LTE/Wi-Fi Coexistence: Challenges and Mechanisms

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***Abstract*— Wireless communications industry foresees an exponential increase of the traffic demand for the next years. Spectrum scarcity for the operation of cellular networks makes the use of unlicensed spectrum an attractive alternative for traffic offload. From the technical perspective, LTE pico/femtocells arise as the preferable traffic offload solution. On the other hand, Wi-Fi broad and low cost deployment makes it a competitive solution. The use of both technologies for traffic offload is thus a possible scenario which brings some challenges. This paper discusses LTE/Wi-Fi coexistence challenges and two enabling mechanisms. Both mechanisms are based on LTE features and have their performance evaluated by simulations.**

***Keywords*— Radio spectrum management, LTE, Wi-Fi, heterogeneous networks coexistence.**

I. INTRODUCTION

Wireless communications industry has been challenged in recent years by the expanding demand for wireless broadband access to Internet. The proliferation of high data rate and new wireless devices leads to the forecast of exponential traffic growth for the next years [1]. Sustained spectral efficiency improvement has been achieved by cellular manufacturers and operators by means of several advanced techniques (optimized macro/pico/femtocells deployments, Multiple-Input, Multiple-Output (MIMO) communications, transmission relay, etc.), but such operation improvement seems to be limited by two aspects: spectrum scarcity and increasing deployment costs.

Radio spectrum is the fundamental resource for wireless broadband access. Although the mentioned usage improvement, radio spectrum is a finite resource and its scarcity is already a serious issue faced by operators worldwide. Some analyses foresee, for instance, a bandwidth shortage of 275 MHz in the United States by 2014 [2]. Regarding the deployment costs limitations, it is well known that smaller cells require lower power transmissions, generate less interference, and provide higher capacity. They are thus attractive solutions. However, the coverage of a certain area requires a number of small cells higher than if conventional cells are adopted. Then, the large scale deployment of small cells increases the costs with acquisition and installation of equipment, as well as maintenance of the structure. Additionally, the common flat rate tariffs do not provide revenue increase in the same scale as expenditures, as pointed out in [1]. Therefore, low cost solutions for enabling capacity expansion are required.

Capacity expansion of cellular networks has been carried out by the so-called mobile traffic offload. It consists in using complementary network technologies to attend part of the traffic demand. Two distinct wireless broadband access technologies are the main candidates: the Long Term Evolution (LTE) and the IEEE 802.11 standard for Wireless Local Area Networks (WLANs), known as Wi-Fi. LTE has a centrally-controlled architecture which makes use of Orthogonal Frequency-Division Multiple Access (OFDMA) as channel access mechanism in licensed bands. On the other hand, Wi-Fi operates in unlicensed bands and is characterized by unplanned deployments and a decentralized channel access mechanism based on Carrier Sensing Multiple Access (CSMA).

Operation in unlicensed frequency bands is an important aspect of traffic offload. Although being conceived to operate in licensed bands, an increasing number of works consider that LTE might be deployed in unlicensed bands in the near future [3], [4]. From the technological perspective, LTE is the preferable choice for traffic offload due to its optimal usage of radio resources. However, it requires backhaul connection to the operator's infrastructure. On the other hand, the low deployment costs of Wi-Fi and its broad adoption make it competitive in spite of its lower radio resource usage efficiency.

Joint operation of LTE and Wi-Fi in the same license-exempt bands is a real possibility [3], [4]. Since they are not currently designed to share the same spectrum band, performance degradation is expected. Performance of LTE and Wi-Fi networks in coexistence is evaluated in [5], [6], where key issues are pointed out. It is generally observed that Wi-Fi performance is severely degraded, while LTE is slightly impacted. This results from the Wi-Fi protocol operation, CSMA, which provides channel access only in low interference situations. Therefore, mechanisms for enabling LTE/Wi-Fi coexistence are needed.

This paper discusses the challenges of LTE/Wi-Fi coexistence and presents two enabling mechanisms. First, an interference avoidance mechanism based on the Release 10 LTE feature called Almost Blank Subframe (ABS) [7] is presented. Proposed in [8], this mechanism improves Wi-Fi performance by allocating LTE subframes to Wi-Fi only transmission. The second approach is an interference management mechanism proposed in [9], where the conventional LTE uplink (UL) power control is modified to reduce the transmit powers of some LTE User Equipments (UEs), improving Wi-Fi performance. Both mechanisms consist in transferring resources from LTE to Wi-Fi, allowing the establishment of a trade-off between LTE and Wi-Fi operation.

The paper is organized as follows. In Section II a brief overview of LTE/Wi-Fi coexistence issues is presented. Section III presents the two approaches for enabling LTE/Wi-Fi coexistence. Simulation results and discussions are found in Section IV. Finally, conclusions are given in Section V.

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II. Challenges for LTE/Wi-Fi Coexistence

The lack of coordination and the inability to manage mutual interference are the main challenges for the coexistence of different wireless technologies as LTE and Wi-Fi. In general, wireless communication systems have interference management or avoidance mechanisms, but these are not designed to work with heterogeneous wireless protocols/standards. Then, such mechanisms may not be effective in coexistence scenarios where the networks have different channel access techniques and transmission/interference ranges, incompatible time slots and communication mechanisms, etc.. This is the general picture of the coexistence between LTE and Wi-Fi in the same frequency bands.

Wi-Fi default channel access mode is known as Distributed Coordination Function (DCF). DCF implements a contention-based channel access with the protocol known as Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). In DCF mode, any Wi-Fi node has to listen to the channel before transmitting. Only if the channel is sensed as vacant, i.e. the observed interference power is below a given threshold, then the node is able to transmit. This procedure is called Clear Channel Assessment (CCA). Therefore, when impacted by interference levels above the CCA threshold, Wi-Fi nodes defer transmissions for a random time (backoff procedure) in order to avoid transmission collisions. This may happen because of interference from other Wi-Fi nodes, or because of interference coming from a coexistent LTE network, and determines a low channel utilization efficiency.

On the other hand, resource allocation in LTE is more efficient and flexible. While Wi-Fi employs OFDM transmission with CSMA/CA protocol, LTE is based on OFDMA channel access technique, thus allowing simultaneous low data rate transmission from several UEs with optimized allocation of frequency and time. LTE does not implement any carrier sensing detection prior to transmission; it has channels reserved for control and management that make possible concurrent transmissions. Also, LTE base stations (eNodeBs) deployment is usually planned, and inter-eNodeB communication may also be used for channel usage coordination.

From the operational structure of both networks, Wi-Fi is likely to be blocked by LTE transmissions in scenarios of coexistence. Recent works on the subject corroborate the analysis [5], [6]. In [5], a semi-static system level simulator with standard-compliant LTE and Wi-Fi networks implemented is used to evaluate the performance of both networks in coexistence for several indoor office scenarios. The simulator includes the modeling of the network layout, nodes distribution, traffic generation, radio environment, physical layer (PHY) and multiple access (MAC) layer. Simulation results indicate that Wi-Fi performance is severely degraded when it operates concurrently with LTE, while LTE performance is marginally affected. High interference caused by LTE in these scenarios makes Wi-Fi nodes mostly stay on listen mode, waiting for a channel access opportunity. Wi-Fi nodes waste at least 96% of time in listen mode in the scenarios considered in [5]. Similar conclusions are obtained in [6], where instead of full buffer traffic, other traffic models are considered. These studies emphasize the need for mechanisms for the implementation of coexisting LTE and Wi-Fi networks.

III. LTE Mechanisms for Coexistence with Wi-Fi

LTE has several mechanisms for interference management. It is reasonable to consider some of such mechanisms to enable or improve the coexistence with Wi-Fi. With this purpose, two approaches are presented in the following with basis on existing LTE techniques.

A. Blank Subframes

LTE Release 10 introduced a key feature for enhanced Inter Cell Interference Coordination (eICIC): the Almost Blank Subframe (ABS) [7]. ABS is a subframe with reduced downlink (DL) transmission power or activity. The use of ABS has as objective to coordinate transmissions of heterogeneous deployments, with macro eNodeBs using less resources and causing less interference to pico eNodeBs during ABS. There is no macro eNodeB data transmission in this time interval, but ABS is required to be compatible with previous LTE Releases 8 and 9, and thus some control channels and synchronization signals are present in ABS, as the Primary and Secondary Synchronization Signals (PSS and SSS), and the Physical Broadcast Channel (PBCH). Moreover, Common Reference Signals (CRSs) are also transmitted for demodulation and Channel State Information (CSI) feedback.

An approach inspired on the ABS feature for the coexistence between LTE and Wi-Fi is discussed in [8]. It consists in a time-domain multiplex for LTE and Wi-Fi networks, where one or more LTE subframes are blanked (no data or reference signals). During blank subframes, Wi-Fi nodes detect the channel as vacant once the sensed interference power is below the CCA threshold, giving opportunity to Wi-Fi transmission. From the LTE side, time resources are lost with blank subframes, leading to throughput decrease. Fig. 1 illustrates possible allocations of blank subframes within an LTE Time-Division Duplex (TDD) frame (10 milliseconds). Downlink and uplink subframes are respectively denoted by "D" and "U", while "B" represents the blank subframe. The special subframe, where the switch from downlink to uplink transmission happens, is represented by "S".

Frame Configuration	Subframe Number									
	0	1	2	3	4	5	6	7	8	9
Common	D	S	U	U	D	D	S	U	U	D
1 Blank Subframe	D	S	U	U	D	D	S	B	U	D
2 Blank Subframes	D	S	U	D	D	D	S	B	B	U
4 Blank Subframes	D	S	B	B	D	D	S	B	B	D

Fig. 1. Examples of subframe allocation.

B. Uplink Power Control

LTE power control procedures are specified and established by 3GPP [10]. For data uplink transmission, the LTE UE uses the Physical Uplink Shared Channel (PUSCH) with the following transmit power setting:

$$P(i) = \min\{P_{\max}(i), P_{OL}(i) + P_{CL}(i)\}, \quad (1)$$

where $P(i)$ is the UE transmit power, $P_{\max}(i)$ is the maximum transmit power, and $P_{OL}(i)$ and $P_{CL}(i)$ are the open loop and closed loop transmit power components for subframe i.

The open loop LTE UL power control is defined as:

$$P_{OL}(i) = P_0(j) + \alpha(j)PL \quad \text{[dBm/PRB]}, \quad (2)$$

where $P_0(j)$ and $\alpha(j) \in \{0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\}$ are cell specific parameters provided by higher layers in subframe $j = 0, 1$ or 2; PL is the downlink path loss estimate in dB. The unit in (2) is dBm per Physical Resource Block (PRB).

In a conventional open loop power control, the transmit power is defined to provide a certain mean target Signal-to-Noise Ratio (SNR), SNR_0, at the receiver. In LTE, power control is fractional (when $\alpha(j) < 1$), reducing the interference caused by cell edge users to adjacent cells. This mechanism leads to a mean target SNR that depends on the UE path loss. The open loop transmit power can be written as [9], [11]:

$$P_{OL}(i) = P_{\max} + \alpha(j)\left(SNR_0 - SNR_{\max}\right), \quad (3)$$

where $SNR_{\max} = P_{\max} - PL - P_N$ is the SNR achieved with $P_{\max}$, and P_N denotes the noise power.

The closed loop term of the LTE UL power control is composed of a Modulation and Coding Scheme (MCS)-dependent component, Δ_{TF}, and a Transmit Power Control (TPC) command, $f_{\Delta TPC}$, both defined in [10], i.e.:

$$P_{CL}(i) = \Delta_{TF}(i) + f_{\Delta TPC}(i) \quad \text{[dBm/PRB]}. \quad (4)$$

The TPC command is UE specific. If accumulation is enabled:

$$f_{\Delta TPC}(i) = f_{\Delta TPC}(i-1) + \delta(i-K), \quad (5)$$

where $\delta(i-K) \in \{-1, 0, 1, 3\}$ dB is signaled in subframe $i-K$, with K varying from 4 to 7. If accumulation is not enabled, the TPC command $f_{\Delta TPC}(i)$ is directly given by $\delta(i-K) \in \{-4, -1, 1, 4\}$ dB. The update δ is determined according to the comparison between the target and the achieved Signal-to-Interference plus Noise Ratio (SINR) at the receiver. The closed loop power control represented by (4)-(5) is vendor or implementation specific.

LTE UL power control can play an important role for the coexistence with Wi-Fi, since it is able to manage the interference caused by LTE UEs to neighboring Wi-Fi nodes. For coexistence purposes the power operating point should be lower for UEs that cause high interference. Since the UE transmit power is set to compensate path loss and interference, UEs experiencing high path loss and/or high interference will transmit with high power and cause high interference. Therefore, an LTE UL power control with interference aware operating point is proposed for the improvement of LTE/Wi-Fi coexistence. The power operating point, P_{OP}, is defined as a function of both path loss and interference, derived from the following general SINR based power control formulation:

$$P_{OP}(i) = P_{\max} + \alpha(j)\left(SINR_0 - SINR_{\max}\right) \quad \text{[dBm/PRB]}, \quad (6)$$

where $SINR_{\max}$ is the SINR achieved with $P_{\max}$, i.e.:

$$SINR_{\max} = P_{\max} - PL - 10\log_{10}\left(\beta \cdot 10^{I/10} + 10^{P_N/10}\right), \quad (7)$$

and I represents the interference power in dBm measured at the eNodeB. Parameter $0 \leq \beta \leq 1$ is introduced to control the penalization of the power operating point according to interference, as discussed in the following.

From expressions (6) and (7), and considering the relationship between target SINR and target SNR given below:

$$SINR_0 = SNR_0 + P_N - 10\log_{10}\left(10^{I/10} + 10^{P_N/10}\right), \quad (8)$$

we rewrite (6) as follows:

$$P_{OP}(i) = P_{OL}(i) + \alpha(j) \cdot 10\log_{10}\left(\frac{\beta \cdot 10^{IoT/10} + 1}{10^{IoT/10} + 1}\right), \quad (9)$$

where $P_{OL}(i)$ is the open loop term defined in (2), and $IoT = I - P_N$ is the interference over thermal noise power in dB. Note that the power operating point P_{OP} now takes into account interference. Furthermore, expression (9) is a generalization of the conventional LTE fractional power control. For $\beta = 1$, P_{OP} is reduced to P_{OL}, i.e. no penalization on the power operating point is imposed due to interference. The same happens if there is no interference. On the other hand, with $\beta < 1$ P_{OP} is always lower than P_{OL} due to the penalization imposed by the right hand second term in (9) as a function of β and the interference level.

Fig. 2 shows the variation of the interference aware penalization over P_{OL} in (9) with β and IoT. Lower values of β impose stronger penalization on P_{OP}. Moreover, for a given β, the penalization increases with IoT until a saturation level, except for $\beta = 0$, which does not saturate.

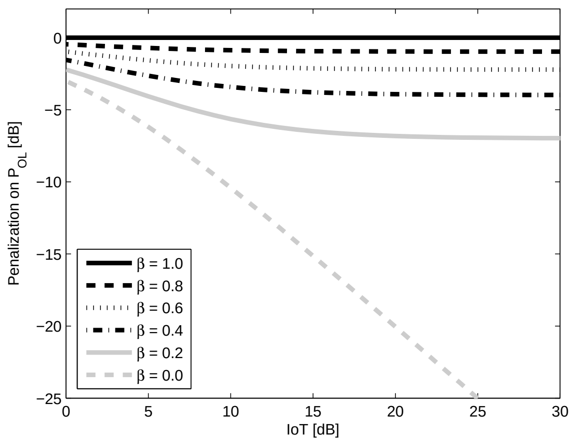


Fig. 2. Penalization over the conventional power operating point P_{OL} with the variation of IoT for different values of parameter β in (9).

A suitable implementation of the LTE UL power control with interference aware power operating point is to consider the penalization term over P_{OL} in (9) as part of the closed loop power control. Precisely, the UE sets the open loop transmit power as usual, while the eNodeB calculates the penalization term and includes it on the calculation of the TPC command. Since the TPC command is determined by the comparison between the target and the achieved SINR at the eNodeB, including it on this calculation corresponds to decreasing the target SINR when high interference is observed. This way, UEs transmit with lower power and cause less interference.

IV. SIMULATION RESULTS

In this section, simulation results of LTE and Wi-Fi networks in coexistence are presented for both approaches: blank subframe allocation and modified LTE UL power control. A brief description of the simulation tool and the scenarios considered in this work is given below.

A. Simulation Tool and Deployment Scenario

We evaluate LTE/Wi-Fi coexistence in an indoor office environment composed of 20 single floor rooms with 10 m $\times$ 10 m area and 3 m height each room. The rooms are arranged on 2 rows with 10 rooms each. Path loss and shadowing are modeled according to TGah indoor propagation model [12], while Rayleigh fading represents multipath propagation effects over information-bearing and interfering signals. Simulations are performed for 900 MHz carrier frequency, but the general conclusions can be extended for any other licensed or unlicensed band. Table I summarizes the simulation parameters.

TABLE I
DEPLOYMENT SCENARIO AND SIMULATION PARAMETERS

Parameter	Value or description
Scenario	Dual stripe single floor
System Bandwidth (BW)	20 MHz
Center frequency	900 MHz
Maximum transmission power	20 dBm
LTE power control	closed loop, $\alpha = 1$ (Section III-B)
LTE target SINR	20 dB
eNodeB/AP height	1.0 m
UE/STA height	1.5 m
Number of Tx/Rx antennas	1/1
Traffic Type	Full-buffer data
Antenna Type	Isotropic
LTE simulation step	1 ms
Wi-Fi Simulation step	8 μs

LTE frame is equally divided into DL and UL subframes. Resources are allocated with a proportional fair scheduler, with MCS chosen according to the Channel Quality Indicator (CQI) of LTE UEs. Packet error correction (chase combining Hybrid Automatic Repeat Request (HARQ)) is used. The simulator frequency resolution is 180 kHz, i.e. a PRB in LTE.

The Wi-Fi network operates on DCF mode, with ACK signaling and retransmission in case of packet reception error. In accordance with Wi-Fi standards, CSMA/CA protocol considers two energy thresholds for channel vacancy detection: -82 dBm for Wi-Fi transmissions, and -62 dBm for other interfering sources.

In the simulation, nodes of both networks are randomly distributed among the rooms. No mixed LTE/Wi-Fi deployment in a single room is considered. LTE eNodeBs and Wi-Fi Access Points (APs) are referenced as APs, and LTE UEs and Wi-Fi Stations (STAs) as STAs. In both networks, STAs are assigned to the best-serving APs.

B. Results

Simulation results for the deployment of 10 APs of each technology among the 20 single floor rooms are presented in the following. Mean user throughput is evaluated for scenarios with 10 STAs and 25 STAs of each technology.

Fig. 3 shows the results for LTE only and Wi-Fi only deployments, as well as for both networks operating in coexistence. The general observations are similar to the ones given in [5], [8], where no LTE power control was considered: LTE is slightly affected by Wi-Fi interference, while Wi-Fi throughput can be hardly degraded according to the scenario. Mean user throughput in the Wi-Fi only deployments is 7 Mbps for 10 STAs and 2.6 Mbps for 25 STAs. In coexistence with LTE, Wi-Fi throughput is reduced to 1.4 Mbps and 0.5 Mbps, respectively. Then, Wi-Fi performance degradation is approximately 80% in both scenarios.

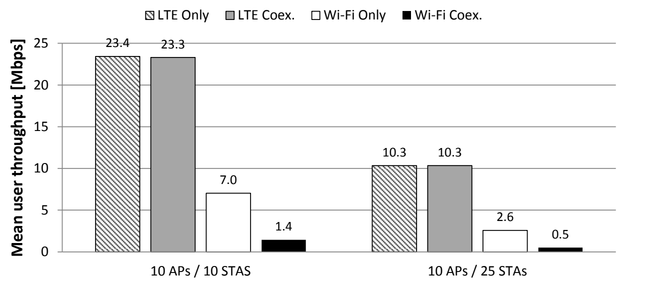
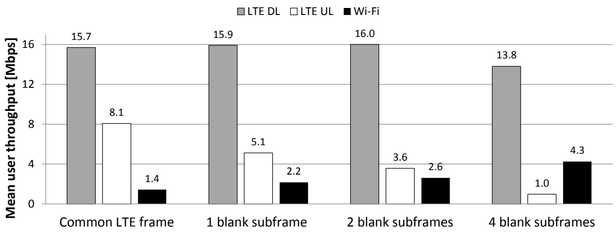


Fig. 3. Mean throughput per user for LTE only, Wi-Fi only, and both networks in coexistence.

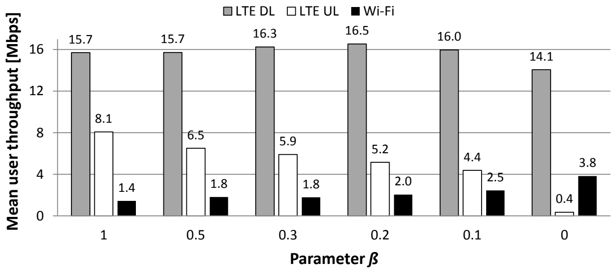
In the following, separate results for LTE DL, LTE UL, and Wi-Fi are shown for both coexistence mechanisms. Blank subframe allocations shown in Fig. 1 are evaluated, while the LTE UL power control with interference aware operating point is evaluated for different values of parameter $0 \leq \beta \leq 1$. Only resources of LTE UL are ceded for Wi-Fi transmission, since no DL subframes are blanked and LTE power control is used only in UL. Results of the common LTE frame (no coexistence mechanism employed) are also shown as reference.

Fig. 4 illustrates the mean user throughput for the 10 AP / 10 STA scenario. The expected behavior regarding the allocation of blank subframes is observed in Fig. 4(a): with more LTE subframes blanked, Wi-Fi throughput is increased at the cost of reducing LTE throughput. Similar behavior is observed in Fig. 4(b) for the modified LTE UL power control. By using $\beta < 1$, only a fraction of the interference is compensated, thus decreasing UEs transmit powers. Then, the lower the value of β, the lower the interference caused by LTE to Wi-Fi, leading to improved Wi-Fi performance.

The second scenario considered is characterized by higher interference due to the increased number of STAs. Fig. 5 shows the mean user throughput performance for 10 APs / 25 STAs.



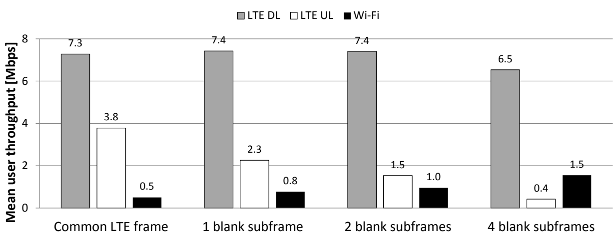
(a) Blank subframes allocation.



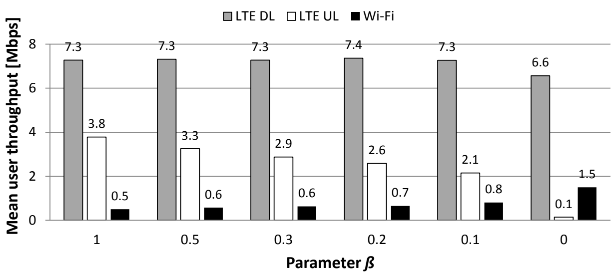
(b) Modified LTE UL power control.

Fig. 4. Deployment of 10 APs / 10 STAs per technology: mean throughput per user for LTE and Wi-Fi in coexistence.

Besides the expected throughput degradation if compared to the previous scenario (Fig. 4), similar behavior is observed for both blank subframe allocation, Fig. 5(a), and modified LTE UL power control, Fig. 5(b).



(a) Blank subframes allocation.



(b) Modified LTE UL power control.

Fig. 5. Deployment of 10 APs / 25 STAs per technology: mean throughput per user for LTE and Wi-Fi in coexistence.

The decrease of LTE DL throughput with 4 blanked subframes results from the increased interference caused by Wi-Fi. With CSMA/CA operation, Wi-Fi nodes are not able to confine their transmissions within the duration of blank subframes, causing interference to subsequent LTE DL subframes. The increased interference caused by Wi-Fi when LTE UL power control is employed with $\beta = 0$ also produces degradation of LTE DL throughput.

As general remark, both approaches are able to define different trade-off configurations for LTE and Wi-Fi in coexistence. Setting the number of blank subframes or the parameter β defines how LTE cedes resources to Wi-Fi. This is an open issue which depends on the communication between LTE and Wi-Fi networks, if it exists, and the possibly agreed parameters according to traffic demands, for instance. This can also be a matter of regulatory decisions for coexistence.

V. Conclusions

Coexistence of LTE and Wi-Fi, especially in unlicensed frequency bands is a possible scenario in the context of traffic offload. This coexistence has been shown challenging, thus requiring some enabler mechanisms. This paper presents and evaluates two possible mechanisms for enabling LTE/Wi-Fi coexistence. Allocation of LTE blank subframes for Wi-Fi only transmission and implementation of an LTE UL power control with interference aware operating point can be considered flexible solutions to deal with the trade-off between LTE and Wi-Fi performances in coexistence.

References

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2011-2016," Technical Report, 2012.

[2] Deloitte, "Airwave overload? Addressing spectrum strategy issues that jeopardize U.S. mobile broadband leadership," Deloitte Development LLC, White Paper, Sep. 2012.

[3] 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 *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, May 2011.

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

[5] A. M. Cavalcante, E. P. L. Almeida, R. D. Vieira, F. S. Chaves, R. C. D. Paiva, F. M. Abinader Jr., S. Choudhury, E. Tuomaala, and K. Doppler, "Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands," in *IEEE Vehicular Technology Conference (VTC-Spring)*, Jun. 2013.

[6] 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 *IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2013.

[7] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, "LTE-advanced: next-generation wireless broadband technology [invited paper]," *IEEE Wireless Communications Magazine*, vol. 17, no. 3, pp. 10–22, Jun. 2010.

[8] E. P. L. 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 *IEEE International Communications Conference (ICC)*, Jun. 2013.

[9] F. S. Chaves, E. P. L. Almeida, R. D. Vieira, A. M. Cavalcante, F. M. Abinader Jr., S. Choudhury, and K. Doppler, "LTE UL power control for the improvement of LTE/Wi-Fi coexistence," in *IEEE Vehicular Technology Conference (VTC-Fall)*, Sep. 2013.

[10] 3GPP, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures," 3rd Generation Partnership Project (3GPP), Technical Specification TS 36.213 (Release 10), Jul. 2012.

[11] B. Muhammad, "Closed loop power control for LTE uplink," Master's thesis, Blekinge Institute of Technology, Nov. 2008.

[12] K. Doppler, S. Yong, and R. Porat, "802.11-11/0968r2 - TGah channel model addendum," IEEE, IEEE P802.11 Sub 1GHz Study Group, Nov. 2011.