Coordinated Dynamic Spectrum Management of LTE-U and Wi-Fi Networks

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***Abstract*—This paper investigates the co-existence of Wi-Fi and LTE networks in emerging unlicensed frequency bands which are intended to accommodate multiple radio access technologies. Wi-Fi and LTE are the two most prominent wireless access technologies being deployed today, motivating further study of the inter-system interference arising in such shared spectrum scenarios as well as possible techniques for enabling improved co-existence. An analytical model for evaluating the baseline performance of co-existing Wi-Fi and LTE networks is developed and used to obtain baseline performance measures. The results show that both Wi-Fi and LTE networks cause significant interference to each other and that the degradation is dependent on a number of factors such as power levels and physical topology. The model-based results are partially validated via experimental evaluations using USRP-based SDR platforms on the ORBIT testbed. Further, inter-network coordination with logically centralized radio resource management across Wi-Fi and LTE systems is proposed as a possible solution for improved co-existence. Numerical results are presented showing significant gains in both Wi-Fi and LTE performance with the proposed inter-network coordination approach.**

***Keywords*—Wi-Fi, LTE-U, dynamic spectrum management, inter-network coordination, optimization**

I. Introduction

Exponential growth in mobile data usage is driven by the fact that Internet applications of all kinds are rapidly migrating from wired PCs to mobile smartphones, tablets, MiFis and other portable devices [1]. The wireless industry is already gearing up for a ∼1000x increase in data capacity associated with the requirements of *5G* mobile networks planned for 2020 and beyond. The 5G vision is not just limited to matching the increase in mobile data demand, but also includes an improved overall service-oriented user experience with immersive applications such as high definition video streaming, real-time interactive games, wearable mobile devices, ubiquitous health care, mobile cloud, etc. [2]–[4]. Such applications not only demand the higher data rates but also require an improved Quality of Experience(QoE) as measured through parameters such as lower latency (round trip time), lower power consumption (longer battery life), better radio coverage (reliable services), cost-effective network, and support for mobility.

To meet such high data rate and QoE demands, three main solutions are proposed [5]: (a) addition of more radio spectrum for mobile services (increase in MHz); (b) deployment of small cells (increase in bits/Hz/km^2); and (c) efficient spectrum utilization (increase in bits/second /Hz/km^2). Several spectrum bands, as shown in Fig. 1, have been opened up for mobile and fixed wireless broadband services. These include the 2.4 and 5 GHz unlicensed bands for the proposed unlicensed LTE operation as a secondary LTE carrier [6]. These bands are currently utilized by unlicensed technologies such as Wi-Fi/Bluetooth. The 3.5 GHz band, which is currently utilized for military and satellite operations has also been proposed for small cell (Wi-Fi/LTE based) services [7]. Another possibility is the 60 GHz band (millimeter wave technology), which is well suited for short-distance communications including Gbps Wi-Fi, 5G cellular and peer-to-peer communications [8]. In addition, opportunistic spectrum access is also possible in TV white spaces for small cell/backhaul operations [9].

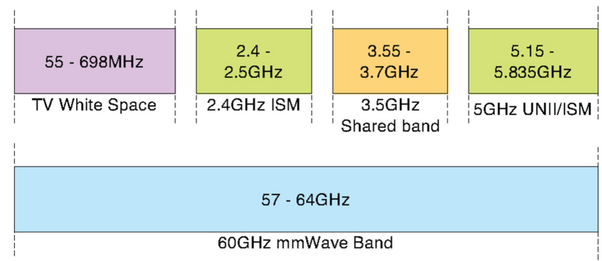

Fig. 1. Proposed spectrum bands for deployment of LTE/Wi-Fi small cells.

These emerging unlicensed band scenarios will lead to co-channel deployment of multiple radio access technologies (RATs) by multiple operators. These different RATs, designed for specific purposes at different frequencies, must now coexist in the same frequency, time, and space. This causes increased interference to each other and potential degradation of the overall system performance due to the lack of inter-RAT compatibility. Fig. 2 shows two such scenarios where two networks with different access technologies interfere with each other. When a Wi-Fi Access Point (AP) is within the transmission zone of LTE, it senses the medium and postpones transmission due to detection of co-channel LTE Home eNodeB's (HeNB) transmission power as shown in Fig. 2(a). Consequently, the Wi-Fi throughput suffers in the presence of LTE transmission. The main reason for this disproportionate drop in the Wi-Fi throughput is due to the fact that LTE does not sense other transmissions before transmitting. In contrast, Wi-Fi is designed to coexist with other networks as it senses the channel before any transmission. However, when LTE works in supplemental downlink-only mode and the UEs do not transmit, there may arise a scenario where a Wi-Fi AP can not sense LTE HeNB's transmission, thus causing interference to nearby UEs, as shown in Fig. 2(b). This problem also arises in multiple Wi-Fi links that overlap in the collision domain, but the network can recover packets quickly as (a) packets are transmitted for a very short duration in Wi-Fi, compared to

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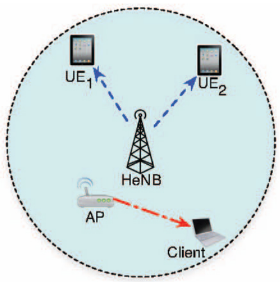
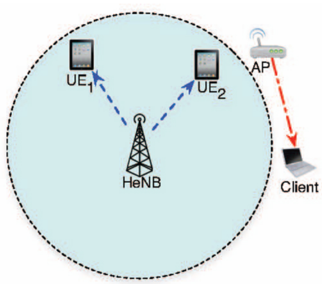


(a) Interference caused by LTE.



(b) Interference caused by Wi-Fi.

Fig. 2. Scenarios showing challenges of LTE and Wi-Fi coexistence in the same unlicensed spectrum.

longer frames in LTE and (b) all the nodes perform carrier sensing before transmission. Therefore, to fully utilize the benefits of new spectrum bands and deployments of HetNets, efficient spectrum utilization needs to be provided by the dynamic spectrum coordination framework and the supporting network architecture.

It is reasonable to forecast that Wi-Fi and LTE will be among the dominant technologies used for radio access over the next few years. Thus, this paper focuses on coordinated coexistence between these two technologies. When LTE is deployed in an unlicensed band, it is termed as LTE-U. It is suggested in 3GPP that LTE-U will be used for supplemental downlink while the uplink will continue to use licensed spectrum. This makes the deployment even more challenging as the UE's do not transmit in unlicensed spectrum yet experience interference from Wi-Fi transmissions. To alleviate these problems, we extend the interference characterization of co-channel deployment of Wi-Fi and LTE using a simplistic but accurate analytical model [10]. We then validate this model through experimental analysis of co-channel deployment in the 2.4 GHz band using the ORBIT testbed available at WINLAB. The ORBIT testbed consists of several radio platforms including USRPs.

To support the co-existence of a multi-RAT network, we propose a dynamic spectrum coordination framework, which is enabled by a Software Defined Network (SDN) architecture. SDN is technology-agnostic, can accommodate different radio standards, and does not require change to existing standards or protocols. In contrast to existing technology-specific solutions, this is a desirable feature in view of the rapid development of the upcoming technologies and the availability of new spectrum bands [11]–[13]. Furthermore, the proposed framework takes advantage of the ubiquitous Internet connectivity available at wireless devices. It also provides the ability to consider policy requirements in conjunction with improved visibility of each of the access technologies, spectrum bands, and clients/operators. Thus, it offers significant benefits for spectrum allocation over radio-based control channels [14] or centralized spectrum servers [15].

SDN-enabled inter-network cooperation can be achieved by optimizing several spectrum usage parameters such as power control, channel selection, rate allocation, duty cycle, etc. In this paper, we focus on power control at both Wi-Fi and LTE nodes to maximizes aggregate throughput across all clients in both Wi-Fi and LTE networks while considering throughput requirement for each client [16], [17]. We also incorporate the proposed interference characterization of Wi-Fi and LTE co-channel deployment in the optimization framework which allows us to account for the specific requirements of each of the technologies. We adopt the geometric programming framework developed in [18] for the LTE-only networks and enhance it to accommodate Wi-Fi networks.

The major contributions of this work are as follows:

- We introduce an analytical model to characterize the interference between Wi-Fi and LTE networks when they coexist in time, frequency and space. The model is also validated by performing experimental analysis using USRP-based LTE nodes and commercial off-the-shelf (COTS) IEEE 802.11g devices in the ORBIT testbed.
- We propose a coordination framework to facilitate dynamic spectrum management among multi-operator and multi-technology networks over a large geographical area.
- We propose a logically centralized optimization framework that involves dynamic coordination between Wi-Fi and LTE networks by exploiting power control and time division channel access diversity.
- We evaluate the proposed optimization framework for improved Wi-Fi and LTE networks coexistence.

The rest of the paper is organized as follows. In §II, we discuss previous work on this topic and distinguish our work from the existing literature. In §III, we propose an analytical model to characterize the interference between Wi-Fi and LTE networks followed by partial experimental validation of the model. In §IV, we propose an SDN-based inter-network coordination architecture that can be used for transferring control messages between the different entities in the network. In §VI, we use two approaches—power control and channel access time sharing, to jointly optimize the spectrum sharing among Wi-Fi and LTE networks. §VII evaluates the proposed approaches. We conclude in §VIII.

II. Background on Wi-Fi/LTE Co-existence

Coordination between multi-RAT networks with LTE and Wi-Fi is challenging due to differences in the medium access control (MAC) layer of the two technologies.

Wi-Fi is based on the distributed coordination function (DCF) where each transmitter senses the channel energy for transmission opportunities and collision avoidance. In particular, clear channel assessment (CCA) in Wi-Fi involves two functions to detect any on-going transmissions [19], [20] -

1) *Carrier sense*: Defines the ability of the Wi-Fi node to detect and decode other nodes' preambles, which most likely announces an incoming transmission. In such cases, Wi-Fi nodes are said to be in the CSMA range of each other other. For the basic DCF with no RTS/CTS, the Wi-Fi throughput can be accurately characterized using the Markov chain analysis given in Bianchi's model [21], assuming a saturated traffic condition (at least 1 packet is waiting to be sent) at each node. Wi-Fi channel rates

used in the [21] can be modeled as a function of Signal-to-Interference-plus-Noise ratio. Our throughput analysis given in the §III is based on the Bianchi's model.
2) *Energy detection*: Defines the ability of Wi-Fi to detect non-Wi-Fi (in this case, LTE) energy in the operating channel and back off the data transmission. If the in-band signal energy crosses a certain threshold, the channel is detected as busy (no Wi-Fi transmission) until the channel energy is below the threshold. Thus, this function becomes the key parameter for characterizing Wi-Fi throughput in the co-channel deployment with LTE.

LTE has both frequency division (FDD) and time division (TDD) multiplexing modes to operate. But to operate in unlicensed spectrum, supplemental downlink and TDD access is preferred. In either of the operations, data packets are scheduled in the successive time frames. LTE is based on orthogonal frequency-division multiple access (OFDMA), where a subset of subcarriers can be assigned to multiple users for a certain symbol time. This offers LTE an additional diversity in the time and frequency domain that Wi-Fi lacks, since Wi-Fi assigns fixed bandwidth to a single user at any time. Further, due to current exclusive band operation, LTE does not employ any sharing features in the channel access mechanisms. Thus, the coexistence performance of both Wi-Fi and LTE is largely unpredictable and may lead to unfair spectrum sharing or the starvation of one of the technologies [22], [23].

In the literature, spectrum management in shared frequency bands has been discussed for multi-RAT heterogeneous networks primarily focusing on IEEE 802.11/16 networks [12]–[14]. For instance, Cognitive WiMAX achieves cooperative resource management in hierarchical networks with power/frequency assignment optimization, Listen-before-Talk (LBT), etc. along with guaranteed QoE [24], [25]. These principles need to be extended to Wi-Fi and LTE coexistence and modified specific to their protocols. Wi-Fi and LTE coexistence has been studied in the context of TV white space [26], in-device coexistence [27], and LTE unlicensed (LTE-U) [28]–[30]. Studies [29]–[31] propose CSMA/sensing based modifications in LTE such as LBT, RTS/CTS protocol, and slotted channel access. Other solustions such as blank LTE subframes/LTE muting (feature in LTE Release 10/11) [26], [32], carrier sensing adaptive transmission (CSAT) [29], interference aware power control in LTE [33] require LTE to transfer its resources to Wi-Fi. These schemes give Wi-Fi transmission opportunities but also lead to performance tradeoffs for LTE. Further, time domain solutions often require time synchronization between Wi-Fi and LTE and increase channel signaling. Frequency and LTE bandwidth diversities are explored in studies [29] and [34], respectively.

In this paper, we propose Wi-Fi and LTE coordination algorithms based on optimization in power and frequency domain, which does not require modifications to existing MAC layer protocols. Our time division channel access (TDCA) algorithm resembles CSAT, but TDCA is a centralized approach with a joint consideration of Wi-Fi and LTE QoE requirements for fairness. Furthermore, limited details of LTE-U co-existence mechanisms (adaptive duty cycle/switch-OFF) and interference model are available in public domain [35]. Also previous studies have yet to consider dense Wi-Fi and LTE deployment scenarios in detail. Notably, in the literature, there are no experimental studies evaluating the coexistence performance of Wi-Fi and LTE. Thus, this paper focuses on these aspects to provide a complete evaluation.

III. Interference Characterization

A. Interference Characterization Model

We propose an analytical model to characterize the interference between Wi-Fi and LTE, while considering the Wi-Fi sensing mechanism (clear channel assessment (CCA)) and scheduled and persistent packet transmission at LTE. To illustrate, we focus on a co-channel deployment involving a single Wi-Fi and a single LTE cell, which involves disseminating the interaction of both technologies in detail and establish a building block to study a complex co-channel deployment of multiple Wi-Fis/LTEs.

In a downlink deployment scenario, a single client and a full buffer (saturated traffic condition) is assumed at each AP under no MIMO. Transmit powers are denoted as $P_i, i \in \{w, l\}$ where w and l are indices to denote Wi-Fi and LTE links, respectively. We note that the maximum transmission power of an LTE small cell is comparable to that of the Wi-Fi, and thus is consistent with regulations of unlicensed bands.

The power received from a transmitter j at a receiver i is given by $P_j G_{ij}$ where $G_{ij} \geq 0$ represents a channel gain which is inversely proportional to d_{ij}^{γ} where d_{ij} is the distance between i and j and γ is the path loss exponent. G_{ij} may also include antenna gain, cable loss and wall loss. Signal-to-Interference-plus-Noise (SINR) of the link i is given as

$$S_i = \frac{P_i G_{ii}}{P_j G_{ij} + N_i}, \quad i, j \in \{w, l\}, i \neq j \tag{1}$$

where N_i is noise power for receiver i. For the case of a single Wi-Fi and LTE, if i represents the Wi-Fi link, then j is the LTE link, and vice versa.

Throughput, $R_i, i \in \{w, l\}$, is represented as a function of S_i as

$$R_i = \alpha_i B \log_2(1 + \beta_i S_i), \quad i \in \{w, l\}, \tag{2}$$

where B is a channel bandwidth; β_i is a factor associated with the modulation scheme. For LTE, α_l is a bandwidth efficiency due to factors adjacent channel leakage ratio and practical filter, cyclic prefix, pilot assisted channel estimation, signaling overhead, etc. For Wi-Fi, α_w is the bandwidth efficiency of CSMA/CA, which comes from the Markov chain analysis of CSMA/CA [21] with

$$\eta_E = \frac{T_E}{\mathrm{E}[S]}, \ \eta_S = \frac{T_S}{\mathrm{E}[S]}, \ \eta_C = \frac{T_C}{\mathrm{E}[S]}, \tag{3}$$

where $\mathrm{E}[S]$ is the expected time per Wi-Fi packet transmission; T_E, T_S, T_C are the average times per $\mathrm{E}[S]$ that the channel is empty due to random backoff, or busy due to the successful transmission or packet collision (for multiple Wi-Fis in the CSMA range), respectively. α_w is mainly associated with η_S.

The term $\{\alpha_i, \beta_i\}$ is approximated based on throughput models given in [10] so that R_l matches with throughput achieved under variable channel quality index (CQI), and R_w matches throughput according to Bianchi's CSMA/CA model.

[1]Throughput the paper, LTE home-eNB (HeNB) is also referred as access point (AP) for the purpose of convenience

1) Characterization of Wi-Fi Throughput: Assuming λ_c is a threshold of CCA energy detection mechanism, if channel energy at the Wi-Fi node is higher than λ_c, Wi-Fi would hold back the data transmission, otherwise it transmits at a data rate based on the SINR of the link. Wi-Fi throughput with and without LTE is given as

Model 1: Wi-Fi Throughput Characterization

Data: P_w: Wi-Fi Tx power; G_w: channel gain of Wi-Fi link; P_l: LTE Tx power; G_{wl}: channel gain(LTE AP, Wi-Fi UE); N_0: noise power; E_c: channel energy at the Wi-Fi (LTE interference + N_0).
Parameter: λ_c: Wi-Fi CCA threshold
Output : R_w: Wi-Fi throughput
if *No LTE* **then**

$$R_w = \alpha_w B \log_2 \left(1 + \beta_w \frac{P_w G_w}{N_0}\right).$$

else When LTE is present
  if $E_c > \lambda_c$ **then**
    No Wi-Fi transmission with $R_w = 0$
  else

$$R_w = \alpha_w B \log_2 \left(1 + \beta_w \frac{P_w G_w}{P_l G_{wl} + N_0}\right).$$

  end
end

2) Characterization of LTE Throughput: Due to CSMA/CA, Wi-Fi is active for an average η_S fraction of time (Eq. (3)). Assuming that LTE can instantaneously update its transmission rate based on the Wi-Fi interference, its throughput can be modeled as follows-

Model 2: LTE Throughput Characterization

Data: P_l: LTE Tx power; G_l: channel gain of LTE link; P_w: Wi-Fi Tx power; G_{lw}: channel gain(Wi-Fi AP,LTE UE); N_0: noise power; E_c: channel energy at Wi-Fi (LTE interference + N_0);
Parameter: λ_c: Wi-Fi CCA threshold
Output : R_l: LTE throughput
if *No Wi-Fi* **then**

$$R_{l_{\text{noW}}} = \alpha_l B \log_2 \left(1 + \beta_l \frac{P_l G_l}{N_0}\right).$$

else When Wi-Fi is present
  if $E_c > \lambda_c$ **then**
    No Wi-Fi transmission/interference

$$R_l = R_{l_{\text{noW}}}.$$

  else

$$R_l = \alpha_l B \log_2 \left(1 + \beta_l \frac{P_l G_l}{P_l G_{lw} + N_0}\right).$$

    Using (3) and $\eta_C = 0$ (a single Wi-Fi)

$$R_l = \eta_E R_{l_{\text{noW}}} + \eta_S R_l$$

  end
end

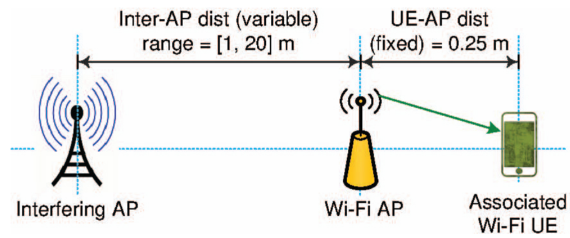


Fig. 3. Experimental scenario to evaluate the throughput performance of Wi-Fi w_1 in the presence of interference (LTE/other Wi-Fi/white noise) when both w_1 and interference operated on the same channel in 2.4 GHz

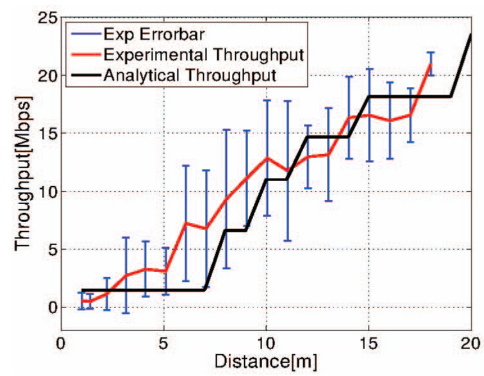


Fig. 4. Comparative results analytical model and experiments to show the effect of LTE on the throughput of Wi-Fi 802.11g when distance between LTE eNB and Wi-Fi link is varied.

B. Experimental Validation

In this section, we experimentally validate proposed interference characterization models using experiments involving the ORBIT testbed and USRP radio platforms available at WINLAB [36], [37]. An 802.11g Wi-Fi link is set up using Atheros AR928X wireless network adapters [38] and an AP implementation with *hostapd* [39]. For LTE, we use *OpenAirInterface*, an open-source software implementation, which is fully compliant with 3GPP LTE standard (release 8.6) and set in transmission mode 1 (SISO) [40]. Currently, *OpenAirInterface* is in the development mode for USRP based platforms with limited working LTE operation parameters. Due to limitations in the available setup, we perform experiments in the 2.4 GHz spectrum. We note that, though channel fading characteristics differ in other spectrum bands, Wi-Fi and LTE coexistence throughput behavior remains the same with appropriately scaled distance.

In our experiment, depicted as the scenario shown in Fig. 3, we study the effect of interference on the Wi-Fi link w_1. For link w_1, the distance between the AP and client is fixed at 0.25 m (very close so that the maximum throughput is guaranteed when no interference is present. Experimentally, we observe a maximum throughput as 22.2 Mbps). The distance between the interfering AP and Wi-Fi AP is varied in the range of 1 to 20 m. The throughput of w_1 is evaluated under two sources of interference - LTE and Wi-Fi, when both w_1 and the interference AP is operated on the same channel in the 2.4 GHz spectrum band. These experiments are carried in the 20 m-by-20 m ORBIT room in WINLAB, which has an indoor Line-

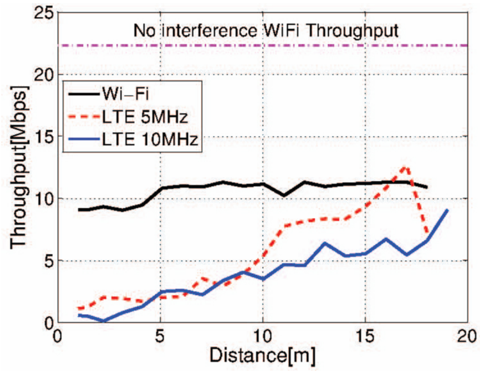


Fig. 5. Comparative results analytical model and experiments to show the effect of LTE on the throughput of Wi-Fi 802.11g when distance between LTE HeNB (AP) and Wi-Fi link is varied.

TABLE I. NETWORK PARAMETERS OF WI-FI/LTE DEPLOYMENT

Parameter	Value	Parameter	Value
Scenario	Downlink	Tx power	20 dBm
Spectrum band	2.4 GHz	Channel bandwidth	20 MHz
Traffic model	Full buffer via saturated UDP flows		
AP antenna height	10 m	User antenna height	1 m
Path loss model	$36.7\log_{10}$(d[m]) + 22.7 + $26\log_{10}$(frq [GHz])		
Noise Floor	-101 dBm, (-174 dBm thermal noise/Hz)		
Channel	No shadow/Rayleigh fading		
Wi-Fi	802.11n: SISO		
LTE	FDD, Tx mode-1 (SISO)		

of-Sight (LoS) environment. For each source of interference, Wi-Fi throughput is averaged over 15 sets of experiments with variable source locations and trajectories between interference AP and w_1.

In the first experiment, we perform a comparison study to evaluate the effect of LTE interference on w_1, observed by experiments and computed by interference characterization model. In this case, LTE signal is lightly loaded on 5 MHz of bandwidth mainly consist of control signals. Thus, the impact of such LTE signal over the Wi-Fi band is equivalent to the low power LTE transmission. Thus, we incorporate these LTE parameters in our analytical model. As shown in Fig. 4, we observe that both experimental and analytical values match the trend very closely, though with some discrepancies. These discrepancies are mainly due to the fixed indoor experiment environment and lack of a large number of experimental data sets. Additionally, we note that even with the LTE control signal (without any scheduled LTE data transmission), performance of Wi-Fi gets impacted drastically.

In the next set of experiments, we study the throughput of a single Wi-Fi link in the presence of different sources of interference - (1) Wi-Fi, (2) LTE operating at 5 MHz, and (3) LTE operating at 10 MHz, evaluating each case individually. For this part, full-band occupied LTE is considered with the maximum power transmission of 100 mW. As shown in Fig. 5, when the Wi-Fi link operates in the presence of other Wi-Fi links, they share channel according to the CSMA/CA protocol and throughput is reduced approximately by half. In the both the cases of LTE operating at 5 and 10 MHz, due to lack of coordination, Wi-Fi throughput gets impacted by maximum upto 90% compared to no interference Wi-Fi throughput and $20 - 80\%$ compared to Wi-Fi thorughput in the presence of

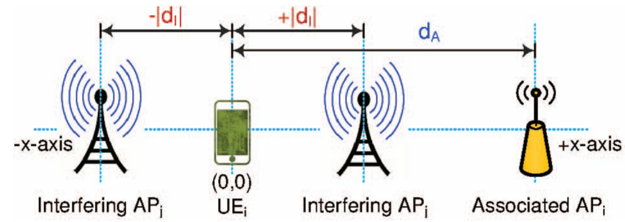


Fig. 6. Experimental scenario to evaluate the throughput performance of Wi-Fi w_1 in the presence of interference (LTE/other Wi-Fi/white noise) when both w_1 and interference operated on the same channel in 2.4 GHz

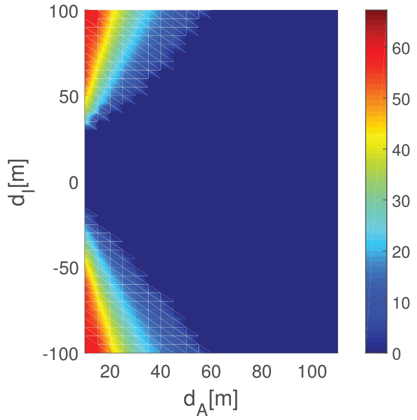
other Wi-Fi link. These results indicate a significant effect of inter-network interference on throughput in the baseline case without any coordination between networks.

C. Motivational Example

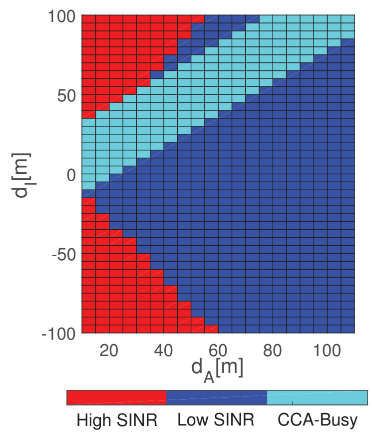
We extend our interference model to complex scenarios involving co-channel deployment of a single link Wi-Fi and LTE for the detailed performance evaluation. As shown in Fig. 6, UE_i, associated AP_i and interfering AP_j, $i, j \in \{w, l\}, i \neq j$, are deployed in a horizontal alignment. The distance, d_A, between UE_i and AP_i is varied between 0 and 100 m. At each value of d_A, the distance between UE_i and AP_j is varied in the range of -100 to 100 m. Assuming UE_i is located at the origin $(0, 0)$, if AP_j is located on the negative X-axis then the distance is denoted as $-d_I$, otherwise as $+d_I$, where d_I is an Euclidean norm $\|\text{UE}_i, \text{AP}_j\|$. In the shared band operation of Wi-Fi and LTE, due to the CCA sensing mechanism at the Wi-Fi node, the distance between Wi-Fi and LTE APs (under no shadow fading effect in this study) decides the transmission or shutting off of Wi-Fi. Thus, the above distance convention is adopted to embed the effect of distance between AP_i and AP_j. Simulation parameters for this set of simulations are given in Table I.

Fig. 7 shows the Wi-Fi performance in the presence of LTE interference. As shown in Fig. 7(a), the Wi-Fi throughput is drastically deteriorated in the co-channel LTE operation, leading to zero throughput for 80% of the cases and an average 91% of throughput degradation compared to standalone operation of Wi-Fi. Such degradation is explained by Fig. 7(b). Region *CCA-busy* shows the shutting off of the Wi-Fi AP due to the CCA mechanism, where high energy is sensed in the Wi-Fi band. This region corresponds to cases when Wi-Fi and LTE APs are within $\sim$ 20m of each other. In the *low SINR* region, the Wi-Fi link does not satisfy the minimum SINR requirement for data transmission, thus the Wi-Fi throughput is zero. *High SINR* depicts the data transmission region that satisfies SINR and CCA requirements and throughput is varied based on variable data rate/SINR.

On the other hand, Fig. 8 depicts the LTE throughput in the presence of Wi-Fi interference. LTE throughput is observed to be zero in the *low SINR* regions, which is 45% of the overall area and the average throughput degradation is 65% compared to the standalone LTE operation. Under identical network parameters, overall performance degradation for LTE is much lower compared to that of Wi-Fi in the previous example. The

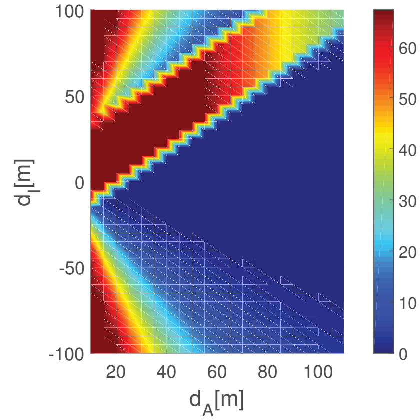


(a) A heat map of Wi-Fi throughput (Mbps)

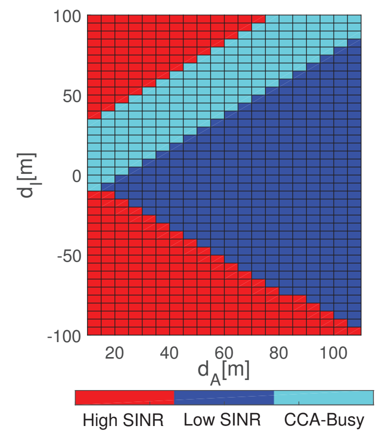


(b) High SINR: non-zero throughput, Low SINR: SINR $<$ minimum SINR requirement, CCA-busy: shutting off of Wi-Fi (channel sensed as busy)

Fig. 7. Wi-Fi performance as a function of distance(Wi-Fi AP, associated Wi-Fi UE) d_A and distance(Interfering LTE AP, Wi-Fi UE) d_I



(a) A heat map of LTE throughput (Mbps)



(b) High SINR: non-zero throughput, Low SINR: SINR $<$ minimum SINR requirement, CCA-busy: shutting off of Wi-Fi (channel sensed as busy)

Fig. 8. LTE performance as a function of distance(LTE AP, associated LTE UE) d_A and distance(Interfering Wi-Fi AP, LTE UE) d_I

reasoning for such a behavior discrepancy is explained with respect to Fig. 8(b) and the Wi-Fi CCA mechanism. In the *CCA-busy* region, Wi-Fi operation is shut off and LTE operates as if no Wi-Fi is present. In both LTE and the previous Wi-Fi examples, *low SINR* represents the hidden node problem where two APs do not detect each other's presence and data transmission at an UE suffers greatly.

IV. System Architecture

In this section, we describe an architecture for coordinating between multiple heterogeneous networks to improve spectrum utilization and facilitate co-existence [11]. Fig. 9 shows the proposed system, which is built on the principles of a Software Defined Networking (SDN) architecture to support logically-centralized dynamic spectrum management involving multiple autonomous networks. The basic design goal of this architecture is to support the seamless communication and information dissemination required for coordination of heterogeneous networks. The system consists of two-tiered controllers: the Global Controller (GC) and Regional Controllers (RC), which are mainly responsible for the control plane of the architecture. The GC, owned by any neutral/authorized organization, is the main decision making entity, which acquires and processes network state information and controls the flow of information between RCs and databases based on authentication and other regulatory policies. Decisions at the GC are based on different network modules, such as radio coverage maps, coordination algorithms, policy and network evaluation matrices. The RCs are limited to network management of specific geographic regions and the GC ensures that RCs have acquired local visibility needed for radio resource allocation at wireless devices. A Local Agent (LA) is a local controller, co-located with an access point or base-station. It receives frequent spectrum usage updates from wireless clients, such as device location, frequency band, duty cycle, power level, and data rate. The signaling between RC and LAs are event-driven, which occurs in scenarios like the non-fulfillment of quality-of-service (QoS) requirements at wireless devices, request-for-update from an RC and radio access parameter updates from an RC. The key feature of this architecture is that the frequency of signaling between the different network entities is less in higher tiers compared to lower tiers. RCs only control the regional messages and only wide-area network level signalling protocols are handled at the higher level, GC. Furthermore, this architecture allows adaptive coordination algorithms based on the geographic area and change in wireless device density and

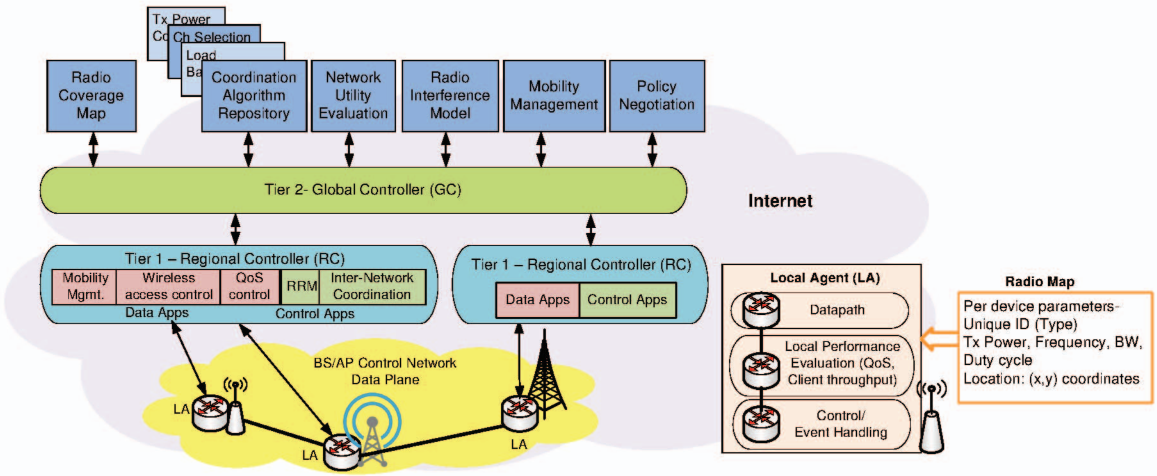


Fig. 9. SDN based achitecture for inter-network cooperation on radio resource management

traffic patterns. We use this architecture to exchange control messages required for the optimization model, as described in §VI.

V. System Model

As seen in the previous section, when two (or more) APs of different Wi-Fi and LTE networks are deployed in the same spectrum band, APs can cause severe interference to one another. In order to alleviate inter-network interference, we propose joint coordination based on (1) power, and (2) time division channel access optimization. We assume that both LTE and Wi-Fi share a single spectrum channel and operate on the same amount of bandwidth. We also note that clients associated to one AP cannot join other Wi-Fi or LTE APs. This is a typical scenario when multiple autonomous operators deploy APs in the shared band. With the help of the proposed SDN architecture, power level and time division channel access parameters are forwarded to each network based on the throughput requirement at each UE. To the best of our knowledge, such an optimization framework has not yet received much attention for the coordination between Wi-Fi and LTE networks. Note that although this work is limited to a quasi-static network, it is possible to incorporate mobile WLAN into the model using co-existence management techniques such as those proposed in [41].

We consider a system with N Wi-Fi and M LTE networks. $\mathcal{W}$ and $\mathcal{L}$ denote the sets of Wi-Fi and LTE links, respectively. We maintain all assumptions, definitions and notations as described in Section III-A. For notational simplicity, we redefine $R_i = \alpha_i B \log_2(1+\beta_i S_i), i \in \{\mathcal{W},\mathcal{L}\}$ as $R_i = \alpha_i \log_2(1+\beta_i S_i)$, where constant parameter B is absorbed with α_i. Additional notation are summarized in Table II.

In order to account for the co-channel deployment of multiple Wi-Fi networks, we assume that time is shared equally when multiple Wi-Fi APs are within CSMA range due to the Wi-Fi MAC layer. We denote the set of Wi-Fi APs within the CSMA range of $\text{AP}_i, i \in \{\mathcal{W}\}$ as M_i^a and those outside of carrier sense but within interference range as

TABLE II. Definition of Notations

Notation	Definition
w, l	indices for Wi-Fi and LTE network, respectively
$\mathcal{W}$	the set of Wi-Fi links
$\mathcal{L}$	the set of LTE links
P_i	Transmission power of i-th AP, where $i \in \{\mathcal{W},\mathcal{L}\}$
G_{ij}	Channel gain between nodes i and j
R_i	Throughput at i-th link, where $i \in \{\mathcal{W},\mathcal{L}\}$
S_i	SINR at i-th link, where $i \in \{\mathcal{W},\mathcal{L}\}$
B	Channel Bandwidth
N_0	Noise level
α_i, β_i	Efficiency parameters of system $i \in \{\mathcal{W},\mathcal{L}\}$
M_i^a	Set of Wi-Fi APs in the CSMA range of AP $i \in \{\mathcal{W}\}$
M_i^b	Set of Wi-Fi APs in the interference range of AP $i \in \{\mathcal{W}\}$
ζ	Hidden node interference parameter
η	Fraction of channel access time for network $i, i \in \{w,l\}$ when $j, j \in \{w,l\}, j \neq i$, access channel for $1-\eta$ fraction of time
λ_c	threshold of Wi-Fi CCA energy detection mechanism

M_i^b. When AP_i shares the channel with $|M_i^a|$ other APs, its share of the channel access time get reduced to approximately $1/(1+|M_i^a|)$. Furthermore, M_i^b signifies a set of potential hidden nodes for $\text{AP}_i, \forall i$. To capture the effect of hidden node interference from APs in the interference range, parameter ζ is introduced which lowers the channel access time and thus, the throughput. Average reduction in channel access time at AP_i is $1/(1+\zeta|M_i^b|)$ where ζ falls in the range $[0.2, 0.6]$ [42]. Therefore, the effective Wi-Fi throughput can be written as

$$\begin{aligned} R_i &= a_i b_i \alpha_w \log_2(1+\beta_w S_i), \quad i \in \mathcal{W}, \\ \text{with } a_i &= \frac{1}{1+|M_i^a|} \text{ and } b_i = \frac{1}{1+\zeta|M_i^b|}. \end{aligned} \tag{4}$$

SINR of Wi-Fi link, $i, i \in \mathcal{W}$, in the presence of LTE and no LTE is described as

$$S_i = \begin{cases} \dfrac{P_i G_{ii}}{N_0}, & \text{if no LTE;} \\ \dfrac{P_i G_{ii}}{\sum_{j\in\mathcal{L}} P_j G_{ij} + N_0}, & \text{if LTE,} \end{cases} \tag{5}$$

where the term $\sum_{j\in L} P_j G_{ij}$ is the interference from all LTE networks at a Wi-Fi link i.

The throughput definition of the LTE link $i, i \in \mathcal{L}$ remains the same as in Section III-A:

$$R_i = \alpha_l \log_2(1 + \beta_l S_i), \ \ i \in \mathcal{L}.$$

The SINR of the LTE link, $i, \forall i$, in the presence of Wi-Fi and no Wi-Fi is described as

$$S_i = \begin{cases} \dfrac{P_i G_{ii}}{\sum_{j \in \mathcal{L}, j \neq i} P_j G_{ij} + N_0}, \text{ if no Wi-Fi;} \\ \dfrac{P_i G_{ii}}{\sum_{j \in \mathcal{L}, j \neq i} P_j G_{ij} + \sum_{k \in \mathcal{W}} a_k P_k G_{ik} + N_0}, \text{ if Wi-Fi,} \end{cases} \tag{6}$$

where terms $\sum_{j \in \mathcal{L}, j \neq i} P_j G_{ij}$ and $\sum_{k \in \mathcal{W}} a_k P_k G_{ik}$ signifies the interference contribution from other LTE links and Wi-Fi links, (assuming all links in $\mathcal{W}$ are active). For the k-th Wi-Fi link, $\forall k$, the interference is reduced by a factor a_k to capture the fact that the k-th Wi-Fi is active approximately for only a_k fraction of time due to the CSMA/CA protocol at Wi-Fi.

For a given model, inter-network coordination is employed to assure a minimum throughput requirement, thus the guaranteed availability of the requested service at each UE. For this purpose, we have implemented our optimization in two stages as described in following subsections.

VI. Coordination via Joint Optimization

A. Joint Power Control Optimization

Here, the objective is to optimize the set of transmission power $P_i, i \in \{\mathcal{W}, \mathcal{L}\}$ at Wi-Fi and LTE APs, which maximizes the aggregated Wi-Fi+LTE throughput. Conventionally, LTE supports the power control in the cellular network. By default, commercially available Wi-Fi APs/routers are set to maximum level [43]. But adaptive power selection capability is incorporated in available 802.11a/g/n Wi-Fi drivers, even though it is not invoked very often. Under the SDN architecture, transmission power level can be made programmable to control the influence of interference from any AP at neighboring radio devices based on the spectrum parameters [44].

For the maximization of aggregated throughput, we propose a geometric programming (GP) based power control [18]. For the problem formulation, throughput, given by Eq. 2, can approximated as

$$R_i = \alpha_i \log_2(\beta_i S_i), \ \ i \in \{\mathcal{W}, \mathcal{L}\}. \tag{7}$$

This equation is valid when $\beta_i S_i$ is much higher than 1. In our case, this approximation is reasonable considering minimum SINR requirements for data transmission at both Wi-Fi and LTE. The aggregate throughput of the WiFi+LTE network is

$$\begin{aligned} \mathbb{R} &= \sum_{i \in \mathcal{W}} a_i b_i \alpha_w \log_2(\beta_w S_i) + \sum_{j \in \mathcal{L}} \alpha_l \log_2(\beta_l S_j) \\ &= \log_2 \left[\left(\prod_{i \in \mathcal{W}} (\beta_w S_i)^{a_i b_i \alpha_w} \right) \left(\prod_{j \in \mathcal{L}} (\beta_l S_i)^{\alpha_l} \right) \right]. \end{aligned} \tag{8}$$

In the coordinated framework, it is assumed that Wi-Fi parameters a_i and b_i are updated periodically. Thus, these are considered as constant parameters in the formulation. Also, $\alpha_i, \beta_i, i \in \{w, l\}$ are constant in the network. Therefore, aggregate throughput maximization is equivalent to maximization of a product of SINR at both Wi-Fi and LTE links. Power control optimization formulation is given by:

$$\begin{aligned} \text{maximize} \quad & \left(\prod_{i \in \mathcal{W}} (\beta_w S_i)^{a_i b_i \alpha_w} \right) \left(\prod_{j \in \mathcal{L}} (\beta_l S_i)^{\alpha_l} \right) \\ \text{subject to} \quad & R_i \geq R_{i,\min}, \ \ i \in \mathcal{W}, \\ & R_i \geq R_{i,\min}, \ \ i \in \mathcal{L}, \\ & \sum_{k \in M_i^b} P_k G_{ik} + \sum_{j \in \mathcal{L}} P_j G_{ij} + N_0 < \lambda_c, \ i \in W, \\ & 0 < P_i \leq P_{\max}, \ \ i \in \mathcal{W}, \\ & 0 < P_i \leq P_{\max}, \ \ i \in \mathcal{L}. \end{aligned} \tag{9}$$

Here, the first and second constraints are equivalent to $S_i \geq S_{i,min}, \forall i$ which ensures that SINR at each link achieves a minimum SINR requirement, thus leading to non-zero throughput at the UE. The third constraint assures that channel energy at a WiFi (LTE interference + interference from Wi-Fis in the interference zone + noise power) is below the clear channel assessment threshold λ_c, thus Wi-Fi is not shut off. The fourth and fifth constraints follow the transmission power limits at each link. Unlike past power control optimization formulations for cellular networks, Wi-Fi-LTE coexistence involves meeting the SINR requirement at a Wi-Fi UE and, additionally, the CCA threshold at a Wi-Fi AP.

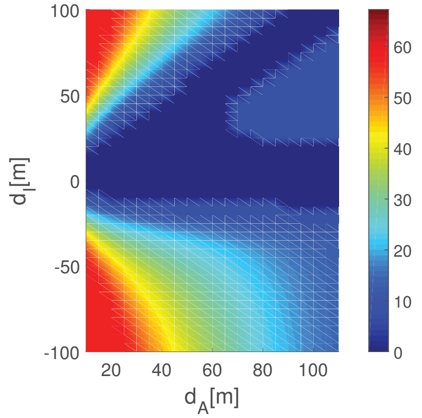
For multiple Wi-Fi and LTE links, to ensure the feasibility of the problem where all constrains are not satisfied, notably for Wi-Fi links, we relax the minimum data requirement constraint for LTE links. In our case, we reduce the minimum data requirement to zero. This is equivalent to shutting off certain LTE links which cause undue interference to neighboring Wi-Fi devices.

B. Joint Time Division Channel Access Optimization

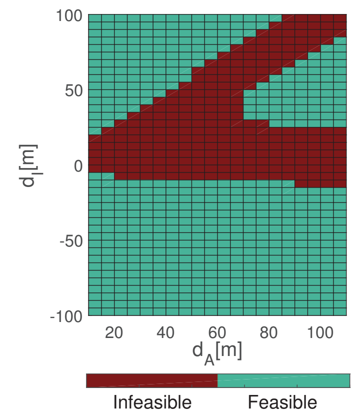
The relaxation of minimum throughput constraint in the joint power control optimization leads to throughput deprivation at some LTE links. Thus, joint power control is not sufficient when system demands to have non-zero throughput at each UE. In such cases, we propose a time division channel access optimization framework where network of each RAT take turns to access the channel. Assuming network $i, i \in \{w, l\}$ access the channel for $\eta, eta \in [0, 1]$, fraction of time, network $j, j \in \{w, l\}, j \neq i$, holds back the transmission and thus no interference occurs at i from j. For remaining $1-\eta$ fraction of time, j access the channel without any interference from i. This proposed approach can be seen as a subset of power assignment problem, where power levels at APs of network $i, i \in \{w, l\}$, is set to zero in their respective time slots. The implementation of the protocol is out of scope of this paper.

In this approach, our objective is to optimize η, the time division of channel access, such that it maximizes the minimum throughput across both Wi-Fi and LTE networks. We propose the optimization in two steps -

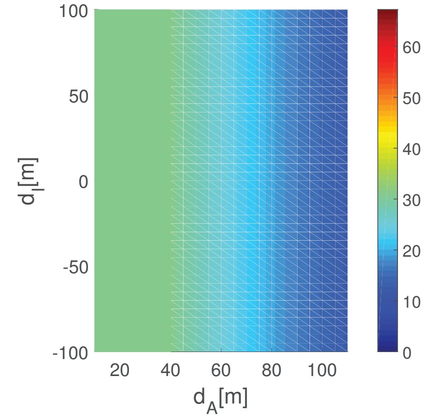
1) Power control optimization across network of same RAT: Based on the GP-formulation, the transmission power of the APs across the same network $i, i \in \{w, l\}$, is optimized for



(a) A heat map of Wi-Fi throughput when joint power Coordination (Mbps)



(b) Feasibility region of joint power Coordination



(c) A heat map of Wi-Fi throughput when time division channel access coordination (Mbps)

Fig. 10. Wi-Fi performance under joint Wi-Fi and LTE coordination (d_A: dist(Wi-Fi AP, associated UE), d_I: dist(Interfering LTE AP, Wi-Fi UE))

Wi-Fi and LTE, respectively, as

$$\begin{aligned} \text{maximize} \quad & \sum_{i \in \mathcal{W}} R_i \\ \text{subject to} \quad & R_i \geq R_{i,\min}, \;\; i \in \mathcal{W} \\ & 0 \leq P_i \leq P_{\max}, \;\; i \in \mathcal{W}, \\ & \sum_{k \in M_i^b} P_k G_{ik} + N_0 < \lambda_c, \; i \in \mathcal{W}. \end{aligned} \tag{10}$$

and

$$\begin{aligned} \text{maximize} \quad & \sum_{i \in \mathcal{L}} R_i \\ \text{subject to} \quad & R_i \geq R_{i,\min}, \;\; i \in \mathcal{L} \\ & 0 \leq P_i \leq P_{\max}, \;\; i \in \mathcal{L}. \end{aligned} \tag{11}$$

Here, the objective function is equivalent to maximizing the product of SINRs at the networks $i, i \in \{w, l\}$. The first and second constraints ensure that we meet the minimum SINR and transmission power limits requirements at all links of i. In this formulation, SINR at Wi-Fi and LTE respectively given as

$$S_i = \frac{P_i G_{ii}}{N_0}, \;\; i \in \mathcal{W},$$

$$S_i = \frac{P_i G_{ii}}{\sum_{j \in \mathcal{L}, j \neq i} P_j G_{ij} + N_0}, \;\; i \in \mathcal{L}.$$

which are first cases in equations (5) and (6), respectively.

2) Joint time division channel access optimization: This is the joint optimization across both Wi-Fi and LTE networks which is formulated using max-min fairness optimization as given below

$$\begin{aligned} \text{maximize} \quad & \min\left(\eta R_{i \in \mathcal{W}}, (1-\eta) R_{j \in \mathcal{L}}\right) \\ \text{subject to} \quad & 0 \leq \eta \leq 1. \end{aligned} \tag{12}$$

Here, throughput values at all Wi-Fi and LTE nodes are considered as a constant, which is the output of the previous step. The Time division channel access parameter η is optimized so that it maximizes the minimum throughput across all UEs.

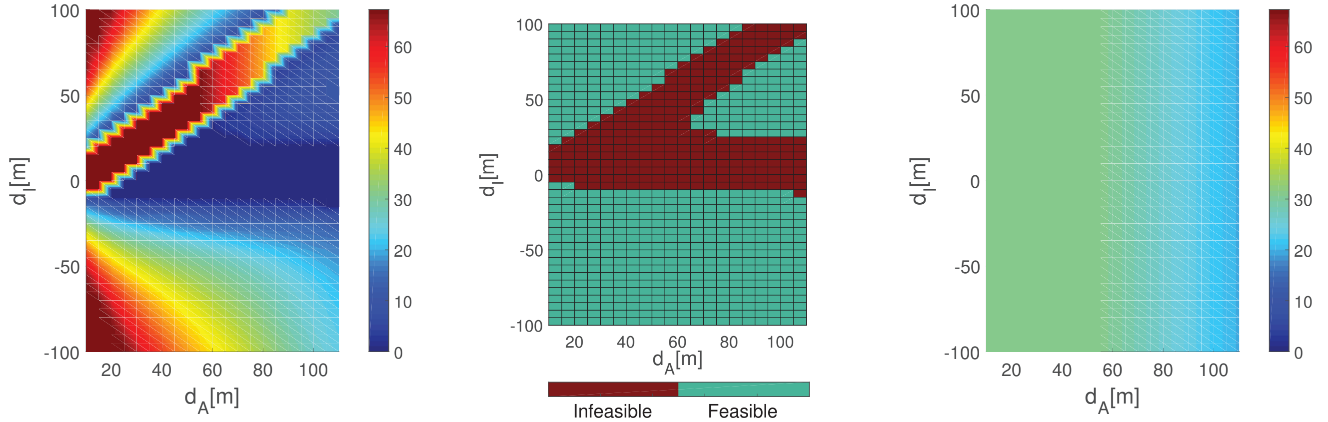
VII. Evaluation of Joint Coordination

A. Single Link Co-channel Deployment

We begin with the motivational example of co-channel deployment of one Wi-Fi and one LTE links, as described in § III-C. Fig. 10 shows the heatmap of improved throughput of Wi-Fi link, when joint Wi-Fi and LTE coordination is provided in comparison with the throughput with no coordination as shown in Fig. 7 . Similarly, Fig. 11 shows the heatmap of improved throughput of LTE link, when joint coordination is provided in comparison with the throughput with no coordination, as shown in Fig. 8.

For both the figures 10 and 11, in their respective scenarios, though joint power control improves the overall throughput for most of topological scenarios (see Fig. (a) of 10 and 11), it is not an adequate solution for topological combination marked by *infeasible* region as given in Fig. (b) of 10 and 11. The infeasible region signifies the failure to attain the CCA threshold at Wi-Fi AP and link SINR requirement when the UE and interfering AP are very close to each other. When we apply time division channel access optimization for a given scenario, we do not observe any infeasible region, in fact optimization achieves almost equal and fair throughput at both Wi-Fi and LTE links, as shown in Fig. (c) of 10 and 11. On the downside, this optimization does not consider cases when Wi-Fi and LTE links can operate simultaneously without causing severe interference to each other. In such cases, throughput at both Wi-Fi and LTE is degraded.

Fig. 12 summarizes the performance of Wi-Fi and LTE links in terms of 10th percentile and mean throughput. We note that the 10th percentile throughput of both Wi-Fi and LTE is increased to $15-20$ Mbps for time division coordination compared to $\sim$ zero throughput for no and power coordination. We observe 200% and 350% Wi-Fi mean throughput gains due to power and time division channel access, respectively, compared to no coordination. For LTE, throughput gains for both of these coordination is $\sim 25-30\%$. It appears that time division channel access coordination does not offer any additional advantage to LTE in comparison with power coordination. But it brings the throughput fairness between



(a) A heat map of LTE throughput when joint power Coordination (Mbps)

(b) Feasibility region of joint power Coordination

(c) A heat map of LTE throughput when time division channel access coordination (Mbps)

Fig. 11. LTE performance under joint Wi-Fi and LTE coordination (d_A: dist(LTE AP, associated UE), d_I: dist(Interfering Wi-Fi AP, LTE UE))

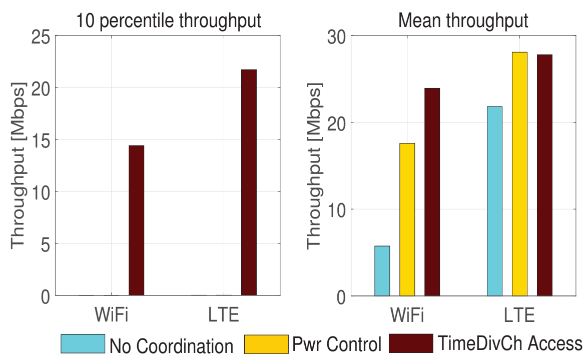


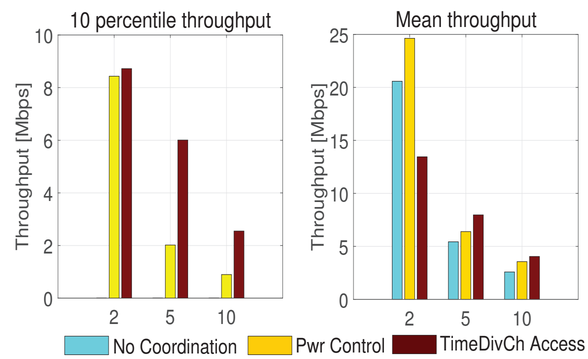
Fig. 12. 10 percentile and mean LTE throughput for a single link Wi-Fi and LTE co-channel deployment

Wi-Fi and LTE which is required for the co-existence in the shared band.

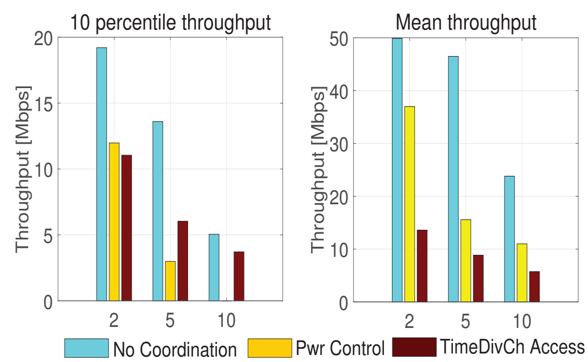
B. Multiple Links Co-channel Deployment

Multiple overlapping Wi-Fi and LTE links are randomly deployed in 200-by-200 sq. meter area which depicts the typical deployment in residential or urban hotspot. The number of APs of each Wi-Fi and LTE networks are varied between 2 to 10 where number of Wi-Fi and LTE links are assumed to be equal. For the simplicity purpose, we assume that only single client is connected at each AP and their association is predefined. The given formulation can be extended for multiple client scenarios. In the simulations, the carrier sense and interference range for Wi-Fi devices are set to 150 meters and 210 meters, respectively. The hidden node interference parameter is set to 0.25.

Figures 13(a) and 13(a) show the percentile and mean throughput values of Wi-Fi and LTE links, respectively, for when number of links for each Wi-Fi and LTE networks is set at $N = \{2, 5, 10\}$. The throughput performance is averaged over 10 different deployment topologies of Wi-Fi and LTE links. From Fig. 13(a), it is clear that 10 percentile Wi-Fi UEs get throughput starved due to LTE interference with no



(a) 10 percentile and mean Wi-Fi throughput for $N = \{2, 5, 10\}$



(b) 10 percentile and mean LTE throughput for $N = \{2, 5, 10\}$

Fig. 13. Multi-link throughput performance under power control and time devision channel access optimization. N = no. of LTE links = no. of Wi-Fi links.

coordination. This is consistent with results from single link simulations. With coordination, both joint power control and time division channel access, we achieve a large improvement in the 10th percentile throughput. Joint power control improves mean Wi-Fi throughput by 15-20% for all N. On the other hand, time division channel access achieves throughput gain (40-60%) only at higher values of $N = \{5, 10\}$.

Throughput performance of LTE, on the other hand, deteriorates in the presence of coordination compared to when no coordination is provided. This comes from the fact that, in case of no coordination, LTE causes undue impact at Wi-Fi nodes causing them to hold off data transmission, while LTE experiences no Wi-Fi interference. Joint coordination between Wi-Fi and LTE networks brings the notion of fairness in the system and allocates spectrum resources to otherwise degraded Wi-Fi links. In the joint power control optimization, though certain LTE links (maximum 1 link for $N = 10$) have to be dropped from network with zero throughput, but overall mean throughput is typically 150 to 400% greater than Wi-Fi throughput.

We observe that for small numbers of Wi-Fi links, joint time division channel access degrades the performance of both Wi-Fi and LTE. But as the number of links grows, coordinated optimization results in allocation of orthogonal resources (e.g. separate channels) giving greater benefit than full sharing of the same spectrum space, as is the case for power control optimization.

VIII. Conclusion

This paper investigates inter-system interference in shared spectrum scenarios with both Wi-Fi and LTE operating in the same band. An analytical model has been developed for evaluation of the performance and the model has been partially verified with experimental data. The results show that significant performance degradation results from uncoordinated operation of Wi-Fi and LTE in the same band. To address this problem, we further presented an architecture for coordination between heterogeneous networks, with a specific focus on LTE-U and Wi-Fi, to cooperate and coexist in the same area. This framework is used to exchange information between the two networks for a logically centralized optimization approach that improves the aggregate throughput of the network. Our results show that, with joint power control and time division multiplexing, the aggregate throughput of each of the networks becomes comparable, thus realizing fair access to the spectrum. In future work, we plan to extend our analytical model and optimization framework to study realistic user applications for which full buffer traffic conditions cannot be assumed. We further plan to extend the optimization framework to exploit the frequency diversity for joint coordination of Wi-Fi and LTE.

Acknowledgment: The research reported in this paper was supported by National Science Foundation grant CNS-1247764 under the EARS (Enhanced Access to Radio Spectrum) program.

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