Modeling the Coexistence of LTE and WiFi Heterogeneous Networks in Dense Deployment Scenarios

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***Abstract*—Rapid increases in mobile data demand and inherently limited RF spectrum motivate the use of dynamic spectrum sharing between different radio technologies such as WiFi and LTE, most notably in small cell (HetNet) scenarios. This paper provides a analytical framework for interference characterization of WiFi and LTE for dense deployment scenarios with spatially overlapping coverage. The first model developed is for single LTE and single WiFi access points separated by a specified distance. Results obtained for that model demonstrate the fact that WiFi is significantly degraded by a nearby LTE system, while LTE degradation is minimal as long as the WiFi system is within carrier sense range. A second model for multiple WiFi and multiple LTE systems further demonstrates the fact that LTE causes significant degradation to WiFi and that overall system throughput first increases and then decreases with growing density. Intra- and inter- system channel coordination schemes are considered as a means of improving system performance, and results are presented showing 4-5x gains in system capacity over comparable no coordination cases.**

***Index Terms*—WiFi, LTE, HetNet, dynamic spectrum access, inter-network coordination, distributed CSMA**

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, mobile APs and other portable devices. To meet such a high demand, several solutions have been proposed including deployment of small cells, addition of new spectrum for mobile services and new unlicensed or white space bands for shared access to spectrum. Recently, Qualcomm has proposed to enable LTE in 2.4 and 5 GHz unlicensed bands as a secondary carrier for downlink-only and/or uplink and downlink [1]. Also both LTE and WiFi based small cell services are expected to be offered in the 3.5 Ghz shared use band currently utilized for military and satellite operations [2]. Thus, in the near future, dense deployments of LTE and WiFi based small cells may be expected to coexist in shared spectrum. This leads to heterogeneous network (HetNet) scenarios with (1) multi-radio access technologies (multi-RAT) intra-network (operated by a single operator) or (2) multi-RAT inter-network (multiple operators). For efficient spectrum utilization in HetNets, coordinated dynamic spectrum management is proposed and evaluated as a means to achieve good performance in extremely dense deployment scenarios.

LTE-WiFi Coexistence Challenges: Coordination between multi-RAT networks with LTE and WiFi is challenging due to the difference in medium access control layer of two technologies. WiFi is based on the distributed coordination function where each transmitter senses the channel energy for transmission opportunities and collision avoidance. In contrast, LTE can be considered as a time division multiple access network in which data packets are scheduled in the successive time frames. Also, LTE does not assume that spectrum is shared and consequently does not employ any sharing features in the channel access mechanisms. Thus, the coexistence performance of both LTE and WiFi would be unpredictable and may lead to unfair spectrum sharing or starvation of one of the technologies [3].

To overcome LTE-WiFi coexistence challenges and obtain the benefits of shared spectrum, in our previous work [4], a dynamic spectrum management framework is proposed to exploit the bandwidth and frequency diversity available at WiFi and LTE via logically centralized network optimization. Such a framework requires detailed co-channel interference characterization which is currently not available. Thus, in this paper, we focus on the WiFi-LTE small cell co-channel throughput performance analysis in the downnlink scenario for saturated traffic conditions at all WiFi/LTE access points (APs).[1]

The key contributions of this paper are as follows:

1) *Interference characterization of WiFi and LTE*: We introduce a novel WiFi-LTE interference model along with the consideration of typical features of each technology and their heterogeneous operation, e.g., carrier sense multiple access (CSMA), clear channel assessment (CCA), for WiFi, scheduled LTE operation, etc. Using the example of a single WiFi and single LTE, we show that the conventional perception of inverse relation of throughput and distance between interfering APs is not valid in the co-channel operation of WiFi and LTE.
2) *Interference characterization of dense WiFi-LTE deployment*: In a dense deployment of WiFi and lTE, interference is characterized in a scenario of distributed CSMA WiFi networks (each WiFi AP senses only subset of WiFi APs) which causes variable WiFi interference pattern to LTE network, which has not been explored before.
3) *Exploration of frequency diversity*: Overall system throughput (i.e. WiFi + LTE) is compared against three channel allocation algorithms- random channel as-

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

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signment, graph multicoloring like channel assignment (GMCA) at each RAT individually, and joint GMCA across both technologies.

The paper is organized as follows: Section II summarizes the related work in the shared spectrum usage. Section III provides a brief discussion on standalone WiFi and LTE models used to analyze the coexistence scenarios. Sections IV and V discuss the coexistence models used for scenarios of single and multiple WiFi and LTE networks, respectively. Section VI explores the frequency diversity against the single channel deployment. Section VII outlines the conclusions and future directions.

II. Related Work

In the literature, several studies have discussed the spectrum management for multi-RAT heterogeneous networks in the shared frequency bands, primarily focusing on IEEE 802.11 and 802.16 networks [5]–[7]. Recently, WiFi and LTE coexistence have been studied in the context of TV white space [8], in-device coexistence [9], LTE-unlicensed (LTE-U) [10]–[12], etc. Several studies [11]–[13] propose CSMA/sensing based modifications in LTE with features like Listen-before-Talk, RTS/CTS protocol, slotted channel access, etc. In other studies, to enable WiFi/LTE coexistence, solutions like blank LTE subframes/LTE muting (feature in LTE Release 10/11) [8], [14], carrier sensing adaptive transmission [11], interference aware power control in LTE [15] have been proposed, which require LTE to transfer its resources to WiFi. These schemes give WiFi transmission opportunities but also leads to performance tradeoff for LTE. Also, time domain solutions often require time synchronization between WiFi and LTE and increase channel signaling. Some aspects of frequency and LTE bandwidth diversity have been explored in studies [11] and [16], respectively. Frequency diversity is the least studied problem in WiFi/LTE coexistence. Also, previous studies have yet to consider dense WiFi and LTE HetNet deployment scenarios in detail.

III. System Setup

A. Modeling of WiFi Performance

In our study, we use a WiFi model based on the basic distributed coordination function (DCF) (i.e no RTS/CTS). The WiFi throughput is characterized using the Markov chain analysis given in Bianchi's model [17] assuming a saturated traffic condition (at least 1 packet is waiting to be sent) at each AP and all APs are in the CSMA range of each other. WiFi channel rate R_w is modeled as a function of Signal-to-Noise-Ratio (SNR) [17], [18].

1) Modeling of Dense WiFi Network: In dense deployment of WiFi over a large area, each link may sense only a subset, but not all, of other links forming distributed CSMA wireless networks. Bianchi's model fails to capture this case; thus we have adopted a Back-of-the-Envelope (BoE) model proposed by Liew et al. [23]. Based on the CSMA contention graph, BoE calculates maximum independent sets (MISs) where each MIS includes maximum number of WiFi links which can transmit at the same time. All MISs are assumed to have equal probability. Based on the number of MISs in which link i appears, normalized throughput $\lambda_i, \forall i$, is calculated. λ_i is converted to throughput T_{w_i} by applying Bianchi's model as if only link i is active in the whole network. BoE assumes no packet collision in the network. See [23] for the detailed BoE model.

2) Clear Channel Assessment: In WLAN, the clear channel assessment (CCA) mechanism is used to detect any on-going transmission in the channel [21]. WiFi transmitter nodes are considered to be in the CSMA range of each other when they can detect and decode a WiFi preamble which announces an incoming transmission (minimum required SNR among WiFi transmitters). For non-WiFi transmissions (in this study LTE) in the channel, WiFi detects the channel busy if energy in the channel (E_c) is above certain threshold (CCA_T). Thus, the CCA mechanism is a key parameter to model the interference between WiFi and LTE.

3) Throughput Formulation: For a single WiFi link (the prominent case for BoE model), firstly, CCA mechanism is initiated as

$$R_w = \begin{cases} 0 & \text{if } E_c \geq \mathrm{CCA}_T; \\ f(\mathrm{SNR}) & \text{if } E_c < \mathrm{CCA}_T \end{cases} \tag{1}$$

and, if $E_c < \mathrm{CCA}_T$, the throughput is formulated as follows:

$$\begin{aligned} T_S =& f(R_w); L = f(R_w); \\ \mathrm{E}[S] =& T_E + T_S; \\ \eta_E =& T_E/\mathrm{E}[S]; \\ \eta_S =& T_S/\mathrm{E}[S]; \\ S_i =& (P_s L)/\mathrm{E}[S] \end{aligned} \tag{2}$$

where P_s is the probability that an AP successfully transmits in a given time slot; $\mathrm{E}[S]$ is the expected time per transmission; T_E, T_S are average times per $\mathrm{E}[S]$ spent in random backoff (empty channel) and successful transmission, respectively; L is the average time spent transmitting payload data; S is the normalized throughput. For a single WiFi link, the possibility of packet collision is dismissed. The notations used are consistent to those used in Bianchi's model.

B. Modeling of LTE Performance

In our model, LTE is assumed to be operated in downlink, FDD mode (dedicated spectrum for downlink), 100% utilization of spectrum band (saturated traffic condition) and no frequency selectivity. Peak LTE throughput (T_L) is based on a LTE channel quality index (CQI) which corresponds to the AP-client SINR [19], [20]. In data transmission, CQI defines the modulation scheme (thus, bits/symbol (B_S)) and coding rate (C_R). Thus, we have

$$\begin{aligned} \mathrm{CQI} =& f(\mathrm{SINR}); \\ B_S =& f(\mathrm{CQI}); \\ C_R =& f(\mathrm{CQI}); \\ T_L[\mathrm{bits/ms}] =& \alpha(R_E B_S C_R) \end{aligned} \tag{3}$$

TABLE I
NETWORK PARAMETERS

Parameter	Value	Parameter	Value
WiFi Parameters			
WiFi Type	802.11n (SISO)	MAC protocol	DCF
RIFS	2 μs	DIFS	20 μs
Payload size	1470 Bytes	MPDUs	4
MAC+PHY hdr	24+16 Bytes	ACK	16 Bytes
CCA Threshold	-62 dBm	Header rate	6.5 Mbps
Channel rate	$(13, 26, 39, 52, 78, 104, 117, 130)$ Mbps		
Required SNR	$(5, 7, 9, 13, 17, 20, 22, 23)$ dB respectively		
ACK frame rate	$\max\{6.5, 13, 26\}$ Mbps $\leq$ Ch rate		
LTE Parameters			
LTE/OFDMA	FDD	Tx mode	1 (SISO)
Block error rate	10%	HARQ	0
Control overhead	30%	Cyclic prefix	5μs
CQI	0(no connection), 1-15		
SINR w.r.t. CQI	(1.95,4,6,8,10,11.95,14.05,16,17.9,19.9,21.5 23.45,25,27.3,29)		

where R_E is a number of resource elements (OFDMA symbols per subcarrier per resource block) for a given bandwidth (BW) (e.g. R_E = 16800 for BW=20 MHz and normal cyclic prefix), and α is the LTE control and signaling overhead.

Selected WiFi and LTE parameters are defined in Table I

IV. INTERFERENCE MODELING: SINGLE WIFI AND SINGLE LTE

This section illustrates the co-channel deployment of a single link of each WiFi and LTE to analyze the interaction between these technologies. Using MATLAB based simulations, throughput and Signal-to-Interference-plus-Noise (SINR) performance is studied when distance D between two APs is varied. Later, this case will serve as a building block to model a dense deployment of WiFi and LTE.

A. Characterization of WiFi Throughput

Model 1: WiFi Throughput Characterization

Data: Φ_w: received power at a WiFi client; R_w: WiFi channel rate; I_L: LTE interference at the WiFi client; N_0: thermal noise; E_c: channel energy at the WiFi AP (LTE interference + N_0); S: see (2)
Parameter: CCA$_T$: WiFi CCA threshold
Output : T_w: WiFi throughput
if *No LTE* **then**

$$R_w = f\left(\frac{\Phi_w}{N_0}\right); T_w = S.R_w.$$

else When LTE is present
  if $E_c > CCA_T$ **then**
    No WiFi transmission with $T_w = 0$
  else

$$R_w = f\left(\frac{\Phi_w}{I_L + N_0}\right)$$
$$T_w = S.R_w.$$

  end
end

TABLE II
NETWORK PARAMETERS (CONSISTENT OVER WIFI/LTE) [22]

Parameter	Value	Parameter	Value
Scenario	Downlink	Tx power	20 dBm
Min AP-AP dist	10m	AP-Client dist	20 m
Spectrum band	2.4 GHz	Bandwidth	20 MHz
Traffic model	Full buffer via saturated UDP flows		
AP antenna ht.	10 m	User antenna ht.	1 m
Path loss model	36.7$\log_{10}$(d[m]) + 22.7 + 26$\log_{10}$(frq [GHz])		
Noise Floor	-101 dBm, (-174 cBm thermal noise/Hz)		
Channel	No shadow/Rayleigh fading		

B. Characterization of LTE Throughput

Model 2: LTE Throughput Characterization

Data: Φ_L: received power at a LTE; I_w: WiFi interference at the LTE client; N_0: thermal noise; E_c: channel energy at the WiFi AP (LTE interference + N_0);
Parameter: CCA$_T$: WiFi CCA threshold
Output : T_L: LTE throughput
if *No WiFi* **then**

$$T_{L_{\text{noW}}} = f(\text{SNR}) = f\left(\frac{\Phi_L}{N_0}\right).$$

else When WiFi is present
  if $E_c > CCA_T$ **then**
    No WiFi transmission with $I_w = 0$ and $T_L = T_{L_{\text{noW}}}$
  else

$$T_{L_{\text{withW}}} = f\left(\frac{\Phi_L}{I_w + N_0}\right)$$

    Using (2) and $\eta_C = 0$ (just a single WiFi link)

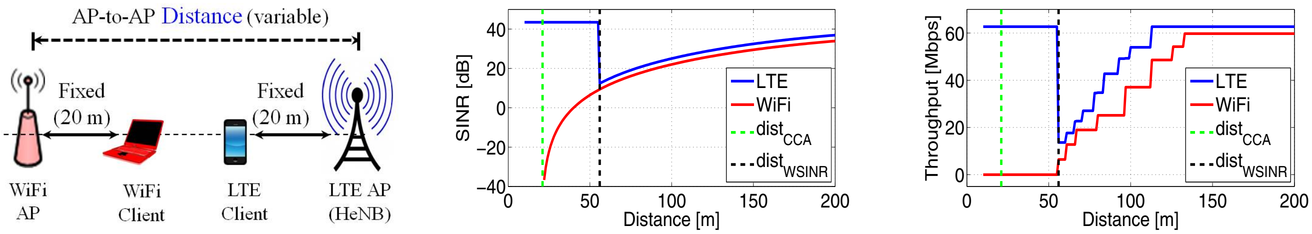
$$T_L = \eta_E T_{L_{\text{noW}}} + \eta_S T_{L_{\text{withW}}}$$

  end
end

C. Evaluation

We consider a network topology as shown in Fig. 1(a) where all nodes are horizontally aligned. For a given D, it is the worst co-channel topology where clients at given locations get affected most due to interference from the AP of other technology (under no shadowing assumption). Simulation parameters are given in Table II.

Fig. 1(b) and 1(c) shows SINR and corresponding throughput at each link, respectively. When $D <$ dist$_{\text{CCA}}$, WiFi CCA mechanism senses channel as busy and hinders WiFi data transmission. Thus, zero T_w (WiFi throughput) and maximum T_L (LTE throughput), with no WiFi interference, is observed. Even when D surpasses dist$_{\text{CCA}}$, T_w continues to be zero due to the high LTE interference at WiFi client which makes WiFi unable to attain minimum SINR (SINR$_m$) required for data transmission. At $D =$ dist$_{WSINR}$, WiFi achieves SINR$_m$ and starts data transmission at lowest channel rate. At this point, T_L drops sharply due to appearance of WiFi interference and the lowest system (WiFi+LTE) throughput is attained. As D



(a) WiFi/LTE nodes in a horizontal alignment (b) WiFi/LTE SINR performance (c) WiFi/LTE throughput performance

Fig. 1. Throughput as function of inter-AP distance D for a given topology

increases beyond dist$_{WSINR}$, interference at both the system decreases resulting in the increase of both T_w and T_L.

It is observed from the results that the conventional perception of inverse proportion of throughput to inter-AP distance D (especially for LTE) is not valid anymore for WiFi-LTE co-channel deployment. Lowest WiFi/LTE throughput or system throughput at distance D is a complex function of overall network topology, WiFi CSMA and CCA mechanisms.

V. Multiple WiFi and Multiple LTE

We extend the model derived in the previous section to the co-channel deployment of multiple WiFi and LTE links.

A. Characterization of WiFi Throughput

WiFi throughput is characterized using the BoE model explained in the section III-A.

Model 3: WiFi Throughput Characterization

Data: N_w: no. of WiFi links; i: WiFi link index; n_i: no. of MISs in which i appears; λ_i: BoE normalized throughput at i; $\Phi_{w_i}, R_{w_i}, E_{c_i}$: Φ_w, R_w, E_c at i respectively; N_L: no. of LTE links; I_L: LTE interference; N_0: thermal noise; S: see (2)
Parameter: CCA$_T$: WiFi CCA threshold
Output : T_{wi}: WiFi throughput at i, $\forall i$
if *No LTE* **then**
  Calculate M MISs for a given WiFi network

$$\lambda_i = n_i/M; R_{w_i} = f\left(\frac{\Phi_{w_i}}{N_0}\right); \quad \forall i$$

$$T_{w_i} = \lambda_i S.R_{w_i}; \quad \forall i$$

else When LTE is present

$$R_{w,i} = f\left(\frac{\Phi_{w,i}}{\sum_{j=1}^{N_L} I_{L(i,j)} + N_0}\right); \forall i$$

  if $E_{c_i} \geq$ *CCA$_T$* ***OR*** $R_{w,i} = 0$ **then**
    No WiFi transmission with $T_{w_i} = 0; \forall i$
  else if $E_{c_i} <$ *CCA$_T$* **then**
    Calculate set of $N \leq N_w$ WiFi links with $R_{w,i} > 0$; $i \in \{1, \ldots, N\}$
    Calculate M_L MISs for N WiFi network

$$\lambda_i = n_i/M_L; \quad T_{w_i} = \lambda_i S.R_{w_i}; \forall i$$

  end
end

B. Characterization of LTE Throughput

Model 4: LTE Throughput Characterization

Data: N_L: no. of LTE links; j: LTE link index; Φ_{L_j}: Φ_L at j; I_L: LTE interference; N_0: thermal noise; N_w: no. of WiFi links; I_w: WiFi interference; M_L: no. of WiFi MISs when LTE is present; η_S, η_E: see (2)
Output : T_{Lj}: LTE throughput at j, $\forall j$
if *No WiFi* **then**

$$(T_{L_{nw}})_j = f\left(\frac{\Phi_L}{\sum_{l=1, l\neq j}^{N_L} I_{L(j,l)} + N_0}\right); \forall j$$

else When WiFi is present
  for *LTE link* $j \in \{1, .., N_L\}$ **do**
    for *WiFi MIS* $m \in \{1, .., M_L\}$ **do**
      Identify P_w, a set of active WiFis in m
      Initialize sets P_{η_S}, P_{η_E} such that $\eta_{S_i} \in P_{\eta_S}$, $\eta_{E_i} \in P_{\eta_E}$, $\forall i$, $i \in P_w$ and $T_{L(j,m)} = 0$
      while $P_w \neq$ *null set* **do**

$$t_L = f\left(\frac{\Phi_L}{\sum_{i \in P_w} I_{wi} + \sum_{l=1, l\neq j}^{N_L} I_{L(j,l)} + N_0}\right)$$

$$T_{L(j,m)} = T_{L(j,m)} + t_L. \min[P_{\eta_S}]$$

        Remove WiFis with $\eta_{S_i} = \min[P_{\eta_S}]$ from P_w and $\eta_{S_i} = \min[P_{\eta_S}]$ from P_{η_S}
      end

$$T_{L(j,m)} = T_{L(j,m)} + (T_{L_{nw}})_j \,. \min[P_{\eta_E}]$$

    end

$$T_{Lj} = (1/M_L) \sum_{m=1}^{M_L} T_{L(j,m)}.$$

  end
end

In co-channel deployment of LTE and WiFi, firstly, some WiFi links get shut off in the presence of LTE interference (I_L) as channel gets detected as busy due to the CCA mechanism. With remaining WiFi links, possibly with reduced and variable channel rate due to I_L, M_L MIS states get rearranged as defined in BoE model. Each MIS offers different WiFi interference at LTE based on active WiFi links in that MIS. Thus, LTE throughput is averaged over all MISs. Furthermore, in each MIS, due to variable channel rates at WiFi links and CSMA, each link is active for variable fraction of time. This leads to heterogeneous WiFi interference at LTE in each

MIS as well. These factors make throughput characterization intractable. But the above model allows us to capture these factors in approximated but simple manner.

C. Evaluation

1) Throughput performance: : Fig. 2(a) depicts the average link throughput for both the RATs in standalone and co-channel operation modes. Fig. 2(b) shows the sum-throughput over all links of each RAT for standalone and co-channel modes. In each case, the number of WiFi and LTE links are varied from 1 to 50 in a 200m-by-200m area and number of links of both the RATs are equal in the co-channel operation. WiFi co-channel throughput is affected dramatically due to the persistent nature of LTE interference leading to decrease of 20 to 97% when compared with standalone operation. But the opposite is not applicable where LTE co-channel throughput is reduced by 10% at lower link densities and the drop is only up to 1% at high link densities.

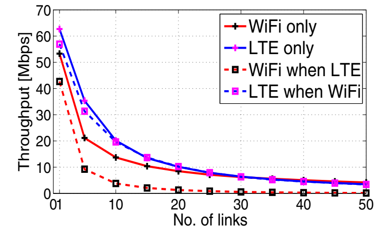
2) Shortcomings of interference model: : In the WiFi CSMA network, as number of contending AP increases, significant fraction of time is spent in the collision state which reduces the time spend in data transmission and effectively link throughput. However, the BoE model used for distributed WiFi networks does not consider packet collisions in the network. Therefore, BoE tends to overestimate WiFi throughput, which is evident in Fig. 2(b) for WiFi standalone case, especially at higher densities. But nonetheless, it allows us to predict upper bound WiFi throughput for this analytically intractable case. For the modeling of WiFi interference to LTE, all WiFis active in each MIS are assumed to begin transmission at the same time and end transmission based on the channel rate. In reality, this is a highly improbable scenario, but it allows for model simplification and upper bound throughput calculation of LTE as well. Nevertheless, WiFi and LTE co-channel performance trends are in consistent with those given by other studies [8], [10].

This throughput analysis emphasizes the necessity of WiFi and LTE inter-network coordination to mitigate throughput starvation at any RAT (in this case WiFi), facilitate fair usage of shared spectrum and increase overall spectrum capacity.

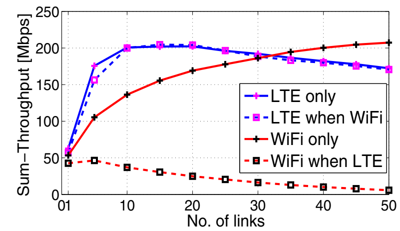
VI. Inter Network Frequency Coordination

In order to increase the individual RAT and system throughput, we explore the WiFi and LTE inter-network coordination in the frequency domain. As an example, three orthogonal channels are assumed to be available for WiFi/LTE shared operation (like channels 1, 6 and 11 in the 2.4 GHz spectrum band). The co-channel performance of WiFi and LTE is evaluated under following channel allocation schemes:

1) *Random Channel Assignment*: channel at APs of both the RATs are allocated selecting one of three orthogonal channels in a uniformly random distribution.
2) *Intra-RAT channel coordination*: A graph multicoloring like channel assignment (GMCA) is implemented across APs of the same RAT only where no two neighboring APs share the same channel. Such channel allocation is commonly referred in the cellular network which dismisses the same channel allocations to adjacent interfering APs [24].
3) *Inter-RAT channel coordination*: A channel is allocated at the AP as a graph multicoloring problem as in previous case but APs of both the RATs are jointly considered for the channel allocation.



(a) Link throughput (averaged over 1000 topologies)

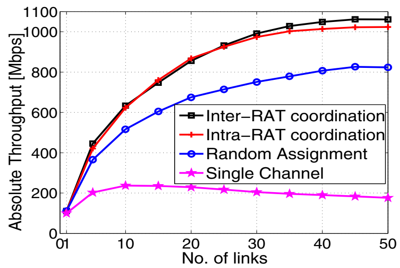


(b) Sum throughput over each RAT

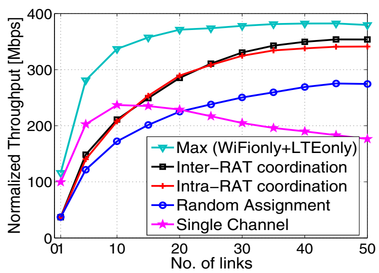
Fig. 2. Throughput as function no. of links (no. of WiFis = no. of LTEs)

Fig. 3(a) shows the absolute system throughput (WiFi + LTE) when channels are allocated using the above schemes. The figure compares performance with the case when same number of links are deployed in the single channel. Fig. 3(b) compares the normalized system throughput per channel for above schemes. It also shows the upper bound on the system throughput (WiFi + LTE in their single channel standalone operations) which can be achieved when perfect interference cancellation is provided between WiFi and LTE. As shown in Fig. 3(b), single channel deployment is channel efficient for lower network density but at higher network densities all 3-channel schemes outnumber the single channel deployment. In comparison with a single channel deployment, maximum absolute throughput gain of is $\sim$ 3.5x for random channel assignment and $\sim$ 4 to 5x for Intra and Inter RAT channel coordination schemes.

Key Observations: Fig. 3 suggests that Inter-RAT channel coordination scheme does not improve throughput significantly over intra-RAT channel coordination scheme and, thus, decreases the need for joint coordination. But in realty, GMCA fails to include WiFi CSMA operation in the joint channel assignment. In CSMA, WiFi throughput is inversely proportional to the number of WiFi transmitters in the CSMA range and WiFis in the same CSMA group does not cause interference to each other. GMCA, though, leads to assigning the least crowded channel (minimizing number of WiFis in the CSMA group) in WiFi only network, it does not guarantee the same



(a) Sum throughput over each RAT



(b) Link throughput (averaged over 1000 topologies)

Fig. 3. Throughput as function no. of links (no. of WiFis = no. of LTEs)

in joint WiFi-LTE channel allocation. The throughput analysis emphasizes the need for more sophisticated joint coordination algorithms [25], which further incorporates the important key features of each technology.

VII. Conclusion

In this paper, we have presented a analytical interference model for WiFi and LTE in the coexistence. In the simulation based study, in the dense deployment, the throughput performance of WiFi get degraded by up to 97% due to LTE interference leading to throughput starvation in WiFi. System throughput is analyzed by exploiting frequency diversity when three orthogonal channels are assumed to be available for shared usage. System throughput is evaluated with respect to the three channel allocation algorithms showing significant gain of $\sim 4-5$x when compared with single channel deployment. In future work, we plan to address some of the shortcomings of the current model and develop corresponding inter-network cooperation algorithms which take into account specific features of WiFi and LTE technologies.

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