LTE/Wi-Fi Co-existence under Scrutiny: An Empirical Study

LTE/Wi-Fi Co-existence under Scrutiny: An Empirical Study

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ABSTRACT

Mobile operators are seeking to increase network capacity by extending Long Term Evolution (LTE) cellular operation into unlicensed frequency bands. While these efforts may respond to the projected exponential growth in mobile data traffic, significant concerns exist about the harmonious co-existence of LTE with incumbent Wi-Fi deployments.

In this paper we characterise experimentally the LTE and Wi-Fi behaviour when sharing the same spectrum while operating under a broad range of network conditions. Specifically, we deploy a test bed with commodity Wi-Fi hardware and low-cost software-defined radio equipment running an open-source LTE stack. We investigate the *user-level performance* attainable over these technologies when employing different settings, including LTE duty cycling patterns, Wi-Fi offered loads, transmit power levels, modulation and coding schemes, and packet sizes. We show that co-existence is feasible without modifications to the Wi-Fi stack, if LTE periodically employs "silent" sub-frames; however, optimising the performance of both requires non-trivial tuning of multiple parameters in conjunction with close monitoring of Wi-Fi operation and detection of application-specific requirements. Our findings lay the foundations for coherent design of practical LTE/Wi-Fi co-existence mechanisms.

CCS Concepts

•Networks → Network experimentation;

Keywords

LTE/Wi-Fi co-existence; Licensed-Assisted Access; experimental characterisation

1. INTRODUCTION

Mobile data traffic accounts today for almost 50% of the total Internet IP traffic and is expected to increase 10-fold by 2021 [1]. Under these predictions, cellular to Wi-Fi offloading practices will be unable to meet the growing traffic demand and thus carriers are considering extending LTE operation into unlicensed frequency bands. In contrast to offloading, LTE in unlicensed spectrum [2] has two major advantages, namely (1) superior spectral efficiency (time-division duplex provides more efficient multiplexing as compared to decentralised contention-based access), and (2) the technology can be seamlessly integrated with the cellular network already operating over licensed spectrum [3].

Extending LTE into unlicensed bands, currently dominated by residential and enterprise Wi-Fi, brings about challenges related to the "friendly" co-existence of the two technologies. In particular, LTE transmits according to precise schedules, distributing users over time-frequency resource blocks, whereas Wi-Fi is governed by a carrier-sense multiple access with collision avoidance (CSMA/CA) protocol, by which stations transmit only when sensing the channel idle. Given these fundamental differences between the two access paradigms, of which LTE is more aggressive, Wi-Fi manufacturers' concerns that LTE unlicensed (LTE-U) will create harmful interference to Wi-Fi are justified.

Experimentation campaigns that assess the performance of the two technologies when sharing the same spectrum have been limited thus far, and extensive operator trials are only scheduled for Q3/2016 [4]. This is in part due to the high cost[1] of the commercially available LTE/Wi-Fi co-existence testing equipment [5]. Preliminary empirical co-existence studies published recently only investigate the impact of LTE bandwidth, centre frequency, and Wi-Fi clear channel assessment (CCA) threshold on Wi-Fi throughput, without careful consideration to LTE performance [6]. Most performance evaluation studies in this space are unfortunately simulation based [7–10], therefore fail to capture accurately system level details of the two technologies and do not give insights into their interactions and attainable performance in real-world deployments.

Contributions: In this paper we present a comprehensive empirical study that sheds light into the LTE/Wi-Fi co-existence performance and limitations. To this end, we deploy a wireless test bed comprising affordable Software Defined Radio (SDR) hardware capable of running an open-source LTE stack, and off-the-shelf Linux-based Wi-Fi devices. As the LTE library used primarily handles base-band processing, multiplexing, and data transmission, while a full-fledged protocol stack is yet to be released, we implement a tunnelling application to conduct our experiments – this

[1] A test bed consisting of one Wi-Fi and respectively one LTE client–base station pair (four devices), and necessary software licenses is in the $70,000 range.

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enables us to *measure for the first time user-level performance over LTE, in the presence of Wi-Fi.* On the other hand, Wi-Fi drivers and configuration tools are mature, allowing us to experiment with a wide range of parameters. We investigate the throughput performance of the two technologies when sharing the same frequency band, with LTE ignoring the presence of Wi-Fi incumbents and respectively employing different duty cycling policies, while the Wi-Fi traffic load is varied. We examine the impact of modulation and coding schemes (MCS) employed by the two technologies, packet size, transmit power used, and contention levels. Further, we shed light on how LTE duty cycling influences the jitter experienced by applications running over Wi-Fi.

The obtained results demonstrate that *(i)* duty cycling patterns are key to the throughput performance attainable by Wi-Fi, but also impact on the jitter performance critical to real-time applications, *(ii)* under homogeneous power settings LTE can lock out Wi-Fi transmissions, if not alternating silent/active periods, *(iii)* as transmit power is increased, Wi-Fi load negatively impacts on LTE throughput, *(iv)* no single LTE transmission strategy ensures Wi-Fi performance is maximised when operating with different MCSs and packet sizes, and *(v)* Wi-Fi contention levels do not affect LTE performance. These results reveal that optimising the performance of both technologies requires non-trivial tuning of several parameters while closely monitoring Wi-Fi operation and application-specific requirements. Our findings provide the necessary foundations for coherent design of practical LTE/Wi-Fi co-existence schemes to be implemented on emerging LTE unlicensed eNodeBs.

2. LTE & WI-FI OVERVIEW

Given the fundamental differences between the medium access paradigms employed in LTE and Wi-Fi, to better understand the co-existence challenges facing the concurrent operation of the two technologies, we first give a brief overview of these approaches.

LTE employs precise time-based scheduling, whereby a base station (eNodeB) divides channel into 10ms frames and assigns users different Physical Resource Blocks (PRBs), implementing both time and frequency multiplexing, as illustrated in Fig. 1. LTE does not give consideration to other users of the same band, since traditionally access has been confined to licensed frequencies to which an operator had

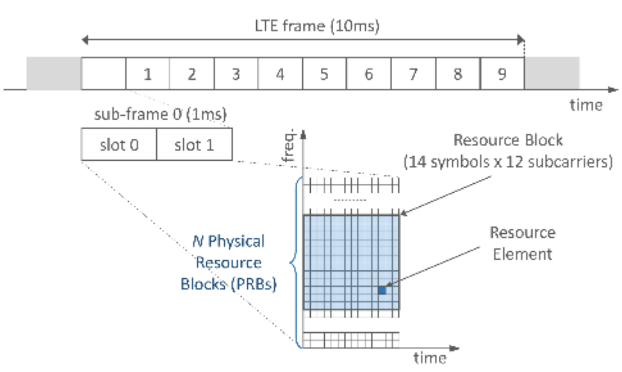


Figure 1: LTE operation – channel divided into frames (10ms); users multiplexed in frequency and time (resource blocks) over sub-frames (1ms).

Figure 2: Wi-Fi operation – decentralised CSMA/CA based channel access; stations transmit when channel is sensed idle, after a back-off procedure.

exclusive access. On the other hand, an eNodeB could be configured to remain silent during certain sub-frames (e.g. to enable macro base stations to create opportunities for cellular femto-cells that extend coverage), though this can only be performed with strict millisecond granularity and involves exact synchronisation across the cellular deployment.

In contrast, Wi-Fi employs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, by which user multiplexing is decentralised and channel is regarded as a sequence of busy/idle slots, as shown in Fig. 2. To transmit a frame, once the channel is sensed idle for DIFS (distributed inter-frame space) time, a station enters a back-off procedure, choosing a random counter uniformly distributed between 0 and CW_{min} (Contention Window minimum) value. The counter is decremented every (idle/busy) slot and when it reaches zero, the station transmits. A success is acknowledged (ACK) by the receiver, whereas in case of collision with another transmission, the CW is doubled and the procedure restarted. The CW is reset to the initial value (CW_{min}) upon success.

It is straightforward to infer that LTE will always transmit, unless some sub-frames are intentionally left blank, while Wi-Fi will only transmit when the channel is sensed idle. Under concurrent operation, a Wi-Fi packet could partially overlap with an LTE sub-frame, but whether data transmitted over Wi-Fi, LTE, both, or none can be decoded by the intended receiver remains to be investigated. Therefore, in what follows we conduct experiments to gain understanding on how different parameters employed by the two technologies, including LTE duty cycling patterns, TX power levels, modulation and coding schemes (MCSs), and packet sizes, impact on the performance each of these can attain under different traffic loads.

3. TEST BED DEPLOYMENT

For our experimentation campaign, we deploy a wireless test bed in a university lab, which comprises one Wi-Fi access point (AP), five client stations, one LTE eNodeB and one LTE user equipment (UE), as shown in Fig. 3. We build the Wi-Fi network with off-the-shelf Alix APU.1D4 embedded PCs by PC Engines, equipped with Atheros AR9280 dual-band (2.4/5GHz) wireless adapters, and running Ubuntu 14.04 LTS Linux (kernel 3.17). The LTE nodes are commodity Linux based desktop computers with RF front-ends based on Ettus USRP B210. These are low-cost software-defined radio (SDR) experimentation platforms that can operate in the 70MHz–6GHz range and are highly programmable.

The Wi-Fi AP is managed using the `hostapd` daemon[2] and the network is set up in the 2.4GHz unlicensed band, on a 20MHz channel where no other deployments were identified following spectral analysis. Client association control and

[2]HostAP daemon `https://w1.fi/hostapd/`

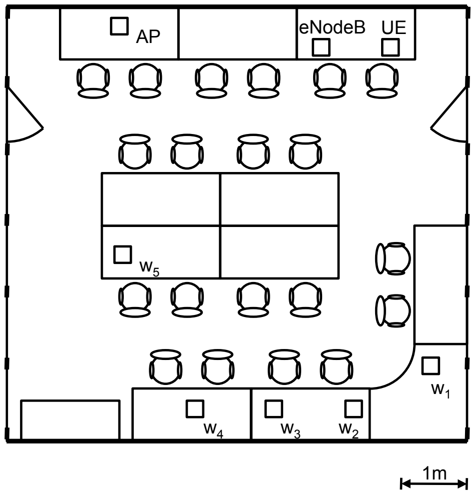


Figure 3: LTE/Wi-Fi co-existence test bed, consisting of 1 AP, 5 stations (w_i), 1 eNodeB, and 1 UE.

authentication is handled by `wpa_supplicant`,[3] all stations run the **ath9k** open-source driver, and employ the IEEE 802.11g standard. We use the `iw` tool to manipulate the transmit power and MCS configurations.

The LTE nodes run the open-source USRP hardware driver (UHD), which enables us to control the SDR boards using GNURadio,[4] an open-source software development toolkit that offers a rich library of signal processing blocks and enables rapid prototyping of protocol stacks using high level programming languages, e.g. Python and C/C++. We implement an LTE Release 8 compliant stack using the recently released `srsLTE` project,[5] which we modify to meet our experimentation requirements. In particular, the current release supports frame transmission over 1.4/3/5/10/15/20 MHz channels, cell search and synchronisation, and PRB allocation, but does not provide a full TCP/IP protocol stack.

Therefore, to be able to conduct application level measurements of throughput, jitter, and packet loss on top of an LTE downlink, *we implement a tunnelling solution based on the Linux TUN/TAP virtual networking kernel extensions.* To the best of our knowledge, application level throughput measurements over LTE-U have not been yet reported. With our approach, at the sender side a `tunnel_entry` application receives user generated packets, performs Ethernet encapsulation, appends a frame check sequence, and sends these to the socket opened by the eNodeB where data is expected for transmission over the air interface. At the UE side, the LTE receiver forwards the data to another socket, to which we connect a `tunnel_exit` application that reconstructs the packets, drops the corrupt ones, and presents them to the receiving user-level application.

Our tunnelling implementation enables us to run a popular traffic generation tool, i.e. `iperf`, between the eNodeB and UE and measure application level performance on the *downlink*. Given the controlled nature of our experiments, the uplink required for `iperf` reports is realised over a wired Ethernet link. We use the same traffic generation tool on the Wi-Fi AP and stations, to measure performance over a wide range of settings employed by the two networks.

[3]Linux WPA supplicant `https://w1.fi/wpa_supplicant/`
[4]GNURadio `http://gnuradio.org/`
[5]srsLTE `https://github.com/srsLTE/srsLTE`

4. WI-FI/LTE CO-EXISTENCE

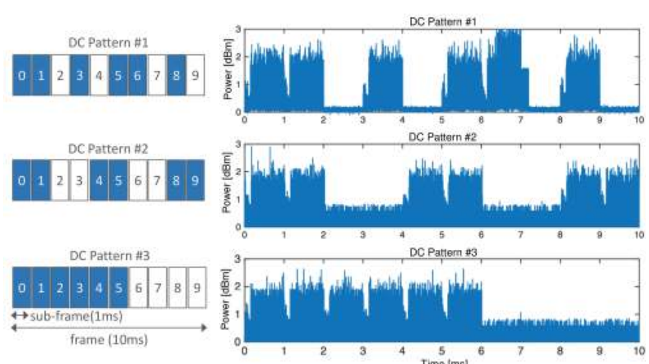
In this section we first present the methodology used to conduct our experiments aimed at characterising the behaviour of Wi-Fi and LTE when sharing the same spectral resources. We then report the results obtained under a broad range of network conditions and summarise the key findings.

4.1 Methodology

We investigate how different settings of the two technologies, including channel bandwidth, MCS, packet size, TX power, sub-frame allocation (duty cycle), and traffic load impact on the performance of the two technologies when operating concurrently.

LTE set-up: For the LTE deployment, given that the USRP boards are not calibrated and the maximum output power is constrained, we keep the TX power constant in all experiments, equivalent to that of a Wi-Fi transmitter configured with 2dBm output, as found through empirical calibration we perform with a spectrum analyser. We experiment with LTE bandwidths in the $\{5, 10, 15, 20\}$ MHz range, and different link spectral efficiency, i.e. QPSK, 16-QAM, and 64-QAM. *Importantly, we study co-existence under different transmission strategies: a "naïve" approach (LTE sends data in all PRBs) and respectively three duty cycling (DC) patterns*, whereby the eNodeB only transmits in a subset of sub-frames withing a frame (channel occupancy 60%), as shown in Fig. 4a. We use again a spectrum analyser to verify that these DC patterns are followed precisely and indeed Fig. 4b confirms this is the case.

Wi-Fi set-up: We investigate how the LTE duty cycling impacts on the Wi-Fi throughput, when the latter works with TX power levels ranging in $\{2, 12, 23\}$ dBm, i.e. whether capture occurs, and whether the Wi-Fi power may affect LTE performance. We also experiment with different OFDM (6 and 36Mb/s) and DSSS (1 Mb/s) MCSs that offer different levels of robustness to channel errors (including due to collisions with LTE transmissions), but affect packet duration. Therefore, we study this in combination with different frame sizes (between 70 and 1470 bytes), which also give insights into the appropriate frame sizes that may fit into silent LTE periods.



(a) Duty cycling (DC) patterns.

(b) Spectrum analyser based validation.

Figure 4: Different active/silent sub-frame strategies used for co-existence experiments.

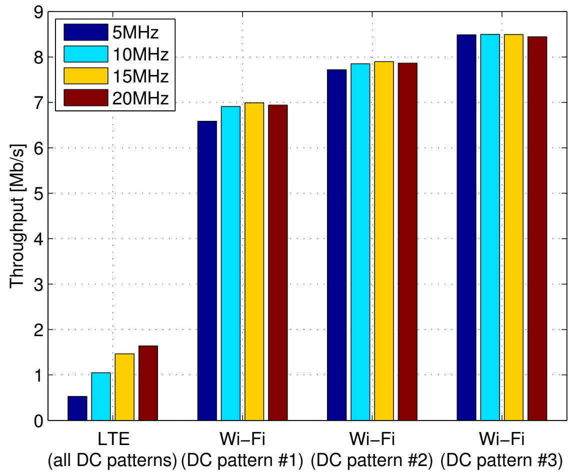


Figure 5: Network w. one LTE and one Wi-Fi connection sharing spectrum. Throughput comparison when LTE works with different bandwidths. Both technologies are backlogged, LTE employs QPSK and different DC patterns. Experimental results.

Key to all the experiments is the Wi-Fi load, as the relationship between LTE duty cycling patters, the throughput and jitter performance of each technology, and the Wi-Fi load is not straightforward to characterise. We thus vary this quantity incrementally, up to close to the maximum rate we measure when Wi-Fi operates in isolation.

For all the experiments we conduct, we run 1-minute tests during which the eNodeB and Wi-Fi client(s) send UDP traffic to the UE and respectively AP. Unless otherwise specified, the LTE link is always backlogged. We repeat each test 7 times, to obtain average values of the metrics of interest with good statistical significance.

4.2 Experimental Results

In what follows we examine the performance of LTE and Wi-Fi under a broad range of configurations employed by the two technologies when operating simultaneously. We look primarily into the achievable throughputs, though as we experiment with different duty cycling patterns, we also shed light into the packet delay variation.

4.2.1 Impact of LTE Bandwidth

We start by investigating the impact of the channel bandwidth used by the LTE deployment, in order to understand how this affects the achievable throughput over Wi-Fi and LTE, when the LTE-U downlink extension works naïvely (i.e. without consideration to Wi-Fi), and respectively with the different DC patterns shown in Fig. 4. For these experiments, we use a single backlogged Wi-Fi client that sends 1470-byte packets to the AP at 36Mb/s (802.11g OFDM), using 2dBm transmit power. The LTE link operates using QPSK and 0.14 code rate, thus the maximum attainable PHY rate ranges between 0.9–3.62Mb/s.

We show in Fig. 5 the user-level throughput obtained with each technology for the different LTE TX strategies considered. As the LTE airtime utilisation is fixed to 60% independently of the DC pattern, throughput only depends on the bandwidth used, which we vary between 5MHz and 20MHz in 5MHz steps. For this reason, we report only one set of bars for LTE on the left in the figure, which confirms an almost linear increase of the LTE throughput with the bandwidth. On the other hand, in the remaining three sets of bars we observe that Wi-Fi throughput depends on the DC pattern, while it is relatively independent of the LTE bandwidth. Note that we do not report the Wi-Fi throughput for the case of continuous LTE transmission, since this "naïve" approach locks out Wi-Fi, as we further discuss in the next sub-sections.

Finding: *LTE bandwidth has little impact on the throughput performance of Wi-Fi, though naturally limits LTE throughput irrespective of the DC pattern.* The LTE TX strategy instead impacts on Wi-Fi, therefore we examine closer the effect of this in conjunction with other settings next.

4.2.2 Duty Cycling Patterns Comparison

To study the effect of DC patterns, we fix the LTE bandwidth to 5MHz and employ QPSK, 16-QAM, and 64-QAM on the cellular link (i.e. 0.90, 4.01, and 7.74 Mb/s bit rates). We continue using a single Wi-Fi client that transmits to the AP at 36Mb/s with 2dBm power, but now vary the Wi-Fi offered load in 2.5Mb/s steps up to 12.5Mb/s, with the first (lower) load set to 100kb/s, to have an initial point close to the origin. We note that with 40% channel time allocated to Wi-Fi, under perfect scheduling we would expect the link to saturate at $\sim$10Mb/s.

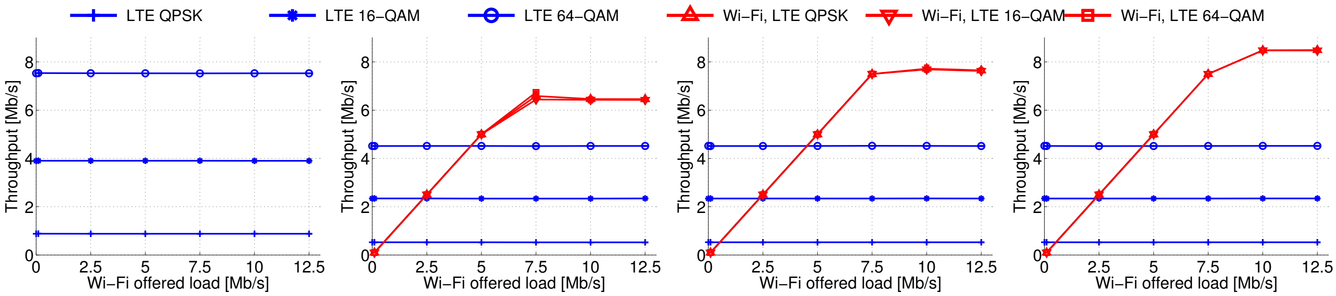
We plot in Fig. 6 the throughput achieved by each technology with the "naïve" approach and the different DC patterns, when the Wi-Fi load increases and respectively LTE operates with one of the three considered MCSs. First, observe that Wi-Fi load does not affect LTE throughput, irrespective of the TX strategy and MCS employed (note the three perfectly flat lines in each figure corresponding to the MCSs considered). On the other hand, the naïve approach/DC strategies impact significantly on Wi-Fi throughput. Namely, if always transmitting, LTE locks out Wi-Fi, while the smaller the number of contiguous silent LTE sub-frames, the earlier Wi-Fi saturates. Specifically, despite LTE occupying the channel 60% of the time, Wi-Fi throughput is capped at 6.5Mb/s with DC pattern #1, though reaches 8.5Mb/s with pattern #3. It is also important to note that as long as the offered load does not approach these limits, the throughput attained matches the load.

Findings: *The larger the number of contiguous silent LTE sub-frames, the higher the attainable Wi-Fi throughput. Wi-Fi offered load does not affect LTE throughput.*

4.2.3 Varying Wi-Fi Power Settings

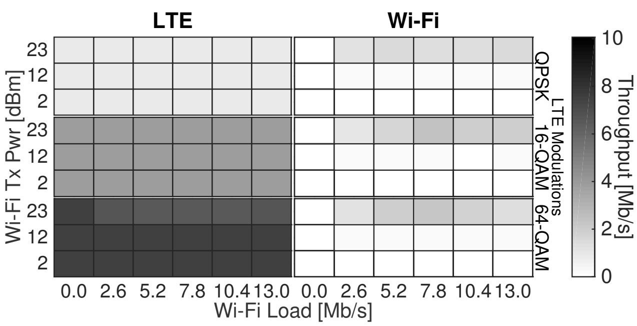
We next turn attention to the Wi-Fi power settings, again when the Wi-Fi offered load varies. Our objective is to understand whether higher Wi-Fi power levels could result into physical capture that may allow the AP to successfully decode packets that (partially) overlap LTE sub-frames. At the same time, we are interested in finding whether the TX power of a Wi-Fi client impacts on LTE throughput, as we hypothesise overlapping Wi-Fi frames may corrupt data transmitted over the LTE downlink.

We keep the same LTE bandwidth (5MHz), fix Wi-Fi MCS to 36Mb/s, and confine consideration to scenarios where the LTE always transmits ("naïve") and alternatively employs DC pattern #3. The eNodeB and AP power is kept constant, and we use TX power levels for the Wi-Fi client

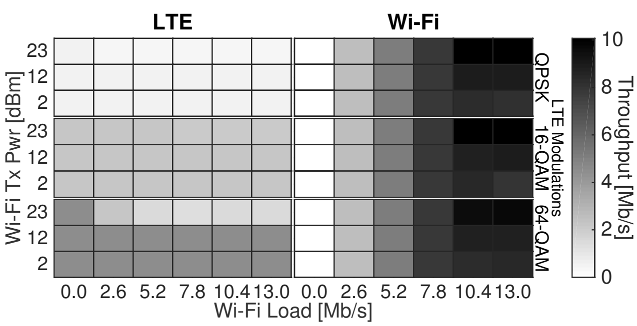


(a) Naïve (b) DC Pattern #1 (c) DC Pattern #2 (d) DC Pattern #3

Figure 6: LTE eNodeB employing different TX strategies and MCSs, while sharing spectrum with a Wi-Fi AP. Wi-Fi client load increased from 0.1 to 12.5 Mb/s. Throughput comparison. Experimental results.



(a) Naïve LTE TX strategy (always on).



(b) LTE using DC pattern #3 (see Fig. 4).

Figure 7: Network w. one LTE and one Wi-Fi connection sharing spectrum. Wi-Fi power ranges in {2, 12, 23}dBm (y-axes) and load is varied (x-axes). Throughput of LTE (left) and Wi-Fi (right) shown as heat maps, when (a) LTE always transmits and (b) employs DC pattern #3. LTE MCS also varied (3-row groups). Experimental results.

in the $\{2, 12, 23\}$ dBm range. The results of these experiments are shown in Fig. 7, where we plot the throughput performance of the two technologies as we increase the Wi-Fi load. We also investigate in parallel the effect of the LTE MCS employed.

Fig. 7 requires closer inspection to understand the co-existence behaviour as the Wi-Fi power is varied. First note that, in the case where LTE is always on ("naïve"), if Wi-Fi transmits at low-moderate powers (2 and 12 dBm), the average throughput it attains is virtually zero, irrespective of the offered load and LTE MCS (Fig. 7a, lower rows on the right). Conversely, the LTE performance is only limited by the MCS employed (left). On the other hand, when Wi-Fi transmits at high-power (upper rows of each group), the AP manages to receive some of the client's packets successfully as packet capture occurs, though the throughput performance does not exceed 1.4 Mb/s. LTE is largely unaffected when employing robust MCSs, but as expected, it experiences a performance hit when transmitting over 64-QAM. Namely, as the Wi-Fi load increases, the LTE throughput drops by 14% (upper row of the lower left map in Fig. 7a).

Turning attention to DC pattern #3, as Wi-Fi load and power is increased (Fig. 7b), we see that the WLAN client successfully fits packets into the LTE silent sub-frames and the throughput it achieves grows naturally with the load, up to ∼8.7 Mb/s. The attainable user-level rate is even higher as Wi-Fi employs 23dBm, namely 10 Mb/s (upper rows on the right in Fig. 7b). LTE throughput is largely unaffected and upper bounded by the MCS employed (left), except when sub-frames are transmitted with 64-QAM, while Wi-Fi uses 23dBm output, where we observe the LTE performance drops as the Wi-Fi load increases.

Findings: *LTE throughput with the "naïve" TX approach is mostly unaffected, while Wi-Fi is locked out irrespective of the power employed, unless LTE uses a superior MCS and Wi-Fi transmits at high power. Duty cycling enables LTE to maintain steady (albeit lower) throughput, while Wi-Fi co-exists smoothly and its performance grows with the load. With duty cycling, Wi-Fi obtains a throughput boost at high TX power, at the expense of LTE.*

4.2.4 Effects of Wi-Fi MCS and Frame Size

So far we have seen that the MCS employed by LTE mostly affects performance of the two technologies if using a large number of bits per symbol (64-QAM) and recall that data transmitted over LTE is always confined to Resource Blocks of fixed size. In what follows we investigate the effects of the MCS employed by Wi-Fi especially on the performance this technology attains under co-existence scenarios. We note that the Wi-Fi MCS and packet size directly influence the frame duration, therefore whether a frame fits within the silent sub-frames of LTE remains to be explored.

We consider the same network set-up as in the previous experiments and first fix the Wi-Fi packet size to 70, 720, and 1000 bytes when transmitting at 1, 6, and respectively 36Mb/s. LTE works using QPSK, naïvely and with DC

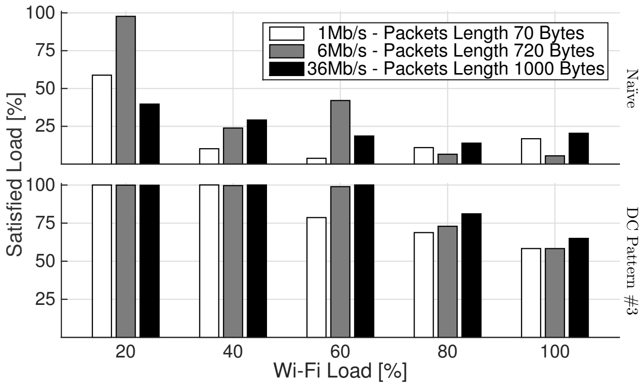


Figure 8: Network w. one LTE and one Wi-Fi link sharing spectrum. LTE always transmits (above) and respectively works with DC pattern #3 (below). Percentage of satisfied Wi-Fi load for different Wi-Fi MCS and packet length combinations, as load is increased. Experimental results.

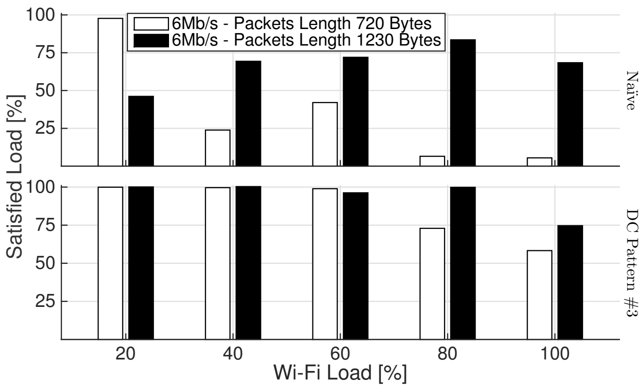


Figure 9: Network w. one LTE and one Wi-Fi link sharing spectrum. LTE always transmits (above) and respectively uses DC pattern #3 (below). Wi-Fi bit rate fixed to 6Mb/s. Satisfied Wi-Fi load percentage as demand increases. Experimental results.

pattern #3, while we increase the Wi-Fi load. Since here we operate with different bit rates which inherently lead to different maximum attainable throughputs, to allow comparison we normalise offered load and express this in percentage of the maximum attainable value. That is, since Wi-Fi can transmit for up to 40% of the channel time (due to duty cycling), assuming a conservative 10% MAC overhead, and considering MCS R is employed, then 100% load corresponds to $0.4 \times 0.9 \times R$ Mb/s. With this convention, we increase the offered load and measure the percentage of satisfied demand, i.e. how much Wi-Fi can actually deliver.

The outcome of this experiments is summarised in Fig. 8. With the naïve LTE approach, as the Wi-Fi load varies, we observe non-monotonic trends of the performance, which depend on the MCS Wi-Fi employs (upper sub-plot). Specifically, at basic DSSS rate (1Mb/s), the percentage of satisfied load initially drops as the load increases, but then increases again as the demand exceeds 60% of the link budget. A similar, but more subtle behaviour is also seen at 36Mb/s, where the satisfied load percentage grows slightly at saturation. More interestingly, when 6Mb/s is used the performance drops sharply from 20 to 40% demand, then increases again at 60% load, and subsequently decreases below 10% as the load grows further.

Before examining closely this configuration, we briefly look into the performance when LTE employs duty cycling (pattern #3) and Wi-Fi MCS is varied. We illustrate this in the lower sub-plot of Fig. 8, where we observe that, as previously suggested by our earlier experiments, the percentage of satisfied load decreases as load increases. On the other hand, the higher the MCS used, the higher the percentage of satisfied load, which indicates that longer frames may be corrupted by LTE. We thus turn attention to the effects of packet size next.

To this end, we fix the Wi-Fi MCS to 6Mb/s and examine the attainable throughput as the load increases, while packets sizes are fixed to 720 and 1230 bytes. Again LTE is always on and respectively uses DC pattern #3, and transmits using QPSK. Since 6Mb/s is the basic rate in 802.11g/a OFDM systems, at which control frames (beacons, RTS/CTS, etc.) are transmitted, this also gives insight into the expected performance at 5GHz. We also note that, with DC pattern #3, a full RTS/CTS exchange could fit in the silent interval LTE leaves within each frame, though whether subsequent data packets are delivered successfully is to be verified.

The results we obtain with different packet sizes are given in Fig. 9. With LTE always on, we see that the satisfied load percentage varies significantly (up and down) with medium size packets (720B), while this almost always increases as the load is increased, if the packet length is large (1230B). As already suggested, demand is satisfied more easily when LTE employs silent sub-frames, while at high traffic volumes performance is superior with larger frames (lower sub-plot in Fig. 9).

Findings: *Wi-Fi throughput performance shows a non-trivial dependency on the MCS and packet length used, as well as on the LTE framing strategy. Maximising the performance of both technologies, would require LTE to infer both Wi-Fi operating conditions and traffic load.*

4.2.5 Impact of Wi-Fi Contention

To isolate the impact of the different PHY and MAC settings LTE and Wi-Fi may employ, up to now we have only considered single client–base station pairs of each technology co-exist on the same channel. At this stage, we investigate whether Wi-Fi contention has any impact on LTE performance. For this purpose, we compare the attainable throughputs when the Wi-Fi AP servers one and five stations, while the LTE eNodeB operates with DC pattern #3.

The results are illustrated in Fig. 10, where each subplot corresponds to a different Wi-Fi bit rate and we show the aggregate throughput performance of each technology as per-client offered load increases. We perform these tests for both numbers of Wi-Fi clients (1 and 5) and two LTE MCSs, i.e. QPSK and 16-QAM. From these results we conclude that, despite Wi-Fi exhibiting intensified activity, contention does not affect LTE throughput (LTE curves with 1 and 5 Wi-Fi stations overlap). On the other hand, as expected Wi-Fi saturates much faster with more clients and suffers a slight total throughput loss in this regime (we quantify this as a few Kb/s drop).

Finding: *The number of Wi-Fi clients does not influence*

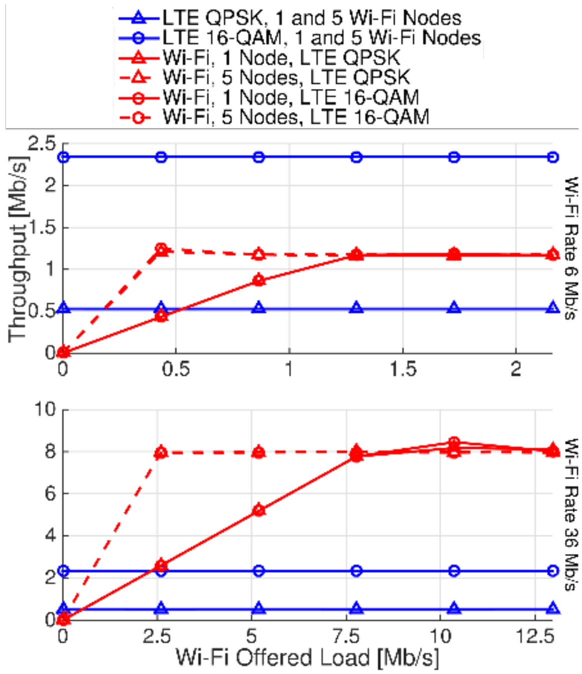


Figure 10: Total LTE and Wi-Fi throughput when one eNodeB transmitting to one UE shares spectrum with a Wi-Fi AP that serves 1 and 5 clients. LTE operates with QPSK and 16-QAM; Wi-Fi stations transmit at 6 and 36Mb/s; Wi-Fi load varies. Experimental results.

LTE performance.

4.2.6 Jitter Performance

Next we examine the packet delay variation (jitter) experienced by Wi-Fi, when LTE employs different duty cycling strategies. To this end, we resort again to the set-up with one eNodeB serving one UE and the Wi-Fi AP receiving UDP traffic from one client station. The LTE link employs QPSK and uses a 5MHz wide channel, while we experiment with the three duty cycling patterns shown in Fig. 4a. The Wi-Fi client is transmitting at 36Mb/s and we increase the offered load from 2.5Mb/s up to saturation.

The obtained results are shown in Fig. 11 for the three DC patterns considered. To add perspective, we also plot the jitter performance when Wi-Fi is operating in isolation (i.e. not sharing spectrum with LTE). We observe that as the load increases, the jitter also increases when LTE works with DC pattern #1, whereas the jitter decreases with the load as LTE leaves a large number of contiguous sub-frames empty within a frame (DC pattern #3). With the second DC approach, jitter behaviour has a non-monotonic dependence on load. Deciding on the most appropriate LTE TX strategy is thus dependant on the Wi-Fi load and, importantly, on the application served. For instance, in case of conversational voice applications (VoWiFi) where the jitter should be maintained below 1ms [11], DC pattern #1 is the most suitable choice, albeit the lower throughput it sustains, as seen previously. We conjecture this is due to the fact that, with DC pattern #1, a lightly loaded Wi-Fi client will sense the channel idle almost every 1ms and will have sufficient

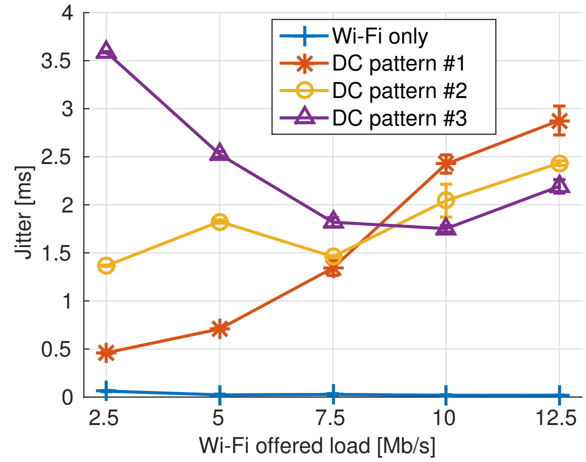


Figure 11: Wi-Fi jitter when an eNodeB shares spectrum with one AP; LTE employs the different DC patterns considered and Wi-Fi load varies. LTE transmits over QPSK and Wi-Fi bit rate is 36Mb/s. Jitter performance when Wi-Fi operates without LTE shown as benchmark. Experimental results.

time to transmit the packets queued before LTE acquires the channel. On the other hand, if LTE keeps the channel occupied for several consecutive sub-frames (as with DC pattern #3) the jitter will be overall higher, but lower at higher loads, since all queued packets will wait approximately the same time for LTE to vacate the channel.
Finding: *Longer silent LTE periods harm the performance of real-time applications with strict jitter requirements, despite offering superior throughput.*

4.2.7 LTE Packet Loss

Lastly, we examine the LTE packet loss for the naïve approach and different DC patterns, with different channel bandwidths. We note that packet loss is not detectable at the user level for Wi-Fi, since this employs a robust retransmission policy which effectively eliminates loss. On the other hand, loss rate is relevant for traffic transmitted over LTE, since the current srsLTE implementation does not implement ARQ. In addition, as Wi-Fi carrier senses LTE activity, we expect the offered load has little impact on this metric. Therefore, in Fig. 12 we show the loss rate (averaged over the Wi-Fi loads considered previously) experienced by `iperf` over LTE when the eNodeB employs QPSK, and different bandwidth and TX configurations. Unsurprisingly, LTE loss increases with the bandwidth and does not depend substantially on the TX strategy employed.
Findings: *As the power spectral density decreases with channel bandwidth, LTE loss rate increases; this is only marginally correlated with the DC pattern used.*

5. RELATED WORK

Since LTE in the 2.4 and 5GHz unlicensed bands became a 3GPP study item, co-existence of LTE with deployed Wi-Fi has been intensively discussed in the research community.
LTE/Wi-Fi Co-existence Analyses: A preliminary co-existence performance evaluation under different LTE arrival rates and TDD configurations is reported in [7]. Nihtilä *et. al* study system performance when a simple fractional

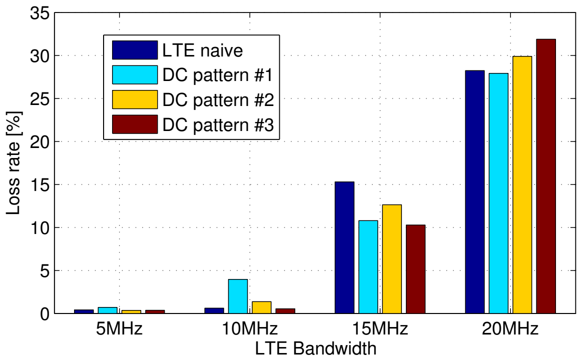


Figure 12: Network w. one LTE and one Wi-Fi link sharing spectrum. LTE employs QPSK, different BW and TX strategies. LTE loss rate averaged over increasing Wi-Fi loads. Experimental results.

bandwidth sharing strategy is used to allow both technologies to transmit [8]. Zhang *et al.* propose a random almost blank frame policy to allow Wi-Fi to coexist with LTE, while increasing the capacity of the cellular network [12]. Cavalcante *et al.* identify challenges faced by the two technologies and suggest LTE performance is marginally affected by co-existence, whereas Wi-Fi suffers significantly [10]. A Markovian framework is introduced in [13] to investigate the downlink performance of the two systems with a simple listen-before-talk (LBT) mechanism. LTE co-existence strategies including static muting, LBT, and sensing-based schemes that employ the existing WLAN channel reservation protocol, are analysed in [9]. *These early studies are however numerical or simulation based and thus fail to capture practical system level details, offering limited insights into co-existence performance in real-world deployments.*

Experimental Studies: Real-world experimentation with LTE/Wi-Fi systems sharing spectrum has been sparse, primarily due to high equipment costs and limited availability of open-source stacks. A proprietary testing solution is outlined in [5] and preliminary results confirm different duty cycle ratios can balance LTE/Wi-Fi performance, while increasing the clear channel assessment (CCA) threshold increases Wi-Fi aggressiveness. A similar platform and advanced FPGA WARP boards are used in [6] to evaluate the impact of LTE bandwidth, centre frequency, Wi-Fi CCA threshold, MIMO features, and TX-RX distance exclusively on the Wi-Fi throughput. Yun and Qiu propose a novel decoding scheme to enable simultaneous Wi-Fi and LTE transmission, and demonstrate remarkable performance with SDR radios, though their co-existence solution requires non-standard 802.11 equipment and thus its practicality is questionable [14]. *In contrast to these works, we present a comprehensive empirical analysis of LTE/Wi-Fi co-existence, under a broad range of network conditions, and develop a tool that enables us to report user-level performance attainable simultaneously over the two technologies.*

6. CONCLUSIONS & FUTURE WORK

In this paper we have reported an extensive empirical study of the LTE and Wi-Fi behaviour when sharing the same frequency band. Our experiments have been underpinned by a test bed deployment with commodity Wi-Fi devices, inexpensive SDR hardware, and open-source LTE stack, Wi-Fi drivers, and performance measurement tools. We have demonstrated that LTE/Wi-Fi co-existence is feasible if LTE employs duty-cycling, thereby silencing a subset of sub-frames, but the user-level performance attainable by the two technologies depends heavily on the various settings these employ. We have shown that maximising throughput and keeping jitter within certain bounds can only be achieved through non-trivial tuning of LTE duty-cycling patterns and MCS, while closely monitoring Wi-Fi operating regime (power, MCS, packet size, and load) and the underlying application requirements.

As open LTE stacks are continuously developed, we plan to further investigate the performance of LTE and Wi-Fi when operating concurrently in scenarios that involve both uplink and downlink traffic, TCP sessions, and user mobility. The findings presented herein and the future experiments planned will provide the necessary foundations for the design of dynamic co-existence mechanisms we intend to develop, deploy, and validate with emerging LTE unlicensed equipment.

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