Enhanced LBT Algorithm for LTE-LAA in Unlicensed Band

Tao Tao, Feng Han and Yong Liu
Bell Labs (Shanghai)
Alcatel-Lucent Shanghai Bell, Shanghai, 201206, China
Email: {Tao.B.Tao, Feng.Han, Yong.g.Liu}@alcatel-sbell.com.cn

***Abstract*—In this paper, we focus on the deployment of LTE technologies coexisting with Wi-Fi technologies in the unlicensed spectrum 5 GHz. Listen before talk (LBT) functionality is required in unlicensed band in order to ensure the fair coexistence among different operators. We propose a LBT enhancement algorithm with contention window size adaptation for LTE with Licensed-Assisted Access (LTE-LAA) in order to achieve not only channel access fairness but also the QoS fairness. Simulation results show that LTE-LAA with LBT mechanism does not impact Wi-Fi services more than an additional Wi-Fi network. Compared with the fixed LBT mechanism, our proposed LBT algorithm could achieve around 4% and 6% LTE-LAA performance gain in user perceived throughput (UPT) and transmission latency, respectively. And, more than 25% Wi-Fi transmission latency gain can be also achieved. Furthermore, the simulation result shows the advantage of proposed LBT algorithm over original LBT procedure in the case of two LTE operators coexistence.**

***Index Terms*—LTE-LAA, unlicensed band, listen before talk**

I. Introduction

In recent years, the use of smart phones, tablets and other wireless devices have caused an exponentially growing data rate, network capacity in wireless communication systems. Increasing bandwidth is a straightforward way to increase capacity but available licensed spectrum is limited and very costly to be obtained. Recently, unlicensed spectrum attracts the interesting of cellular operators as a complimentary tool to augment their service offering [1]. A study item, "Study on Licensed-Assisted Access Using LTE (LTE-LAA)", was approved at 3GPP TSG RAN #65 [2], in which the deployment of LTE technologies coexisting with Wi-Fi technologies in the unlicensed spectrum 5G Hz would be studied.

Unlike licensed spectrum, an unlicensed band is an open resource and can be used by anyone as long as basic constraints on the transmit power spectral density are satisfied. Coexistence issues will arise if every operator is encourage to overuse the "free" unlicensed spectrum [3]. Therefore, a critical element of the design for LTE in unlicensed band is to ensure LTE-LAA co-exists with current access technologies such as Wi-Fi on fair and friendly bases.

In [4], the concept of LTE in unlicensed spectrum was first addressed with a focus on LTE usage in TV white spaces at 900 MHz band. In [5], coexistence performance with a simple coexistence scheme that reuses the concept of almost blank sub-frames in LTE is provided. They observe that Wi-Fi is hampered much more significantly than LTE in coexistence scenarios under such policy. [6] presents the system performance analysis of LTE-WiFi coexistence scenario with a simple fractional bandwidth sharing mechanism. [7] investigates deploying LTE on a license-exempt band as part of the pico-cell underlay and discusses several modifications for LTE operations. It includes the adoption of listen before talk mechanism by LTE eNB before transmission. Furthermore, in order to ensure the fair coexistence and to meet regulatory requirements in some regions/bands, listen before talk functionality is agreed to be required for a LTE-LAA system in RAN1 #78bis meeting [8] for the new 3GPP study item.

According to requirement of Harmonized European Standard in ETSI EN 301 893 V1.7.1 (2012-06) [9], LBT mandates performing a clear channel assessment (CCA) prior to a new transmission and occupying the channel with limited duration after successful access in the load based equipment (LBE). Such opportunistic channel access mechanism guarantees the access fairness among different nodes over unlicensed channel. As specified in [9], the equipment shall perform an extended CCA (eCCA) check when a channel is checked to be occupied by CCA. During eCCA, the channel is continuously observed for the duration of a random factor N multiplied by the CCA observation time. The value of N shall be randomly selected in the range $1 \ldots q$, in which the value of q shall be selected by the manufacturer in the range $4 \ldots 32$. If the equipment finds the channel to be clear, it can enjoy a continuous transmission burst time less than $(13/32) \times q$ ms. Fig. 1 depicts one example of LBE, where the backoff number for eCCA is 5.

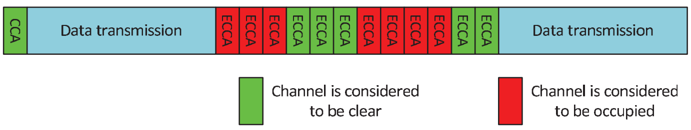

Fig. 1. An example of LBE frame structure.

Current LBT mechanism is a simple and fixed mechanism for sharing the medium, but lacks the ability to guarantee the service fairness of different types of traffic since multiple nodes experience different situations. With fixed contention window (CW) size and maximum channel occupancy time, different nodes have the same transmission opportunity regardless its traffic demand and the channel condition. The service fairness among multiple nodes is difficult to be achieved, if the LBT mechanism is designed without taking the factors such as the buffer state, the channel occupancy rate, and the channel condition into consideration. Furthermore, some traffic type such as VoIP and digital video, the quality of voice or video may deteriorate as a result of packet loss and large delay. For the same traffic type, the quality of service (QoS) should be maintained at the same level to handle the efficiency of multiservice traffic. Therefore, the transmission probability of each base station should be appropriately controlled to maintain the service fairness of multiple nodes, especially if there are lots of nodes wish to contend with the same spectrum.

In this paper, we focus on enhancing current LBT algorithm with contention window size adaptation for LTE-LAA so as to achieve not only the channel access fairness but also the QoS fairness. The basic idea of proposed algorithm is that the CW size of each node can be adaptively adjusted to an appropriate value by means of collecting the QoS metric signals from neighbor nodes. In case of intra-operator coordination, the information can be exchanged over the X2 interface. For inter-LTE operator or LTE and Wi-Fi operator coordination, these signaling and information can be also exchanged over the X2 interface if it is available. In this work, the approximated average transmission delay is deduced and considered as an example of the QoS metric. Furthermore, a gradient approaching algorithm is proposed as a semi-static and smooth CW size adjustment procedure to avoid disordered adjustment.

The remaining paper is organized as follows. Section II presents the system model and summarizes the problem as a Markov chain model. Section III presents the detailed design of our enhanced LBT algorithm with CW size adaptation. Simulation results and analysis are given in Section IV followed by a conclusion in Section V.

II. System Model

In this work, we focus on LTE technologies coexisting with Wi-Fi technologies in the unlicensed spectrum 5 GHz. In LTE-LAA, the data service is an opportunistic transmission. The channel availability should be checked before the transmission to guarantees no huge transmission quality impact on other nodes over unlicensed channel. As specified in [9], the file status in an eNB can be classified into two stages, the buffer state and the backoff state in a LAA system. In this work, we assume a non-saturated condition (the number of arrived files will never exceed the buffer size), which is more general and meaningful. In addition, first come first served (FCFS) algorithm is considered as the stack protocol in this work [10]. Furthermore, it is assumed that the traffic model for each base station is FTP-3, i.e., the arrival of request files follows an exponential process. Therefore the probability P_k of k-th files entering the buffer can be express as:

$$P_k = \Pr(X = k) = \lambda \exp^{-\lambda k}, \tag{1}$$

where, λ is the file arrival rate of the eNB.

To model the problem, the file access activities in a LAA eNB are summarized as a Markov chain model in Fig. 2. A file

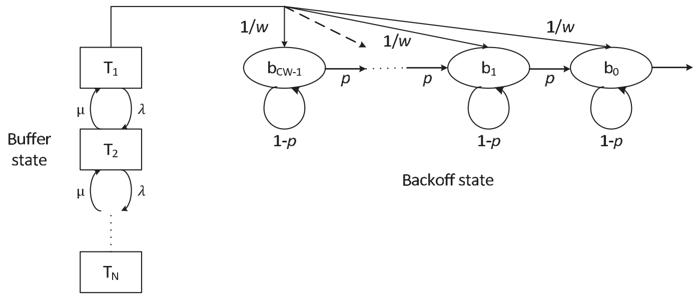

Fig. 2. Transition model of file activities in an eNB.

status transits from the buffer state to the backoff state (from T_1 to b_i) when it is scheduled by the eNB. A backoff counter w for the file is firstly generated in the range $[0, \mathrm{CW}-1]$ randomly fulfilling the uniform distribution. That means the file has the same probability dropping into the state b_i, where $i \in [0, \mathrm{CW}-1]$. In the backoff state, the equipment shall perform a CCA check to observe the channel availability. If the channel is checked as free, the backoff counter can be decreased by 1 (i.e. the file status moves from b_i to b_{i-1}). Otherwise, the backoff number maintains the same value since the channel is occupied by other nodes. The transition probability of this process is assumed to be p, which is related to the collision rate, is determined by many factors such as the number of competition nodes, the channel condition and the traffic demand of a given node. In this contribution, we assume that backoff transition probability p can be approximated by the channel occupancy rate or sensing results of a given node. For instance, if a historical sensing result of a node is that with 80% of the case the channel is sensed as free and with 20% of the case the channel is sensed as busy. In this case, p can be approximated to be $4/5$.

Therefore, the transition probabilities in the whole Markov chain can be summarized as:

$$\begin{cases} P\left(\mathrm{b}_i|\mathrm{T}_1\right) = 1/w \\ P\left(\mathrm{b}_{i-1}|\mathrm{b}_i\right) = p \\ P\left(\mathrm{b}_i|\mathrm{b}_i\right) = 1-p \end{cases}. \tag{2}$$

Here, $P(Y|X)$ represents the conditional probability of a transition from state X to state Y. The first equation in (2) indicates a file transits from the buffer state to backoff state, and T_1 indicates the latest state when file is ready to be transmitted, w is the backoff counter. The second and the third equations in (2) indicate the transition probability of backoff counter decreased by 1 or not, respectively.

III. Proposed LBT procedure enhancement

In this section, we elaborate our designs of adjusting contention window size for LBT procedure.

A. QoS Metric Design

The transmission latency is a very sensitive QoS index, especially when the real-time service is adopted. In the following, the approximated average transmission delay is deduced and considered as an example of the QoS metric. According to (2), the average transition duration for backoff counter decrease by 1 can be calculated as:

$$\begin{aligned} t_{\text{1-backoff}} &= \lim_{n\to\infty} (p \cdot t_{\text{slot}} + p \cdot (1-p) \cdot 2t_{\text{slot}} + \\ & \quad p \cdot (1-p)^2 \cdot 3t_{\text{slot}} + \cdots + p \cdot (1-p)^{n-1} \cdot nt_{\text{slot}}) \\ &= \frac{t_{\text{slot}}}{p}, \end{aligned} \tag{3}$$

where, t_{slot} is the CCA observation time.

Since the backoff counter w is uniformly generated in the range $[0, \text{CW}-1]$, the average time spend on backoff state can be calculated straightforward:

$$t_{\text{All-backoff}} = \left(\frac{t_{\text{slot}}}{p} \cdot \frac{\text{CW}}{2}\right), \tag{4}$$

where, CW is the contention window size. It can be concluded that the average time spend in the backoff state is proportion to CW size and inverse proportion to p.

With above assumptions, the file connection activities can be modeled as M/M/1 queuing system. According to [11], we can conclude that the average time spend in the system is $W_s = \frac{1}{\mu-\lambda}$. Here, λ is the file arrival rate and μ is the system service rate. In this assumption, the service rate is related to the backoff delay and the file transmission time and can be calculated as:

$$\mu = \frac{1}{t_{\text{transmission}} + t_{\text{All-backoff}}}. \tag{5}$$

Furthermore, the average time spend in the system of a file can be expressed as:

$$W_s = \frac{1}{\mu-\lambda} = \frac{1}{\frac{1}{t_{\text{transmission}} + \left(\frac{t_{\text{slot}}}{p}\right) \cdot \frac{\text{CW}}{2}} - \lambda} \tag{6}$$

For the same type of traffic, the average time spend in the system W_s, which is also can be considered as the average transmission delay, should be maintained at the same level in order to achieve the file connection fairness among different nodes. In this work, the average transmission delay related to the contention window size as shown in (6), are considered as the QoS metric.

B. Adaptive CW Size Adjustment

By collecting the QoS metric information from neighbor nodes via X2 interface, the node is able to adjust its CW size to achieve service fairness. For example, it is assumed that node A and node B shares the same spectrum resource and has the same type of traffic. If node A approximates its average transmission delay to be 50 ms, and node B approximates its average transmission delay to be 600 ms. By exchange these delay information, node A finds that it performs far better than node B. If a desirable QoS is already achieved by node A, node A could enlarge its contention window value to release some resource to node B so as to achieve fairness between these two nodes. At the same time, node B notices that it does not work in a good situation, it decreases the contention window to grab more channel access opportunity. Furthermore, the QoS metric

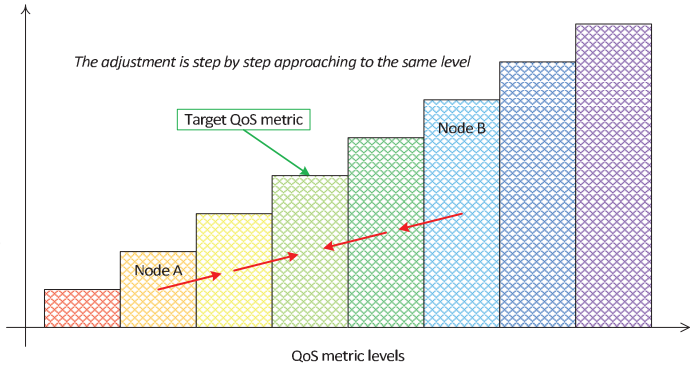

Fig. 3. Procedure of contention window size adjustment.

can be classified into multiple levels due to limited number of exchange information. For instance, the transmission delay can be cataloged into 8 levels, i.e., 3 bits feedback information. The Nodes, that content on the same channel, aim to approach the same level of QoS as shown in Fig. 3.

It has to be mentioned that the CW adjustment should be a semi static and smooth procedure, since slight contention window size adjustment will affect the channel competition result of all contenders and the communication via X2 interface is a relatively slow behavior. For instance, the CW value of each node can be updated every second or tens of seconds, which depends on the speed of information exchange.

Furthermore, a gradient approaching algorithm is proposed for the CW size adaptive adjustment.

- Firstly, a node collects the QoS metric from nearby nodes to design a target metric. The target QoS metric of a given node can be calculated by averaging all QoS metrics with the same traffic type. Take the average transmission delay as an example:

$$W_s{}^{avg} = \sum_{i=1}^{N} W_s(i)/N, \tag{7}$$

  where N is the number of neighbor nodes with the same traffic type and $W_s(i)$ is the approximated average transmission delay for node i. In addition, prioritized QoS should be considered in multiservice traffic, e.g., real-time sensitivity service should have better QoS metric than non-realtime service from the fairness point of view.
- Then, each node compares its own QoS metric with the target metric and selects an appropriate CW value to increase/decrease its own QoS metric approaching to the target one as the following expression:

$$\begin{aligned} & if \quad W_{s_i} < W_s^{avg} - \text{TH} \\ & \quad \text{CW}_i = \text{CW}_i + \text{Step}; \\ & elseif \quad W_{s_i} > W_s^{avg} + \text{TH} \\ & \quad \text{CW}_i = \text{CW}_i - \text{Step}; \\ & else \\ & \quad maintain \quad \text{CW}_i; \end{aligned} \tag{8}$$

Here, ”TH” is a threshold to trigger the CW size adjustment and ”Step” is the adjustment granularity which controls the speed of the adjustment.

- By adjusting the contention window size adaptively, the QoS fairness for multiple nodes can be finally achieved.

IV. Simulation Results and Analysis

A. Simulation Environment

In our work, a comprehensive system level simulator of 3GPP LTE-A with small cell enhancement scenario 2a and 3 is carried out. We consider a cellular network with 7 hexagonal cell sites and 3 sectors per site in an outdoor scenario as shown in Fig. 4. In each sector, four LTE eNBs and four Wi-Fi APs are randomly dropped and grouped as a cluster.

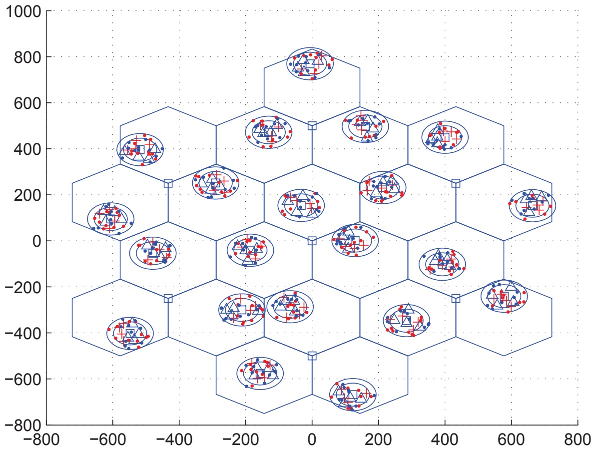

Fig. 4. Network Layout for the outdoor scenario, 7 macro sites, 3sectors/site, 4 LTE nodes and 4 Wi-Fi APs/sector.

All simulation parameters follow the latest simulation methodology agreed in 3GPP [12] and summarized in Table I. Two coexistence cases are evaluated: LAA-WiFi coexistence and LAA-LAA coexistence.

B. Simulation Results

Table II shows the system performance of LAA-WiFi coexistence scenario with fixed LBT mechanism and our proposed LBT strategy with CW adaptation. The average user perceived throughput (UPT) and the transmission latency are considered as the performance metrics. Here, the Wi-Fi performance in the WiFi-WiFi coexistence scenario is given as a performance baseline. In our simulation, we assume ”step” in (8) to be 1 and ”TH” to be 0.1, which indicates a relatively conservative adjustment. The periodicity of CW size adaptation is 100 ms.

From our simulation results, it can be observed that LTE-LAA provides fair coexistence with Wi-Fi, while sacrificing a little performance itself. This is because LTE has more efficient physical layer spectrum efficiency and less access opportunity than Wi-Fi. Hence, LTE-LAA with LBT mechanism does not impact Wi-Fi services more than an additional Wi-Fi network. Comparing the LAA performance between LBT with fixed CW size and proposed enhanced LBT, our algorithm shows around 4% and 6% gain in mean UPT and mean transmission latency, respectively. For the performance of Wi-Fi, the proposed LBT algorithm can achieve more than 25% average latency gain compared with original LBT mechanism. And better fairness of UPT and latency can be achieved among WiFi UEs due to CW size adaptation in LAA. Fig 5 shows the average transmission latency C.D.F with different LBT schemes (fixed CW size = 10; fixed CW size = 16; and proposed adaptive CW size with initial value 16). It can be observed that our proposed adaptive CW size strategy outperforms original fixed LBT approaches with different CW sizes.

TABLE I
Coexistence Evaluation Assumptions

Parameter	**LAA**	**Wi-Fi**
Outdoor scenario layout	Based on SCE #2a + unlicensed band; X=4, Y=1; 10 UEs per operator per carrier	
Indoor scenario layout	Based on SCE #3 + unlicensed band; X=4, Y=1; 10 UEs per operator per carrier	
Carrier frequency	5 GHz	5 GHz
System bandwidth	1 unlicensed carrier with 20 MHz	1 unlicensed carrier with 20 MHz
MCOT	4 ms	3 ms
Traffic model	Single traffic type: FTP Model 3; File size: 0.5 Mbytes	
File arrival rate	Randomly between $[0.6, 0.8]$ for each node	
Total BS TX power	18 dBm	18 dBm
Antenna configuration	2Tx2Rx in DL; adaptive stream	2Tx2Rx in DL; 2 fixed streams
CCA-ED	-55 dBm	-62 dBm
Channel coding	BCC	BCC
MCS	Based on TM10, QPSK/16QAM/64QAM	802.11ac MCS table without 256 QAM
Link adaptation	Realistic	Rate control - Minstrel algorithm
Network synchronization	For the same operator, the network is ideally synchronized; Small cells of different operators are not synchronized	

MCOT indicates maximum channel occupancy time

TABLE II
System performance in LAA-WiFi coexistence scenario

Performance		Baseline	Fixed q=16		Adaptive q	
		WiFi	WiFi	LTE	WiFi	LTE
UPT	5%	12.77	9.94	12.71	17.92	16.71
	50%	58.04	64.61	46.49	62.89	50.54
[Mbps]	95%	97.03	100.77	78.25	97.98	85.09
	mean	56.70	61.14	47.48	61.52	49.30
Latency	5%	32	33	38	33	38
	50%	77	68	89	70	84
[ms]	95%	630	814	500	639	457
	mean	175.47	211.36	164.55	168.16	154.95

Furthermore, we evaluate different LBT approaches in a two different LAA operators coexistence scenario as shown in Table III. In our simulation assumption, the initial value of contention window size in proposed LBT algorithm is consid-

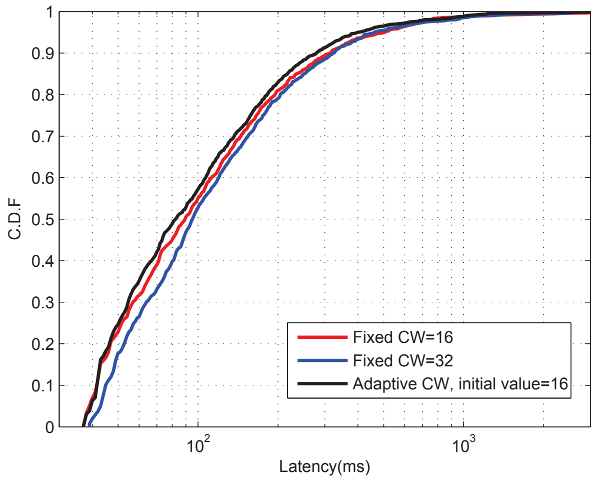

Fig. 5. Averaged transmission latency per LTE UE in LTE-WiFi coexistence scenario.

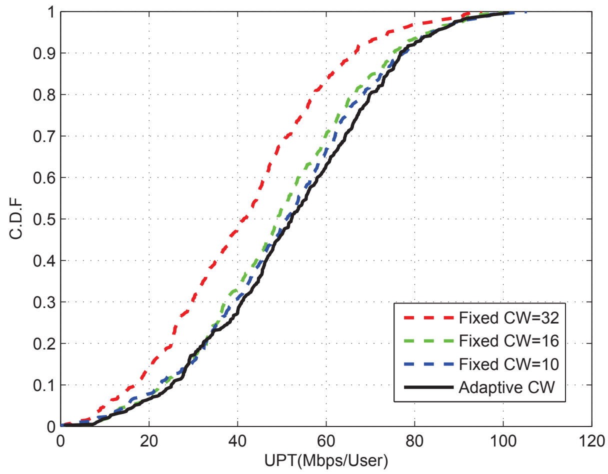

Fig. 6. User perceived throughput per LTE UE in LAA-LAA coexistence scenario.

ered to be 16 for fair comparison with fixed CW approaches. In addition, the presented performance is the aggregated value of both LTE operators. From our simulation results, it can be observed that the system performance is very sensitive to the LBT contention window size configuration. The maximum performance difference is more than 25% and 40% in term of UPT and latency, respectively. From this point of view, it proves that LBT parameters should be adjusted adaptively based on the traffic load, sensing results or the traffic type to achieve service fairness. Our enhanced LBT algorithm with contention window size adaptation outperforms fixed CW size mechanism in the case of two LAA operator coexistence. It shows that intrinsically selfish operators can cooperate for their mutual benefit.

TABLE III
AGGREGATED LTE PERFORMANCE IN LAA-LAA COEXISTENCE SCENARIO

Performance		CW=32	CW=16	CW=10	Adaptive CW
UPT [Mbps]	5%	9.76	15.13	15.35	16.61
	50%	41.28	48.96	50.93	52.13
	95%	73.88	83.28	83.57	84.33
	mean	41.45	49.44	50.66	52.05
Latency [ms]	5%	41	38	37	38
	50%	110	84	83	81
	95%	577	397	425	392
	mean	184.20	135.55	139.85	131.52

V. CONCLUSION

Within this contribution an enhanced LBT algorithm is proposed to achieve the QoS fairness for LTE-LAA coexisting with Wi-Fi in the unlicensed band. The approximated average transmission delay is deduced and considered as an example of the QoS metric. Furthermore, a gradient approaching algorithm is proposed as a semi-static and smooth CW size adjustment procedure to avoid disordered adjustment. The simulation results show that the proposed LBT enhancement with contention window size adaptation outperforms original fixed LBT procedure in the case of LAA-WiFi coexistence and LAA-LAA coexistence.

REFERENCES

[1] Qualcomm, “LTE in unlicensed spectrum: Harmonious coexistence with Wi-Fi,” *white paper*, June 2014.
[2] 3GPP TD RP-141664, “Study on Licensed-Assisted Access using LTE,” Sept. 2014.
[3] 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 *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, June 2013, pp. 1–6.
[4] M.I. Rahman, A. Behravan, H. Koorapaty, J. Sachs, and K. Balachandran, “License-exempt LTE systems for secondary spectrum usage: Scenarios and first assessment,” in *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, May 2011, pp. 349–358.
[5] E. Almeida, A.M. Cavalcante, R.C.D. Paiva, F.S. Chaves, F.M. Abinader, R.D. Vieira, S. Choudhury, E. Tuomaala, and K. Doppler, “Enabling LTE/WiFi coexistence by LTE blank subframe allocation,” in *Communications (ICC), 2013 IEEE International Conference on*, June 2013, pp. 5083–5088.
[6] T. Nihtila, 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 *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, April 2013, pp. 1038–1043.
[7] R. Ratasuk, M.A. Uusitalo, N. Mangalvedhe, A. Sorri, S. Iraji, C. Wijting, and A. Ghosh, “License-exempt LTE deployment in heterogeneous network,” in *Wireless Communication Systems (ISWCS), 2012 International Symposium on*, Aug 2012, pp. 246–250.
[8] RAN1, “Chairmans Notes for 78bis meeting,” Oct. 2014.
[9] Harmonized European Standard ETSI EN 301 893 V1.7.1, “Broadband Radio Access Networks (BRAN); 5GHz high performance RLAN,” June 2012.
[10] R.G. Gallager, “A perspective on multiaccess channels,” *Information Theory, IEEE Transactions on*, vol. 31, no. 2, pp. 124–142, Mar 1985.
[11] Dimitri P Bertsekas, Robert G Gallager, and Pierre Humblet, *Data networks*, vol. 2, Prentice-Hall International New Jersey, 1992.
[12] 3GPP TR 36.889, “Study on licensed-assisted access to unlicensed spectrum (release 13),” 2015.