2015, url: https://ruckus-www.s3.amazonaws.com/pdf/wp/wp-making-sense-of-convergence.pdf, visited:03/03/19.

[15]. R. Burbidge, "LTE-WLAN Aggregation (LWA) and LTE WLAN radio level integration with IPsec tunnel (LWIP)", 3GPP RAN2 WG, Mar. 2016.

[16]. 3GPP TR 36.889 V13.0.0, "3rd Generation Partnership Project; Technical specification group radio access network; study on licensed-assisted access to unlicensed spectrum", 2015.

[17]. S. Yun and L. Qiu, "Supporting WiFi and LTE co-existence", IEEE, 2015, pp.810-818, ISSN: 0743-166X, DOI: 10.1109/INFOCOM.2015.7218451.

[18]. Sasha Siroktin et al., "LTE-WLAN Aggregation (LWA): Benefits and Deployment Considerations", White Paper, 2016.

[19]. Durga Malladi, "LTE-U/LAA, MuLTEfire and Wi-Fi; making best use of unlicensed spectrum", Qualcomm Technologies Inc, 2015, url: https://www.qualcomm.com/media/documents/files/making-the-best-use-of-unlicensed-spectrum-presentation.pdf, visited:03/03/19.

[20]. "LTE-U CSAT Procedure TS V1.0", 2015, url: http://www.sharetechnote.com/html/Handbook_LTE_LTEU_LTER.html, visited:03/03/19.

[21]. ZTE, "Frame structure design for LAA considering LBT," 3GPP TSG RAN WG1 Meeting #80, Feb. 2015.

[22]. Z. Jiang and S. Mao, "Opportunistic spectrum sharing in LTE-unlicensed with Lyapunov optimization-based auction", IEEE, 2016, Volume: 66, Issue: 6, pp. 5217-5228, DOI: 10.1109/TVT.2016.2613444.

[23]. Hongyu Sun et al., "Enabling LTE and WiFi Coexisting in 5 GHz for Efficient Spectrum Utilization", Hindawi, 2017, Volume 2017, Article ID 5156164, 17 pages, DOI: 10.1155/2017/5156164.