Experimenting on LTE-U and WiFi coexistence

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***Abstract*— LTE technologies for unlicensed spectrum (LTE-U) are receiving an increased attention and gain momentum in an effort to tackle the rising demand for higher connection rates and better quality of experience. Unfortunately, a number of well-established technologies such as WiFi operate in the same frequency bands especially on the ISM range of 2.4GHz. In this paper, we investigate the impact of LTE-U and WiFi coexistence in a number of different environments and examine the performance of an adaptive duty cycle mechanism on the LTE side. We evaluate its impact not only on network throughput but on power consumption as well for all involved nodes. We analyse a number of variables such as the length of duty cycle, the ratio of silent vs active periods and the transmission power. In parallel, we assess the effect of a fully saturated WiFi network on an LTE-U deployment taking into account the WiFi radio transmission power and RTS threshold.**

Keywords—LTE-U, WIFI, Experimenting, Duty Cycle, Offloading

I. INTRODUCTION

Data congestion is a major problem in wireless networks because of the skyrocketing usage of social networks, the widespread smartphone adoption and the bandwidth-intensive services such as streaming video that come on top. A number of protocols have been proposed to address aforementioned demand by re-using unlicensed spectrum for commercial deployments [1]. An emerging technology that aims to reduce data congestion is LTE-U, which targets to offload traffic onto unlicensed spectrum without modifying LTE protocol parameters [2]. However, LTE-U poses serious technical burdens to telecom operators, organizations and citizens. Extra interference is introduced to the unlicensed Industrial, Scientific, and Medical (ISM) spectrum bands [3], affecting both LTE-U and WiFi systems. In contrast to other approaches such as LAA [4], or Multefire [5], that require modifications on LTE air interface with possible implications on existing deployments, LTE-U only requires proper optimization techniques to limit its impact on WiFi performance.

To achieve optimal spectrum efficiency, novel dynamic sharing techniques and strategies for interference coordination between LTE-U and WiFi in ISM bands are highly important [6]. Spectrum efficient allocation schema is of high importance for all stakeholders (manufacturers and Service providers) especially when considering 5G resource requirements [7]. Existing literature demonstrates that LTE-U and WiFi can facilitate 5G standardization and optimal deployment especially in dense environments [8].

But coexistence of LTE and WiFi can have negative effects not only to the overall throughput of the mobile terminal but on the terminal power consumption as well. Since per byte power consumption of LTE interface is much higher than the WiFi interface, retransmissions or lower saturation of WiFi interface will lead to significant power loses on handset level [9]. Keeping in mind that more than 12.3 Billion mobile terminals [10] are expected to be connected on wireless networks by 2020 (compared to 8.6 in 2017), further research in this domain is required to ensure that not only overall performance is kept but that power consumption of UE and WiFi nodes remain within nominal values. Despite the fact that a number of experiments address the power consumption of LTE and WiFi networks, there is a lack of experimental results regarding LTE-U and WiFi power consumption when deployed in the same environment.

In this paper we study the impact of introducing a duty cycle mechanism to LTE-U on both power consumption and interference mitigation. Namely, we modify the LTE transmission schema and we add a silent period where eNB enters a “sleep” state and transmit no data or control signals. During this silent LTE period, WiFi nodes are free to transmit without being impaired by LTE interference. The Duty Cycle concept in other wireless communications environments is widely adopted [11], but not for the purpose of interference mitigation. Since it can be easily implemented on SDR nodes, without modifications on the air interface and LTE protocol, it is easy to get real life measurements and evaluate its impact on already deployed production WiFi networks. In Fig 1. we depict the implementation of duty cycle concept in a waterfall diagram.

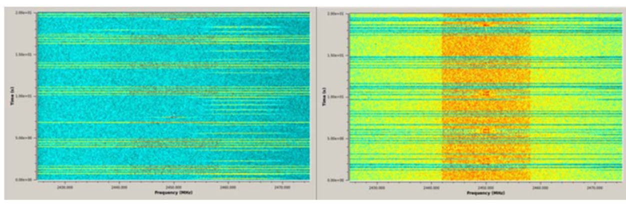

Fig. 1 LTE-U transmissions for duty cycle 10% and 90% respectively

In order to evaluate both the performance and energy impact, we split our analysis in two different sections. The first part of our experiments is focused on the performance implications of LTE-U deployment on WiFi. We performed two series of experiments in order to better understand the effect of LTE-U transmission on WiFi performance and vice versa. We showed that the duty cycle implementation is a viable solution allowing both RAT (Radio Access Technologies) coexistence. We also demonstrated that a number of parameters should be tuned, mostly on LTE side to assure that impact on WiFi performance is kept at acceptable levels. On the second part of our analysis, we evaluated the impact on the overall power consumption of all involved elements, namely UE, eNB, Access Point and WiFi client.

The key findings of our analysis demonstrate that when LTE-U is deployed with a duty cycle mechanism, WiFi can still perform in a viable manner if LTE's eNB transmit within nominal transmitting gains and with a high number of subcarriers. Moreover, even though our proposed mechanism can minimize eNB's power consumption, the terminals tend to consume far more energy and, in contradiction to existing behavior, WiFi becomes less optimal in power consumption terms.

II. EXPERIMENTAL SETUP

We used the srsLTE software [12], a well-known open source implementation of LTE, ePC and UE emulation, as the basis for experimentation by implementing our Duty Cycle concept in its software libraries. We contributed to srsLTE by extending the reference applications with two more functions providing the options for configurable silent periods and their length. Its modular architecture and short learning periods make it appropriate for such modifications. In particular, we added two more arguments on pdsch_enodeb reference application to facilitate our experiments. The first parameter (namely "C") defines the ratio of silent periods as a percentage of the total duration of silent and active time. The second parameter (namely "S") defines the total length of the active and silent period in milliseconds. Furthermore, we extended the logging capabilities of pdsch_ue reference application so as to store throughput results permanently on a log file in a format that suits our analysis.

The high level architecture deployed for our experiments is depicted in Fig. 2. As radio front-haul systems we utilized SDR (Software Defined Radio) platforms widely adopted by research community due to their low cost and sufficient performance [13]. Since we wanted to evaluate the impact of LTE-U introduction in existing production environments, we took into consideration COTS (common-of-the-self) access points and WiFi terminals. We used standard Access Points from Cisco and ASUS as well as wireless 802.11 adapters in Laptops and Intel NUCs. We evaluated our approach on two separate environments. The first environment [14] consists of SDR nodes and ASUS Access Points and commercial laptops as WiFi clients and is hosted in Iris testbed. The second environment is hosted in Computers Network Laboratory of NTUA following a similar architecture.

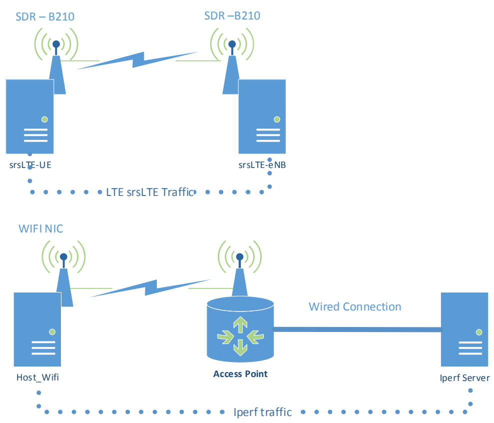

Fig. 2 The experimental topology

In more details, in IRIS testbed we facilitated the following devices:

- 2x X310 Ettus SDR nodes
- 2x Ubuntu 16.04 servers with latest srsLTE libraries [15]
- 2x Commercial Laptops used as WiFi client and iperf3 server
- 1x ASUS RT-AC53 Access Point

Similarly, in CN-Lab we used the following devices

- 2x B210 Ettus SDR nodes
- 2x Ubuntu 18.04 nodes on Intel NUC hardware platform
- 1x Intel NUC as wireless client
- 1x VM as iperf3 server
- 1x Cisco 1242 AG access Point

We chose to experiment in two different environments in order to limit the probability of our results being biased by specific radio or hardware characteristics. Our results can easily be generalized since both environments produced equivalent results regardless of the SDR platform or WiFi manufacturer.

III. PERFORMANCE EVALUATION OF LTE-U

Our target was to find the optimal values of a number of parameters like (a) Duty Cycle Ratio, (b) Silent period duration, (c) transmitter gain and (d) number of subcarriers to allow LTE-U and WiFi co-exist. In the first round of our experiments we evaluated the impact of LTE-U transmissions on WiFi maximum throughput when LTE-U is deployed with a duty cycle mechanism. We used srsLTE software library and SDR in eNB and UE mode to completely saturate the LTE connection between eNB. In order to measure the maximum value of WiFi throughput in Mbps, we used the iperf3 software in TCP mode with the WiFi client downloading traffic from the server (a single flow was used for the measurement in an average measurement period of for 20 seconds).

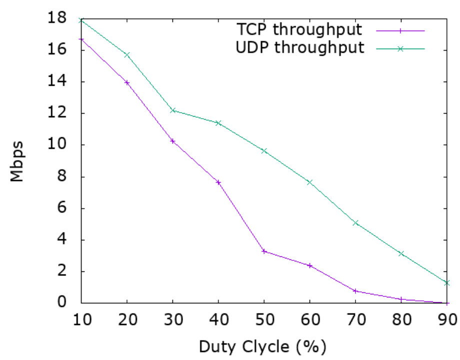

Fig. 3 LTE Duty Cycle impact on WiFi performance

As depicted in Fig 3, we modified the Duty Cycle of LTE from 10% (almost always silent) to 90% (almost no silent period) in steps of 10%. It is clearly shown that LTE-U has a huge impact on WiFi throughput as LTE-U transmissions tend to eliminate WiFi transmissions. For duty cycle larger than 40%, the average throughput of WiFi network is less than 50% of the maximum throughput achieved when deployed without LTE-U interference. Furthermore, regarding the overall stability of the connection between UE and eNB, we experienced a number of detaches from LTE network when using silent periods with value less than 30%. Likewise, WiFi terminals tended to disconnect from the WiFi network for duty cycle values larger than 80%.

The main issue regarding poor maximum throughput performance is the congestion control of TCP protocol. UDP traffic as depicted in Fig.3 showed a linear decrease compared to TCP behaviour. Since UDP has recently gained a lot of focus mostly for video streaming due to the adoption of QUIC protocol, as a conclusion, the length of the silent period may have an impact on WiFi throughput performance only for specific traffic patterns that rely heavily on TCP as a transport protocol. In Fig 4 we explored the performance of various TCP congestion control algorithms. Algorithms such as Westwood that are designed for wireless networks tend to perform better in higher values of Duty Cycle whereas traditional algorithms, such as Reno and Cubic, demonstrated lower throughput values for in extreme scenarios.

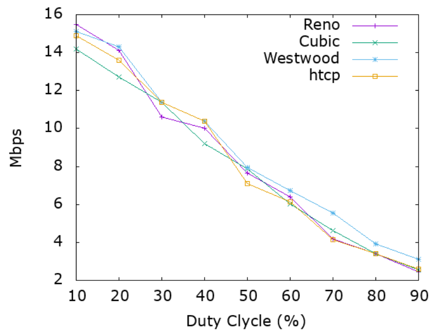

Fig. 4 Performance of various TCP congestion control algorithms

For our next experiment we kept the LTE duty cycle value stable at 50% and investigated the impact of the sleep period duration. The default value for our implementation was 150 ms as in similar approaches in existing literature. In order to investigate possible fluctuations in WiFi performance, we modified the duration from 100 ms to 200 ms in steps of 10 ms between each measurement. Again, we used iperf3 in TCP mode to measure the WiFi terminal throughput.

The overall WiFi performance seems to be rather unaffected by the length of the Sleep period as depicted in Fig 5. Nevertheless, we can identify that for longer sleep periods the throughput of WiFi terminal tends to increase slightly. In addition, observations during the experiment showed that LTE and WiFi links tend to be more stable for higher values whereas smaller values of sleep duration (and thus longer periods) tend to cause disconnections on UE side.

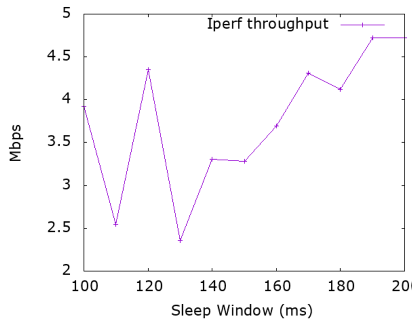

Fig. 5 Impact of Sleep period duration on WiFi performance

In the next experiment with LTE parameters, we considered the effect of transmitter gain on the node acting as eNB. We kept the LTE Duty Cycle and sleep period duration stable at values that allowed both WiFi and LTE to perform adequately. Namely, the sleep period length was defined at 150 ms and the duty cycle was set at 50%. As depicted in Fig 6, after a certain threshold (90 dB) of transmitter gain on LTE's eNB, there is a linear decrease of WiFi terminal throughput. Extreme values of transmitter gains tend to limit WiFi throughout even more than 50% of normal operational values.

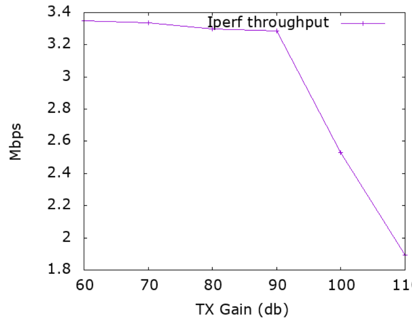

Fig. 6 Tx Gain of LTE radio impact on WiFi performance

In our experimental setup, due to near perfect radio conditions in both lab environments, LTE performance was not affected by fluctuations of transmitter gain and the UE demonstrated consistent throughput behavior.

In the final experiment of this group, we dealt with the LTE eNB number of available subcarriers. We examined PRB (Physical Resource Blocks) values of 25, 50, 75 and 100 in accordance with LTE standards. Fig 7 demonstrates that the overall performance of WiFi link increases more than 350% as the number of carriers used by LTE eNB increases. By increasing the number of subcarriers, the interference with WiFi is minimized and WiFi terminal throughput can reach up to 30% of the reference throughput as measured without LTE interference.

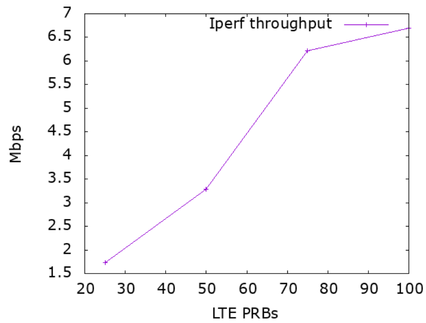

Fig. 7 Impact of LTE sub-carriers on WiFi performance

On the second group of experiments, we investigated the impact of WiFi transmissions on LTE-U performance. We employed iperf3 on UDP mode so as to fully saturate the WiFi link by always having data to be transmitted on the sender's queue. We experimented with two different settings that can be modified in commercial APs, (a) the transmitter gain and (b) the value of RTS threshold values.

The first experiment dealt with the effect of transmitter power levels in commercial Access Points on LTE-U terminals. As shown in Fig 8, the WiFi Tx power level has negligible impact on LTE-U performance since both average and maximum values of LTE-U throughout are unaffected.

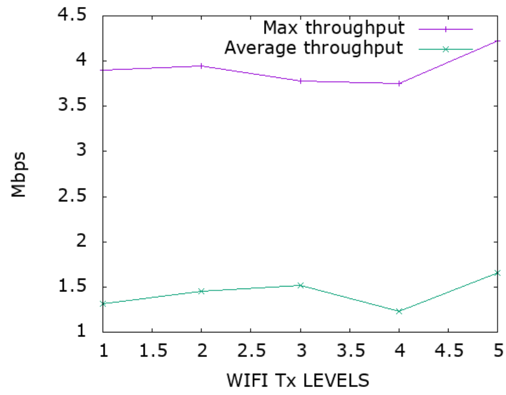

Fig. 8 Impact of WiFi Tx power levels on LTE-U performance

In our final experiment of this section, we considered various RTS (Request to Clear) values for the WiFi link and examined the maximum and average values of the LTE-U terminal throughput. As shown in Fig. 9, there is only a slight deterioration of LTE terminal throughput for some values, especially of the average throughput, but in general there is no obvious association between RTS threshold values and LTE-U UE throughput.

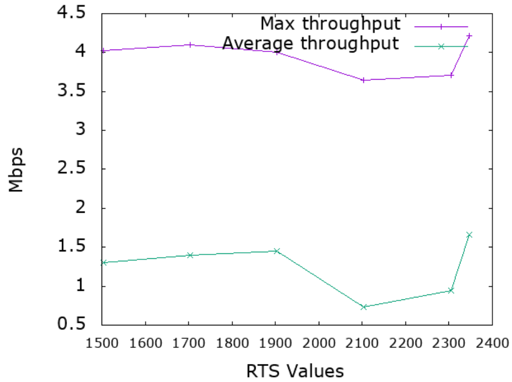

Fig. 9 *WiFi RTS values impact on LTE-U performance*

IV. ANALYSIS ON POWER CONSUMPTION OF LTE-U

On the next phase of our experimentation we assessed the impact of LTE-U and WiFi co-existence from the power consumption perspective. Approaches in existing literature have demonstrated that average power consumption per byte is 4.5 times higher in LTE networks compared to WiFi values [16]. We focused on real life measurements to complement existing theoretical approaches. A number of smart-plugs (HS-110 TP Link) were connected to monitor in real-time the power consumption of all devices under examination. Namely, the power supplies of all devices depicted in Fig 2 where connected via a smart plug so as to easily measure the impact of our duty-cycle approach on the terminal energy profile.

In the first experiment of this section we measured the power consumption of LTE-U eNB and UE modified by the introduction of duty cycle operation. We examined the increase of power consumption compared to the base consumption of the node when no processes are running on the device. As depicted in Fig 10, the Duty Cycle operation of LTE-U has a negative effect on the overall eNB power consumption. Because of the silent periods, eNBs tended to consume more energy when active periods increase in length (compared to silent ones). The increase of the value of Watts per Mbps is constant so there is a linear correlation between the duty cycle value and increase of consumed energy (since there is also a linear correlation between duty cycle value and LTE-U throughput).

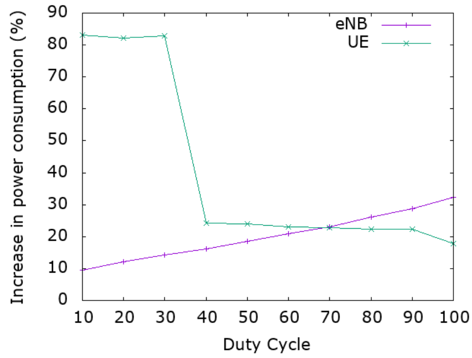

Fig. 10 LTE's UE and eNB power consumption when Duty Cycle concept is implemented

On the other hand, using smaller values of Duty Cycle tended to detach the UE from the LTE network and thus caused extra CPU cycles to handle with the re-attach procedure. Although we intuitively expected an increase in power consumption due to higher packet rates for larger duty cycles (more CPU cycles to process received frames), the role of LTE channel stability was a more dominant factor that caused a slight decrease in overall power consumption.

To further investigate the impact of WiFi on LTE-U power consumption we performed two more experiments. The first explored the impact of a fully saturated WiFi link on LTE-U when varying the Duty Cycle values. As discussed previously, this has a negligible impact on LTE-U throughput performance. By comparing eNB consumptions presented in Fig. 10 (without WiFi interference) and Fig 11 it is clear that eNB is unaffected from WiFi transmissions. The only parameter that seems to get slightly impacted is CPU utilization but this is mostly caused by the increased rate of packets to be transmitted over the LTE-U network.

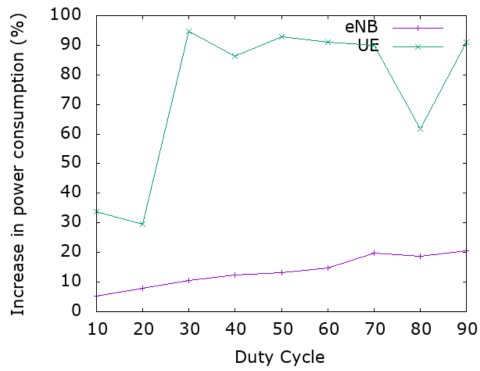

Fig. 11 LTE's UE and eNB power consumption with a fully saturated WiFi link

On the other hand, the UEs power consumption is dramatically impacted by interference of LTE-U to WiFi. In order to maintain the received rate, the UE fully utilizes CPU resources and its power consumption was increased up to 100% compared to the do-nothing condition.

We also investigated a possible correlation between the transmitter power gain and the power consumption. We kept a Duty Cycle value of 50% that allows WiFi to operate adequately and fully saturated the WiFi link using iperf3 in TCP mode. As depicted in Fig. 12 the eNB power consumption is slightly affected by the LTE transmitter gain. This is due to the additional power required to further amplify the transmitted signal. Instead, on the UE side, there is a significant difference (more than 6 Watts in power consumption at low TX levels) due to the decreased signal strength that reaches the receiver side.

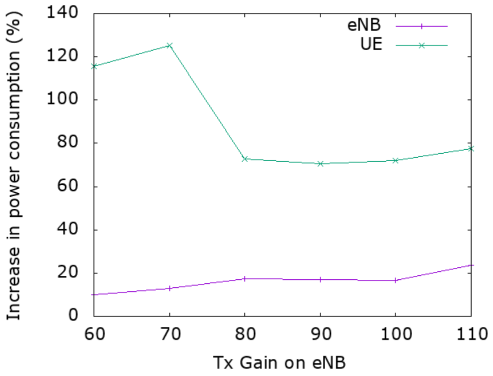

Fig. 12 Tx Gain of LTE eNB impact on UE and eNB power consumption

As a final step we expanded our measurements on the WiFi network elements. Initially, we verified that the power consumption of all network elements involved is proportional to the traffic load as depicted in Fig. 13.

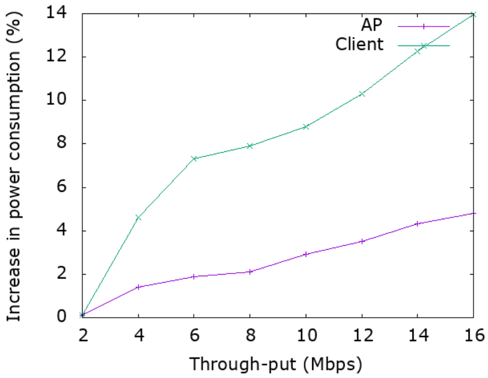

Fig. 13 Measure of WiFi node power consumption for various traffic loads

Since LTE-U deployment has a dramatic impact on WiFi throughput performance, the direct power consumption is not an appropriate indicator of WiFi network power efficiency. Instead we used the Watt per Mbps metric to demonstrate the cost of maintaining a specific rate on an interface. A similar approach expressed in Joule per Byte is used in other attempts to express energy efficiency [17]. As expected, the overall power consumption of WiFi nodes decreased as duty cycle values increased, since less traffic can be served due to interference from LTE-U transmissions. On the other hand, the value of Watt per Mbps drastically increased making WiFi network less optimal than LTE-U from the power consumption perspective. This outcome is contradicting the fact that in general WiFi is more power efficient than LTE (when deployed in licenced spectrum).

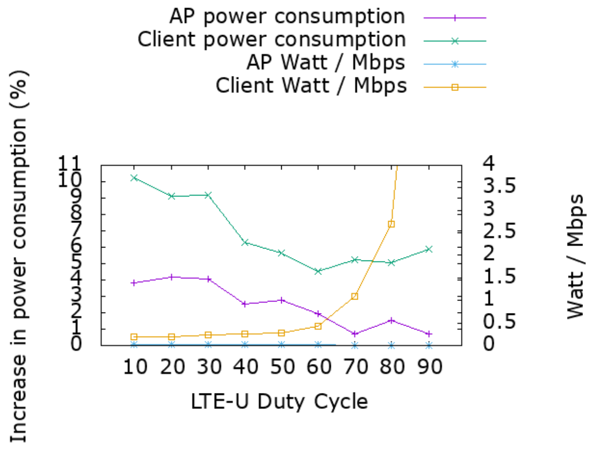

Fig. 14 Measure of WiFi node power consumption for various traffic loads with LTE-U interference

To further emphasize the negative impact of LTE-U deployment on WiFi power efficiency, we compared the power consumption of WiFi AP and client when operating without LTE-U interference compared to a co-existence scenario where LTE-U is operating with a 50% duty cycle. As illustrated in Fig.15, the Access Point tended to consume more power when operating in co-existence with LTE-U transmissions while supporting equivalent traffic rates. This phenomenon becomes more intense for higher transmitting rates (up to 8Mbps throughput since LTE-U didn't allow WiFi achieve higher rates).

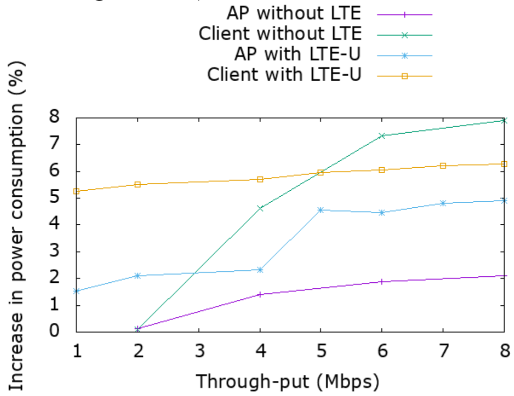

Fig. 15 Comparison between the scenarios with or without LTE-U interference

Similarly, the WiFi client power consumption increases proportionally to the traffic volume. For lower rates, LTE-U interference causes the WiFi client to consume more power for the same traffic volume.

V. Conclusion

In our experiments we clearly demonstrated that LTE-U when deployed in ISM bands has a significant effect on WiFi performance. It is obvious that LTE-U transmissions tend to dramatically deteriorate overall throughput. On the other hand, WiFi transmissions have a negligible effect on LTE-U throughput. The proposed implementation of silent periods in LTE transmission schema can facilitate the coexistence of aforementioned RATs (Radio Access Technologies), but fine tuning is required for optimal deployment. We proved that smaller values of LTE-U transmitter gain with higher number of sub-carriers can further improve the performance of WiFi network. Finally, even though WiFi is considered as more energy efficient compared to LTE, it becomes significantly more power consuming when used in coexistence with LTE-U irrespective of the use of silent periods.

ACKNOWLEDGMENT

Part of this work was funded from First ORCA project Open Call for Experimenters (ORCA-OC1-EXP)

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