SBT (Sense Before Transmit) Based LTE Licenced Assisted Access for 5 GHz Unlicensed Spectrum

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Accepted: 18 February 2021 / Published online: 3 March 2021
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Abstract

Utilization of unlicensed spectrum under licensed assisted access ensuring fair co-existence with Wi-Fi networks is a good solution to address immense usage of mobile data. Radio communication operation of LTE in unlicensed frequency band is referred as LTE-unlicensed (LTE-U) or LTE-licensed assisted access. In this paper, we consider a HGNW in which coverage area of Wireless-Fidelity (Wi-Fi)'s Access Point is integrated within the LTE-U small base station's cellular network coverage area. To overcome the disadvantages of existing LTE-U technics like carrier sense adaptive transmission and listen before talk, we proposed a new methodology i.e., sense before transmit in this paper by adopting a transmit power control mechanisms using reciprocity theorem based on the channel state information to assign the secondary carriers in the uplink as well as in the downlink directions in the unlicensed spectrum to carry the traffic. In our proposal, LTE-U users are allowed to use the unlicensed spectrum provided that the interference produced at Wi-Fi users due to LTE-U activities is remained below a certain threshold. We evaluated the performance of proposed network model in terms of outage probability and achievable throughputs.

Keywords LTE-U small base station (SBS) · Channel state information (CSI) · Enhanced-user equipment (E-UE) · Carrier aggregation (CA) · Listen before talk (LBT) · Carrier sense adaptive transmission (CSAT) · Throughput and outage probability

1 Introduction

To address the consumer driven demand as well as network driven demand, the extension of LTE/LTE-A cellular system operations to unlicensed spectrum is given renaissance for the modern way of wireless radio communication system. Assurance of faire co-existence between LTE-U and other networks which are operated in unlicensed bands

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such as Wi-Fi (802.11), Bluetooth (802.15.1) and ZigBee (802.15.4) is a major concern. Performance of these networks should not be degraded due to LTE-U operations and friendly co-existence on 5 GHz band is the on-going discussion on the 3GPP [1]. Among them Wi-Fi is the most successful technology to serve the wireless broad band coverage in a local area and operates in 2.4 GHz and 5 GHz spectrum bands. Recently after FCC freed 295 MHz bandwidth in the Unlicensed National Information Infrastructure (U-NII) band, over 400 MHz unlicensed spectrum is available for commercial use. A lot of research has been proposed based on either listen before talk (LBT) [2–8] or duty cycle based (CSAT) [9–12] approaches to carry the LTE-U activities in unlicensed spectrum. In LBT method similar to the Wi-Fi carrier sensing, it senses the channel before transmitting the data which is required for few markets like in Japan and Europe, on other hand in the CSAT mechanism irrespective of channel state, LTE-U transmissions will be scheduled as per the desired duty cycle which is suitable for China, U.S. and South Korea as these do not require any LBT. Hence changes to LTE protocol specifications are required for LBT mechanism only. Available bands in 5 GHz spectrum across different countries is shown in the Fig. 1 [13].

An inter RAT request based approaches are proposed in [11] to notify the upcoming measurement gaps on unlicensed spectrum for friendly co-existence in unlicensed spectrum using CSAT approach. We can find a well-presented comparison between CSAT and LBT mechanisms in [12], in this the author showed that the same level of fairness to Wi-Fi due to these methods under appropriately configured scenarios but for the shorter transmission times, CSAT results in the lower throughput, higher collision probability and longer Wi-Fi packet delays. The authors proposed a fair and quality based unlicensed spectrum sharing between Wi-Fi and femtocell networks in [14] but changes to existing Wi-Fi network is required. In [15], the author discussed achievable sum-rate in standalone mode (we will discuss clearly about standalone mode in the Sect. 2) using the dual mode small cell base station without considering the Wi-Fi fairness. In [16], the author estimated the contention window size by estimating the number of STAs from collision probability to improve the throughput. A channel reservation mechanism based on synchronous and asynchronous approaches has been proposed in [17] to improve the co-existence.

From the above discussion, we can conclude that by using CSAT approach there must be interference during on duration and in case of LBT approach, we can't use the spectrum if the Wi-Fi user is detected as active. To address these challenges, we proposed a new approach "sense before transmit" to use the unlicensed spectrum in this manuscript. The major contributions of this paper are listed below:

- In the considered HGNW model, Wi-Fi network is integrated within the LTE SBS coverage area to realise the LTE-U system.

Fig. 1 Illustration of available bands and their frequency ranges under 5 GHz unlicensed spectrum

- We proposed sense before transmit (SBT) method in this paper by adopting a transmit power control mechanisms using reciprocity theorem based on the channel state information to assign the secondary carriers.
- We propose CA approaches of LTE in unlicensed bands without degrading existing Wi-Fi performance.
- We restrict the interference generated to Wi-Fi-system due to LTE-U based on the channel state information by controlling transmit power to satisfy the QoS of Wi-Fi user.
- Simulation and analytical models are proposed for Wi-Fi and LTE-U users constrains.
- We contemplate the performance evaluation metrics in terms of the outage probability of LTE-U user under Wi-Fi user outage constrains.
- The effect of the scaling factor of tolerable threshold and outage constraint impacted by Wi-Fi system on LTE-U user's performance.

The remaining sections of the paper are prepared as follows: Sect. 2 enlightens the system architecture proposed and different modes of unlicensed LTE operations including 3GPP certified modes. In Sect. 3, we discuss the performance analysis in terms of metrics throughput and outage probability. Finally, the results and discussions are covered in Sect. 4 followed by conclusion of the paper in Sect. 5.

2 System Model

The integrated HGNW system model assumed is as shown in Fig. 2, in which a Wi-Fi AP is collocated in the coverage area of LTE-U SBS. It is considered that the links among the LTE-U SBS or Wi-Fi AP and users are complex Gaussian random variables, which are identically distributed independent variables. The cellular users and Wi-Fi users are represented with different symbols as shown in the figure.

Before extending our proposed approach to LTE-U, we discuss briefly about the carrier aggregation (CA) of LTE-advanced (LTE-A) [18] system. Whenever an E-UE

Fig. 2 System model. Outer circle represents coverage area of SBS and inner circle represents the coverage area of an AP and respective associated users

establish a session with cellular base station, in general uplink and downlink channel pair will be assigned for transmission in both the directions so called uplink primary component carrier (UL PCC) and downlink primary component carrier (DL PCC) respectively. Jointly these carrier components called as PCC. Based on the traffic load and QoS requirements, E-UE can be attached with additional one (or more) CC, called as secondary CC (SCC) which corresponds to the secondary serving cell (SCell). Max we can use up to 5 SCC's [19] and with different combinations of bandwidths in inter CA or intra CA which is out of scope of this paper. The PCC serves as an anchor CC for the user and it is used for basic connectivity functionalities. The SCCs carry only user data and dedicated signalling information—PDSCH (physical DL shared channel), PUSCH (physical UL shared channel), and PDCCH (physical DL control channel). As the user connection greatly depends on PCC and it to be robust in both the UL/DL directions and to provide ubiquitous coverage it must be in licensed band to guarantee the QoS. For SCCs, unlicensed spectrum can be employed by CA method of LTE-U in one of the three modes whenever the achievable data rates using licensed spectrum is not enough to serve the E-UE. These three modes are:

1. *Supplemental downlink mode*: In this mode, an extra dedicated downlink path i.e., SCC is assigned in unlicensed spectrum to carry the data in downlink only. While the control channels information and the UL/DL transmissions of PCC remains in the licensed spectrum. The pictorial representation is shown in Fig. 3a for FDD and TDD scenarios.
2. *Carrier aggregation mode*: In this mode, a separate TDD channel is assigned in unlicensed spectrum to carry the both UL and DL data traffic. Similarly in this mode also,

Fig. 3 The channel allocation of FDD/TDD LTE-U modes in licensed and unlicensed spectrums for PCC/SCC. Here E-UE refers to the user equipment, triangles named with PCC and SCC indicates transmitter/receiver antennas: **a** supplemental downlink mode, **b** standalone mode and **c** carrier aggregation mode

the control channels remain in the licensed bands. Figure 2c shows the graphical representation.

3. *Standalone mode*: All channels i.e., UL, DL data traffic channels of all carriers and control channels are assigned in unlicensed spectrum in this mode. As it is not using any licensed spectrum there is no guarantee for QoS. The representation is shown in Fig. 2b.

Out of these three modes, only the supplemental downlink and the carrier aggregation modes are supported by 3GPP release12 [20] as in the standalone mode the transmissions using unlicensed spectrum in UL as well as in DL is not guaranteed the QoS. In supplemental and carrier aggregation modes it is not the case as the control signals and PCC will be assigned in the licensed band and in the unlicensed band SCCs will be assigned.

We assumed that the air interference links Among the SBS, WiFi AP and E-UEs are independent complex Gaussian random variables and the channel co-efficient of intra and inter licensed/unlicensed spectrums are g_{ll}, g_{ul}, g_{ul} and g_{lu} respectively. The additive noise is considered with sigma variance and mean zero. The received signal at LTE-U user is given by,

$$r_i(n) = \begin{cases} w(n) & \text{if medium is free} \\ g_{ul} * s(n) + w(n) & \text{if medium is busy} \end{cases} \quad (1)$$

where the $s(n)$ is the transmitted signal in the unlicensed spectrum and it is assumed as an iid random process with mean 0 and variance σ_s^2 . Furthermore, $s(n)$ is independent of $w(n)$.

3 Performance Analysis

In this section, we analyse the performance of LTE-U in the presence of the Wi-Fi network coverage. The main fundamental necessity of LTE-U/Wi-Fi co-existence is, activities of LTE-U network in the unlicensed spectrum shouldn't create interference to Wi-Fi system. Wi-Fi system uses carrier sense multiple access/ carrier avoidance (CSMA/CA) as channel access technology which can be considered as time division duplexing (TDD) because discontinuous transmission (DTx) and discontinuous reception (DRx) activities occurred in the same unlicensed band. So using channel reciprocity [21] to our proposed system model to overcome the feedback problem, we propose a transmit power control (TPC) strategy for LTE-U carriers which are operated in the unlicensed band, i.e.

1. Interference power sensed at the Wi-Fi user should be always less than the threshold limit P_λ due to SCC assignments in the unlicensed band which is given by Eq. (2).

$$E(g_{lu} * P_{LTE-U}(n)) \leq P_\lambda \quad (2)$$

Here P_{LTE-U} denotes the transmit power of the LTE-U system, P_λ is the average interference constraint to the Wi-Fi network, and $E(\cdot)$ is the expectation.

2. Once we have decided the interference threshold, we can estimate the allowable transmit power of a LTE-U based on CSI by measuring the channel co-efficient i.e.,
 - a. When LTE-U user is within the interference range of Wi-Fi user then the allowable Tx power of LTE-U user in this case can be expressed as [22],

$$P_{LTE-U} = \frac{P_\lambda}{\hat{g}_{lu}} \quad (3)$$

where $\hat{g}_{lu}$ is the actual estimated channel gain at LTE-U user.

- b. When it is detected as free medium, LTE-U user can transmit with desired closed loop power control set by cellular BS.

So, the allowable transmit power of LTE-U is given by,

$$P_{LTE-U}(n) = \begin{cases} P_{\max}, & \text{if } \hat{g}_{lu}(n) \leq \frac{P_\lambda}{P_{\max}} \\ \frac{P_\lambda}{\hat{g}_{lu}(n)}, & \text{elsewhere} \end{cases} \quad (4)$$

In practical, as the channel information estimation of links between LTE user and Wi-Fi network is imperfect, we consider power control parameter γ ($0 < \gamma < 1$) to assure the faire co-existence. By considering the power control parameter the maximum transmittable power by LTE-U system is given by

$$P_{LTE-U}(n) = \begin{cases} P_{\max}, & \text{if } \hat{g}_{lu}(n) \leq \frac{P_\lambda}{P_{\max}} \\ \gamma * \frac{P_\lambda}{\hat{g}_{lu}(n)}, & \text{elsewhere} \end{cases} \quad (5)$$

We can regulate the maximum allowable transmit power for a desired outage constrain at Wi-Fi user by calculating the γ as follows,

$$\begin{aligned} P_{O, Wi-Fi} &= \Pr(p_{LTE-U} * g_{lu} > P_\lambda) \leq \xi \\ &= \Pr\left(\frac{g_{lu}}{\hat{g}_{lu}} > \frac{1}{\gamma}\right) \leq \xi \\ &= 1 - F_{\frac{g_{lu}}{\hat{g}_{lu}}}\left(\frac{1}{\gamma}\right) \leq \xi \\ &= \frac{1}{2} \left\{ 1 - \frac{1 - \gamma}{\sqrt{(1 + \gamma)^2 - 4\sigma^2\gamma}} \right\} \leq \xi \end{aligned} \quad (6)$$

$$P_{O, Wi-Fi} = \frac{1}{2} \left\{ 1 - \frac{1 - \gamma}{\sqrt{(1 + \gamma)^2 - 4\sigma^2\gamma}} \right\} \leq \xi \quad (7)$$

From the above equation we can find the maximum possible value of λ so that maximum allowable P_{LTE-U} can be calculated. Having calculated the allowable transmitted power, we can now analyse the two metrics namely throughput and outage probability of SCC assignments in unlicensed spectrum.

3.1 Throughput

The mean capacity achieved by SCC of LTE-U system via unlicensed system can be calculated as follows:

$$\begin{aligned}
 C_{LTE-U} &= W \int_0^{\infty} \log_2(1+x) f_{\chi}(x) dx \\
 &= \frac{W}{\log_e 2} \int_0^{\infty} \frac{1 - F_{\chi}(x)}{1+x} dx
 \end{aligned} \tag{8}$$

where “W” is the unlicensed spectrum band width used, χ is the signal-to-interference-plus-noise ratio and it's pdf and cdf functions are denoted by $f_{\chi}(x)$, $F_{\chi}(x)$ respectively. Let the power transmitted by LTE-U in unlicensed spectrum is P_{LTE-U} and P_W is the power transmitted by Wi-Fi system, then the throughput in case of (i) maximum transmittable power and (ii) restricted power transmit case can be calculated as follows:

Case-i When LTE-U is allowed to transmit with maximum power, under the considered case the $F_{\chi}(x)$ can be expressed as,

$$\begin{aligned}
 F_{\chi}(x) &= P_r \left(\frac{P_{LTE-U} * g_{ll}}{N_o} < x \right) \\
 &= P_r \left(g_{ll} < \frac{x N_0}{P_{LTE-U}} \right) \\
 &= 1 - \exp \left\{ \frac{-x * N_0}{P_{LTE-U}} \right\}
 \end{aligned}$$

Thus, the capacity is expressed as,

$$C_{LTE-U}^i = \frac{W}{\log_e 2} \int_0^{\infty} \frac{1 - (1 - \exp(-x N_0 / P_{LTE-U}))}{1+x} dx \tag{10}$$

Using [23] and after some algebra, (11) can be expressed as,

$$C_{LTE-U}^i = - \left(\frac{W}{\log_e 2} \right) \exp(N_0 / P_{LTE-U}) E_i(N_0 / P_{LTE-U}) \tag{11}$$

Case-ii when LTE-U user is allowed to transmit with restricted power in which the CDF can be expressed as,

$$F_{\chi}(x) = P_r \left(\frac{P_{LTE-U} * g_{ll}}{N_o + P_W * g_{ul}} < x \right) = P_r \left(g_{ll} < x \left(\frac{N_0 + P_W * g_{ul}}{P_{LTE-U}} \right) \right) \tag{12}$$

We can reduce above equation as,

$$F_{\chi}(x) = 1 - [\exp((P_{\lambda} + x * N_0) / x * P_{W-U}) E_i(-(P_{\lambda} + x * N_0) / x * P_{W-U})] \tag{13}$$

Thus, the capacity is expressed as,

$$C_{LTE-U}^{ii} = - \left(\frac{B}{\log_e 2} \right) \int_0^{\infty} (-P_{\lambda} / x * P_W) \exp(P_{\lambda} + x N_0 / x * P_W) E_i(P_{\lambda} + x * N_0 / x * P_W) dx \tag{14}$$

3.2 Outage probability

Outage probability is defined as the probability that the mutual information rate is less than the minimum required threshold information rate. Here we assume that the LTE-U has expected this threshold value as R for the faithful communication and an outage will be resulted if the information rate is less than the desired rate R . Therefore, the outage probability of LTE-U in the integrated system for two mentioned scenarios can be expressed as:

Case-i The LTE-U will be allowed to transmit with maximum power during absence of the Wi-Fi user i.e., no Wi-Fi user is detected as active. Therefore, the outage probability in this scenario can be found as follows,

$$P_{O,LTE-U}^i = P_r \left(\log \left\{ 1 + \frac{P_{LTE-U} * g_{ll}}{N_o} \right\} \leq R \right) = 1 - \exp \left\{ -\frac{(2^R - 1) * N_o}{P_{LTE-U}} \right\} \quad (15)$$

Case-ii In this case the outage probability can be expressed as,

$$\begin{aligned} P_{O,LTE-U}^{ii} &= P_r \left(\log \left\{ \frac{P_{LTE-U} * g_{lu}}{N_o + P_W * g_{ul}} \right\} \leq R \right) \\ &= \int_0^\infty P_r \left\{ \frac{g_{lu}}{N_o + P_W * g_{ul}} \leq \frac{(2^R - 1)}{\eta * P_\lambda} \right\} f_{lu}(x) \\ &= 1 + \frac{1}{P_W * a * (1 - \sigma_e^2)} \exp(\alpha\beta) Ei(\alpha\beta) \end{aligned} \quad (16)$$

where $a = \frac{(2^R - 1)}{\gamma * P_\lambda}$, $\alpha = \frac{N_o a + 1}{1 - \sigma_e^2}$, $\beta = \frac{1}{P_W - Ua}$ and $Ei(x)$ is the exponential integral function which can expressed as, $Ei(x) = \int_0^\alpha \frac{e^{-t}}{t} dt$ [23].

4 Results and Discussion

In this section, we have evaluated analytical and simulation results based on above investigation using MAT LAB test bed. The following default values of the parameters are considered in this: $f_s = 5.6$ MHz, $P_{\max} = 20$ dB, outage constrain $\delta = 0.01$, $I_{th} = 10$ dB, SCC B.W = 20 MHz, data rate = 1, error variance = 0.01 and we assume the noise variance of AWGN as unity.

In Fig. 4, we represented Wi-Fi user's outage probability as a function of scaling factor of LTE-U transmit power for several values of correlation co-efficient which are indicated by legends $r=0.2$, $r=0.6$ and $r=0.9$. From the plot, it is clear that the outage probability of Wi-Fi user increases as the value of n increases while other parameters are kept constant and the effect of correlation co-efficient on the outage probability is also depicted. With the increased value of n , the effective transmitted power of LTE-U user is increased so the interference at Wi-Fi user. With the higher correlation co-efficient value i.e., estimation of CSI closer to the perfect case, allows higher transmit power level of LTE-U user which reduces outage probability. So, from the graph one can decide LTE-U transmitted power by choosing a proper value of n to restrict the desired outage constrain at Wi-Fi user.

Fig. 4 The outage constrain of Wi-Fi user versus scaling factor n for different values of correlation co-efficient

The throughput of LTE-U system for case-1 is shown as a function of transmitted power in the Fig. 5. Legends in the graph indicates simulation and analytical results for $N=1$ and 5. Figure 5 depicts the variation of throughput of LTE-U as a function of its Transmitted power. As the throughput is the function of SNR value and it increases with Transmitted power of the E-UE of the interest, throughput is increasing with the transmitted power. It is also observed that the effect of the background noise as well from the graph and it decreases the throughput as overall SNR value is decreased with the increment of background noise.

Fig. 5 Throughput versus transmit power of LTE-U user for different values of N of case-i

In Fig. 6, the throughput of LTE-U user is shown as a function of interference limit I_{th} for case-ii. As shown in the figure the throughput of LTE-U user is increasing monotonically with the allowable interference threshold value at Wi-Fi user. In the figure, the legends indicate analytical and simulation results for different values of scaling factor (n) and correlation variance. One can observe the effect of I_{th} from the graph that the throughput of LTE-U user is increased with interference limit by keeping other values constant. Increase in interference limit is nothing but allowing E-UE of interest to transmit with higher Tx levels. As it is allowed to transmit with the higher Tx levels, its achievable throughput values also increases for fixed values of n and p . It is also observed that the gain in the throughput of LTE-U user with incremented n and p values. However further increase in Tx level doesn't produce any significant improvement as it achieves saturated throughput.

In the Fig. 7, the analytical and simulation results of the outage probability is shown as the function of the Tx power of E-UE with separate legends. It is observed that the outage probability of LTE-U in unlicensed spectrum decreases with the transmit power. As we already discussed in the earlier plots, the achievable throughput will be increased if the Tx power increases. Hence the increment of Tx power results in lower outage probability. The effect of background noise is also depicted in the graph. The signal quality at the receiver will be worsen with the increased N_o is the reason for the further increased outage probability.

In Fig. 8 the Outage probability in case-ii is represented as the function of Interference threshold for the proposed TPC methodology. Legends in the plot indicate the simulation and analytical results for the different set of r , p values. In all the cases, the outage probability is decreasing with the interference threshold as shown in the figure. As the interference threshold is increased, E-UE is allowed to transmit at the higher power levels is the reason for reduction of outage probability. The considered higher values of n , p result in lower outage constrain. With the increased value of n , E-UE can transmit at higher levels for the same given interference threshold value and the higher value of p indicates the estimated channel is close to perfect. Hence these values together increase the SNR value and lower the outage probability.

Fig. 6 Throughput of LTE-U user versus interference threshold I_{th} for case-ii

Fig. 7 The outage probability of LTE-U as a function of Tx power for case-i

Fig. 8 The outage probability of LTE-U user versus interference threshold value for case-ii

5 Conclusion

In this paper, we have evaluated the channel access mechanism for the LTE-U SBS to utilize the unlicensed spectrum by developing the SBT approach without modifying the existing Wi-Fi protocol. Under the condition of E-UE association, we categorise two practical scenarios based on channel reciprocity theorem in which the way of utilizing the unlicensed spectrum is defined and we have derived a closed form expression for the outage probability and achievable data rates for each case. We have contemplated the performance evaluation in terms of allowable interference threshold, outage constrains and maximum

transmittable power of LTE-U. With the increase in the channel estimation error, the LTE-U users performance will be degraded. From the simulation results, it is observed that the higher interference threshold reduces the LTE-U outage, the Wi-Fi user's interference is found to degrade the LTE-U performance and the outage of LTE-U user increases with increase in Wi-Fi user interfering power. The comparison of the analytical and the simulation results hold good and well agreed.

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References

1. 3GPP. (2009). Evolved universal terrestrial radio access (E-UTRA); radio resource control (RRC); protocol specification. TS 36.331, Sophia-Antipolis, France, Technical Report.
2. 3GPP. (2015). 3rd generation partnership project; feasibility study on licensed assisted access to unlicensed spectrum; study on licensed-assisted access to unlicensed spectrum (release 13). 3GPP, Sophia Antipolis, France, TR 36.889 V13.0.0.
3. Chen, C., Ratasuk, R., & Ghosh, A. (2015). Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listenbefore- talk scheme. In *Proceedings of IEEE 81st vehicular technology conference (VTC)*, Glasgow, UK (pp. 1–5).
4. Ratasuk, R., et al. (2012). License-exempt LTE deployment in heterogeneous network. In *Proceedings of IEEE international symposium on wireless communication system (ISWCS)*, Paris, France (pp. 246–250).
5. Ratasuk, R., Mangalvedhe, N., & Ghosh, A. (2014). LTE in unlicensed spectrum using licensed-assisted access. In *Proceedings of IEEE GLOBECOM*, Austin, TX, USA (pp. 746–751).
6. Bhorkar, A., & Ibarr, C., Papathanassiou, A., & Zong, P. (2015). Medium access design for LTE in unlicensed band. In *Proceedings of IEEE international workshop on wireless communication network conference (WCNC)*, New Orleans, LA, USA (pp. 369–373).
7. Ko, H., Lee, J., & Pack, S. (2021). A fair listen-before-talk algorithm for coexistence of LTE-U and WLAN. *IEEE Transactions on Vehicular Technology*.
8. Li, Y., Zheng, J., & Li, Q. (2015). Enhanced listen-before-talk scheme for frequency reuse of licensed-assisted access using LTE. In *Proceedings of IEEE 26th international symposium on personal indoor mobile radio communications (PIMRC)*, Hong Kong (pp. 1918–1923).
9. Cano, C., & Leith, D. J. (2015). Coexistence of WiFi and LTE in unlicensed bands: A proportional fair allocation scheme. In *Proceedings of IEEE international conference on communications (ICC) workshop LTE unlicensed bands (LTE-U)*, London, UK (pp. 2288–2293).
10. Nihtilä, T., et al. (2013). System performance of LTE and IEEE 802.11 coexisting on a shared frequency band. In *Proceedings of IEEE international workshop on wireless communications network conference (WCNC)*, Shanghai, China (pp. 1038–1043).
11. Sadek, A. K. (2015). Carrier sense adaptive transmission (CSAT) in unlicensed spectrum. U.S. Patent 20,150,085,841 A1.
12. Cano, C., & Leith D. J. (2016). Unlicensed LTE/WiFi coexistence: Is LBT inherently fairer than CSAT? In *IEEE ICC 2016-mobile and wireless networking symposium*.
13. Interdigital. (2014). A look at the requirements for LTE in the unlicensed spectrum. In *3GPP RAN1 standard contribution, RWS-140006*.
14. Hajmohammad, S., & Elbiaze, H. (2013). Unlicensed spectrum splitting between Femtocell and WiFi. In *2013 IEEE international conference on communications (ICC)*, Budapest (pp. 1883–1888).
15. Bairagi, A. K., Tran, N. H., & Hong, C. S. (2017). LTE-U sum-rate maximization considering QoS and co-existence issue. In *2017 IEEE international conference on big data and smart computing (Big-Comp)*, Jeju (pp. 352–357).

16. Syed, I., Shin, S. H., Roh, B. H., & Adnan, M. (2011). Performance improvement of QoS-enabled WLANs using adaptive contention window backoff algorithm. *IEEE Systems Journal*, PP(99), 1–11.
17. Bhorkar, A., Ibars, C., Papathanassiou, A., & Zong, P. (2015). Medium access design for LTE in unlicensed band. In *2015 IEEE wireless communications and networking conference workshops (WCNCW)*, New Orleans, LA (pp. 369–373).
18. Berardineli, G., Sorensen, T. B., Mogensen, P., & Pajukoski, K. (2011). Transmission over multiple component carriers in LTE—A uplink. *IEEE Wireless Communications*, 18(4), 67–73.
19. 3GPP. (2011). Evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-UTRAN); Overall description; Stage 2 (Release 10), 3rd Generation Partnership Project, Valbonne, France, 3GPP TS 36.300, v.10.3.0.
20. 3GPP. (2014). 3rd generation partnership project; requirements for further advancement for evolved universal terrestrial radio access (E-UTRA) (LTE-advanced) (Rel 12). 3GPP, Sophia Antipoles, France, TR 36.193 V12.0.0.
21. Abdulkadir, Y., Simpson, O., Nwanekezie, N., & Sun, Y. (2016). Space–time opportunistic interference alignment in cognitive radio networks. In *Proceedings of the IEEE wireless communications and networking conference (WCNC)*, Doha, Qatar.
22. Bhowmick, A., Prasad, B., Roy, S. D., & Kundu, S. (2016). Performance of cognitive radio network with novel hybrid spectrum access schemes. *Wireless Personal Communications*, 91(2), 541–560.
23. Gradshteyn, I. S., & Ryzhik, I. M. (2007). *Table of integrals, series, and products* (7th ed.). London: Academic Press.

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