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Enabling a Win-Win Coexistence Mechanism for WiFi and LTE in Unlicensed Bands

(Invited Paper)

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***Abstract*—The problem of WiFi and LTE coexistence has been significantly debated in the last years, with the emergence of LTE extensions enabling the utilization of unlicensed spectrum for carrier aggregation. Since the two technologies employ completely different access protocols and frame transmission times, supporting coexistence with minimal modifications on existing protocols is not an easy task. Current solutions are often based on LTE unilateral adaptations, being LTE in unlicensed bands still under definition. In this paper, we demonstrate that it is possible to avoid a subordinated role for WiFi nodes, by simply equipping WiFi nodes with a sensing mechanism based on adaptive tunings of the ambient noise thresholds (as indeed considered by several commercial cards). Under this assumption, we propose a win-win coexistence mechanism between the two technologies, that does not require modifications on legacy WiFi access operations. We model the interactions between the two technologies in terms of a game and demonstrate the feasibility of the approach in simulation and in real experiments.**

***Index Terms*—WiFi, IEEE 802.11, LTE-U, ISM coexistency**

I. INTRODUCTION

Recent LTE extensions are including the possibility of performing carrier aggregation on the unlicensed bands. Indeed, many operators argue that LTE operation in unlicensed band has the potential to offer significantly better coverage and higher spectral efficiency compared to WiFi. From the user perspective, this means an enhanced broadband experience, higher data rates, seamless use of both licensed and unlicensed bands, with high reliability and robust mobility through licensed anchor carrier. However, because of the impressive success of WiFi technology, a critical element to be guaranteed for enabling the operation of LTE in unlicensed band is ensuring that WiFi networks are not impaired by incumbent LTE links. Coexistence between WiFi and LTE is not an easy task, because the two technologies employ completely different medium access protocols [1]. Moreover, there is not a uniform approach for defining coexistence criteria which guarantee a fair share of the unlicensed band. For example, some solutions propose to *equally share* the channel utilization between the two technologies, while some other solutions take into account the traffic offered in each network for identifying a *load-dependent channel share for each technology*.

Different LTE variants have been considered for working in unlicensed bands, driven in part by the development of two recent standardization efforts: LTE-U [2], developed by the LTE-U Forum, and LTE-LAA developed by 3GPP [3]. The two specifications differ in the way coexistence is implemented. LTE-U uses a duty cycling approach to determine (unilaterally from the LTE side) the duty cycle to be employed by LTE as a function of WiFi traffic. An example of this duty cycle adaptation mechanism is the Carrier Sense Adaptive Transmission (CSAT) scheme proposed by Qualcomm. Conversely, LTE-LAA is based on a contention-based mechanism between LTE and WiFi, which suffers of potential inefficiencies for guaranteed that LTE frames are transmitted at regular time instants. When the medium is sensed as busy, the deferral time is given by a fixed time of 10 msec for maintaining the synchronization of frame starting times (with the so called FBE mechanism) or it is given by a random slotted deferral time compensated by a varying channel occupancy time (with the so called LBE mechanism). Apart from the channel inefficiencies, it is not obvious how assuring a fair coexistence between the two technologies under random contention, because the two standards employ heterogeneous contention parameters, sensing capabilities, inter-frame spaces and channel occupancy times [4]–[6].

In this paper, we chose to focus on the solution based on duty-cycle adaptations (also the approach can be generalized to the LTE-LAA case, as described in §III), by considering the possibility of implementing a distributed network intelligence on both the LTE and WiFi networks, able to achieve a win-win coexistence equilibrium. Differently from previous work, working on LTE unilateral adaptations [7], non-standard mechanisms [8], or centralized coordination [6], [9], we proposed a coexistence mechanism in which, by using legacy functionalities, each technology can impair the other one or decide for cooperation. The scheme is a variant of the CSAT solution [10]: LTE eNB senses the medium during inactivity for quantifying the competing WiFi traffic and adjusting accordingly the LTE duty-cycle. Duty cycle adaptations can be implemented by exploiting the possibility of using blank subframes, as considered in [8], or by working on the frame scheduling interval. To some extent, CSAT is similar to the concept of inter-technology TDM coexistence. In particular, CSAT defines a time cycle in which LTE eNB schedules one or more frame transmissions and gates off in the remaining duration. CSAT has also the same spirit of CSMA,

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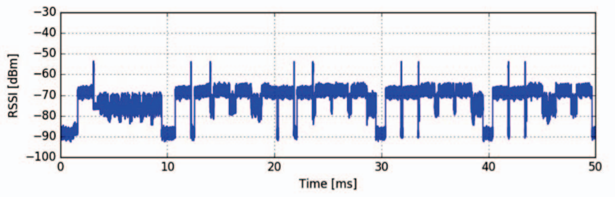

Fig. 1. Example of overlapping between WiFi and LTE transmissions in a real experiment.

because medium access is regulated by means of carrier sense, except that it has longer latency [11].

The rest of the paper is organized as follows. After discussing some general considerations about WiFi and LTE coexistence in §II, we introduce our coexistence scheme and derive the strategies to be implemented by each technology in §III. An experimental validation is presented in §IV. Finally, conclusions are drawn in §V.

II. INTERACTIONS BETWEEN WIFI AND LTE

We assume that a LTE download link is set-up by an LTE eNB in the unlicensed 5 GHz band in a channel overlapping with a coexisting WiFi network. Uplink LTE traffic (acknowledgments and control) is transmitted on a licensed paired channel, according to the case considered in LTE Release 13, while WiFi traffic is generated by a high number of stations, associated to an Access Point, with both downlink and uplink flows.

A. LTE perspective

In case frame transmissions are performed at regular scheduling intervals, without sensing the channel as in the case of LTE-U, the portion of channel time taken by LTE is unilaterally controlled by the LTE eNB by tuning the duty cycle (and/or the number of blank subframes not filled with block transmissions). However, this does not mean that this channel portion can be used in an effective way: on one side, in case of coexistence with a saturated WiFi network, it is very likely that LTE transmissions are scheduled during an overlapping WiFi transmission, thus resulting in a frame loss for both the technologies; on the other side, it is not guaranteed that WiFi nodes are able to correctly sense LTE frames and prevent collisions. While the first consideration is pretty obvious, to demonstrate the second phenomenon, we run a coexistence experiment between LTE and WiFi nodes, by using the USRP SDR platform and the srsLTE [12] software for implementing LTE nodes, and two Broadcom cards for implementing WiFi nodes. LTE nodes are configured for sending frames at regular intervals of 10 msec lasting only 6 subframes.

Figure 1 shows a channel activity trace, in terms of RSSI values measured by another monitoring USRP placed in proximity of the nodes, in which we can easily recognize different technologies and nodes in terms of different channel occupancy times and received power levels. For example, LTE frame transmissions are characterized by a RSSI level equal to -70dBm; in the first part of the figure (the initial interval of 10 msec) we can easily recognize 6 consecutive LTE subframes. WiFi data transmissions are identified by a power level equal to -66dBm, while acknowledgments correspond to the spikes at -53dBm. From the figure it is evident that WiFi transmissions overlap with LTE subframes, leading to a collision (for which WiFi data frame are not followed by acknowledgments). For the same collision events, we found that also LTE blocks are not correctly received. Finally note that in some cases, when the collision only affects a part of WiFi data frame at the beginning of the LTE frame, WiFi frames can be correctly acknowledged.

The reason for the phenomenon discussed above is due to the implementation of the sensing mechanism in WiFi nodes. When nodes detect energy on the channel, without synchronizing a valid preamble, after a given tunable interval, they increase the energy threshold for considering the medium as busy, by assuming that the energy is due to some background noise. This mechanism, often called ambient noise immunity [13] mechanism, can completely prevent WiFi nodes from detecting LTE transmissions. We conclude that *LTE transmissions could result in a deterministic channel waste for both the technologies*. Only for low-loaded WiFi networks, for which the probability of starting a new channel contention during LTE transmissions is low, LTE throughput can be different from zero.

In case a carrier sensing mechanism is available for LTE, eNB is prevented from starting a frame transmission overlapping with an ongoing WiFi transmission. LTE frame transmission times are no more regular, both in terms of starting times (which result randomly distributed because of the backoff mechanism), and in terms of channel holding times (which can be modulated at the resolution of 1 msec). It results that LTE channel share is no more unilaterally decided by LTE. Indeed, it is now depending on the total number of WiFi competing nodes, on the channel holding times employed by each one, as well as on the employed contention parameters. Regardless of the achieved channel share, *the problem of mis-detection of LTE frames is not solved when LTE eNB implements carrier sensing*. The only strategy that can be adopted by eNB is transmitting one subframe only at each channel access, in order to avoid the adjustment of the ambient noise thresholds.

B. WiFi perspective

In case WiFi network is not saturated, i.e. the transmission queues of WiFi nodes are likely to be empty when new packets are generated, there is a portion of the channel time (much longer that usual backoff times), called white space, which remains idle between consecutive transmissions. Previous coexisting works have considered to statistically characterize the distribution of the WiFi white spaces, in order to predict their occurrence for performing LTE transmissions [14]. In principle, *if LTE transmissions start and end within a WiFi white space, they do not affect at all the performance of WiFi nodes*. Conversely, if the WiFi white space ends before the completion of LTE transmission, it is very likely that the sensing mechanism will fail because of the noise immunity scheme, thus resulting in a collision.

In case WiFi network is saturated, the channel access probability experienced by a generic WiFi node is usually different from the one experienced by eNB. This is due not only to the heterogeneous contention parameters employed by the two technologies, but also to different collision rates (being LTE frames often mis-detected by WiFi nodes using noise immunity schemes). If the number of WiFi nodes is extremely high, as in the case of high-density WiFi networks currently experienced in urban scenarios, the channel access probability of a single eNB tends to be very small regardless of the configuration of the contention parameters.

III. COEXISTENCE MECHANISM

We consider a scenario in which a single eNB link coexists with a non-saturated WiFi network. Indeed, the coexistence between LTE and WiFi saturated networks, under the assumption that WiFi nodes employ a noise immunity scheme, can lead to a non-null LTE throughput only if LTE reduces its transmission times down to 1 msec (i.e. a single subframe). In this case, LTE and WiFi basically operate in a very similar manner and coexistence is only a matter of opportunistically configuring the contention parameters. Conversely, in non-saturated scenarios, defining a coexistence mechanism taking into account the peculiarities of heterogeneous (scheduled-based and contention-based) access modes can be relevant for improving the performance of both WiFi and LTE technologies.

From the analysis of the interactions discussed in the previous section, it clearly emerged that:

- for a given WiFi load, LTE can adapt its duty cycle for scheduling frame transmissions at regular time intervals, without affecting WiFi performance, as long as the WiFi network keeps unsaturated (i.e. the remaining channel capacity is enough for supporting the WiFi load);
- for a given LTE duty-cycle, WiFi performance can be optimized if LTE transmissions start and are entirely accommodated during WiFi white spaces.

Taking into account these considerations and the control mechanisms defined in standard protocols, we envisioned the design of a coexistence mechanism based on two main mechanisms: i) using contention-free periods, indicated into periodic beacons loosely synchronized with LTE regular schedules, for creating an artificial aggregated white space; ii) regulating LTE duty-cycles (for example modulating the number of subframes sent at each channel access) in order to guarantee that WiFi stations remain unsaturated.

A. Scheme description

The scheme works as follows. Assuming that the WiFi AP is able to identify an LTE frame transmission and scheduling interval, by monitoring frame durations or receiver error statistics [15], it can schedule the beacon transmission right before the expected scheduling time of LTE frames. The size of the contention-free period can be tuned by estimating the WiFi offered load (for example, in terms of consumed air time). For sake of simplicity, we express each time interval in terms of slotted units of 1 msec (i.e. one LTE subframe).

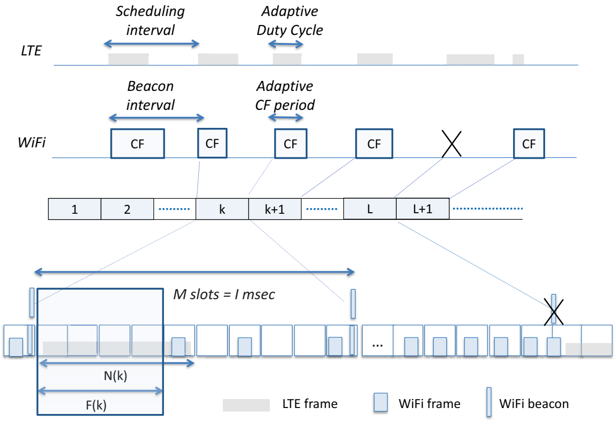

Fig. 2. Example of coexistence scheme: WiFi AP acts by tuning a periodic contention free period, while LTE eNB acts by tuning the duty cycle.

Figure 2 shows an exemplary channel access sequence obtained under the envisioned coexistence scheme, with a scheduling interval of $I = 10$ msec, corresponding to $M = 10$ slots of 1 msec each. After the initial configuration of the beacon scheduling time, each beacon transmission guarantees that F subframes sent by eNB can be accommodated during the contention-free period; WiFi nodes generating packets during the contention-free period will wait till the end of this period for accessing the channel. If the network keeps unsaturated, beacon transmissions are performed without delays and contention-free periods are available at each LTE scheduling time. If eNB transmits $N > F$ subframes (thus destroying part of the channel capacity available for WiFi), or the network load is suddenly increased, it may happen that the channel contention level prevents the transmission of the beacon at the expected time. In such a case, the normal deferral of the beacon transmission can result in a collision with the next LTE frame, i.e. with the lack of a contention-free period in a given beacon interval. This happens either in case of LTE-U (when LTE frames are scheduled at regular time intervals, regardless of the channel state) or in case of LTE-LAA (when eNB wins the contention against the AP and its transmission anticipates the beacon one). The probability of WiFi transmissions overlapping with LTE depends on the amount of backlogged traffic.

From the previous description, we can easily imagine that eNB is motivated to control its channel share in each scheduling interval (i.e. N/M) for avoiding the saturation of WiFi network, while the AP is motivated to use the contention-free period because, for a given LTE duty cycle, its adoption results in a more stable throughput for WiFi nodes.

B. Channel access model

The coexistence mechanism described above can be modeled in terms of a game. In our model, we consider that LTE transmissions are scheduled at regular time intervals and performed without carrier sensing (i.e. according to LTE-U), but it is possible to extend the model to the case of LTE-LAA by simply considering that, in case of WiFi congestion, beacon transmissions can contend not only with WiFi nodes but also with LTE eNB.

Assume that each WiFi data/ack handshake lasts approximately 1 msec (including a DIFS interval), the number of WiFi stations is extremely high, and backoff times are almost negligible (being in most cases transmissions performed without backoff). Let A be the average channel airtime observed in a scheduling interval by aggregating the frame transmissions originated by multiple independent non-saturated flows (without considering re-transmissions). As long as the collision rate is almost zero, this airtime corresponds to the average number of frames successfully sent in the scheduling interval, while the specific number of frames generated in each interval can be modeled as a Poisson variable. Let $N(k)$ be the number of subframes sent by the eNB and $F(k)$ be the length of the contention-free period set-up by the AP in the k-th scheduling interval. Being the number of WiFi nodes very high, we also assume that the number of stations with non-empty queues at the end of a scheduling interval corresponds exactly to the number of generated packets $Q(k)$ that have not been successfully transmitted until this time instant. We evaluate the probability of delaying or losing a beacon transmission as the probability that, right after the end of the scheduling interval, at least one of the contending stations with non-empty queues has a residual backoff counter equal to zero. In such a case, the next contention-free period is not reserved and WiFi stations can collide with the LTE transmission.

We can now formulate the channel access model describing the number of WiFi and LTE successful transmissions at the k-th scheduling interval. Assuming that WiFi nodes are able to ideally schedule up to $M - max\,(F(k), N(k))$ packet transmissions (by neglecting DIFS or contending times) in the channel share available for WiFi, the number of WiFi successful transmissions $S_{WiFi}(k)$ in a given scheduling interval can be evalauted as[1]:

$$S_{WiFi}(k) = min(Q(k-1)+X(k), M-max\,(F(k), N(k))).$$

where $X(k)$ is a random Poisson variable whose average value is A, corresponding to the WiFi packets generated during the whole scheduling interval It follows that the enqueued packets obey to the following equation:

$$Q(k) = Q(k-1) + X(k) - S_{WiFi}(k)$$

Let $P_{CF}(k)$ the probability to start a contention-free interval lasting $F(k)$ slots. When the collision rate in the WiFi network is low, we can approximate the channel access probability of stations in contention right before the end of the scheduling interval as $\tau = 2/CW_{min}$ and evaluate the probability of scheduling a contention-free period as:

$$P_{CF}(k) = (1-\tau)^{Q(k)}$$

The number of LTE successful subframes is equal to the minimum between $F(k)$ and $N(k)$, in case the contention-free period is scheduled; if $N(k) > F(k)$, we assume that additional subframes can be successful if no packet is enqueued at the end of the contention-free interval and no new packet is generated in each subframe. When the contention-free period is not scheduled because of WiFi congestion (i.e. $Q(k) > 0$), all the subframes are lost except the first one (needed by WiFi stations to adjust the noise thresholds). Being $CF(k)$ a binary variable equal to 1 with probability $P_{CF}(k)$, LTE throughput can be expressed as:

$$S_{LTE}(k) = (1 - CF(k)) \cdot 1 + CF(k) \cdot [min(F(k), N(k)) +$$
$$+ max(1 - Q(k-1), 0) \cdot \sum_{i=1}^{max(N(k)-F(k),0)} e^{-A/M\cdot(F(k)+i)}]$$

where the last addend of the throughput in intervals with contention-free periods can be usually neglected (unless the WiFi load is much lower than the available channel time).

C. Game definition

We consider a dynamic game between LTE and WiFi technologies, in which at each scheduling interval k it is possible to adjust the parameters $N(k)$ from the LTE side and $F(k)$ on the WiFi side. We also assume that LTE utility is optimized when the number of successful subframes is maximized, while WiFi utility in non-saturated conditions is optimized when the average number of packets enqueued at the end of each scheduling interval is minimized. In other words $J_{LTE}(N(k), F(k)) = S_{LTE}(k)$ and $J_{WiFi}(N(k), F(k)) = -Q(k)$.

For numerically studying the utility functions, we implemented some MATLAB-based simulations under varying network scenarios, based on the channel access model defined in the previous sub-section. Figure 3 shows the LTE average utility (in terms of successful subframes per scheduling interval I and $I = 10msec$) as the number of subframes N utilized for transmitting LTE blocks is increased from 1 to 10, under varying WiFi load conditions and for two different configurations of the contention free period (namely $F(k) = M - 1 - A\ \forall k$ and $F(k) = M - 2 - A\ \forall k$). WiFi load is expressed in terms of airtime in $msec/10msec$. From the figure, we can easily recognize the LTE best response: for each A value, the optimal value of N roughly corresponds to 9 slots-A. Indeed, it is not possible to allocate the whole channel time, even when the WiFi network is not saturated, because some intervals are wasted for the contention mechanism and for the scheduling of the beacon frames.

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[1] This expression is actually an upper bound, because we are considering that all the available channel slots can be used by the packets generated during the k-th interval, regardless of the timings at which packets are generated. However, the bound is tight: in high load conditions (when the maximum channel capacity $M - max(F(k), N(k))$ is required), it is unlikely that some channel time is wasted beacause no WiFi frame has been buffered during the previous $N(k)$ slots.

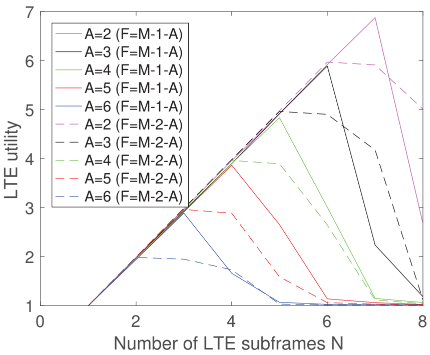


Fig. 3. Impact of different LTE strategies as the WiFi offered load varies from 2msec/10msec to 6msec/10msec.

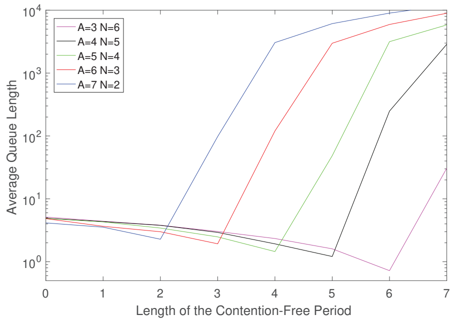


Fig. 4. Impact of different WiFi strategies under varying network load and LTE configuration options.

Figure 4 shows the WiFi average utility as the length of the contention-free period increases from 1 to 10, under varying load conditions. In this case, we always assumed that N is set to the optimal one under a fixed WiFi load equal to A. It is evident that, when LTE is configured for exploiting as much as possible the airtime left by WiFi, the optimal F setting corresponds exactly to the number of subframes utilized by LTE.

Finally, we considered the dynamic game, in which each technology adjusts at regular time intervals its strategy as a function of some network parameters estimated from the channel monitoring. In particular, for implementing the best response strategies N_{br} and F_{br}, each technology has to estimate the average channel time consumed by the WiFi network, taking into account both the observable channel time consumed by successful WiFi transmissions and the collisions with LTE subframes (when contention-free periods cannot be scheduled). Assuming that the best response strategy is implemented at generic discrete intervals (lasting for example L scheduling intervals), by averaging the WiFi throughput and contention-free scheduling probability observed on the channel, we have:

$$N_{br}(l) = 0.9 \cdot M - (E[S_{WiFi}] + (1 - E[P_{CF}]) \cdot (N_{br}(l-1))$$
$$F_{br}(l) = N_{br}(l)$$

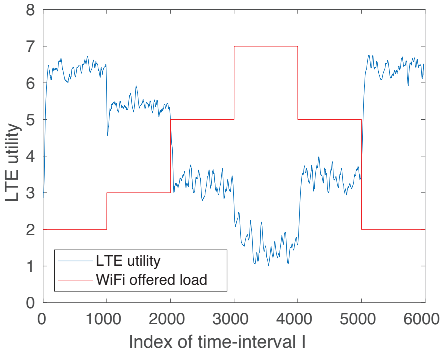


Fig. 5. LTE utility over time in presence of time-varying WiFi load under the dynamic game.

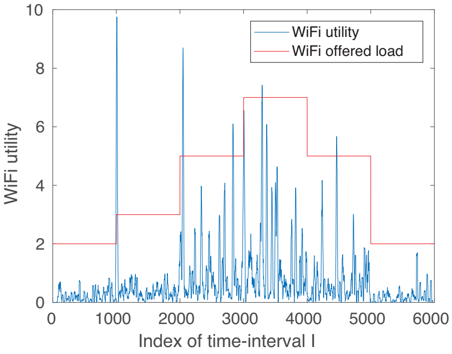


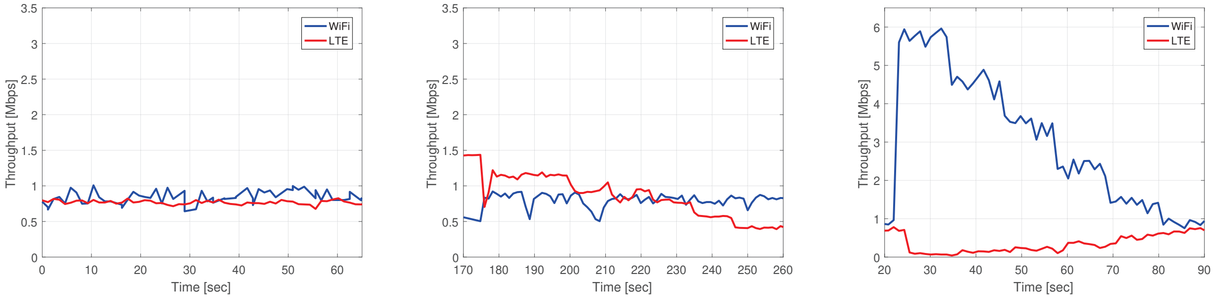
Fig. 6. Number of WiFi queued packets over time in presence of time-varying WiFi load under the dynamic game.

where the average values $E[S_{WiFi}]$ and $E[P_{CF}]$ depend on the previous best response settings, according to the system dynamic described in the previous subsection.

Figures 5 and 6 show the LTE and WiFi utility achieved when the WiFi offered load (in $msec/10msec$) varies according to the red curve of the figure, under the dynamic game described above and for $L = 10$. The scheme allows to achieve an utility which is on average close to the maximum utility found in the static load scenario and by exactly knowing the offered WiFi load.

IV. EXPERIMENTAL VALIDATION

In order to demonstrate the technical feasibility of the previous scheme and evaluate the performance benefits, we implemented a minor variant of the proposed coexistence game on a real testbed. LTE eNB was implemented on the USRP B-210 SDR platform by using the srsLTE software framework [12]. We considered a downlink stream with 5MHz of bandwidth centered on channel 11, with a modulation format MCS=4 [16]. For implementing our rational WiFi nodes we worked on the WMP [17] platform, for which it was already available a radio program able to dynamically pause the MAC scheme employed by all the nodes at the occurrence



(a)

(b)

(c)

Fig. 7. Throughput performance perceived by WiFi and LTE networks, without cooperation, in different scenarios: (a) saturated DCF vs. LTE with two blank subframes; (b) unsaturated TDM/DCF vs LTE with increasing offered load; (c) saturated DCF vs LTE with increasing number of blank subframes.

of a beacon frame transmission or regular channel slots. Node intelligence for both the technologies has been implemented by exploiting the controller developed within the EU project WiSHFUL [18]: a unified interface allows the access to low-level statistics of the nodes (e.g. the block error rate BER experienced on LTE frame transmissions and the measurement of channel occupancy times) and dynamically tune the number of allocated subframes on LTE eNB and the length of the contention-free period on the WiFi AP.

The scheduling interval of LTE transmissions and the corresponding beacon interval have been set to $I = 10msec$. Although, in principle, each subframe can be dynamically allocated or left empty, the first and the sixth subframe need to be transmitted in each interval in order to keep alive the LTE network, e.g. they delivery the synchronization virtual channel. For simmetry, we also pre-allocated two other subframes to WiFi nodes and leave the adaptation scheme working on the remaining $M - 4$ subframes. It results that our implemented scheme is slightly different from the scheme depicted in figure 2, because the adaptation scheme works with the constraints that $N_{min} = 2$ and $F_{max} = M - 2$. For introducing the possibility of allocating non-consecutive subframes to a given technology (being the sixth subframe pre-allocated to LTE), thus improving the channel utilization, we used an hybrid TDM/DCF access mechanism for WiFi nodes, for implementing a contention-free mask in terms of channel slots whose access is prevented to WiFi nodes. In other slots, channel access is performed at beginning of the slot if the medium is sensed as idle; otherwise, a random contention is performed. To assue that potential contentions are completed by the end of the slot, the selected packet size corresponds to a transmission time of about $400\mu s$, smaller than the slot size. Note that in case of non-saturated links, we can expect that performance of the hybrid TDM/DCF scheme and DCF are not very different. In the WiFi controller, we also exploited an interference recognition module already available [15] for identifying the start of the LTE scheduling interval. A WiFi link with bi-directional traffic flows is activated between the AP and one WiFi station: packet size is set-up to 600 bytes at a data rate of 24Mbps. Figure 8 shows a channel trace acquired by a monitoring USRP by measuring consecutive RSSI samples, when the LTE and WiFi networks operated under the envisioned cooperation scheme with 3 subframes allocated for WiFi transmissions. Beacon frames are used as synchronization signals and can be recognized by the lack of the spikes representing the data acknowledgments.

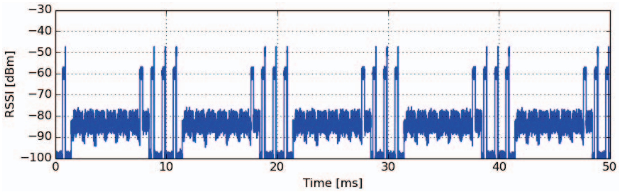


Fig. 8. Example of LTE and WiFi coordination, with $N = 7$ and $F = 3$.

A. Numerical Results

We first studied the interactions between the LTE and WiFi networks in absence of cooperation.

Figure 7 shows the throughput of the LTE (red line) and WiFi (blu line) network in three different scenarios: a) legacy DCF with saturated traffic and legacy LTE with two empty subframes in each transmitted frame; b) hybrid TDM/DCF access scheme for WiFi nodes, with an increasing number of allocated slots over time (from 2 to 8) and LTE with two empty subframes; c) legacy DCF in saturation conditions and legacy LTE with a decreasing number of empty subframes (from 8 to 2) over time. From case a, we can see that both the technologies are able to achieve a non-null throughput even in absence of cooperation, but such a throughput is very low. From figure b it clearly emerges that WiFi nodes are not prevented from colliding with LTE frames, thanks to the ambient noise immunity scheme, being the LTE throughput significantly affected by the increment of WiFi traffic (figure a). Finally from figure c we see that WiFi saturation throughput is limited by the number of subframes left empty by LTE eNB. and the WiFi throghput . Figure 9 shows the effect of the cooperation scheme in case of time-varying load conditions in the WiFi network (from zero to an offered load of

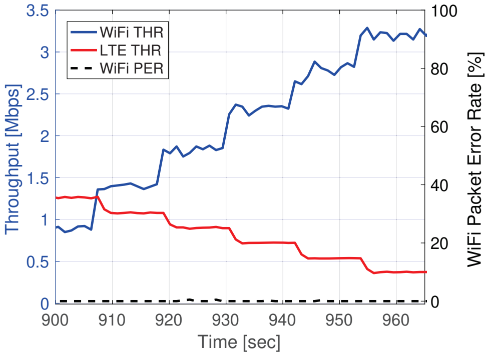


Fig. 9. WiFi and LTE performance in case implemented scheme

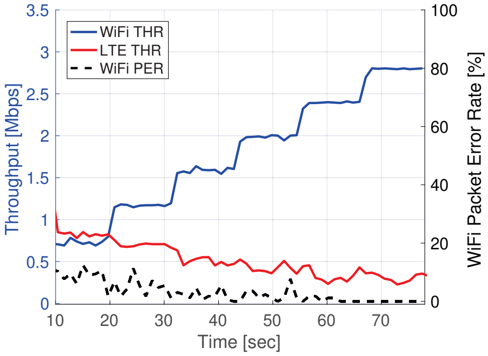


Fig. 10. WiFi wariable source rate when LTE remove subframe every 10 seconds

5msec/10msec). Both the LTE eNB and WiFi AP are able to dynamically adjust the number of empty subframes and the contention-free mask in order to successfully accommodate the WiFi load. The figure also shows the packet error rate (black dashed line) of the WiFi network, which is almost negligible by demonstrating that it is very rare that beacon frames cannot be scheduled because of high contention levels. In order to demonstrate that coexistence between WiFi and LTE can benefit when WiFi white spaces under unsaturated network conditions are aggregated, figure 7 shows WiFi and LTE throughput, as well as WiFi packet error rate, under the same traffic scenario of figure 9, but under legacy DCF. We can observe that, although the channel is still able to guarantee a throughput equal to the time-varying offered load, the packet error rate experienced by WiFi node is much higher.

V. CONCLUSION

In this paper we discussed several aspects related to the problem of coexistence between WiFi and LTE nodes. Starting from the observation that is not generally true that WiFi carrier sense prevents from undefinitively accessing the channel in presence of continous LTE frame transmissions, we proposed to exploit different functionalities offered by LTE and WiFi legacy protocols to implement a coexisting strategy. Despite of the strong simplificative assumptions used for modeling the WiFi/LTE interactions under the envisioned coexisting strategy, we defined the best responses that should be implemented on both the technologies in case of coexistence and validated their implementation feasibility and performance benefits in real experiments.

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