# Measuring LTE and WiFi coexistence in Unlicensed Spectrum

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*Abstract*—**The exponential growth in mobile services demand, along with the scarce licensed spectrum in the sub-6GHz bands, mandate the exploitation of bands other than the traditionally used by mobile broadband technologies. An example of such operation is the opportunistic access of the unlicensed bands by the LTE technology, as a means to increase the delivered end-user capacity and enhancing the overall quality of experience. In this paper, we present some extensive testbed measurements used for modeling the coexistence of LTE and WiFi technologies when operating within the same unlicensed environment. The experiments deal with different bandwidth settings for both the WiFi and LTE technologies, when LTE is operating closely or inside the primary or secondary channels of IEEE 802.11, taking into account the different threshold values for the Clear Channel Assessment functions that WiFi entails. We present exhaustive experimental measurements, collected under a real testbed setup, and present a cognitive algorithm for minimizing the impact of the two technologies to each other.**

## I. INTRODUCTION

Long Term Evolution (LTE) is the state-of-the-art solution for the 4th Generation (4G) mobile broadband network access. Through its introduction with Rel. 8, and the subsequent amendments since then, the overall supported wireless medium capacity has multiplied. By aggregating carriers and employing MIMO techniques, late LTE releases can deliver speeds of over 1Gbps in the downlink channel. This enhanced capacity has created fertile ground for the development of new services exchanging massively data over the network, like for example IoT related services, delivery of UHD video, etc.

As LTE is a mobile broadband network technology, its medium access method is supposing that it operates under licensed spectrum. Nevertheless, a number of different technologies need to be accommodated within similar/adjacent frequency bands with GSM/UMTS. As a means to increase the overall network capacity, LTE in Unlicensed spectrum (LTE-U) has been proposed [1], initially by Qualcomm. With LTE-U, LTE is able to access the currently unlicensed spectrum that exists in the 5GHz band, originally designated for WiFi networks. LTE can potentially use more than 400MHz of wireless spectrum, thus increasing the overall capacity that the channel can transfer.

Yet, the different access mechanisms of the protocols need to be tailored in order to accommodate these heterogeneous technologies within the same frequency band. The Listen Before Talk (LBT) nature of CSMA/CA, adopted by the IEEE 802.11 protocol family, can seriously degrade their performance when operating in the same frequency band with the LTE medium access mechanism. Moreover, WiFi highly depends on the Clear Channel Assessment (CCA) functions that it employs, in order to determine whether the channel is occupied by another transmitter of either the same technology or not and subsequently backoff. In case that the transmitter belongs to another technology (e.g. LTE), CCA outcome is determined by the overall energy that it detects on the channel (CCA-ED). CCA-ED thresholds vary, based on the different channel bandwidth that is used by the WiFi technology, and whether the transmission is detected on the primary/secondary channel [2]. To this aim, a number of different parameters need to be taken into consideration for the successful coordination between contending technologies in order to facilitate their channel access and yield better performance results.

In this work, we conduct extensive measurements under a real testbed setup for different coexistence cases of the two technologies. We use a testbed topology, operating in the 2.4GHz unlicensed band, in a fully interference-controlled environment, and evaluate the impact that uncoordinated coexistence has on the two technologies under a diverse number of settings regarding the overlapping factor between them. Based on these results, we derive and evaluate a cognitive learning algorithm for negotiating the spectrum usage between the two technologies.

The rest of the paper is organized as follows. Section II presents some indicative related work on LTE and WiFi coexistence. In Section III we present the testbed setup and our experimental methodology, while in section IV we showcase our experimental findings. In Section V we present a coexistence mechanism based on the collected measurements. Finally Section VI concludes our work.

## II. RELATED WORK

Coexistence of heterogeneous wireless technologies, within the same shared spectrum, is a thoroughly investigated subject from various perspectives, each taking into account different

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properties of the under study technologies. Using the unlicensed band of 5GHz for the opportunistic access of LTE-A has been initially proposed by Qualcomm, as a means to maximize the overall capacity, by using a secondary LTE carrier within these bands for downlink, or both downlink/uplink [1]. Following up this work, Zhang et al. in [3] present the challenges that need to be addressed for the coexistence of LTE and WiFi. Authors in [4] propose some coexistence mechanisms by utilizing the Almost Blank Subframe (ABS) and adjusting the uplink (UL) transmit power used in LTE. Simulation results are presented demonstrating significant improvement on the WiFi performance. Cavalcante et al. in [5] observe the coexistence and conclude that WiFi spends most of the time listening the medium rather than transmitting, thus resulting in the degradation of the achieved throughput. In addition, authors pinpoint the Enhanced Inter-Cell Interference Coordination (eICIC) function and building on it, they introduce a novel coordination scheme as a coexistence solution.

Nonetheless, all of the proposed solutions rely solely on simulation results. The emergence of some revolutionary open source platforms, like OpenAirInterface [6], srsLTE [7] and openLTE [8] has rendered these coexistence experiments feasible under realistic settings in real world setups. Works that address this experimentally driven approach include [9], where the authors analyze the impact of LAA-LTE-U on WiFi and introduce a MAC protocol for LTE addressing coexistence with WiFi. Similarly, authors in [10] examine the interference impact of each technology to each other and in [11] a channel model for this cross-technology interference is introduced.

In this work, we extend these approaches, by modeling the WiFi and LTE behavior for a diverse set of configurations, where the LTE cell is set to overlap either completely or partially with the WiFi cell, inside the primary or secondary channel. The experiments are executed with different channel settings, with cells spanning from 5MHz up to 40MHz of channel bandwidth. We employ 2 different open source tools for the LTE network configuration: initially we measure the mutual interference that LTE and WiFi technologies create to each other using srsLTE and OpenAirInterface, and propose a cognitive algorithm for coordinating the spectrum usage in our testbed setup.

## III. TESTBED SETUP

In order to observe the behavior of LTE and WiFi coexistence in a real-world environment, we employ the NITOS testbed [12], along with the LTE extensions that are provided [13]. NITOS is a large-scale wireless testbed consisting of 50 RF-isolated indoor and 50 outdoor nodes, featuring multiple wired and wireless interfaces, as well as Software Defined Radio components. For the collection of measurements in our setup, we employ a set of LTE nodes, using the srsLTE and OpenAirInterface platforms. USRP B210 devices [14] are the RF-frontends, all set to operate in the 2.4 GHz band. We choose to experiment in this band as the RF devices seem to be yielding better performance rather than using higher frequencies, e.g. the 5GHz band. By tuning the channel parameters (e.g. transmission power, channel bandwidth), we place the LTE cell within the coverage of a WiFi network, where the channels can be partially/fully/non overlapping, inside the primary or the secondary channel of WiFi.

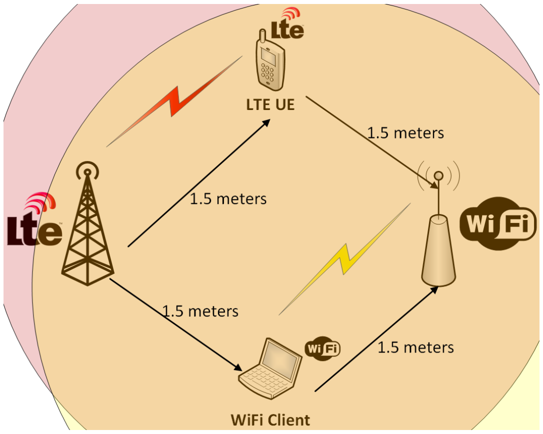


Fig. 1. Experimental topology used for the modeling experiments: LTE and WiFi Base Stations and Clients are under heavy interference conditions

Regarding the WiFi network, we employ a second set of nodes configured as an Access Point (AP) and a Station (STA). In order to have more thorough results on the interference modeling of our setup, we set the WiFi network to operate using channels of 5MHz, 10MHz, 20MHz and aggregated channels of 40 MHz. Coexistence measurements for channels over 40MHz are not described in our measurements, but based on the CCA-ED thresholds in the WiFi standards, our algorithms can be extended to support them. Although the 5 and 10MHz channel widths are not described by the IEEE a/b/g/n specification, we configure them in order to have a direct comparison for every bandwidth that the LTE channel is supporting. In fact, these bandwidth channels have been proposed in subsequent amendments of the IEEE 802.11 for more application-specific deployments (e.g. DSRC/IEEE 802.11p, sub-1GHz transmissions - IEEE 802.11ah). This is, to the best of our knowledge, the first work that considers such an approach. For a given value of transmission power set to the WiFi driver, the total energy that will eventually be used to send data over the air is highly dependent on the bandwidth of the channel. If the channel bandwidth is lessened, more energy will be used in each transmission. In order to manage such experiments, we employ the ath9k driver, for IEEE 802.11n operation, and appropriately alter it in order to support WiFi APs with 5 and 10MHz channel width.

For the initial characterization of the coexistence, we use a part of the testbed based on the topology indicated in Figure 1, where all the nodes are static and equidistant from each other (NITOS nodes are organized in a grid topology). We saturate the channel for both WiFi and LTE transmissions, by generating traffic at least equal to the largest transferable bitrate, per each physical bitrate (MCS profile). Table I summarizes all the configurations that are used to setup the testbed components. All the experiments have been conducted for 10 times per measurement, whereas we use the *iperf* application

TABLE I
TESTBED SETUP PARAMETERS

| **Network Parameters** | **Values** |
|---|---|
| LTE mode | FDD Custom Band |
| LTE Frequency | 2412 MHz (DL) |
| No RBs | 25, 50 |
| LTE Transmission Mode | SISO |
| UE type | OpenAirInterface UE, srsLTE |
| UE Transmission Mode | SISO |
| WiFi driver | ath9k |
| WiFi Bandwidth | 5, 10, 20, 40 MHz |
| WiFi Transmission Mode | SISO |

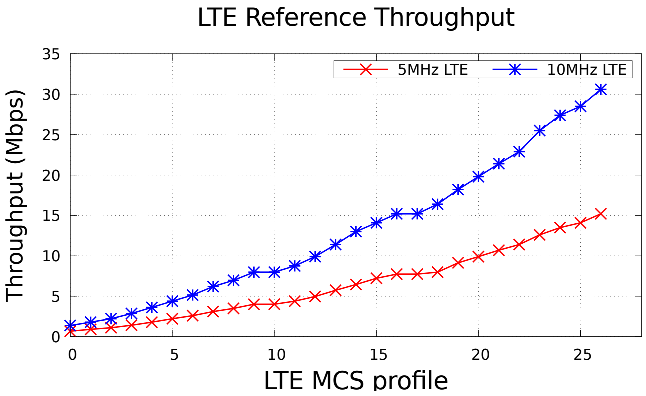


Fig. 2. srsLTE reference throughput for 5 and 10MHz channel width configuration (w/o interference)

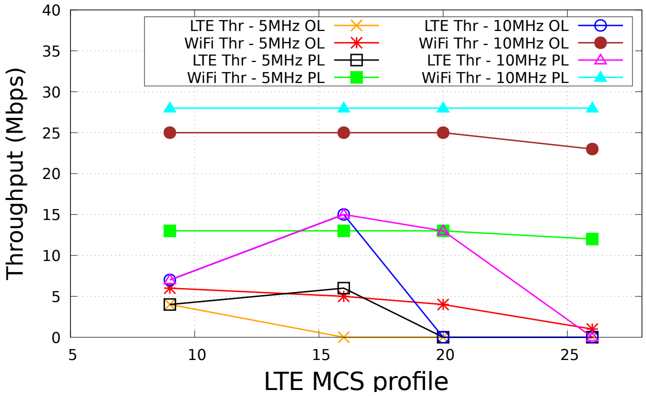


Fig. 3. srsLTE measurements in an uncoordinated environment; OL is for fully overlapping channels, PL is for partially overlapping by half channel width

as our traffic generator, set to generate standard sized UDP packets.

## IV. EXPERIMENTAL EVALUATION

In this section we present some experimental results that can be used for modeling the coexistence of the two technologies. We initially present the measurements derived from the srsLTE platform, by using the physical data shared channel (PDSCH) application that is provided, without any other operation taking place on top of it. Following this, we present the OpenAirInterface experiments, which are used by running the LTE networking stack as both an eNodeB application, and a UE.

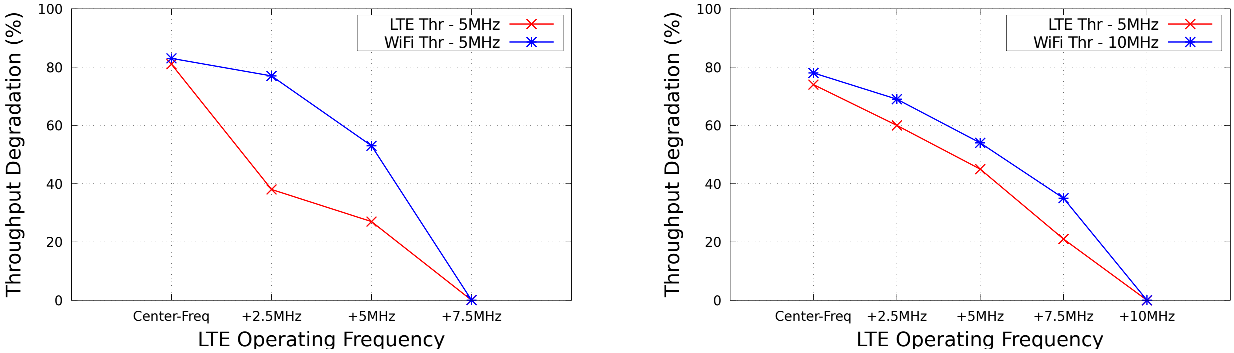
Regarding the first set of experiments, we repeat them for four different MCS profiles: 26, 20, 16 and 9. These profiles include both robust schemes that can yield better performance results in the cases of heavy interference that we consider, and modulation alphabets used to increase the throughput over the channel. The throughput that srsLTE platform can achieve, measured in an uncoordinated environment, for every MCS profile and using one antenna for transmission and reception, is shown in Figure 2. Regarding the WiFi experiments, we use the highest possible MCS profile (MCS 7), and a configuration with one antenna (SISO). Finally, the thresholds for CCA-ED, as defined by the WiFi standards for all the cases of the under-study bandwidth schemes are given in table II.

Figure 3 is illustrating our results taken for channels of equal width for both LTE and WiFi. The under investigation coexistence is considered for channels of 5 and 10 MHz of bandwidth, where LTE and WiFi may be either fully overlapping (OL), or partially overlapping (PL) by half a channel. For the second case, the LTE channel is transmitting with an offset of 2.5MHz from the center frequency of the WiFi AP for the 5MHz case, and respectively 5MHz for the 10MHz case. This subsequently means that the technologies overlap by a half channel size, based on their width configuration. For both cases, the transmission power of the two technologies is set to be the same and equal to 16dBm.

As we observe from the experimental results, and given the benchmarking results in Figure 2, the LTE performance for the case of fully overlapping cells has an on/off switch-like behaviour. For high modulation and coding schemes LTE transmissions do not manage to be decoded at the receiver. Contrary to that, WiFi manages to take advantage of the empty air time, and is achieving slightly better performance. The WiFi performance is not decreasing, due to the different SINR sensitivity thresholds of the two technologies. For lower MCS profiles, the LTE receiver is able to decode the transmissions and therefore data is pushed through the channel, achieving performance similar to the benchmarking results.

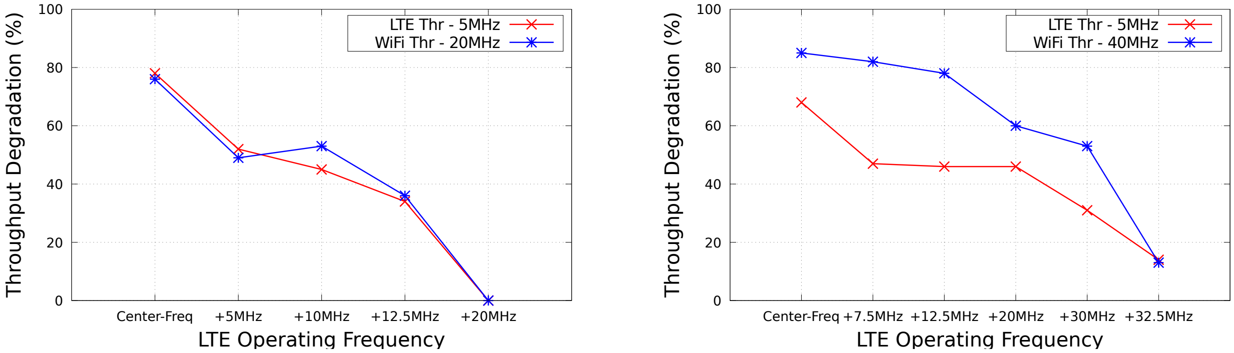
For the cases that LTE and WiFi overlap by half channel, both LTE and WiFi manage to get better performance over the channel. Since only half channel is overlapping, only half the energy used to transmit the respective packets is compromised. Therefore, the decoding of the transmitted signal can be conducted more efficiently, thus leading to superior performance compared to the fully overlapping experiments.

Driven through these results, and given that secondary channels in cases of channel aggregation in WiFi use smaller energy detection thresholds, we broaden our experiments to include a full LTE-stack platform. Since no commercial solution exists for an LTE UE that operates in unlicensed spectrum, we employ the OpenAirInterface UE platform for our measurements. The experiments investigate again the DL channels, and are using the fixed MCS profile of 9 for the LTE (16-QAM modulation order) and 7 (64-QAM) for the WiFi. We choose to use this specific MCS profile for the LTE channel since our first set of results demonstrates that using these robust modulation alphabets and coding schemes



(a) Coexistence with 5MHz WiFi APs

(b) Coexistence with 10MHz WiFi APs



(c) Coexistence with 20MHz WiFi APs

(d) Coexistence with 40MHz WiFi APs

Fig. 4. Testbed experimental results using OpenAirInterface

can deliver better performance when coexisting with the WiFi technology.

Figure 4 is representing our experimental results for the second set of experiments involving the OpenAirInterface based setup. OpenAirInterface is running using 5MHz channel bandwidth, whereas WiFi is set to use 5, 10, 20 or an 802.11n channel of 40 MHz configured with sort guard intervals. The limitation in the existing OpenAirInterface UE does not allow us to conduct experiments with more channel bandwidth. We present percentages regarding the throughput degradation of the two technologies.

As we can see in Figure 4a, both technologies suffer from about 80% throughput degradation in the case of overlapping cells. This effect is lessened as we move the LTE cell outside the frequency spectrum of the WiFi AP. Yet, even for the cases of adjacent cells, we see that both technologies suffer from this cross-talk effect. This is even more highlighted in the WiFi plots, caused due to significant out-of-band emissions induced by the Software Defined Radios executing the LTE cell. If we move to non-adjacent frequencies, this cross-talk effect ceases to exist and both of the technologies achieve their expected throughput.

In the second case, WiFi is using a channel twice the size of the LTE (10MHz channel). For this case, similar behavior is also observed (Figure 4b). As the LTE center frequency is moved away from the WiFi, the throughput of both networks is improving. A secure distance between the two center frequencies of the technologies in order not to interfere with each other is 10MHz.

For the third case in Figure 4c, we see similar patterns. Yet, the cross-talk effect is more evident when using adjacent cells in this case as well, and for even more frequency spectrum. For the cases of the LTE cell located at least 15MHz away from the center frequency of the AP, this effect stops to happen.

Finally, in the case of an aggregated channel of 40MHz for the WiFi transmissions, we see that for same center frequencies, the results regarding throughput resemble a similar behavior as in the previous two cases. However, for the cases where the LTE cell is operating inside the secondary channel of WiFi, even in the case when they use the same central frequency, the coexistence effect on the LTE throughput is milder. This is happening due to the different thresholds that WiFi is using for the CCA-ED (see Table II). Lower values mean that the technology will need to measure more power

TABLE II
CCA-ED THRESHOLDS FOR DETECTING LTE TRANSMISSIONS

| Primary Ch. Width | Secondary Ch. Width | CCA-ED Primary | CCA-ED Secondary |
|---|---|---|---|
| 5 MHz | - | -78 dBm | - |
| 10 MHz | - | -75 dBm | - |
| 20 MHz | - | -72 dBm | - |
| 20 MHz | 20MHz | -72 dBm | -72 dBm |
| 40 MHz | 40 MHz | -72 dBm | -69 dBm |
| 80 MHz | 80 MHz | -72 dBm | -66 dBm |

over the air in order to consider the medium busy. If these values are not met, WiFi will transmit and suffer from over the air collisions.

**Algorithm 1** LTE WiFi Cognitive Coordination Algorithm

```
$Threshold = Init$
$CCAThreshold = Init$
$Interval = t$

procedure SPECTRUM-SENSING($enodebID$)
    Scan the band using energy detection
    Get measurements from other sensing
        engines in the area from database
    Determine if there are channels free of
        transmissions/interference based on
        the scan results and the database
    if There is no empty channel then
        Determine the WiFi channel filling any
            possible spectrum gap
        Instruct WiFi network to change its channel
        Determine a channel which partially overlaps
            with another network
    else
        Determine the channel with the lowest noise
    end if
    Send center frequency to eNodeB
    Update REM database
end procedure

for new enodebID do
    SPECTRUM-SENSING($enodebID$)
end for

while 1 do
    while InterferenceDectected $>= Threshold$ do
        Do Energy Detection in the LTE Cell
            Operating Frequency
        if Transmissions are Detected then
            SPECTRUM-SENSING($enodebID$)
        else
            Use the current Frequency
        end if
        Readjust($Threshold$, $Interval$)
    end while
    sleep($Interval$)
    if new enodebID then
        SPECTRUM-SENSING($enodebID$)
    end if
end while
```

## V. COEXISTENCE ALGORITHM

Based on the results that we observed during our experiments, we come up with a LTE-WiFi cognitive coordination algorithm (LWCCA) for handling the coexistence of the two technologies. The algorithm is extending our previous work in [15] in order to support multiple technologies with some learning elements. It is relying on distributed spectrum sensing mechanisms, located on the eNodeBs, and on an energy detection mechanism. For setups with more than one eNodeBs we utilize the Radio Environment Map (REM) tool in order to construct a map of the local area exploiting measurements from multiple sensing engines [16]. Towards this direction, the sensing engines use the backbone network to communicate with the database, retrieve the necessary information for spectrum usage of the area, upload their RF measurements and instruct other networks to change frequency/channel.

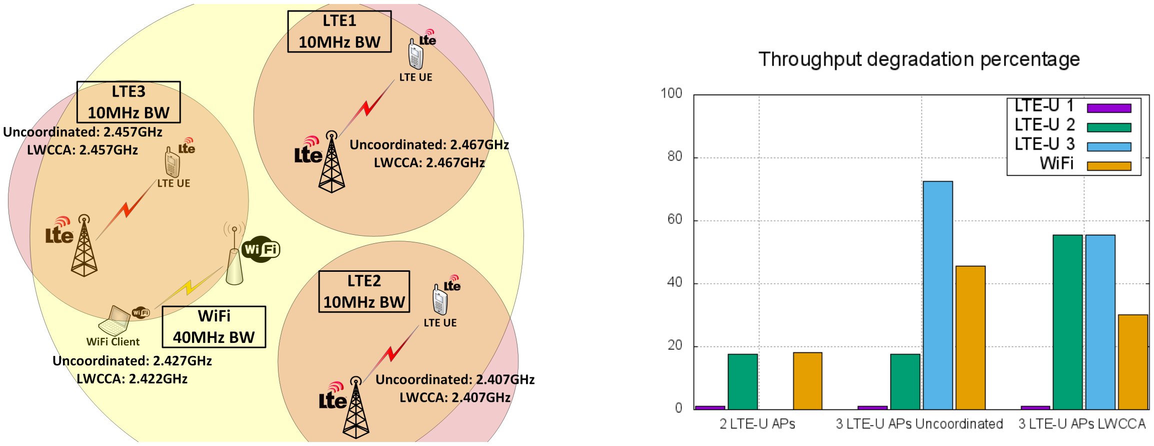
Possible coexistence with WiFi is investigated, and based on the detected transmissions and bandwidth of measurements, the algorithm is able to determine the best frequency that ensures the least-destructive operation of both technologies within the same band. If there is no free space for all the networks to operate without overlapping, the LWCCA examines the possibility to determine the frequencies of all existing wireless networks targeting on the grouping of the empty slots on the spectrum for fitting the new cell. If no interference-free cell is found, the channel that induces the least performance degradation to both technologies is used. Upon determining this frequency, the algorithm will instruct the LTE cell to operate with this central frequency.

Algorithm 1 is detailing our cognitive algorithm design. Using the testbed measurements, we are able to set the energy detection thresholds that can affect both technologies, depending on whether the cell is operating inside a primary/secondary channel and based on its width. The algorithm is running periodically with an interval that is dynamically set during its operation and based on the frequency that other coexisting technologies are detected. Moreover, for every incoming cell on the area, LWCCA triggers the procedure for finding the appropriate channel for it.

In order to test our proposed algorithm we select a setup with 1 WiFi network using an aggregated channel of 40MHz bandwidth and 3 LTE femtocells using 10MHz bandwidth. The WiFi AP chooses as the center frequency of the primary channel the 2.427GHz and for the secondary channel the 2.447GHz. The first LTE femtocell is using the spectrum-sensing procedure of the LWCCA algorithm; it is scanning the band and chooses the 2.467GHz as center frequency. Similarly, the second LTE femtocell will select the 2.407GHz as its center frequency. With these 3 networks operating on the 2.4GHz only two gaps are available for any new wireless networks, each one of 5 MHz width. Without any coordination the third LTE femtocell would choose to partially or fully overlap with another network resulting to significant throughput degradation for both networks (see Figure 5). The LWCCA algorithm instructs the WiFi network to relocate its frequency by -5MHz in order to create a 10MHz slot using now the 2.422GHz and 2.442GHz. Subsequently, the third LTE femtocell selects the 2.457GHz as its center frequency.

## VI. CONCLUSION

In this work we demonstrate an experimentally driven analysis of the coexistence between LTE and WiFi, when



(a) Topology used for evaluating the LWCCA algorithm; 4 cells are considered to coexist in the same frequency band

(b) Throughput degradation evaluation for our setup

Fig. 5. Testbed experimental results for the LWCCA scheme

the technologies are operating within the same unlicensed frequency band. Using two different open source platforms for LTE we presented the coexistence impact that each technology has on each other for a diverse number of settings. We compared the two protocols for the cases where they are using the same bandwidth, as well as when the LTE cell is operating within the primary and secondary channel of aggregated WiFi channels. Our results show that depending on the different type of coexistence (e.g. fully overlapping, partially overlapping, overlapping with a secondary channel) different network performance can be induced. Finally, based on the results that we extracted, we present a cognitive-based algorithm with learning elements for coordinating such heterogeneous cells within the same frequency band.

In the near future we foresee extending our work by allowing the contending cells to dynamically reconfigure their channel bandwidth settings. Moreover, we will pursue the definition of the optimum values for the LTE-LAA operation and experiment with it within a real testbed environment.

## ACKNOWLEDGMENTS

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## REFERENCES

[1] Qualcomm, "Extending the Benefits of LTE to Unlicensed Spectrum," in *LTE in Unlicensed Spectrum workshop, Paris, France*, 2014.

[2] "IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz," *IEEE Std 802.11ac - 2013*, 2013.

[3] R. Zhang, M. Wang, L. X. Cai, Z. Zheng, X. Shen, and L. L. Xie, "LTE-unlicensed: the future of spectrum aggregation for cellular networks," *IEEE Wireless Communications*, vol. 22, no. 3, pp. 150–159, June 2015.

[4] 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 *2013 IEEE International Conference on Communications (ICC)*, June 2013, pp. 5083–5088.

[5] A. M. Cavalcante, E. Almeida, R. D. Vieira, S. Choudhury, E. Tuomaala, K. Doppler, F. Chaves, R. C. D. Paiva, and F. Abinader, "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.

[6] N. Nikaein, M. K. Marina, S. Manickam, A. Dawson, R. Knopp, and C. Bonnet, "OpenAirInterface: A Flexible Platform for 5G Research," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 5, pp. 33–38, Oct. 2014. [Online]. Available: http://doi.acm.org/10.1145/2677046.2677053

[7] I. Gomez-Miguelez, A. Garcia-Saavedra, P. D. Sutton, P. Serrano, C. Cano, and D. J. Leith, "srsLTE: An Open-Source Platform for LTE Evolution and Experimentation," *ArXiv e-prints*, Feb. 2016.

[8] B. Wojtowicz, "OpenLTE," *An open source 3GPP LTE implementation (http://openlte.sourceforge.net)*, 2016.

[9] Y. Jian, C. F. Shih, B. Krishnaswamy, and R. Sivakumar, "Coexistence of Wi-Fi and LAA-LTE: Experimental evaluation, analysis and insights," in *2015 IEEE International Conference on Communication Workshop (ICCW)*, June 2015, pp. 2325–2331.

[10] S. Sagari, S. Baysting, D. Saha, I. Seskar, W. Trappe, and D. Raychaudhuri, "Coordinated dynamic spectrum management of LTE-U and Wi-Fi networks," in *Dynamic Spectrum Access Networks (DySPAN), 2015 IEEE International Symposium on*, Sept 2015, pp. 209–220.

[11] S. Sagari, I. Seskar, and D. Raychaudhuri, "Modeling the coexistence of LTE and WiFi heterogeneous networks in dense deployment scenarios," in *2015 IEEE International Conference on Communication Workshop (ICCW)*, June 2015, pp. 2301–2306.

[12] "NITOS - Network Implementation Testbed using Open Source platforms". [Online]. Available: http://nitlab.inf.uth.gr

[13] N. Makris, C. Zarafetas, S. Kechagias, T. Korakis, I. Seskar, and L. Tassiulas, "Enabling open access to LTE network components; the NITOS testbed paradigm," in *1st IEEE Conference on Network Softwarization (NetSoft), 2015*, April 2015, pp. 1–6.

[14] "USRP B210 board". [Online]. Available: https://www.ettus.com/product/details/UB210-KIT

[15] V. Passas, N. Makris, S. Keranidis, T. Korakis, and L. Tassiulas, "Towards the efficient performance of LTE-A systems: Implementing a cell planning framework based on cognitive sensing," in *1st International Workshop on Cognitive Cellular Systems (CCS)*. IEEE, 2014, pp. 1–5.

[16] Y. Zhao, B. Le, and R. J. H., "Network Support - The Radio Environment Map," *Cognitive Radio Technology*, pp. 337–363, 2006.