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Opportunistic Coexistence of LTE and WiFi for Future 5G System: Experimental Performance Evaluation and Analysis

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ABSTRACT To alleviate the problem of scarce spectrum resources and meet the ever-increasing of mobile broadband data traffic demands, Licensed Assisted Access (LAA)-Long Term Evolution (LTE), operating in the unlicensed spectrum, is a promising solution. Considering that the unlicensed spectrum is shared by a few incumbent systems, such as IEEE 802.11 (i.e., WiFi), one main target is to guarantee the friendly and harmonious coexistence of LTE with other wireless systems in the unlicensed spectrum. Both listen-before-talk (LBT) and duty cycle methods are regarded as effective ways to solve the coexistence problem in academia and industry so far. Although there are a large number of theoretical researches on LTE in unlicensed spectrum (LTE-U), field trail results are still lacking. In this paper, an experimental testing platform is deployed to model the realistic environment. This paper focuses on three aspects. First, a typical indoor field trial scenario in 5.8 GHz unlicensed bands is deployed, and the performance of LTE-U and WiFi, including coverage and capacity, is evaluated. Specifically, a methodology to determine the proper clear channel assessment energy detection (CCA-ED) threshold for LTE-U is proposed to implement the friendly coexistence between LTE-U and WiFi systems. Second, supplementary downlink (SDL) and Cell ON/OFF mechanisms are investigated to verify the fair coexistence between LAA and WiFi in the unlicensed spectrum. Third, the Enhanced Cell ON/OFF scheme, which introduces Clear to Send (CTS)-to-Self (CTS2S) message, is discussed and evaluated. Based on the built testbed, we obtain threefold conclusions. First of all, introducing LTE into unlicensed spectrums can greatly improve the spectrum efficiency and optimize wireless resources. Furthermore, test results and analyses show that a proper CCA-ED threshold is necessary for coexisting friendly and fairly among different systems, and experiments are also provided to validate the feasibility of the suggested method in various scenarios. Second, experimental results show that SDL mechanism guarantees relatively friendly and harmonious coexistence between LAA and WiFi only in the sparse scenario, while basic Cell ON/OFF mechanism is more effective to ensure coexistence between LAA and WiFi than the SDL. Finally, with the introduction of CTS2S message, the Enhanced Cell ON/OFF scheme is able to achieve more peaceful coexistence between LTE and WiFi users employed in the same bands compared with the Basic Cell ON/OFF scheme.

INDEX TERMS Licensed Assisted Access (LAA)-Long Term Evolution (LTE), LTE in unlicensed spectrum (LTE-U), field trial, clear channel assessment energy detection (CCA-ED) threshold, supplementary downlink (SDL), Cell ON/OFF, CTS-to-Self (CTS2S).

I. INTRODUCTION

With the emergence of new wireless devices and applications, the demand for radio spectrum resources has dramatically increased over last decades. According to the Cisco report [1] global mobile data traffic will increase nearly eightfold between 2015 and 2020. However, licensed

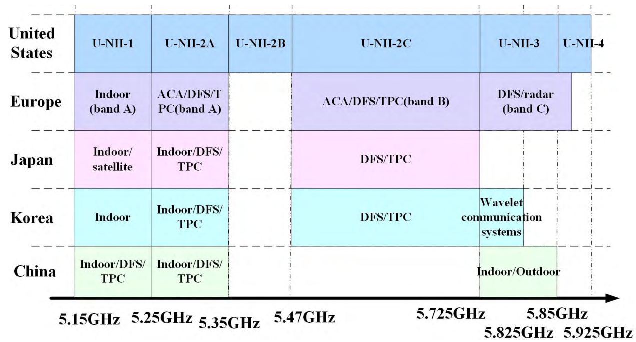


FIGURE 1. 5 GHz Unlicensed National Information Infrastructure (U-NII) bands in different countries and areas.

spectrum resources have been becoming increasingly scarce, which easily results in network congestion of the indoor and public hotspots and impacts the performance of Long Term Evolution (LTE) network. Thus, 3rd Generation Partnership Project (3GPP) decided to embark in the specification of Licensed Assisted Access (LAA) to provide operators and consumers with an additional mechanism to utilize unlicensed spectrums [2]. Compared with a licensed band, rich spectrum resources, such as the 500 MHz bandwidth are available in the 5 GHz band [3]. Therefore, an efficient way to tackle the problem of spectrum scarcity is to extend LTE system to the unlicensed spectrum [4].

Fig. 1 shows allocated bands for 5 GHz Unlicensed National Information Infrastructure (U-NII) deployment in different countries [5]. In the United States, the spectrum 5.15–5.35 GHz (U-NII-1, U-NII-2A) and 5.47–5.85 GHz (U-NII-2C, U-NII-3) are used for unlicensed wireless access, whereas 5.35–5.47 GHz is being considered to extend unlicensed use. In Europe, Japan and Korea, 5.15–5.35 GHz and 5.47–5.725 GHz are unlicensed for indoor wireless access systems. In Europe, 5.725–5.875 GHz is used for radar communication and now it is considered for unlicensed wireless access systems. In China, 5.15–5.35 GHz unlicensed spectrum is used for the indoor environment and 5.725–5.85 GHz can be used for both indoor and outdoor unlicensed systems [5].

The main incumbent system in the 5 GHz band is the WiFi [5]–[7], which is designed in the premise of trading off the performance for low cost and simple implementation for spectrum sharing. The spectrum efficiency of LTE is generally larger than that of current WiFi systems complying with IEEE 802.11 standard [8], [9]. From perspective of users, this means an enhanced experience and higher data rates with high reliability [10].

The baseline to allow LTE to fairly coexist with WiFi is that a higher throughput can be achieved by coexisting with LTE devices instead of an 802.11station [11]. At present, there have been several companies and research institutions deploying the LTE technology in the unlicensed band to improve LTE indoor transmission [12]. Being a groundbreaking technology to enable the high data rate, the most critical challenge is to guarantee the performance of incumbent systems operating in the unlicensed spectrum. This is the basic requirement of LAA design [11], [12]. Generally, the coexistence mechanism can be divided into two categories, namely, collaborative and non-collaborative. The typical collaborative access is the listen-before-talk (LBT) scheme where the LTE equipment should periodically check (listen) the presence of other occupants in the channel before transmitting (talk) [13]. Contrarily, the non-collaborative access is to define a specific Time Division Multiplex (TDM) pattern in which LAA secondary cells (SCells) switch on or off periodically [14]. This scheme is also called the duty cycle method. LBT is mandatory in many countries and areas, such as Europe, Japan and India [15]. To provide a single global framework, 3GPP defines LAA as a part of Release 13 [12]. However, Rel-10/11/12-based LTE in the unlicensed spectrum (LTE-U) is proposed to meet all applicable regulatory requirements for 5 GHz unlicensed bands in regions where LBT is optional, such as US, Korea and China [15].

After the successful study, 3GPP specified LAA for downlink operation in Release 13 and is currently working on specifying LAA for uplink operation in Release 14. 3GPP has been working on the conformance and compliance tests for LAA and test specifications were approved for Release 13 [16]. In addition, 3GPP Radio Access Network (RAN) has now tasked RAN4 to develop additional tests defining multi-node testing guidelines which are due to be finalized in June 2017. The multi-node testing will provide additional verification of coexistence at a system level [17].

The main operation modes of LAA are Dual Connection (DC) and Standalone technology. The primary idea of LAA is to use the carrier aggregation (CA) to aggregate a primary cell (Pcell) and one or more secondary cells. Carrier aggregation can be employed to integrate the unlicensed spectrum into the overall LTE system. Unlicensed carriers can be operated as Scells to offload some best effort traffic at the assistance of a Pcell in the existing licensed spectrum which is dedicated to serve the delay-sensitive traffic and provide seamless coverage [18]. In September 2014, LAA was listed as an LTE enhanced communication technology of the next generation in Release 13 [19].

Some coexistence schemes have been proposed and their performance has been widely studied. [5], [9], and [15] offer a comprehensive overview of LTE-U technology from the perspective of both operators and users, the impact of unlicensed spectrum operation on the current LTE systems and the possible enhancements on the future 5G networks is also discussed. Different coexistence schemes can be classified into LBT based mechanisms [13], [14], [20]–[24] and duty cycle based approaches [25]–[28]. For the LBT-based mechanisms, the size of the adaptive contention windows is suggested to achieve the access fairness [13]. Xiao and Zheng [14] put forward the improved LBT mechanisms after introducing a new time-frequency structure. A cross-layer proportional fairness (PF)-based framework to jointly optimize the protocol parameters of the medium access control layer and physical layer of an LTE-U network is proposed in [20]. To minimize the collision probability of WiFi users and satisfy the Quality of Service (QoS) requirements of LTE devices, the backoff window size is adaptively adjusted in [21]. In [22], a Clear to Send (CTS) message has been utilized in LBT scheme to achieve better system performance. Nevertheless, research on how to use the CTS message in the duty cycle method is rarely given. By jointly considering the total system throughput and the fairness between LTE-U and WLAN, an appropriate idle period is allocated for WLAN [23]. A matching theory framework is proposed to solve the unlicensed resource allocation problem in [24]. Different from the LBT, which is mandatory in some regions of world, duty cycle method is deemed to be more compatible with the current LTE standards. In [25], the total channel airtime is divided into two orthogonal intervals and LAA maximizes the access time without degrading WiFi throughput. A Multi-Armed Bandit (MAB) based dynamic duty cycle selection method is proposed in [26] for configuration of transmission gaps ensuring better coexistence for two systems. Additionally, a simple coexistence scheme that reuses the concept of almost blank subframes in LTE system is proposed to improve WiFi throughput per user up to 50 times in the studied scenarios [27]. Work in [28] considers joint allocation of the licensed and unlicensed spectrums and guarantees the fair resource sharing between WiFi and LTE systems.

Although large numbers of coexistence schemes have been proposed, comprehensive performance studies are very limited, especially the literature lacks experimental studies with real equipment in realistic scenarios. The existing works are mainly based on the simulation platforms [27], [29]–[33]. The LTE muting scheme is simulated in [27] in which the LTE eNodeBs (eNBs) follow a predetermined muting pattern. Carrier-sensing adaptive transmission (CSAT) has been proposed to utilize the spectrum sources rationally with a TDM pattern, and its efficiency is verified and evaluated using experimental data in [29]. Galanopoulos *et al.* [30] implement LBT and discontinuous transmission (DTX) for efficient carrier selection procedure based on an LTE simulation platform and some initial results are obtained. The experimental verification is done in [31] with open source where LTE and WiFi are implemented on real equipment without taking into account any coexistence mechanism. Based on the simulation platform of different network densities and deployment scenarios, [32] presents a comprehensive study on different coexistence mechanisms and concludes that if LTE is a good neighbor or not depends on the effective node density. In [33] the indoor field trial results for the coexistence of LTE-U and WiFi on 5GHz band by using cell on/off mechanism are evaluated.

To the best of our knowledge, the majority of existing studies are based on simulations with only a few exceptions rather than the actual measurements. Aiming to close the gap of coexistence evaluation obtained from real field trails, we establish an experimental testing platform to study the performance of coexistence between LAA and WiFi systems in the unlicensed spectrum, which can adequately demonstrate the experimental verification of LAA and WiFi coexistence on real equipment in a controlled wireless environment. In our previous work [34], supplementary downlink (SDL) and Basic Cell ON/OFF mechanism are investigated to verify the fair coexistence between LAA and WiFi in the unlicensed spectrum. This paper extends our previous work and its main contributions are summarized as follows.

- An experimental platform for LTE-WiFi coexistence in the 5 GHz band is constructed from the view point of system capacity and coverage.
- Based on the experimental platform, SDL and Basic Cell ON/OFF mechanisms are investigated to verify the fair coexistence between LAA and WiFi in the unlicensed spectrum with different experimental tests.
- At the same time, we discuss the influence of CTS message on enabling the friendly coexistence of LTE-U and WiFi. The actual test results demonstrate that with the introduction of CTS-to-Self (CTS2S) message, the Enhanced Cell ON/OFF scheme can achieve peaceful coexistence between LTE and WiFi systems in the same band.
- A methodology to determine the Clear Channel Assessment energy detection (CCA-ED) threshold for LTE-U is proposed to ensure the friendly coexistence between LTE-U and WiFi with LBT in various deployments.

Finally, fourfold conclusions are made from our field trials as follows.

- Utilization of LTE in unlicensed bands improves spectrum efficiency and significantly optimizes wireless resources. More specifically, without any coexistence mechanisms, WiFi performance drops obviously while LAA performance is less impacted.
- A proper CCA-ED threshold is necessary for friendly and fair coexistence and efficiency of the proposed method is validated in various scenarios.
- Only in the sparse scenario, LAA SDL has a relatively friendly coexistence with WiFi, but severely impacts the WiFi performance in dense scenarios. In terms of Basic Cell ON/OFF mechanism, it is obvious that the performance of LAA and WiFi coexistence with Basic Cell ON/OFF is superior to that with SDL.
- With the introduction of CTS2S message, the Enhanced Cell ON/OFF scheme achieves more friendly coexistence between LTE and WiFi users deployed in the same band compared to the Basic Cell ON/OFF scheme.

The paper is organized as follows. Section II presents an overview of several related concepts and mechanisms in WiFi and LTE-U. The field test campaign, including the evaluation environment, devices and evaluation parameters are described in Section III. The test results and performance analyses are presented and discussed in Section IV. Finally, Section V concludes this paper.

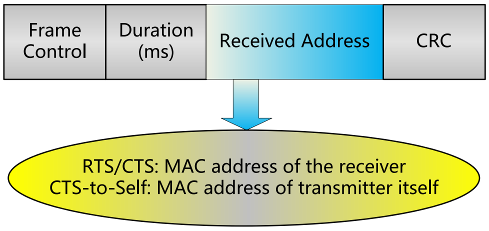


FIGURE 2. Difference between RTS/CTS and CTS-to-Self in the frame structure.

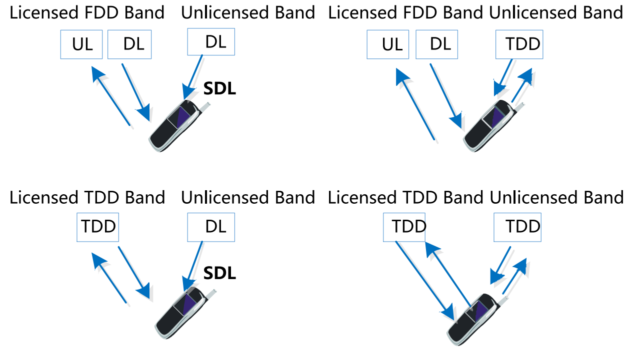


FIGURE 3. LTE Carrier Aggregation with unlicensed bands.

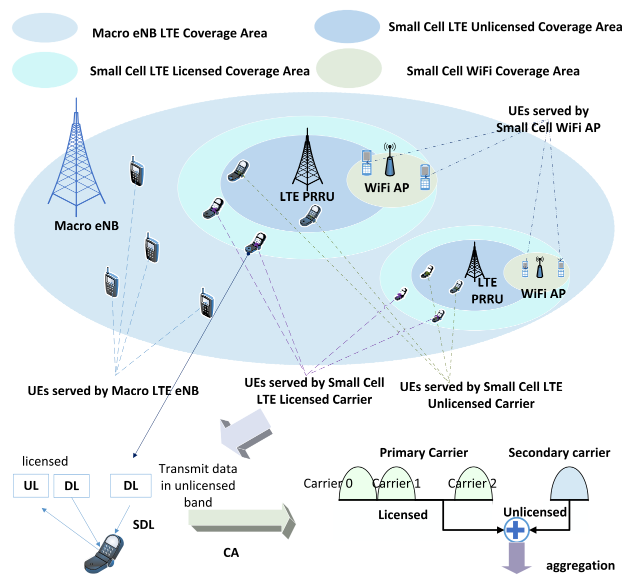


FIGURE 4. An example of LTE-U deployment in a heterogeneous network.

II. CONCEPT OVERVIEW

In this section, we briefly outline preliminaries necessary for better understanding of this work.

A. RTS/CTS PROTOCOL

IEEE 802.11 standard defines the Request-to- Send/Clear-to-Send (RTS/CTS) protocol to provide more reliability for transmission of large data packets. In the RTS/CTS scheme, the source device listens to the channel for a period and if no ongoing transmission is observed, the device sends a RTS message to the destination. The destination responds with a CTS signal and then data transmission occurs. During the exchange of RTS and CTS between the source and destination devices, the channel is reserved for the entire duration to avoid the interference of adjacent nodes.

Similarly, CTS-to-Self (CTS2S) is a protection mechanism originally proposed in 802.11g to prevent disturbances from 802.11b sites [35]. As depicted in Fig. 2, the main difference between the RTS2S and the RTS/CTS in the frame structure is that the Receiver Address field of CTS2S is filled with the transmitter's own MAC address rather than the receiver's address. The duration field of the CTS2S packet implies the period of the following traffic frame. Therefore, transmitting CTS2S before data sequences reserves the channel for the source device itself during the transmission [36]. Another benefit of using CTS2S over RTS/CTS is higher system throughput due to less signaling [37].

B. LTE CARRIER AGGREGATION AND SYSTEM NETWORKS

LAA has potential to offer better coverage and higher spectral efficiency in comparison with WiFi, while allowing seamless data flow across licensed and unlicensed bands in a single network. The main concept of LAA is to use carrier aggregation framework across licensed and unlicensed bands.

As illustrated in Fig. 3, LTE-U is an extension of the LTE carrier aggregation protocol with four types of CA modes supported by 3GPP R12. Among them, the mode of frequency division duplex (FDD) with SDL is popular. Here, both downlink (DL) and uplink (UL) transmissions are performed in the licensed band whereas only DL transmission is permitted in the unlicensed band. SDL has been considered with a high priority in 3GPP standardization under current discussion. The unlicensed spectrum is only exploited to transmit downlink data in SDL mode, due to high downlink traffic load in comparison with uplink traffic. TDD mode uses unlicensed bands for both downlink and uplink transmissions and targets scenarios with high uplink rates such as file transfer protocol (FTP) or voice and video chatting. It allocates resources reasonably and flexibly, but the implementing complexity is high.

Fig. 4 depicts an example of the LTE-U deployment scenario in heterogeneous network comprising of a Macro Cell, LTE-U capable small cells, WiFi APs and users served by different cells and LTE CA. In our work, users in the licensed spectrum utilize either FDD or TDD mode on the UL and DL. The unlicensed spectrum in the SDL mode is used to carry data on DL, while the uplink transmission and control channels remain in primary carriers in the licensed spectrum.

C. CLEAR CHANNEL ASSESSMENT (CCA)

WiFi systems use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for channel access. In WiFi networks, each potential transmitter performs one or more CCA checks to determine if the channel is busy. Each CCA slot is of $9\mu s$ duration with two types of CCA techniques defined as follows.

1) CARRIER SENSE BASED CCA (CCA-CS)

A Preamble based channel sensing is used to detect other WiFi signals. Once the header in the signal preamble is successfully decoded other stations back off until the end of concurrent transmission. When the received power is above −82 dBm, Media Access Control (MAC) layer would confirm the channel busy and the preamble is decoded successfully in 20 MHz band.

2) ENERGY DETECTION BASED CCA (CCA-ED)

Using this scheme, the transmitter declares the operating channel as busy if the total received power is larger than −62 dBm in a 20 MHz signal band. The station does not need to know the signal's preamble structure and the packet format. The energy detection threshold is 20 dB higher in comparison with that of WiFi preamble detection. When the medium is busy, the station would sense the channel to determine whether the energy still exists. In principle, CCA-CS is 10–20dB more reliable than CCA-ED [36].

However, in order to improve the LTE-U throughput and coexist with WiFi or other access systems, LTE-U needs to adopt LBT mechanism with CCA before data transmission. In addition, CCA threshold should be carefully configured to ensure a proper sensitivity range to detect the existence of ongoing transmissions. Actually, if the CCA threshold is too low, the transmitter sensitivity is increased which leads to loss of transmit opportunities and lower spectrum efficiency. On the contrary, a higher threshold increases transmission opportunities, but deprives other systems of their transmit opportunities and coexistence is not guaranteed.

D. CELL ON/OFF MECHANISM

The basic idea of Cell ON/OFF mechanism is to define a TDM communication (ON and OFF) cycle with a fraction used by the LAA small cell. The rest of the cycle is utilized by other systems. The cyclic ON/OFF ratio can be adaptively adjusted based on the sensed channel activities of the other systems during the off period [38]. In essence, the ratio of ON and OFF-state can be either constant or adaptive.

The Cell ON/OFF scheme discussed in this section is one of the duty cycle methods. During its operation, the PCell remains connected all the time, while SCells switch on or off periodically. It is worth mentioning that almost all the coexistence methods assume WiFi nodes are able to sense LTE system when they operate in the same band. As stated in [39], the WiFi received signal strength indicators (RSSIs) are above the CCA-ED threshold (−62 dBm). It means that these methods assume WiFi equipment will take CSMA/CA when it coexists with LTE systems. However, if a WiFi node fails to detect LTE signal for the observed energy below the threshold, these methods may no longer be applicable. The proposed Cell ON/OFF scheme in this paper aims at those scenarios where detected power of LTE signals is below the

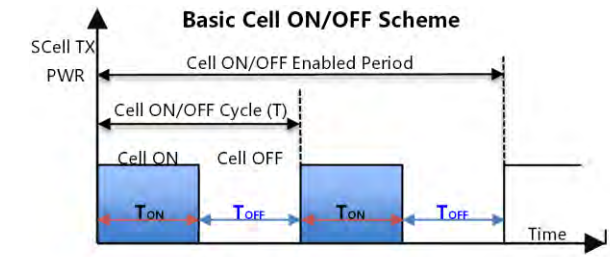


FIGURE 5. Basic Cell ON/OFF mechanism.

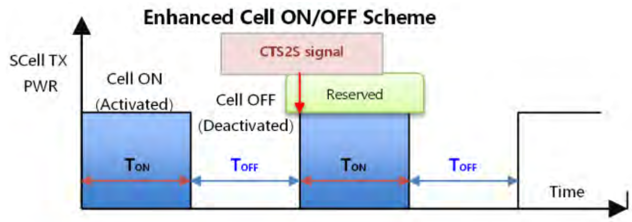


FIGURE 6. Enhanced Cell ON/OFF mechanism.

inter-Radio Access Technology (RAT) threshold. There are two kinds of Cell ON/OFF schemes so far, we will elaborate them in the following subsections.

1) BASIC CELL ON/OFF MECHANISM

Fig. 5 illustrates the Basic Cell ON/OFF mechanism in accordance with a TDM communication pattern. Whenever there is a substantial amount of traffic as well as an unavailable clean channel, the LTE-U node will invoke the Cell ON/OFF mechanism to mitigate the potential impact on coexistence. The SCell operation is cycled between Cell ON (T_{ON}) and Cell OFF (T_{OFF}) periods within a given cycle T. During the activated period of T_{ON}, LTE transmits data on the unlicensed band and blocks the transmission of WiFi systems. During the deactivated period T_{OFF}, LTE SCell shuts down its transmission to yield the channel sources to WiFi.

WiFi nodes may not be aware of LTE activity in some actual scenarios. Although LTE equipment takes the Basic Cell ON/OFF approach to make a concession to WiFi during the OFF-state, WiFi causes interference to LTE in the ON-state period. Since WiFi can not identify the structure of signals from non-IEEE systems, when the CCA-ED measurement is below the predefined inter-RAT threshold, it regards the ongoing LTE messages as strong interference signals. In this case, the CSMA/CA is not able to avoid collisions between two systems. To address this shortcoming, we propose the Enhanced Cell ON/OFF mechanism.

2) ENHANCED CELL ON/OFF SCHEME

As shown in Fig. 6, a CTS2S message can be inserted to reserve the channel resources for LTE transmission during the next ON-state period [36], [37], [40]. The duration of upcoming ON-state is included in the CTS2S message. With the introduction of CTS2S message, two systems can perfectly coexist. Fig. 7 illustrates the function of CTS2S message.

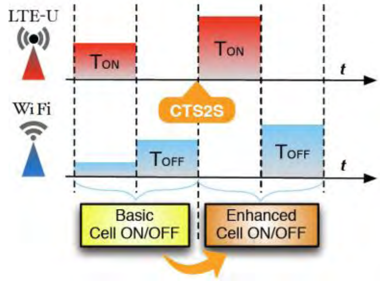


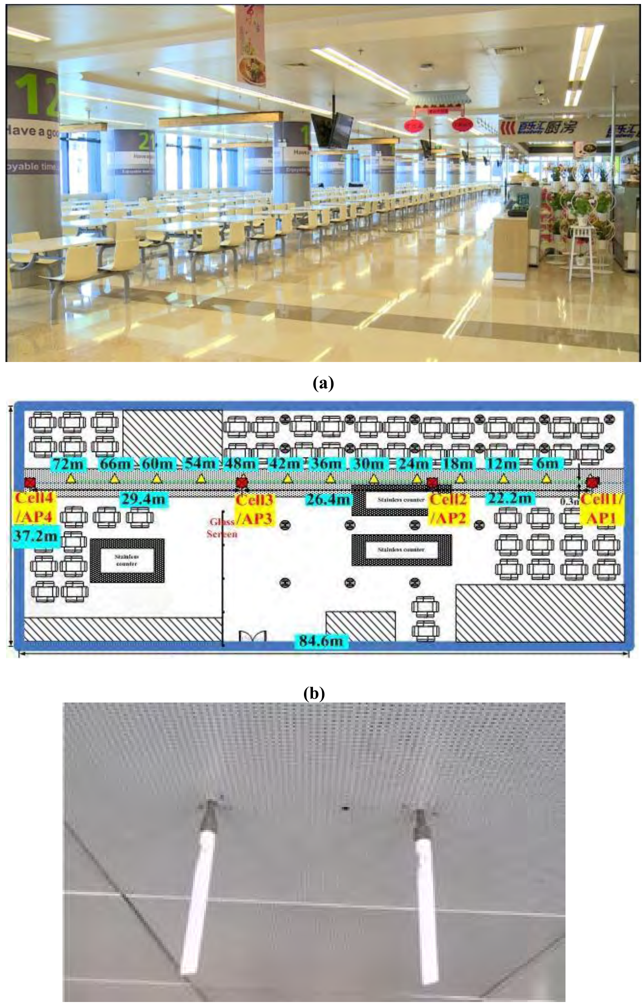
FIGURE 7. Function of CTS2S message.

As we can see in Fig. 7, the Basic Cell ON/OFF mechanism ensures LTE-U to perform the periodical ON/OFF pattern. However, if WiFi can not identify the ongoing LTE signals below the inter-RAT threshold, corresponding backoff mechanism can not be triggered. Thus, signals transmitted by WiFi have rather low Signal-to-Interference-plus-Noise-Ratio (SINR) during T_{ON}, since LTE signals are observed as interference. Nevertheless, after the introduction of CTS2S message in the structure of LTE-U signals, the above problem can be resolved by preventing the transmission of adjacent WiFi nodes. As shown in Fig. 7, receiving and decoding the CTS2S, the neighboring WiFi system will back off until the LTE user completes its transmission during the reserved T_{ON}. As a result, possible interference between these two systems is avoided and both LTE-U and WiFi improve their achievable throughputs.

Actually, utilizing a CTS2S message enables peaceful coexistence between the WiFi and other wireless communication systems is not a new idea. [37] proposed a system architecture to realize the coexistence between the WiFi and ZigBee by using a virtual AP. About the implementation details to introduce CTS2S in an LTE frame can be found in [36] and [40]. In this paper, a similar method is utilized to implement the Enhanced Cell ON/OFF scheme in the testbed devices.

III. EXPERIMENTAL SETUP

Recently, there has been a number of works on LTE and WiFi coexistence in the unlicensed band. Nevertheless, experimental studies are lack. In this section, to practically study this problem we first establish a field trial platform. Our study focuses on the following three points. Firstly, although some works theoretically addressed the methods to adjust the detection threshold, practical aspects of this problem are still pending. To the authors' best knowledge, detailed experimental evaluation on the influence of the threshold has not been presented until now. Furthermore, a method to determine the threshold is proposed and confirmed through experimental methodology. Secondly, an experimental testing platform is built to verify the efficiency of SDL and Basic Cell ON/OFF scheme. Thirdly, practical tests are performed to investigate the efficacy of the Basic and Enhanced Cell ON/OFF schemes. Specifically, the influence of CTS mechanism on the coexistence of LTE-U and WiFi is investigated. The experimental results demonstrate that with the introduction of CTS-to-Self (CTS2S) message, the Enhanced Cell ON/OFF scheme is able to achieve peaceful coexistence between LTE and WiFi users in the same bands.



(a)

(b)

(c)

FIGURE 8. Field trial environment. (a) View of field trial environment. (b) Field trial environment map. (c) Antennas in 5 GHz.

A. EVALUATION ENVIRONMENT AND DEVICES

In this section, we describe the experiment platform that is used to evaluate the performance of LAA systems. Our field test is performed in an indoor environment in the canteen of Huawei company, as shown in Figs. 8(a) and (b), where the 5 GHz band antennas are fixed without obstacles on the ceiling vertically as shown in Fig. 8(c). 14 test points are distributed under station sites from 0 to 78 m, and the distance between adjacent points is 6 m. However, due to the building's limitation, the distribution of WiFi Access Points (APs) and LTE Pico Radio Remote Units (PRRUs) could not be completely unified. Thus, some obstacles such as pillars, cashier

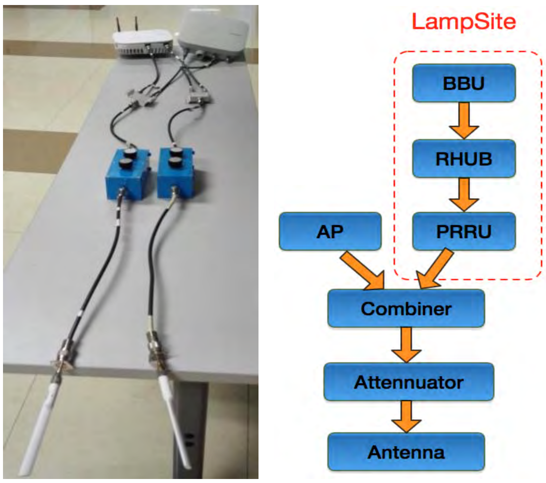


FIGURE 9. Schematic of Base Station.

(a) (b)

FIGURE 10. LAA TUE and WiFi STA. (a) LAA TUE. (b) WiFi STA.

desks and glass screens are present next to APs/RRUs and test points.

The related instruments and equipment adopted in our experimental tests are shown in Figs. 9 and 10.

1) LAA PLATFORM

The Base Station (BS) and User Equipment (UE) in LAA system are LampSite/PRRU and Huawei Test User Equipment (TUE) respectively, and they are shown in Figs. 10(a) and (b). LampSite mainly utilizes the connection way in that Building Base Band Unit (BBU) connects to a radio HUB (RHUB), followed by PRRU. About LampSite/PRRU, we make the following explanations:

a) PRRU supports LTE / WCDMA system.

b) PRRU and RHUB is connected with Unshielded Twisted Pair (UTP) cable to supply power.

c) Optical fiber is used for the connection between RHUB and BBU.

The TUE is developed based on Software Development Platform (SDP) and supports LTE and quick customization with services such as data collection and video surveillance. The LAA system is based on standard LTE-A (Release 10) PHY implementation.

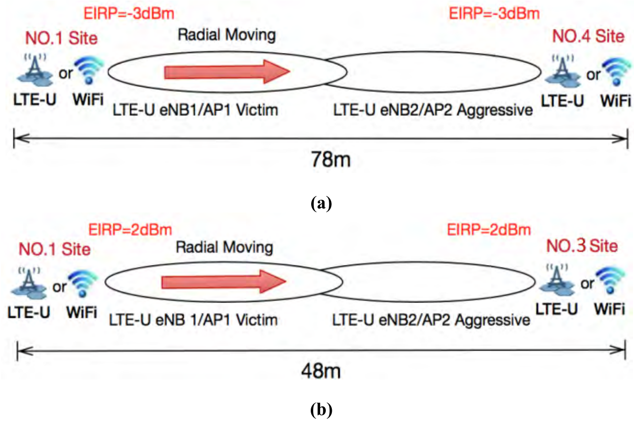


FIGURE 11. The definition of deployment scenarios. (a) Site layout in the sparse scenario. (b) Site layout in the dense scenario.

2) WIFI PLATFORM

The 251DT WiFi AP and Thinkpad X230 are used as Access Points and STAs, respectively, for the WiFi testbed. The 251DT WiFi AP, supporting 802.11n in 5 GHz band represents the typical commercial WiFi node.

B. EVALUATION PARAMETERS

Due to the limitations of transmission power in unlicensed bands, the LTE-U technology is more suitable for a small area. Note that the energy detection threshold of WiFi is −82 dBm for intra-system and −62 dBm for inter-RAT respectively. Consequently, to better evaluate current coexistence technologies in different scenarios, we define two deployments as follows which are illustrated in Fig. 11.

1) INDOOR SPARSE SCENARIO

LAA eNB or WiFi AP is placed in No. 1 and No. 4 Site, respectively. and the Effective Isotropic Radiated Power (EIRP) of LAA eNB and WiFi AP are both −3 dBm and the inter site distance (ISD) is set to 78 m. For this case, the first WiFi node is out of the sensing range of the second WiFi node and the LTE eNB is at the same location. In other words, the RSSI from the Site 1 WiFi AP on the test terminal devices is lower than −82 dBm between two sites.

2) INDOOR DENSE SCENARIO

LAA eNB or WiFi AP is placed in NO. 1 and NO. 3 Site respectively and the EIRP of LAA eNB and WiFi AP are both 2 dBm and the ISD is set to 48 m. In this scenario, the first WiFi node can sense the second WiFi node when there is an ongoing data whereas it can not be aware of the LTE eNB at the same location. Namely, the RSSI from the Site1 WiFi AP on the test terminal devices is above −82 dBm and no more than −62 dBm between two sites.

In our test environment, multipath propagation is caused by the reflection and refraction of surrounding objects. There has always been a line of sight (LOS) between all the nodes in the test. For every test point the measurement value would be

TABLE 1. System parameters.

Items		LTE-U eNB	WiFi AP
Protocol Version		3GPP Rel.10	802.11n
Scenario		Indoor Dense Deployment	
Frequency		5.745GHz @ Unlicensed Spectrum 2.630GHz @ Licensed Spectrum	
Bandwidth		20MHz	
Antennas	Configuration	Co-antenna, 2T2R, Omni-directional	
	Height	3.1m	
	Gain	3dBi	
Traffic Type		DL traffic only, UDP full buffer	
Base Station		LampSite	251DT WiFi AP
Terminal		Huawei TUE	ThinkPad X230

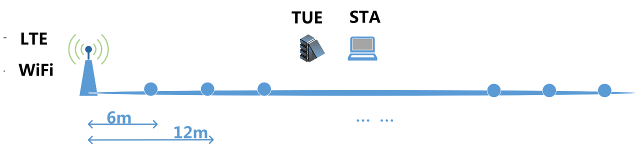


FIGURE 12. Coverage trial of WiFi and LTE-U.

recorded for at least 60 seconds and be averaged to obtain the final peak throughput. Besides, all of the associated parameters are predefined by the LTE eNB, including duty cycle, cycle time, and the transmission power, etc. In our study, to assess the impact of CTS2S on system performance, we have assigned certain parameters to simplify the system model. The ON/OFF ratio is 1:1 and both the ON-state and OFF-state duration are 100 ms which is the default value of the beacon interval in WiFi systems. Other system parameters are listed in Table 1.

IV. MEASUREMENT RESULTS AND ANALYSES

In this part, threefold experiment results are presented and analyzed in the sparse and dense scenarios separately. Firstly, coverage performance and the capacity of multi-users in a single cell and multiple cells of LTE-U and WiFi systems are evaluated. In addition, the mechanism to determine CCA-ED threshold is proposed and experiments are conducted to prove the feasibility of the proposed method. Secondly, the coexistence scheme of SDL and Basic Cell ON/OFF between LAA and WiFi in the unlicensed spectrum is verified. Our results show that in general Basic Cell ON/OFF outperforms SDL in similar scenarios. Thirdly, the Enhanced Cell ON/OFF scheme is tested to demonstrate that with the introduction of CTS2S message, peaceful coexistence between LTE and WiFi users in the same bands can be achieved.

A. COVERAGE TRIAL

The coverage trial is firstly considered and is shown in Fig. 12. During the test, the test terminal moves from left to right and RRU is switched on when LTE-U transmits data while the WiFi AP is off. On the contrary, when WiFi APs work, the RRU is turned off. Experimental results are plotted in Fig. 13. Due to the space constraint, the EIRP is firstly set to 12 dBm corresponding to the distance between

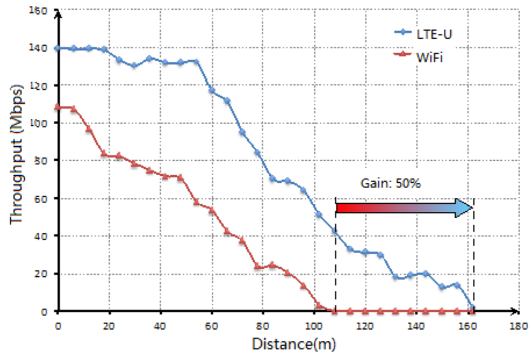


FIGURE 13. Coverage results of WiFi and LTE-U.

the RRU/AP and the test terminal from 0 to 36 m. And then decreasing the EIRP to 0 dBm to measure the distance from 36 m to 90 m. Finally, −18 dBm is set from 90 m to 162 m. From Fig. 13, we can make three observations. Firstly, the maximum throughput of LTE-U and WiFi are 139 Mbps and 109 Mbps, respectively. When EIRP is in the maximum value of 12 dBm, we can observe that LTE-U can still obtain the throughput as high as 83.97 Mbps as compared with that of a WiFi system of 23.844 Mbps even in the test line's farthest point of 78 m. Secondly, the coverage of LTE-U is larger than that of WiFi. Actually, for a single cell, coverage of LTE-U is 1.5 times larger than that of WiFi. Thirdly, when the distance between the base station and the terminal is 114 m, the throughput of WiFi has been reduced to zero while the LTE throughput still has 33.171 Mbps. Moreover, at the distance of 60 m, the throughput of WiFi is reduced by half while LTE-U only is reduced about 16%. Thus, we can conclude that as the distance reduces, the rate in WiFi throughput decreases faster than that in LTE system.

The main reason that LTE has better coverage performance is that LTE has better mechanisms to assign bandwidth and the spectrum. Moreover, centralized controlling and advanced capacity-approaching techniques, such as adaptive coding and modulation, interference management, and dynamic resource optimization can be utilized more efficiently. However, it should be noted that LTE outperforms WiFi at the original point is only due to its better design in the MAC layer.

B. CAPACITY TRIAL

To study the capacity performance of LTE-U and WiFi systems in the unlicensed spectrums, we perform experiments in the single cell and multiple cells respectively.

1) CAPACITY TRIAL OF MULTIPLE USERS IN THE SINGLE CELL

For capacity of multiple users in a single cell experiment, as shown in Fig. 14, EIRP is 2 dBm for both LTE-U and WiFi. In 3 m, 12 m, 21 m and 30 m, we place terminals separately and adjust the transmission power to be the maximum. These terminals access to a common cell to implement a

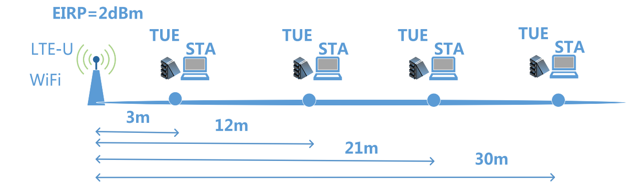


FIGURE 14. Capacity trial of multiple users in the single cell of WiFi and LTE-U.

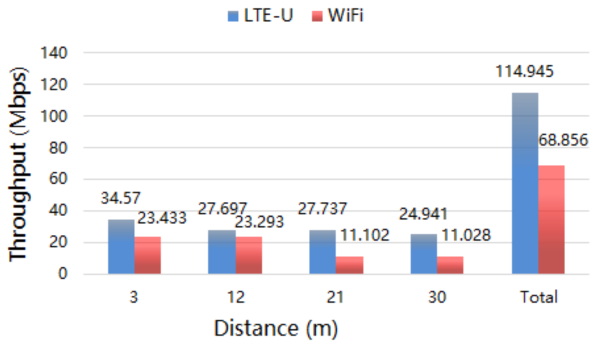


FIGURE 15. Single cell capacity comparison between WiFi and LTE-U.

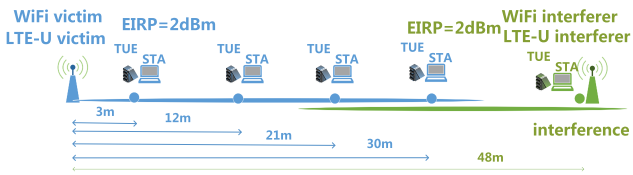


FIGURE 16. Capacity trial for multiple users in multiple cells of WiFi and LTE-U.

multi-user test. The sum throughput of 4 terminals is counted to be the system capacity. We can observe from Fig. 15 that the capacity of LTE-U could reach to 114.945 Mbps while the capacity of WiFi is only 68.856 Mbps. Therefore, the capacity of LTE-U is improved about 67% by WiFi.

2) CAPACITY TRIAL FOR MULTIPLE USERS IN MULTIPLE CELLS

To investigate the multi-cell capacity, as shown in Fig. 16, several WiFi APs coexist in the TDD mode and CSMA/CA mechanism is utilized. Nevertheless, LTE is in the space division multiplexing mode, interference exists between two cells and no any backoff mechanism is used in our field trial.

In our test, the distance between two base stations are 48 m and EIRP is 2 dBm separately for the victim RRU and the interferer RRU. Laptops/TUEs under the WiFi interferer/LTE-U interferer transmits data. We mainly focus on 4 users in the WiFi victim/LTE-U victim cell. From the result shown in Fig. 17 we can see that the capacity of LTE-U could reach to 41.493 Mbps, but the capacity of WiFi is only 23.685 Mbps. Consequently, the capacity of the LTE-U in the multi-cell scenario is about 75% improvement by WiFi. The reason why LTE-U capacity performance is better than WiFi

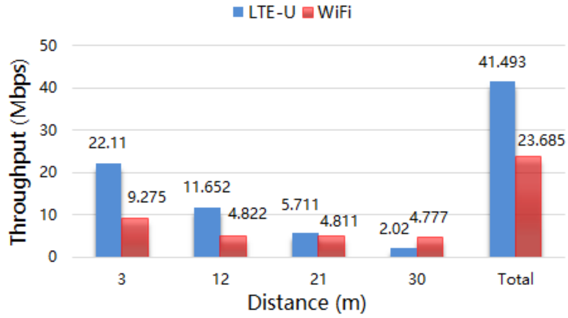


FIGURE 17. Multi-cell capacity comparison between WiFi and LTE-U.

can be explained as follows. Firstly, LTE has better physical design. Secondly, in such a multi-cell scenario, Turbo coding may be used in LTE which is closer to the Shannon limit. Thirdly, compared to WiFi, the better scheduling algorithm in LTE systems would also bring gains.

C. THRESHOLD TRIAL

1) IN THE HIGH-DENSE SCENARIO

In some ultra-dense scenes such as residential areas, offices and stadiums, the traffic demand is so high that the heterogeneous network is required to coexist friendly. As we have known that WiFi systems which use CSMA/CA could hear data transmission in different systems to avoid collisions. Similarly, LTE-U systems should also detect data transmission of WiFi or other systems and do not cause interference in return and thus motivating us to initiate the third test, namely, how to determine the detection threshold for LTE-U to realize the friendly coexistence with WiFi. Since the incumbent LTE system could not detect the threshold of WiFi, if an LTE-U user wants to coexist with other systems friendly in a scene in which different systems could 'hear' each other, what we need firstly is to build a high-dense scenario and find a reasonable CCA detection threshold. Our field trial goal is to determine a reasonable detection threshold for LTE-U when LBT is utilized. The proposed methodology to determine the threshold is summarized as follows.

Step 1: The LBT thresholds are traversed firstly for different throughput of WiFi to obtain the experimental duty cycle values on the detected channel.

Step 2: To substitute the LTE-RRU in *step 1* for a WiFi AP and to use the known CCA-ED threshold for WiFi, same procedures are performed to obtain the experimental duty cycle values for an AP.

Step 3: To compare the experimental duty cycle values for LTE-U with that of an AP obtained from *Step 2*, and to refer to the theoretical duty cycle value, a suitable threshold for LTE-U using LBT can be determined finally.

To realize the test target and validate the feasibility of the proposed threshold determination scheme, a test field is constructed firstly in the high-dense scenario illustrated in Fig. 18 where the distance between two stations is 22 m

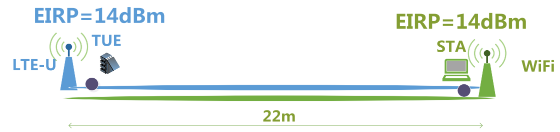


FIGURE 18. Trial of the LTE-U threshold for different WiFi loads.

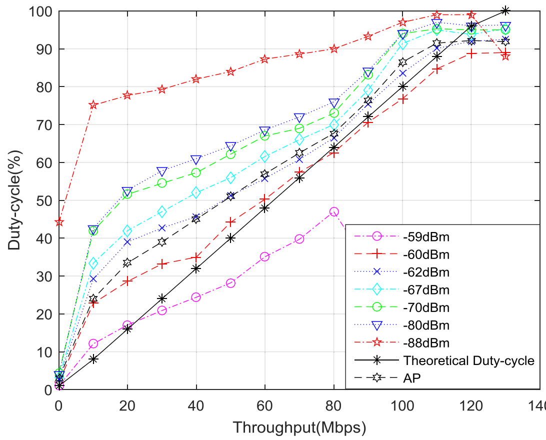


FIGURE 19. Trial of the LTE-U threshold in the ultra-dense scenario (EIRP = 14 dBm).

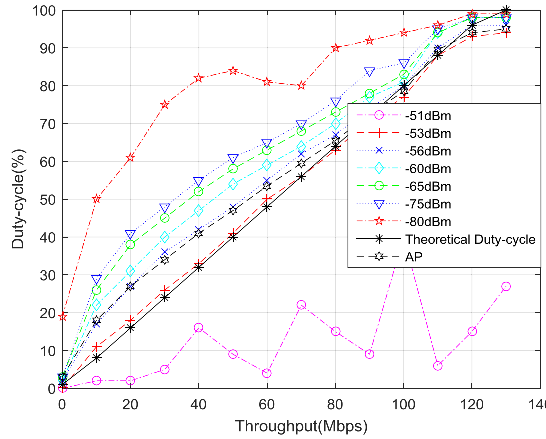


FIGURE 20. Trial of the LTE-U threshold in the high-dense scenario (EIRP = 11 dBm).

TABLE 2. Dense scenario parameters.

	EIRP of the RRU (dBm)	EIRP of the AP (dBm)	Distance Between RRUs and Aps (m)
Scenario 1	14	9	22
Scenario 2	14	4	22
Scenario 3	2	2	48

and the maximum EIRP is set to 14 dBm. LTE-U only listens to the duty cycle on the tested channel without transmitting data. The traversed LTE-U thresholds change from −88 dBm to −59 dBm. On the contrary, WiFi always transmits data and the packet size is increased from 0 to 130 Mbps with a step of 10 Mbps. The test results are presented in Figs. 19 and 20.

Because the WiFi AP always transmits data, the channel duty cycle can be maintained from 90% to 95% when the packet size is maximum. We can observe from Fig. 19 that the threshold in the range of [−80 dBm, −60 dBm] can be consistent with the theoretical reference value and the measurement result of an AP.

Furthermore, we reduce EIRP on both sides to 11 dBm and maintain other parameters unchanged in the experiment. From Fig. 20, it can be seen that the threshold setting from −75 dBm to −53 dBm is optimal for LTE-U when EIRP on both sides are 11 dBm. In brief, in a high-dense environment, a threshold in the range of [−65 dBm, −60 dBm] is optimal for LTE-U.

2) IN THE DENSE SCENARIO

Just as aforementioned, the WiFi detection threshold of CCA-ED is 20 dBm higher than that of WiFi preamble detection which leads to the interference and LTE-U signal transmissions can not be detected in some scenarios that is defined as Dense Scenario in Part *B* of Section III. To investigate the feasibility of the proposed threshold determination method in the dense scenario we change the scenario by adjusting the transmitting power and the distance between RRUs and APs. The methods of testing and deployments are similar to the previous trial. The test results in Figs. 21(a), (b) and (c) corresponds to detailed testing parameters of Scenario 1, 2 and 3 in Table 2.

We can observe from Fig. 21(a) that the threshold of LTE-U is set from −87 dBm to −65 dBm matches the theoretical reference value and the measurement value of an AP. From Figs. 21(b) and (c), it is observed that the optimal threshold is in the range of [−87 dBm, −70 dBm] and [−87 dBm, −81 dBm]. Besides, we can make a conclusion that the LTE-U CCA threshold setting is closely related to the distance and power settings. However, a CCA-ED threshold in the range of [−87 dBm, −81 dBm] or even lower leads to few chances for LTE-U to send data and thus being very unfavorable for LTE system throughput although it can guarantee WiFi performance. To achieve the win-win aim, an algorithm to adjust the threshold dynamically is needed under the dense scenario.

In a nutshell, from Part *A*, *B* and *C* the measurements illustrate the potential capacity and coverage improvements from LTE-U. Specifically, a CCA-ED threshold determination method for LTE-U using LBT is proposed and experiments validate the feasibility of this method in various scenarios.

D. SUPPLEMENTARY DOWNLINK (SDL) AND BASIC CELL ON/OFF COEXISTENCE

Based on the above measurements, in the following part, we conduct a performance evaluation of LAA and WiFi coexistence with SDL mechanism and the Basic Cell ON/OFF mechanism.

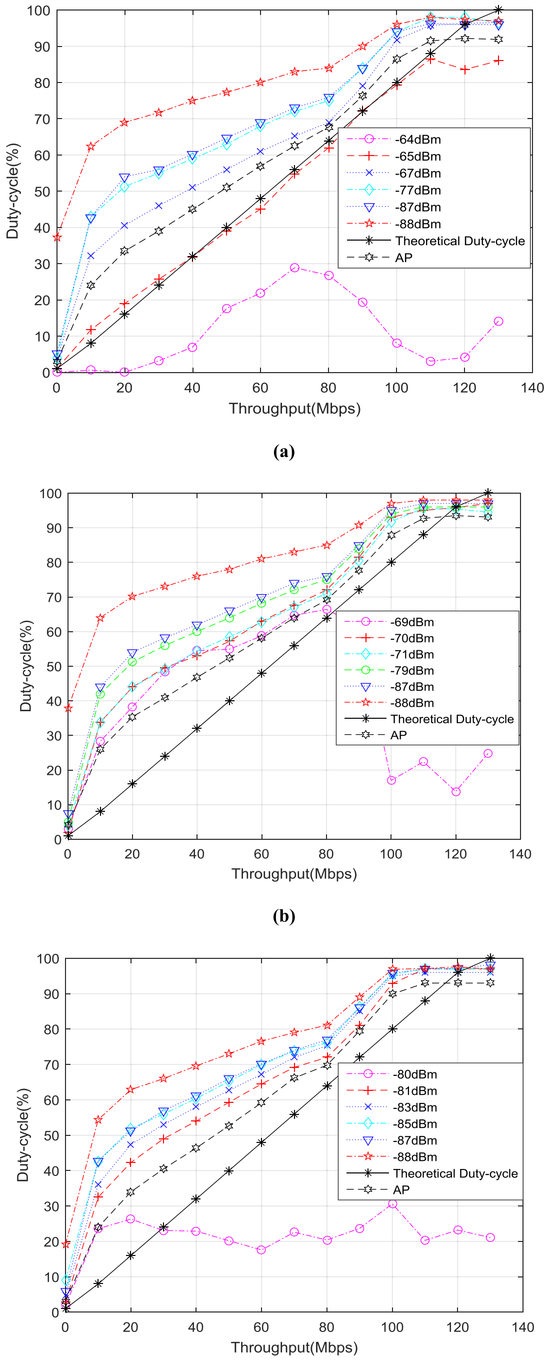


FIGURE 21. Trials of the threshold setting in the dense scenario. (a) Scenario 1. (b) Scenario 2. (c) Scenario 3.

1) SDL SCHEME

Two kinds of test scenarios, the sparse scenario and the dense scenario which are defined in Fig. 11(a) and (b), are considered in the experiments. Table 3 lists the test cases adopted in the following experimental tests. Considering the experimental results, it should be emphasized that the horizontal axis represents the distance between LAA TUE or WiFi STA and NO.1 Site while the vertical axis represents the average UPT measured by LAA TUE or WiFi STA. For adequacy of experiments, we will analyze the performance of coexistence between LAA and WiFi from two perspectives, namely, WiFi affected by LAA SDL/WiFi and LAA SDL affected by LAA SDL/WiFi respectively.

TABLE 3. Test cases.

Test Case		Victim	Aggressor
		No. 1 Site	No. 4 (No. 3) Site
1	WiFi Single	WiFi AP	\
2	LAA Single	LAA eNB	\
3	WiFi intra-RAT	WiFi AP	WiFi AP
4	WiFi inter-RAT	WiFi AP	LAA eNB
5	LAA intra-RAT	LAA eNB	LAA eNB
6	LAA inter-RAT	LAA eNB	WiFi AP

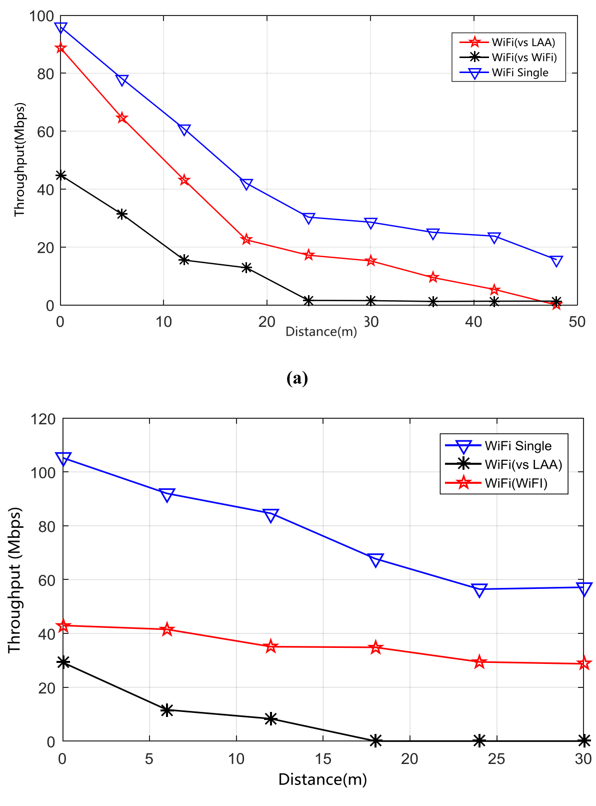


FIGURE 22. WiFi performance with SDL mechanism in different scenarios. (a) WiFi performance with SDL mechanism in the sparse scenario. (b) WiFi performance with SDL mechanism in the dense scenario.

a: WIFI AFFECTED BY LAA SDL/WIFI

This section primarily presents WiFi UPT with different ways of coexistence, WiFi intra-Radio Access Technology (RAT) and WiFi inter-RAT.

(i) SPARSE SCENARIO

From Fig. 22(a) it can be observed that LAA has less interference on WiFi than WiFi intra-RAT when WiFi is employed in WiFi inter-RAT. Considering the performance of WiFi Single, the average UPT of WiFi under WiFi inter-RAT decreases approximately 10–20 Mbps while that has a sharp deterioration under WiFi intra-RAT. Moreover, WiFi inter-RAT has a maximum 100% gain in the average UPT compared with that of WiFi intra-RAT. As a result, LAA SDL is already a friendly and harmonious neighbor for WiFi in the sparse scenario.

(ii) DENSE SCENARIO

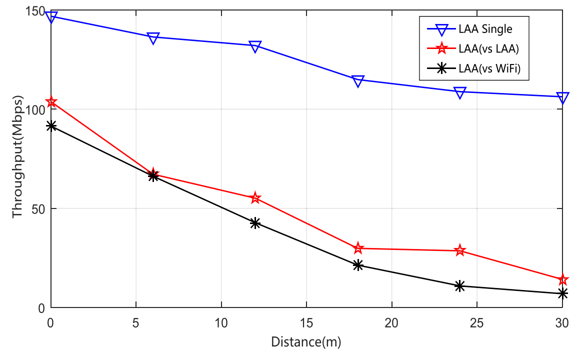
The unexpected degradation of WiFi UPT is surprisingly observed when WiFi coexists with LAA in the dense scenario as shown in Fig. 22(b). More specifically, WiFi UPT under WiFi inter-RAT deteriorates seriously and even drops to below 30 Mbps, far lower than that under WiFi intra-RAT as well. The reason for the poor performance of WiFi under WiFi inter-RAT is that, the continuous decrease in the distance between WiFi and LAA and the constant increase in the interference power make LAA become more and more dominant so that LAA obtains more channel resources for data transmission. When the interference power exceeds a certain level, WiFi performance suffers much more severe degradation than LAA. Comparing with that in the dense scenario, WiFi performance in the sparse scenario has significant improvement regardless of under WiFi intra-RAT or WiFi inter-RAT. This is mainly due to the fact that, the cell radius of a WiFi system is constantly shrinking with the deployment being increasingly intensive, which can significantly degrade WiFi performance. Therefore, LAA also needs a proper coexistence technology to be a good neighbor with WiFi in the dense scenario.

b: LAA SDL AFFECTED BY LAA SDL/WIFI

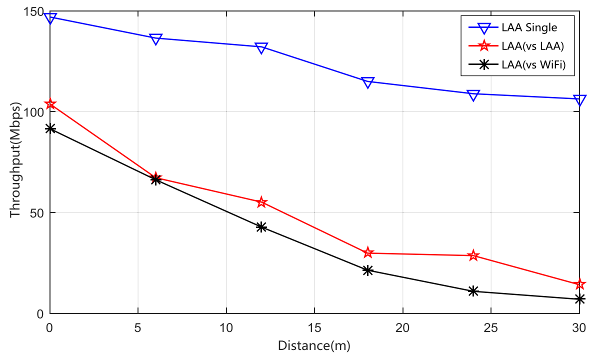
Furthermore, we evaluate LAA performance under LAA intra-RAT and LAA inter-RAT. Results in Fig. 23 apparently indicate that LAA performance under LAA intra-RAT is superior to that under LAA inter-RAT regardless of in the sparse or dense scenario, which is attributed to LTE's centralized scheduler, better channel reporting mechanisms, Radio Resource Management (RRM), Hybrid automatic repeat request (HARQ), strong interference handling capabilities etc.

(i) SPARSE SCENARIO

Results in Fig. 23(a) indicate that LAA UPT under LAA intra-RAT is close to that under LAA Single at the near-point, and have a good gain compared with that under LAA inter-RAT in the sparse scenario as well. Comparison of LAA UPT under LAA intra-RAT and LAA inter-RAT shows that the decline of the median user is about 40% while the degradation of the edge user is even up to 66%. In other words, the impact of WiFi on LAA is significantly larger than that of LAA on LAA. Therefore, LAA has an advantage on anti-interference over WiFi.



(a)



(b)

FIGURE 23. LAA performance with SDL mechanism in different scenarios. (a) LAA performance with SDL mechanism in the sparse scenario. (b) LAA performance with SDL mechanism in the dense scenario.

(ii) DENSE SCENARIO

Comparing with Figs. 23(a) and (b), one can observe that LAA UPT has a similar trend, whereas the gap of LAA UPT between LAA intra-RAT and LAA inter-RAT in the dense scenario has become smaller (only 10–20 Mbps) with the deployment being increasingly intensive.

We conclude results from above experimental tests that LAA is more dominant than WiFi in SDL coexistence, which is so detrimental to WiFi. Thus, SDL mechanism is not a proper coexistence mechanism. Suitable coexistence mechanisms are indeed needed to prevent the degradation of WiFi performance from the impact of LAA.

2) BASIC CELL ON/OFF SCHEME

In this part, we illustrate a comparison of UPT improvement induced by the application of Basic Cell ON/OFF mechanism under LAA inter-RAT, WiFi inter-RAT and WiFi intra-RAT in the dense scenario. It should be noted that the ratio of ON-state and OFF-state in our experimental tests is constant (1:1). Two deployment scenes are considered to evaluate the performance of LAA and WiFi coexistence as shown in Fig. 24(a) and Fig. 25(a).

As shown in Fig. 24(b), LAA UPT under LAA inter-RAT has a substantial increment at middle and far points (6–30 m) compared with WiFi UPT under WiFi intra-RAT. Moreover,

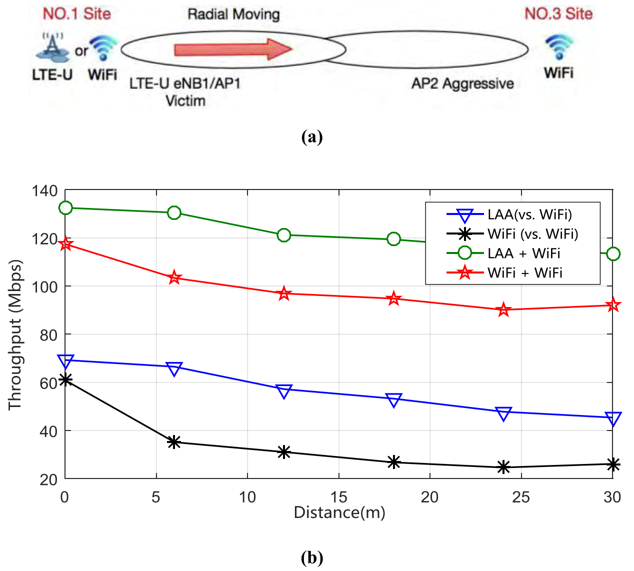


FIGURE 24. **LAA and WiFi coexistence with Basic Cell ON/OFF mechanism in the dense scenario corresponding to the first site layout. (a) The first site layout in the dense scenario.(b) Basic Cell ON/OFF mechanism corresponding to the first site layout.**

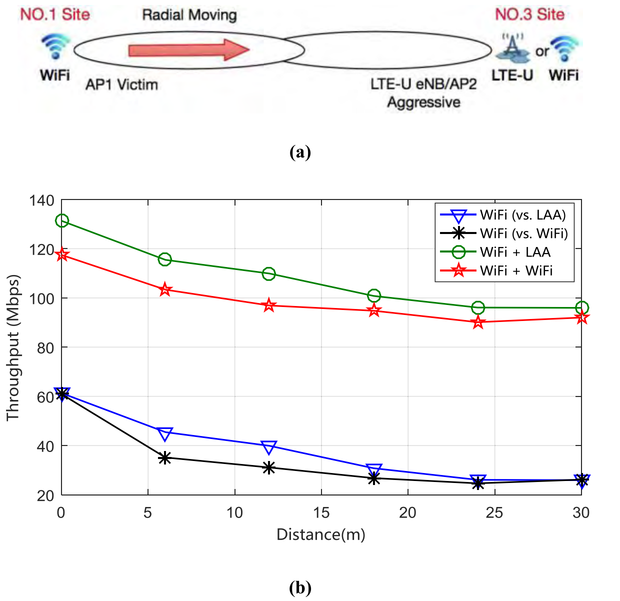


FIGURE 25. **LAA and WiFi coexistence with Basic Cell ON/OFF mechanism in the dense scenario corresponding to the second site layout. (a) The second site layout in the dense scenario.(b) Basic Cell ON/OFF mechanism corresponding to the second site layout.**

results in Fig. 24(b) and Fig. 25(b) show that LAA in Basic Cell ON/OFF coexistence is not as dominant as in SDL coexistence. With Basic Cell ON/OFF mechanism, LAA and WiFi have gradually coexisted in a more and more friendly and harmonious manner. More specifically, when LAA and WiFi coexist with Basic Cell ON/OFF mechanism, the gap of LAA UPT and WiFi UPT is no longer large as that in SDL coexistence. The reason for the above phenomenon is that LAA and WiFi have almost equal opportunities to occupy the channel, which is in accordance with the 1:1 design of Basic ON/OFF. Therefore, Basic Cell ON/OFF mechanism has the ability to guarantee that LAA and WiFi coexist in a friendly manner and has a larger performance gain than SDL as well.

All in all, our results show that, in general, LAA outperforms WiFi and Basic Cell ON/OFF outperforms SDL in the similar scenario. More specifically, WiFi performance would drop significantly while LAA performance is less affected without any coexistence mechanisms. Only in the sparse scenario, LAA SDL has a relatively friendly coexistence with WiFi, but severely influences the performance of WiFi in the dense scenario. In terms of Basic Cell ON/OFF mechanism, it is obvious that the performance of LAA and WiFi coexistence with Basic Cell ON/OFF is superior to that with SDL. To a certain extent, Basic Cell ON/OFF is able to guarantee the friendly and harmonious coexistence between LAA and WiFi. However, improved coexistence mechanisms based current technologies are necessary to obtain better coexistence performance.

E. PERFORMANCE OF ENHANCED CELL ON/OFF MECHANISM

Motivated by Part *D* of this section, in this part, our goal is to evaluate the performance of the Enhanced Cell ON/OFF

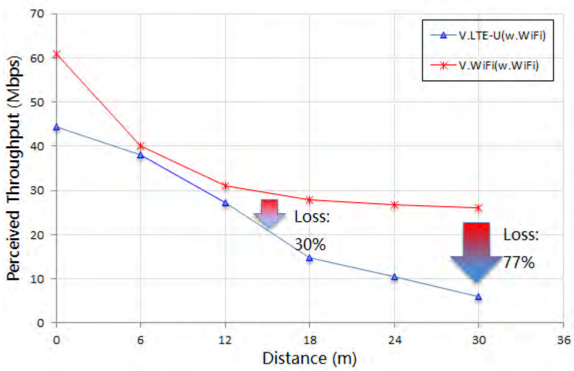
TABLE 4. **Test case options.**

Test Case	BS *Victim*	BS *Aggressor*	Terminal *Victim*	Terminal *Aggressor*
Case 1	WiFi AP	WiFi AP	STA (move from 0 to 30 m)	STA (right below the antennas, stationary)
	LTE-U RRU		UE (move from 0 to 30 m)	
Case 2	WiFi AP	WiFi AP	STA (move from 0 to 30 m)	STA (right below the antennas, stationary)
		LTE-U RRU		UE (right below the antennas, stationary)

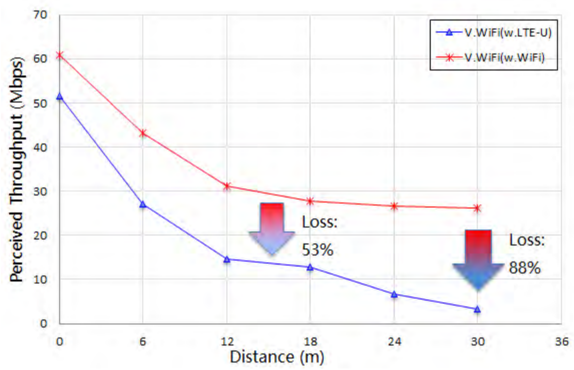
mechanism by comparing with the Basic Cell ON/OFF mechanism. Last but not least, we will analyze the role of CTS2S message in improving throughput of both systems.

Our test case options can be found in Table 4. In each test case, there is one LTE-U eNB and one WiFi AP in the respective system, both LTE-U eNB and WiFi AP serve only one user since we aim to assess the behavior of two Cell ON/OFF mechanisms and leave multi-user situations to be considered in the future study.

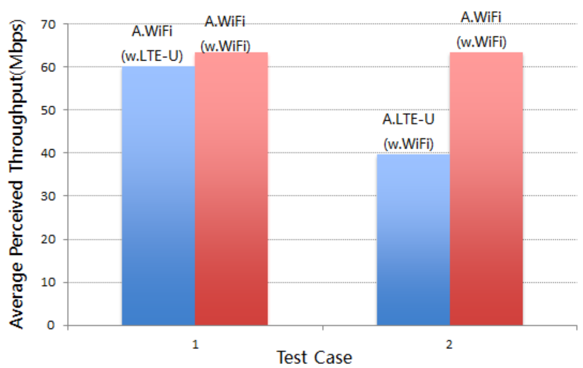
In Case 1, we intend to evaluate whether WiFi station (STA) or UE in LTE-U performs better under the impact of STA in the Aggressor Site. In the accessed WiFi networks, the aggressor STA has a full buffer transmission which means it achieves the peak data rate. At the same time, STA/UE in the victim network moves from 0 m to 30 m along with the test path straightly. The purpose of Case 2 is to observe throughput in the victim WiFi when the aggressor WiFi is



(a)



(b)



(c)

FIGURE 26. Average throughput of Basic Cell ON/OFF mechanism. (a) Average throughput of a victim user in Case 1.(b) Average throughput of a victim user in Case 2.(c) Average throughput of an aggressor user.

replaced by LTE-U. We record the perceived throughput of two users for at least 120 seconds in each test point. Before each test, the transmitting power calibration and adjusting the placement of terminal devices to achieve its peak rate are necessary. Values used in all the test results are linear average of 120 sampling points in 2 minutes.

1) RESULTS OF BASIC CELL ON/OFF MECHANISM

According to the previous test results, the peak rate of the LTE-U user in the near point can reach to about 140 Mbps when there is only one user accessing to the network without interference from adjacent nodes. And the WiFi user is about 125 Mbps in the same situation. The average throughput of the victim and an aggressor user in two cases are respectively shown in Figs. 26 (a), (b) and (c).

To our disappointment, in Fig. 26(a), compared to the average throughput of a WiFi user in the Victim Site which has been interfered by another WiFi user in the Aggressor Site, the average throughput of the LTE-U user which is impacted by the identical aggressor is much lower. The decline of the median user is about 30% as well as the degradation of the edge user even up to 77%. A similar situation was found in the other test case. Obviously in Fig. 26(b), when WiFi is employed in the Victim Site, LTE-U has more interference than the WiFi aggressor. In Fig. 26(c), from the perspective of the aggressor user, since it has a stationary position under the antennas, average throughput is relatively stable. However, WiFi still performs better than LTE-U in the coexisting scenario.

The reasons for the poor performance of LTE-U can be explained as follows. Firstly, WiFi does not block its data transfer when coexisting with LTE-U during T_{ON}. Because the CCA-ED for inter-RAT is set to -62 dBm whereas -82 dBm for intra-RAT in CSMA/CA, the WiFi node can not detect the transmission of LTE networks in the dense scenario. When the co-channel adjacent node is transmitting data, WiFi user is able to detect the WiFi signals and then triggers CSMA/CA to avoid the collisions. But it could hardly identify the LTE-U signal and just simply takes it as noise or interference from radio propagation environments, therefore, there are much more inevitable collisions between two systems. As a result, WiFi interferes with transmission of LTE-U during the T_{ON}. Secondly, LTE-U performs as an interferer on WiFi in the ON-state duration. Complying with some protection mechanisms stipulated in the 802.11n protocol, the Modulation and Coding Scheme (MCS) values decrease dramatically due to the poor channel conditions or severe mutual interference. Actually, the lower MCS values mean the lower perceived throughput of the user. When the next OFF-state comes, MCS values of a WiFi user can not increase rapidly to adapt the changed state leading to the unsatisfactory performance.

2) RESULTS OF ENHANCED CELL ON/OFF MECHANISM

To tackle the above problem, CTS2S is introduced into the Basic Cell ON/OFF mechanism to enable the Enhanced Cell ON/OFF. CTS2S message transmitted in the switching moment can avoid the mutual interference during next ON-state duration. It stops data transmission of WiFi within a certain range which achieve truly TDM compared to the Basic Cell ON/OFF scheme. Fig. 27 presents the test results of Enhanced Cell ON/OFF where CTS2S message is introduced.

As observed, the average throughputs of the victim user in Case 1 and 2 are improved significantly. Compared to intra-RAT coexistence, the median user in inter-RAT obtains the gain of 88% while the edge user has the gain of 74% in Case 1.

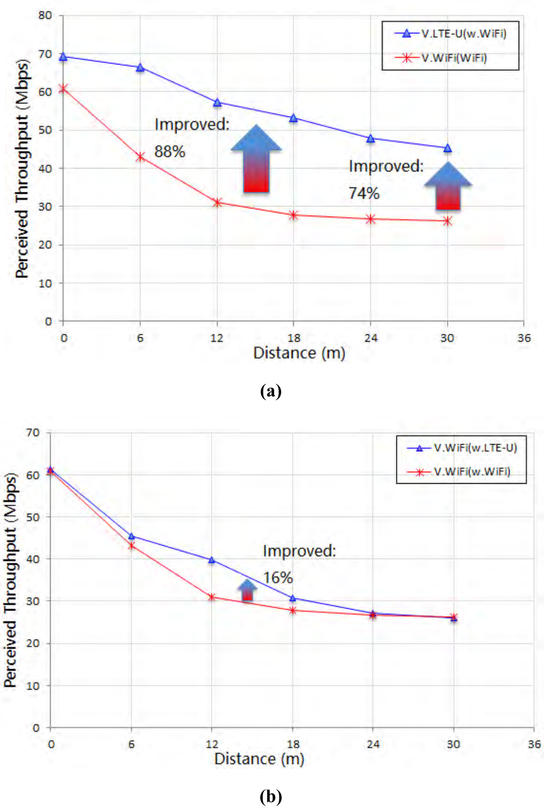


FIGURE 27. Average throughput of Enhanced Cell ON/OFF mechanism. (a) Average throughput of a victim user in test case 1.(b) Average throughput of a victim user in test case 2.

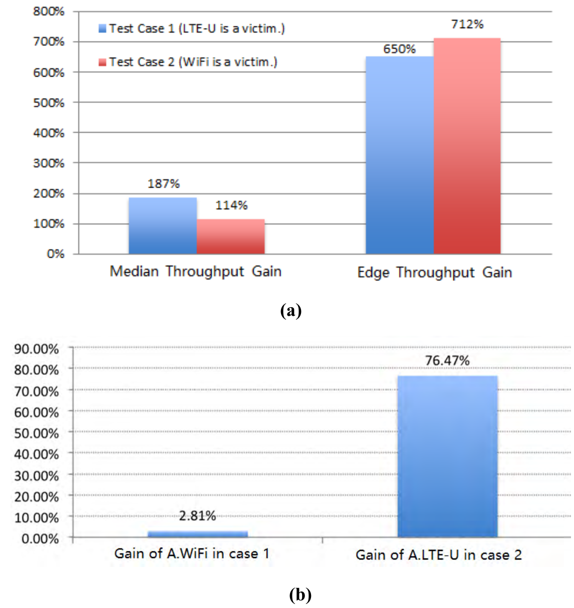


FIGURE 28. Throughput comparison of both the victim and the aggressor sites. (a) Throughput gain of a victim LTE-U user.(b) Average throughput gain of an aggressor user.

For the same reason, increases in Case 2 is remarkable. It should be noted that we assume that the WiFi node is able to close its data transmission during the ON period in our test. So both WiFi aggressors in two test cases have constant average throughputs in the inter-RAT situation, which is equal to half of the peak rate. That is the reason why the throughput of the WiFi aggressor is not shown in any figure. It can be seen that LTE-U and WiFi can peacefully share the unlicensed bands with the introduction of CTS2S message in the Enhanced Cell ON/OFF scheme. To further evaluate the function of CTS2S message, user throughput comparison of both the Victim and the Aggressor Sites are shown in Fig. 28.

Fig. 28(a) shows that whether the LTE-U eNB is employed in the Victim or Aggressor Site, throughput of the victim user is significantly increased after the CTS2S is introduced in the Cell ON/OFF mechanism. Performance of both the median and edge users is significantly improved. Furthermore, in Fig. 28(b), the average throughput of the aggressor user is increased in a different extent. These results further prove that the CTS2S message is helpful to achieve friendly coexistence between WiFi and LTE-U sharing the same spectrum.

As a summary, test results show that although Basic Cell ON/OFF scheme has complied with the TDM pattern, it can not achieve satisfying fair and friendly coexistence between WiFi and LTE-U for their mutual interference still existing during ON-state period. As a result, the performance of both WiFi and LTE systems is decreased. To introduce the CTS2S message in the Enhanced Cell ON/OFF scheme, a friendly coexistence is achieved. And the average throughput of both systems is increased substantially.

V. CONCLUSIONS

In this paper, we present a coexistence study of LTE-U and WiFi in the 5.8 GHz unlicensed spectrums based on the experimental testing platform which is deployed to model the realistic environment. Threefold test results are obtained from our work. First of all, the potential capacity and coverage improvements from LTE-U is achieved. Specifically, a CCA-ED threshold determination method for LTE-U using LBT is proposed and experiments validate the feasibility of this method in various scenarios. Secondly, in general, LAA outperforms WiFi and Basic Cell ON/OFF outperforms SDL in similar scenario. More specifically, WiFi performance would drop significantly while LAA performance is less affected without any coexistence mechanisms. Finally, a friendly coexistence has been achieved and the average throughput of both systems is increased substantially after the introduction of the CTS2S message in the Enhanced Cell ON/OFF scheme.

We will continue to study the coexistence mechanisms on unlicensed spectrums. Considering the constant ON/OFF ratio we adopted in these tests, we may explore the adaptive ratio in varied channel conditions and the multi-user situations in the near future.

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