LTE in the Unlicensed Spectrum: Evaluating Coexistence Mechanisms

Jeongho Jeon, Huaning Niu, Qian (Clara) Li†, Apostolos Papathanassiou, Geng Wu

Mobile and Communications Group
Intel Corporation, Santa Clara, CA 95054, USA
Email: {jeongho.jeon, huaning.niu, apostolos.papathanassiou, geng.wu}@intel.com, †liqian@ieee.org

***Abstract*—The *Long Term Evolution (LTE) in unlicensed spectrum* is an emerging topic in the 3rd Generation Partnership Project (3GPP), which is about an operation of the LTE system in the unlicensed spectrum via license-assisted carrier aggregation. The 5 GHz Unlicensed National Information Infrastructure (U-NII) bands are currently under consideration, but these bands are also occupied by Wireless Local Area Networks (WLAN), specifically those based on the IEEE 802.11a/n/ac technologies. Therefore, an appropriate coexistence mechanism must be augmented to guarantee a peaceful coexistence with the incumbent systems. With this regard, our focus lies on the evaluation of all the proposed coexistence mechanisms so far in a single framework and making a fair comparison of them. The coexistence mechanisms covered in this work includes static muting, listen-before-talk (LBT), and other sensing-based schemes that make a use of the existing WLAN channel reservation protocol.**

I. Introduction

A workshop on *Long Term Evolution (LTE) in unlicensed spectrum* was held during the 3rd Generation Partnership Project (3GPP) plenary meeting this June [1]. The exploitation of unlicensed spectrum in the LTE system is considered as an important complement to meet the ever increasing demand for mobile data rate due to the limited availability of licensed spectrum [2]–[4]. At the time when this manuscript is prepared, a study item proposal on LTE in unlicensed spectrum is likely to be discussed in 3GPP starting from the next meeting in this September. Initial focus will be on the License-Assisted Access (LAA) in carrier aggregation of a primary cell on licensed spectrum and a co-located secondary cell on unlicensed spectrum to boost downlink data rate in the frequency-division duplexing (FDD) mode. The uplink operation can be considered in the later phase.

The unlicensed spectrum of interest in the current discussion is the 5 GHz Unlicensed National Information Infrastructure (U-NII) bands but the core technology should and will be as frequency agnostic as possible. The U-NII bands are comprised of U-NII-1 (5.15-5.25 GHz), U-NII-2A (5.25-5.35 GHz), U-NII-2C (5.47-5.725 GHz), and U-NII-3 (5.725-5.825 GHz). The Federal Communications Commission (FCC) rules vary even among the U-NII bands such as, for example, the maximum conducted in-band output power and power spectral density. Particularly, the Dynamic Frequency Selection (DFS) and Transmitter Power Control (TPC) are mandated in U-NII-2 bands. In the First Report and Order (R&O) released in this April, the FCC removed the indoor-only restriction in U-NII-1 band and increased the maximum conducted in-band output power to 1 W, as permitted in the U-NII-3 band [5]. The in-band power spectral density is increased to 17 dBm in any 1 MHz band accordingly. The FCC further extended the upper edge of the U-NII-3 band to 5.85 GHz and consolidated rules so that the 5 GHz bands will operate under single discipline[1]. These modifications are made to better accommodate the next generation Wi-Fi technology, the IEEE 802.11ac. For the up-to-date regulations by FCC, please refer to [6].

The main incumbent system in the 5 GHz band is the Wireless Local Area Networks (WLAN), specifically those based on the IEEE 802.11 a/n/ac technologies. Since WLAN systems are widely deployed both by individuals and operators, significant care must be taken before allowing LTE operation in the unlicensed band. There has been some previous work in this context. In [7], the inter-system interference when LTE and WLAN systems coexist in a plain manner with no coexistence mechanism was studied analytically. In [8], the same study was performed for complex indoor deployment scenarios through simulation. In [9], the use of listen-before-talk (LBT) was proposed and simulated, which requires an additional step of sensing the medium at the Evolved Node B (eNB) before transmission. It was also considered in the work that the eNB transmits the WLAN clear-to-send (CTS) message after sensing to reserve the medium over the duration of time that it plans to transmit, which is called *self-CTS* in the WLAN terminology. In [10] and [11], the LTE muting scheme was simulated in which the LTE eNBs follow a predetermined muting pattern to open up the chances for WLAN systems to access the medium.

The main goal of this work is to evaluate all the proposed coexistence mechanisms so far in a single framework such that a fair comparison between different mechanisms is achieved. For this, we developed a system-level simulator which is compliant with 3GPP performance evaluation methodology [12]. Both outdoor deployment and indoor/outdoor mixed deployment scenarios are considered. To model the bursty traffic, we adopted the 3GPP File Transfer Protocol (FTP)

[1]The FCC rules permitted the certification of devices that operate in 5.725-5.85 GHz band under two different rule sections: the Section 15.247 technical rules for digitally-modulated devices and the Section 15.407 U-NII rules. The Section 15.247 rules are now consolidated with the Section 15.407 rules.

978-1-4799-7470-2/14/$31.00 ©2014 IEEE

traffic model and simulated at different loading points ranging from being the system under-utilized to over-utilized. The results and observations made in this work can enrich the future discussion on the standardization of the LTE LAA operation.

The rest of the paper is organized as follows. In Section II, we make a brief comparison between LTE and WLAN systems, which will provide a basis of our following discussion. In Section III, various coexistence mechanisms are described in detail. In Section IV, we describe the simulation setup and discuss the results. Finally, we draw conclusions in Section V.

II. Comparison between LTE and WLAN

The Wi-Fi technologies based on the orthogonal frequency-division multiplexing (OFDM), such as IEEE 802.11a/g/n/ac, has the fixed subcarrier spacing of 312.5 kHz regardless of the transmission bandwidth, which gives 3.2 μs symbol length [13]. The standard OFDM symbol has a 0.8 μs guard interval (GI) and, therefore, the overall symbol length is 4 μs[2]. The LTE system has much narrow subcarrier spacing of 15 kHz, which gives approximately 66.7 μs symbol length [14]. LTE defines two cyclic-prefix lengths, the *normal* cyclic prefix and the *extended* cyclic prefix; The normal prefix is 5.2 μs for the first symbol in a slot and 4.69 μs for the remaining symbols, while the extended prefix is 16.67 μs for all symbols. In our performance evaluation, 0.8 μs GI is used for WLAN and normal cyclic prefix is assumed for LTE.

Note that in the current phase of discussion, the unlicensed spectrum is mainly considered as supplemental downlink component carrier. Therefore, the LTE traffic served over the unlicensed spectrum is all in the downlink direction and the multiplexing to different UEs is done by means of scheduling at the eNB. The WLAN system is different in that the channel access is based on the contention even between the access point (AP) and stations (STAs) in the same basic service set (BSS). The medium access control (MAC) protocol is called carrier sense multiple access with collision avoidance (CSMA/CA), which does not require a centralized controller. A node having data to transmit first perform a clear channel assessment (CCA). The additional backoff mechanism aims for the collision avoidance aspect to cope with the situation when more than one nodes sense the medium idle at the same instance. The optional request-to-send/clear-to-send (RTS/CTS) messages can be exchanged between source and destination nodes to further minimize the cost of collision given that the duration of data transmission is usually much longer than that of the control messages. The sensitivity requirements for CCA vary according to the transmission bandwidth but, for the primary 20 MHz operation, the thresholds have always been -82 dBm for the detection of the start of a valid WLAN signal and -62 dBm for the detection of any signal. They are referred to as signal detect and energy detect CCA, respectively. Due to the physical layer discrepancy, the LTE signals are not decodable by WLAN nodes and, thus, the energy detection applies.

[2]To further increase the efficiency, an optional short GI of 0.4 μs was adopted in IEEE 802.11n.

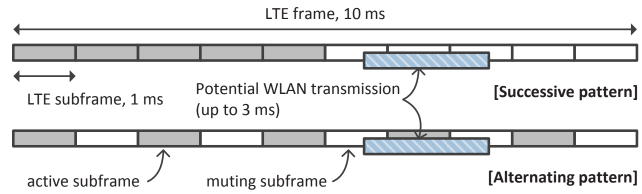


Fig. 1. LTE eNB muting

III. LTE-U Coexistence Methodologies

A. Static Muting

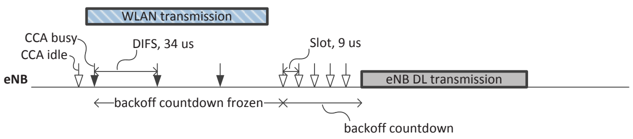
In [10], the use of LTE almost-blank subframes (ABS) was proposed for the coexistence with WLAN systems. The ABS was initially introduced in LTE Release 10 for the purpose of enhanced inter-cell interference coordination (eICIC) [1]. For the backward compatibility, the Primary and the Secondary Synchronization Signals (PSS and SSS), cell-specific reference signals (CRS), and the Physical Broadcast Channel (PBCH) need to be transmitted even during ABS subframes. Since however the considered unlicensed frequency band is new to the legacy system, it was assumed in [10] that there is no backward compatibility issue and the muting subframes can be just blank subframes. The same assumption is made in this work as well.

As illustrated in Fig. 1, even for the same fraction of muting subframes, one could think of different patterns of allocating muting subframes over frame or even longer time scale. One apparent advantage of the successive pattern over the alternating one is that the active LTE subframes will statistically less frequently intervene the ongoing WLAN transmissions. However, the long successive muting will induce larger delay jitter, which makes it inappropriate for real-time service. In a densely deployed small cell scenario, the neighboring eNBs belonging to a same operator may follow the same muting pattern synchronously or may follow the same pattern but asynchronously, i.e., shifted versions of the pattern. The former is expected to provide a cleaner channel environment to WLAN systems since all the eNBs mute at the same time, whereas the latter has the effect of interference avoidance between the neighboring eNBs.

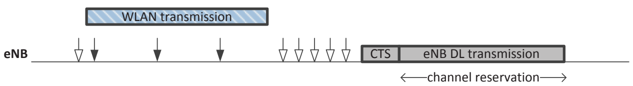
B. Sensing-based Coexistence Methodologies

The listen-before-talk (LBT) by LTE eNB first appeared in [9] and is further elaborated in this work. The LBT operation is illustrated in Fig. 2(a). Here, we employ an additional backoff mechanism in LBT such as the one used in WLAN, since otherwise the eNBs will seize and monopolize the channel given that other WLAN nodes follow the backoff mechanism[3]. Both the CW size and the CCA threshold for

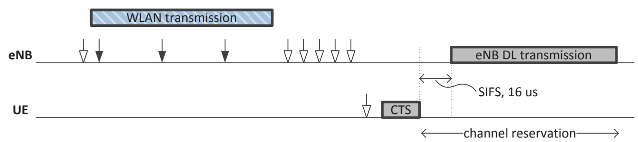
[3]It is required for STAs to follow the backoff mechanism as specified in the IEEE Std 802.11-2012 [15], but the AP's operation is up to implementation and could vary between vendors.



(a) Listen-before-talk (LBT)



(b) Self-CTS



(c) RTS/CTS

Fig. 2. Sensing-based LTE coexistence mechanisms

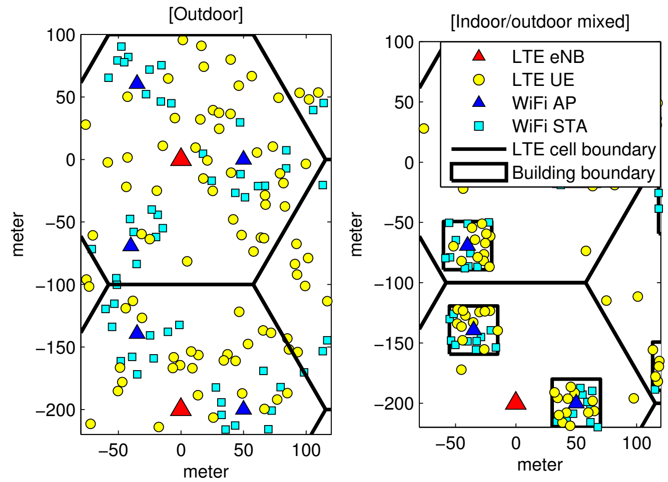


Fig. 3. Deploy scenarios

detecting the WLAN activity configured at the eNB allow us to control the aggressiveness/friendliness of the LTE system to the incumbent systems. Instead of the binary exponential backoff adopted in the WLAN system, in which the CW size is doubled when the previous transmission failed and is reset to the minimum value when the previous transmission succeeded, the CW size is fixed for the LTE eNBs in our evaluation. The use of network allocation vector (NAV) by LTE eNBs can also be considered if they have the capability of decoding WLAN signals.

Next consider the scheme in which the eNB transmits CTS message before its downlink transmission as demonstrated in Fig. 2(b). The CTS message transmitted by eNB is identical with the authentic one used in the WLAN system, and this requires the eNBs to be equipped with WLAN transceiver. It has the duration field pointing the end of following downlink transmission and the receiver address (RA) field set to the transmitting eNB's own MAC address, which is thus called *self-CTS* or *CTS-to-self* [13]. The self-CTS scheme has dual effect: It can help protect the eNB transmission since the CTS message has better detectability by WLAN system as the -82 dBm signal detection threshold applies and can set the NAV of the neighboring WLAN nodes. This can be also beneficial to WLAN nodes as they can avoid unnecessary energy consumption for channel sensing during while the eNB is transmitting.

Note that the rationale behind the exchange of RTS/CTS messages in the WLAN system is to protect the destination node from the hidden nodes. The self-CTS scheme may not be effective especially when the outdoor eNB is serving indoor UE and the neighboring indoor WLAN nodes are not able to decode the CTS message from the outdoor eNB due to high penetration loss. We thus propose the UEs to send the CTS message as illustrated in Fig. 2(c). It is assumed that the RTS message is sent to one or a group of scheduled UEs through a reliable control channel over a licensed spectrum, which is the reason why the RTS transmission is not shown in the figure. As appeared in the figure, the scheduled UE or UEs need to perform sensing before transmitting the CTS message and in case of seeing medium busy, such a UE may indicate its incapability of sending CTS message to eNB via uplink feedback channel.

IV. Performance Evaluation

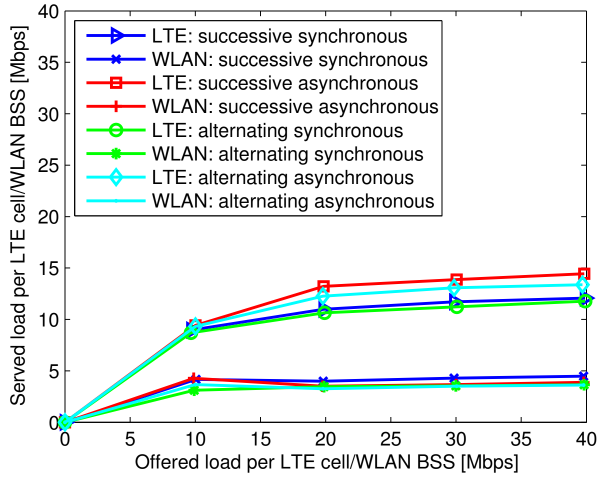
A. Simulation Setup

Consider the deployment of small-cells in which the outdoor eNBs are located at the center of each cell of radius 100 meters as depicted in Fig. 3. In the outdoor deployment scenario, 3 outdoor WLAN BSSs are deployed within each small cell area. The AP is located at the center of each WLAN BSS of radius 35 meters[4]. The number of UEs and STAs are not specified here as they are varying over the course of simulation run under the used FTP traffic model. In the indoor/outdoor mixed deployment scenario, the WLAN BSSs are now located in a separate building of size 40 meters by 40 meters. In each cell, 20% LTE UEs are outdoor and the remaining 80% UEs are located in one of the 3 buildings in each of which the WLAN BSS is operating.

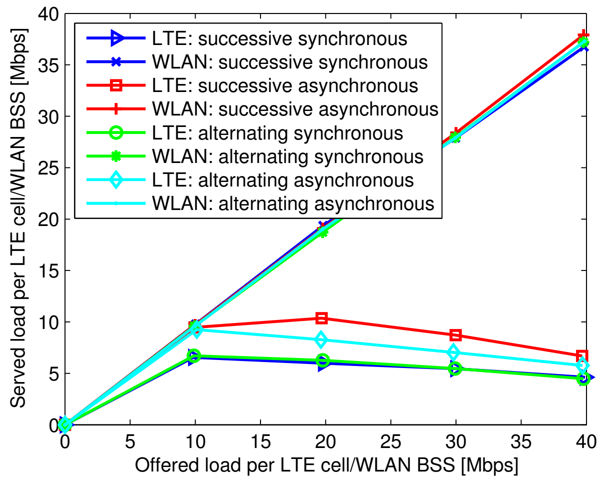
20 MHz frequency band at 5.8 GHz is shared by LTE and WLAN systems. The transmit power of eNB, AP, UE, and STA is set to 30 dBm, 20 dBm, 17 dBm, and 17 dBm, respectively[5]. The Urban Micro (UMi) channel model is used between outdoor nodes. Optional O-to-I loss is applied when the signal penetrates into the building. Indoor Hotspot (InH) model is used between indoor nodes. The distance-dependent randomized LOS/NLOS decision was made for each path. For more details about the used channel model, please refer to Annex B of [12].

[4]The WLAN BSS radius is chosen such that a reliable communication between AP and an outermost STA is possible at the used transmit power levels and channel model.

[5]The UE transmits only when the RTS/CTS coexistence mechanism is used such that it needs to transmit CTS message when scheduled.



(a) Outdoor deployment



(b) Indoor/outdoor mixed deployment

Fig. 4. Performance of various muting patterns (all 50% muting)

To model the bursty traffic, the 3GPP FTP traffic model 1 is used [12]. Under the chosen model, user arrival is modeled as a Poisson process with rate λ per cell and each arriving user downloads a single file of fixed size S, which is set to 0.5 MBytes in our simulation. The *offered load* per cell is, thus, equal to the number of user arrivals multiplied by S and divided by total simulation run time. The *served load* per cell is the total amount of served data divided by total simulation run time. The arrival rate λ and file size S are set identical to both LTE small cells and WLAN BSSs. For WLAN, the offered load is randomly split to both downlink and uplink directions with equal probability. The licensed band of the LTE system is not simulated and, thus, all the offered traffic goes through unlicensed band. The users leave the system upon the download completion. Since each user downloads a single file, the *user-perceived throughput* is obtained by dividing the file size S with the time spent for downloading each file.

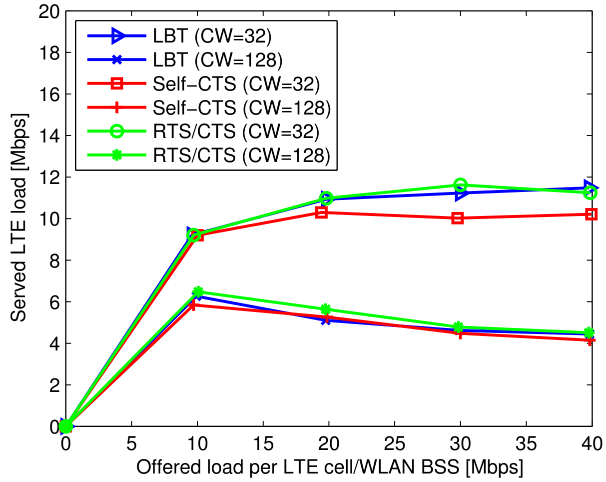
The RTS/CTS exchange is enabled in the WLAN BSSs and the Transmit Opportunity (TXOP) limit is set to 3 ms.

B. Simulation Results

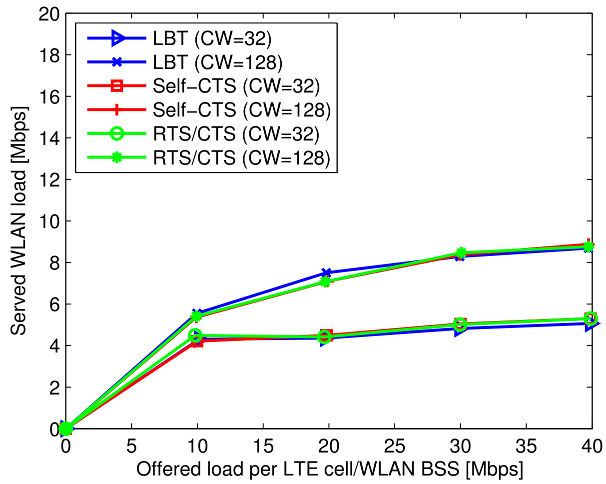
Let us first examine the performance of various LTE muting options, which is illustrated in Fig. 4. In the outdoor deployment scenario, it can be seen that the LTE performance is better with asynchronous muting than synchronous one due to the interference avoidance between LTE eNBs. The WLAN performance is better with synchronous muting than asynchronous one since all the eNBs mute at the same time. On the other hand, the successive pattern is good to both systems. This is because LTE transmissions are less frequently initiated while WLAN transmissions are ongoing and, thus, they are less interfering with each other. In the indoor/outdoor mixed scenario, it is seen that regardless of the used muting pattern, the WLAN performance is fairly good since indoor WLAN BSSs are anyway not much affected by the outdoor eNBs given the high penetration loss. Like the outdoor deployment scenario, the LTE performance is best with the successive asynchronous pattern. Since the combined LTE and WLAN performance is also best with successive asynchronous pattern for both outdoor and indoor/outdoor mixed deployment scenarios, it is chosen for the comparison with other coexistence mechanisms.

Next discuss the performance of sensing-based coexistence mechanisms. Here, we fixed the eNB CCA threshold at -82 dBm and play with the CW size only. The results for the outdoor deployment scenario is illustrated in Fig. 5 from which it can be seen that each system performance is not much different among different sensing-based coexistence mechanisms, if the same CW size is used. This is because in the outdoor deployment, the eNB sensing itself is working quite well and the hidden node problem to UEs is not so significant. The result for the indoor/outdoor mixed deployment scenario is given in Fig. 6. From the fact that LTE performance is better with RTS/CTS mechanism than LBT only, it can be inferred that the hidden node problem at the UEs does exist. As expected, it is difficult for indoor WLAN nodes to detect the outdoor eNB's transmissions as they are penetrating through the building wall and detected with energy detector. It is also observed that the RTS/CTS mechanism can boost both the LTE and WLAN performance when compared to the self-CTS mechanism. The reason is twofold: First, sensing at the eNB only is not enough in this scenario as it is difficult for outdoor eNBs to detect the indoor transmissions. Secondly, the self-CTS at the eNB is not effective in solving the hidden node problem as the CTS message is transmitted at the transmitter of the actual data transmission rather than at the receiver. In reverse, given that the eNB sensing is not functioning well, the self-CTS could be just an additional source of interference to the WLAN system. Instead, sensing the medium locally at the UE and reserving the medium locally by the UE with low transmit power is more benign to neighboring WLAN systems and an effective solution to the hidden node problem.

In Table I and Table II, we made a quantitative comparison for each deployment scenario. The standalone LTE implies that



(a) LTE

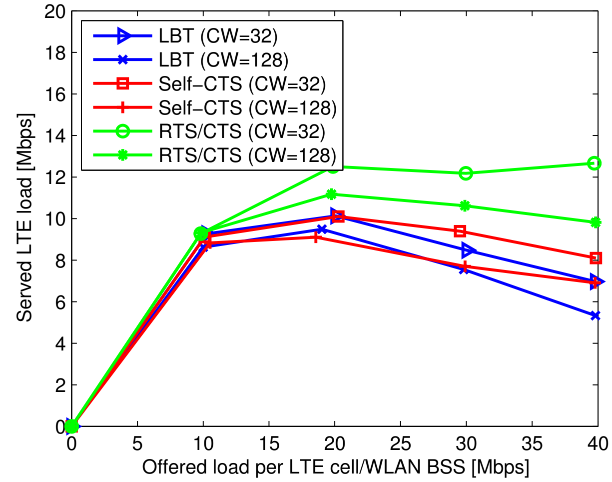


(b) WLAN

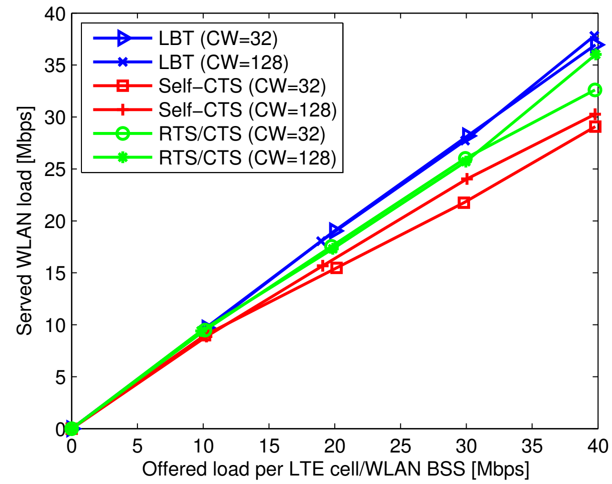
Fig. 5. Performance of sensing-based coexistence mechanisms under the outdoor deployment scenario (-82 dBm CCA threshold)

TABLE I
COMPARISON FOR THE OUTDOOR DEPLOYMENT SCENARIO AT 30 MBPS OFFERED LOAD PER LTE CELL/WLAN BSS

Served load [Mbps]	LTE	WLAN
Standalone	27.74 (100%)	10.28 (100%)
Plain coexistence	21.45 (77%)	1.88 (18%)
Muting	13.87 (50%)	3.66 (36%)
LBT	11.22 (40%)	4.82 (47%)
Self-CTS	10.02 (36%)	5.04 (49%)
RTS/CTS	11.62 (42%)	5.01 (49%)



(a) LTE



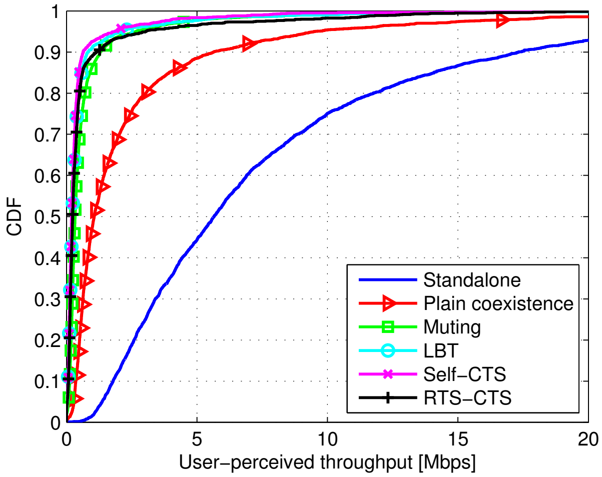
(b) WLAN

Fig. 6. Performance of sensing-based coexistence mechanisms under the indoor/outdoor mixed deployment scenario (-82 dBm CCA threshold)

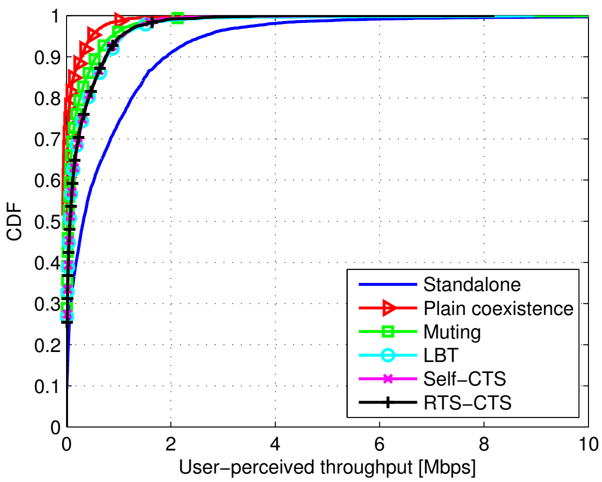
TABLE II
COMPARISON FOR THE INDOOR/OUTDOOR MIXED DEPLOYMENT SCENARIO AT 30 MBPS OFFERED LOAD PER LTE CELL/WLAN BSS

Served load [Mbps]	LTE	WLAN
Standalone	16.33 (100%)	28.73 (100%)
Plain coexistence	9.67 (59%)	27.66 (96%)
Muting	8.71 (53%)	28.39 (99%)
LBT	8.48 (52%)	28.17 (98%)
Self-CTS	9.39 (58%)	21.75 (76%)
RTS/CTS	12.18 (75%)	26.02 (91%)

the WLAN system is completely turned off or, equivalently, the offered load to each and every WLAN BSS is set to zero. The standalone WLAN system can be understood in the similar way. The plain coexistence refers to when both systems coexist with no coexistence mechanism. For muting, the successive asynchronous pattern of 50% muting subframes over frame was used. For sensing-based coexistence mechanisms, the CCA threshold and CW size are set to -82 dBm and 32, respectively. The percentage in the parentheses is the normalized performance with respect to the standalone case. From Table I, it is apparent that the plain coexistence is not acceptable in the outdoor deployment scenario due to the severe ill-balancing between LTE and WLAN performance. In the case of muting, the balance between the systems can be manually controlled by adjusting the muting subframe percentage. The sensing-based mechanisms automatically do



(a) LTE



(b) WLAN

Fig. 7. The CDF of user-perceived throughput at 30 Mbps offered load per LTE cell/WLAN BSS under outdoor deployment scenario

balance and the RTS/CTS mechanism slightly outperforms among others. From Table II, in the indoor/outdoor mixed deployment, it is seen that the use of self-CTS mechanism deteriorates the WLAN performance and, at the same time, the LTE performance is not good either. The RTS/CTS mechanism shows outstanding gain; LTE achieved 75% of its standalone performance, which comes at the cost of only 9% loss in the WLAN performance.

In Fig. 7, we plotted the empirical cumulative density function (CDF) of the user-perceived throughput in the outdoor deployment whose data is extracted from the same set of simulations used for Table I. The CDF for the indoor/outdoor mixed deployment scenario is omitted due to the lack of space.

V. Concluding Remarks

Various mechanisms for the coexistence of LTE and WLAN systems in the same unlicensed spectrum are discussed and compared in this work, and the key observations are as follows. The plain coexistence of LTE and WLAN with no additional mechanism is not suitable especially when both LTE eNBs and WLAN BSSs are located outdoor since the WLAN performance is penalized too much. Therefore, it is evident that an appropriate coexistence mechanism is required to achieve a balance between the LTE and WLAN system performance such as static muting and sensing-based adaptive mechanisms. When WLAN BSSs are located indoor, their performance is not much degraded by outdoor eNBs owing to the separation effect due to the high penetration loss. However, indoor UEs coexisting with WLAN BSS in the same indoor space suffer from the hidden node problem since the sensing at the outdoor eNB does not function well. In such a case, the RTS/CTS coexistence mechanism can provide a significant performance gain over other mechanisms as it is the most effective way of solving the hidden node problem.

References

[1] The 3rd Generation Partnership Project. [Online]. Available: http://www.3gpp.org/

[2] J. Jeon, M. Codreanu, M. Latva-aho, and A. Ephremides, “The stability property of cognitive radio systems with imperfect sensing,” *IEEE Journal on Selected Areas in Communications*, vol. 32, pp. 628–640, Mar. 2014.

[3] ——, “On hybrid access for cognitive radio systems with time-varying connectivity,” in *Proceedings of IEEE International Symposium on Information Theory (ISIT)*, Jul. 2013.

[4] N. Pappas, J. Jeon, A. Ephremides, and A. Traganitis, “Optimal utilization of a cognitive shared channel with a rechargeable primary source node,” *Special Issue on Energy Harvesting in Wireless Networks, Journal of Communications and Networks*, vol. 14, no. 2, pp. 162–168, Apr. 2012.

[5] FCC 14-30. [Online]. Available: http://www.fcc.gov/document/5-ghz-u-nii-ro

[6] The Federal Communications Commission. [Online]. Available: http://www.fcc.gov/

[7] J. Jeon, Q. C. Li, H. Niu, A. Papathanassiou, and G. Wu, “LTE in the unlicensed spectrum: a novel coexistence analysis with WLAN systems,” *To appear in the Proceedings of IEEE Global Communications Conference (GLOBECOM)*, Dec. 2014.

[8] A. M. Cavalcante, E. Almeida, R. D. Vieira, F. Chaves, R. C. D. Paiva, F. Abinader, S. Choudhury, E. Tuomaala, and K. Doppler, “Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands,” in *Proceedings of IEEE Vehicular Technology Conference*, Jun. 2013.

[9] R. Ratasuk, M. A. Uusitalo, N. Mangalvedhe, A. Sorri, S. Iraji, C. Wijting, and A. Ghosh, “License-exempt LTE deployment in heterogeneous network,” in *Proceedings of International Symposium on Wireless Communication Systems (ISWCS)*, Aug. 2012.

[10] E. Almeida, A. M. Cavalcante, R. C. D. Paiva, F. S. Chaves, F. M. Abinader Jr., R. D. Vieira, S. Choudhury, E. Tuomaala, and K. Doppler, “Enabling LTE/WiFi coexistence by LTE blank subframe allocation,” in *Proceedings of IEEE International Conference on Communications (ICC)*, Jun. 2013.

[11] T. Nihtilä, V. Tykhomyrov, O. Alanen, M. A. Uusitalo, A. Sorri, M. Moisio, S. Iraji, R. Ratasuk, and N. Mangalvedhe, “System performance of LTE and IEEE 802.11 coexisting on a shared frequency band,” in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2013.

[12] 3GPP TR 36.814 v9.0.0. [Online]. Available: http://www.3gpp.org/DynaReport/36814.htm

[13] E. Perahia and R. Stacey, *Next generation Wireless LANs: 802.11n and 802.11ac*. Cambridge, UK: Cambridge University Press, 2013.

[14] E. Dahlman, S. Parkvall, and J. Sköld, *4G LTE/LTE-Advanced for mobile broadband*. Oxford, UK: Elsevier, 2011.

[15] IEEE Std 802.11-2012. [Online]. Available: http://ieeexplore.ieee.org/