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

"Interference modeling: a step towards coordination"

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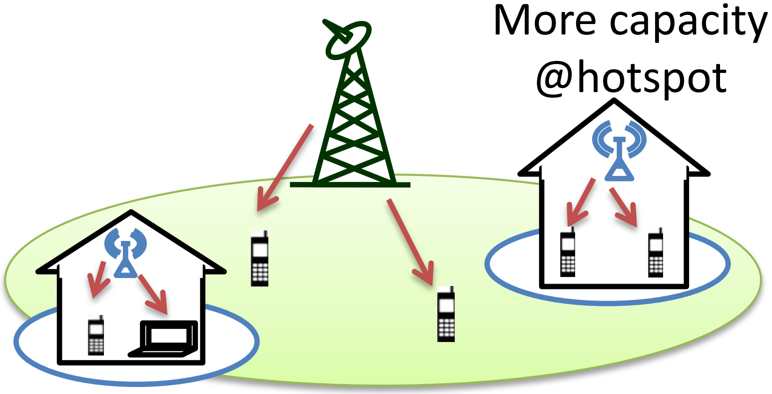
Increase in Data Demand…

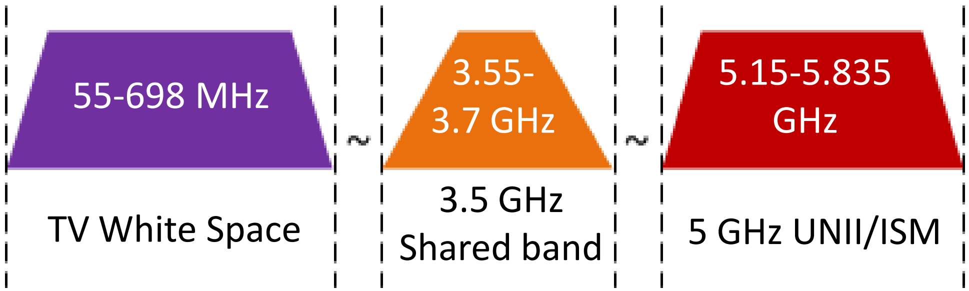
Exponential growth in mobile data demand

1. Deployment of small cells

2. Addition of more spectrum



To fill coverage holes



TV White Space	3.5 GHz Shared band	5 GHz UNII/ISM
LTE/Wi-Fi secondary users	Possible deployment of **LTE** and **Wi-Fi** small cell	Currently used by **Wi-Fi** & proposed use of **LTE** small cell

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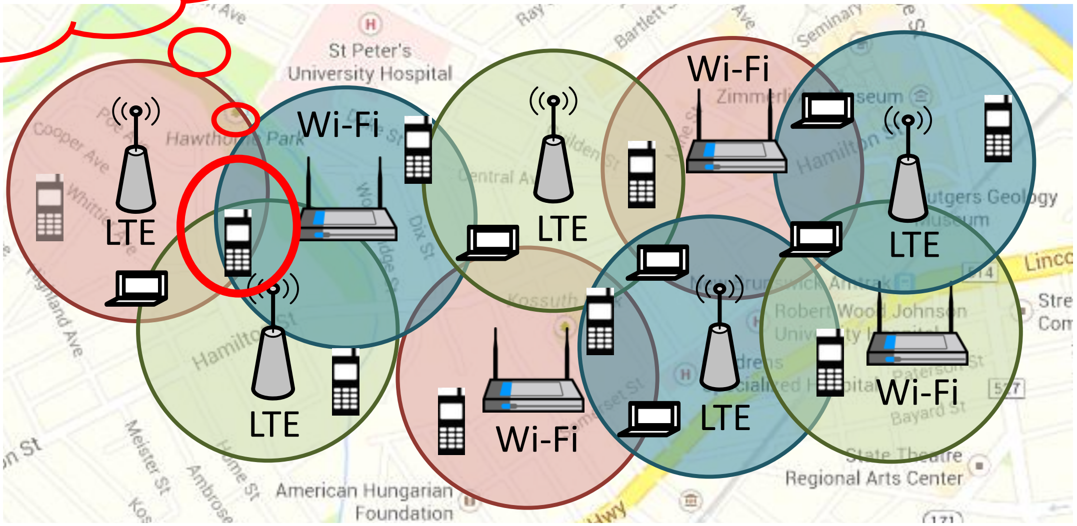
LTE and Wi-Fi in Shared Spectrum

Coexistence of LTE and Wi-Fi in same frequency band

Interference from LTE and Wi-Fi



Need interference coordination to avoid performance degradation!

Challenge: Difference in their MAC operation

Objective

To provide analytical framework for downlink interference characterization of densely deployed Wi-Fi and LTE

Key evaluations:

- Identification of throughput model of Wi-Fi and LTE along with their key features
- Interference characterization of single Wi-Fi and LTE
- Extension of interference model to dense co-channel deployment
- Throughput evaluation with exploitation of frequency diversity under three channel assignment approaches

Characterization of performance of:

1) Wi-Fi only
2) LTE Only

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Wi-Fi Throughput Model

Clear Channel Assessment (CCA)

1) Carrier Sense

- Ability to detect and decode other Wi-Fi's preamble (CSMA/CA)
- Bianchi's throughput model for saturated traffic for *N* nodes
- Wi-Fi throughput

$$R_i = \alpha_i (\text{channel rate}_i), \quad i = 1,..,N$$

with

α_i = Fraction of time to transmit payload at Wi-Fi *i*
= $f(N$, random back-off, successful transmission, packet collision)

channel rate $_i$ = $f(\text{SINR}_i)$

[Ref: G. Bianchi, 'Performance analysis of the IEEE 802.11 distributed coordination function']

Wi-Fi Throughput Model

Clear Channel Assessment (CCA)

2) Energy Detection

- Ability to detect non-Wi-Fi energy (e.g. LTE) in channel
- Wi-Fi throughput

$$R = \begin{cases} 0 & \text{if } E_c \geq \lambda_c \\ f(\mathrm{SINR}) & \text{if } E_c < \lambda_c \end{cases}$$

where

E_c = received channel energy

λ_c = CCA threshold (typically, 62 dBm)

MCS Index	Date Rate (Mbps)	Link SNR (dB)
0	6.5	9.3
1	13	11.3
2	19.5	13.3
3	26	17.3
4	39	21.3
5	52	24.3
6	58.5	26.3
7	65	27.3

IEEE 802.11n parameters (BW = 20 MHz, guard interval = 800 ns, SISO)

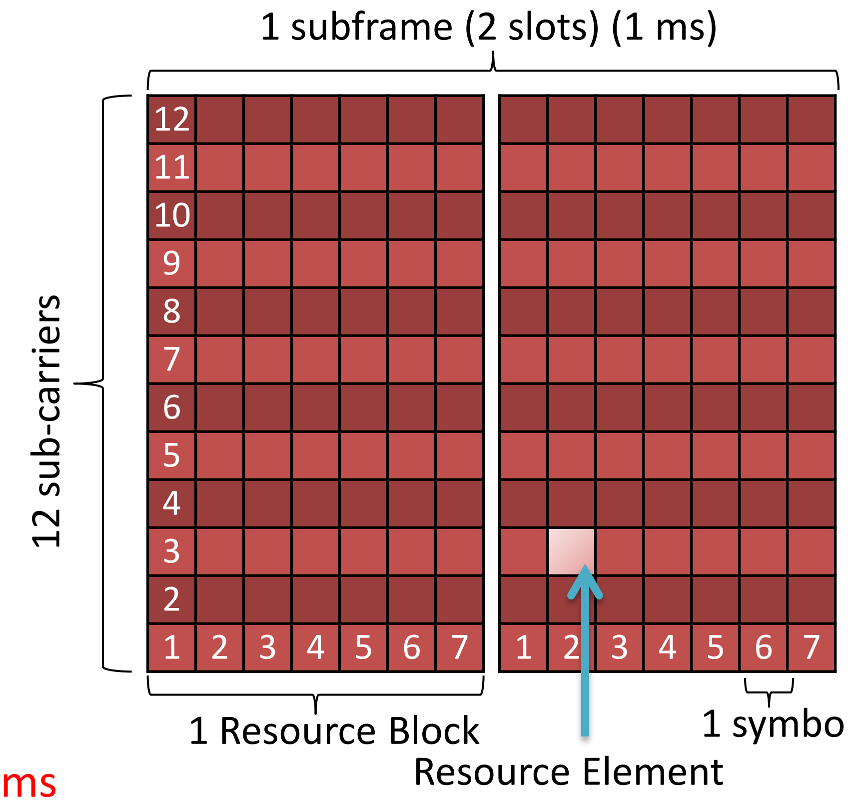
LTE: Throughput

Resource Block (RB)

- BW of 1 RB = 180 kHz
- Duration = 1 time slot of 0.5 ms
- Each time slot: 7 OFMA symbol (cyclic prefix = 5 µs)
- Resource elements: smallest unit of transmission of LTE

1 RB = 12 subcarriers * 7 symbols
= 84 resource elements

LTE @20MHz BW: 16800 resource elements/ms



Subcarriers: 15 kHz separation

Structure of a resource block in LTE

LTE: Throughput

- CQI: based on link SINR
- bits/symbol: modulation w.r.t CQI
- coding rate: corresponding to CQI

Peak Throughput (bits/ms)
= (RBs in given BW) * (bits/symbol) * (coding rate) * (channel overhead)

Parameter	Value
LTE	OFDMA FDD
Block error rate	10%
Transmission mode	1 (SISO)
Channel	Flat Rayleigh
Channel overhead (controlling)	30%

CQI	SINR (dB)	Modulation	Coding rate
1	1.95	QPSK	0.10145
2	4.00	QPSK	0.10145
3	6.00	QPSK	0.16232
4	8.00	QPSK	0.318841
5	10.00	QPSK	0.44221
6	11.95	QPSK	0.568116
7	14.05	16-QAM	0.365217
8	16.00	16-QAM	0.469565
9	17.90	16-QAM	0.563768
10	19.90	64-QAM	0.484058
11	21.50	64-QAM	0.60
12	23.45	64-QAM	0.692754
13	25.00	64-QAM	0.76087
14	27.30	64-QAM	0.888406
15	29.00	64-QAM	0.888406

LTE CQI and corresponding parameters
(CQI: channel quality index)

Interference Characterization of Coexistence

Wi-Fi Throughput in LTE Interference

Modeling throughput of a single Wi-Fi in the presence of a single LTE interference

If No LTE *then*

$$C_w = f\left(\frac{P_w G_w}{N_0}\right)$$

$$R_w = \alpha C_w$$

else when LTE is present

If $E_c > \lambda_c$ *then*

No Wi-Fi Transmission, $R_w = 0$

else

$$C_w = f\left(\frac{P_w G_w}{P_l G_{wl} + N_0}\right)$$

$$R_w = \alpha C_w$$

end

end

Notation	definition
$\{w,l\}$	WiFi and LTE indices, respectively
R_w	WiFi Throughput
C_w	Wi-Fi channel rate
α	Fraction of time for Wi-Fi payload transmission
P_i	Transmission power, $i \in \{w,l\}$
G_w	Channel gain of Wi-Fi link
G_{wl}	Channel gain(LTE HeNB Wi-Fi UE)
N_0	Noise power
E_c	Channel energy at Wi-Fi AP
λ_c	CCA Threshold

LTE Throughput in Wi-Fi Interference

Modeling throughput of a single LTE in the presence of a single Wi-Fi interference

If No Wi-Fi *then*

$$R_l^{nw} = f\left(\frac{P_l G_l}{N_0}\right)$$

else when Wi-Fi is present

If $E_c > \lambda_c$ *then*

No Wi-Fi interference

$$R_w = R_l^{nw}$$

else

$$R_l^{w} = f\left(\frac{P_l G_l}{P_w G_{lw} + N_0}\right)$$

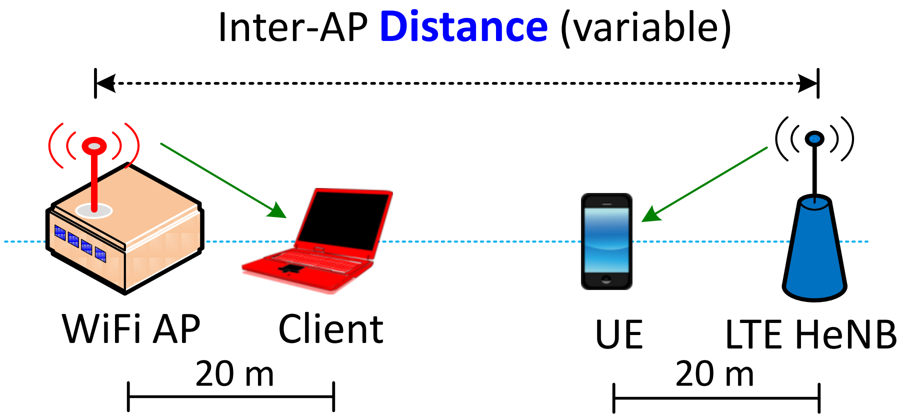
$$R_l = \eta_E R_l^{Nw} + \eta_S R_l^{w}$$

end

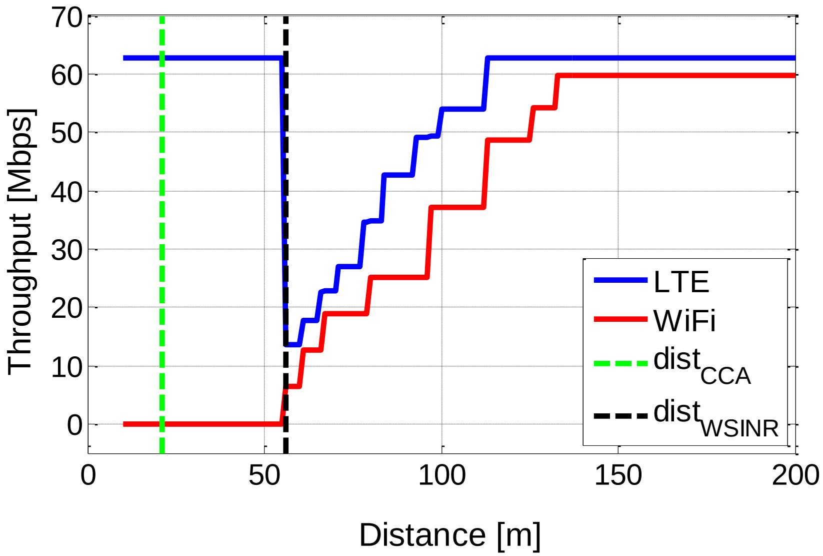
end

Notation	definition
$\{w,l\}$	WiFi and LTE indices, respectively
R_l	LTE Throughput
P_i	Transmission power, $i \in \{w,l\}$
G_l	Channel gain of LTE link
G_{lw}	Channel gain(Wi-Fi AP, LTE UE)
N_0	Noise power
E_c	Channel energy at Wi-Fi AP
λ_c	CCA Threshold
η_E, η_S	Fraction of time of Wi-Fi random backoff and successful transmission, respectively

Evaluation



Distance [m]	Throughput [Mbps]
< 21	R_w = 0 (CCA threshold)
< 56	R_w = 0 (SINR < min SINR)
56	$R_w + R_L$ = lowest (~20)
≥ 133	R_w = highest (~60)
< 56, ≥ 104	R_L = highest (~63)



Throughput as a function inter-AP distance
Equal Tx Power : 20 dBm (at maximum)

Key Observations

Non-applicability of conventional inverse relation of throughput with interference distance for co-channel Wi-Fi-LTE

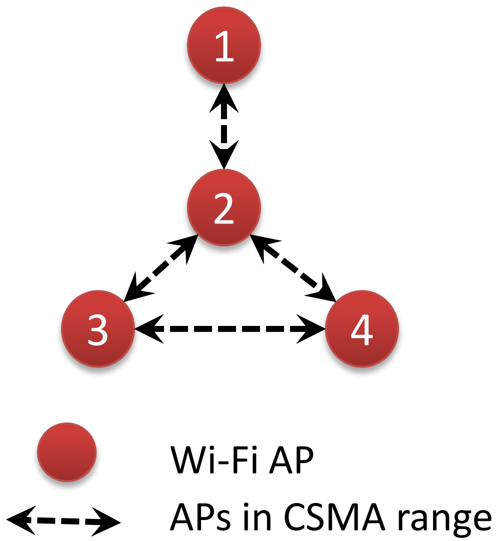
Aggregated system throughput

$= f($network topology, Wi-Fi CSMA and CCA$)$

Interference Characterization of Dense Deployment

Distributed Wi-Fi CSMA

Graph theory based CSMA contention graph



- No simultaneous transmission of APs in CSMA
- Maximum Independent Sets (MIS)
  - Maximum cardinality
  - Equal probability for all MIS
- Throughput at Wi-Fi *i*

$$C_i = f(\mathrm{SNR}),$$

$$\beta_i = \frac{\text{no. of MIS i belongs}}{\text{total no. of MIS}},$$

$$R_i = f(\beta_i C_i)$$

	Independent Sets (IS)	# AP in IS
MIS	[1, 3]	2
MIS	[1, 4]	2
	[2]	1

Ref: S.C. Liew, et al. 'Back-of-the-envelope computation of throughput distributions in csma wireless networks'.

Dense Wi-Fi/LTE Throughput

Wi-Fi Throughput

If No LTE *then*

- Compute *M* MIS for Wi-Fi
- Calculate $R_i, i \in W$

else when LTE is present

- CCA: Identify *W'* shut-off Wi-Fi

$$R_i = 0, i \in W'$$

- Compute *M'* MIS for ON Wi-Fi
- Calculate $R_i, i \in (W - W')$ considering LTE interference

end

LTE Throughput

If No Wi-Fi *then*

- Calculate $R_i, i \in L$ considering interference from other LTE links

else when Wi-Fi is present

For each *M'* MIS

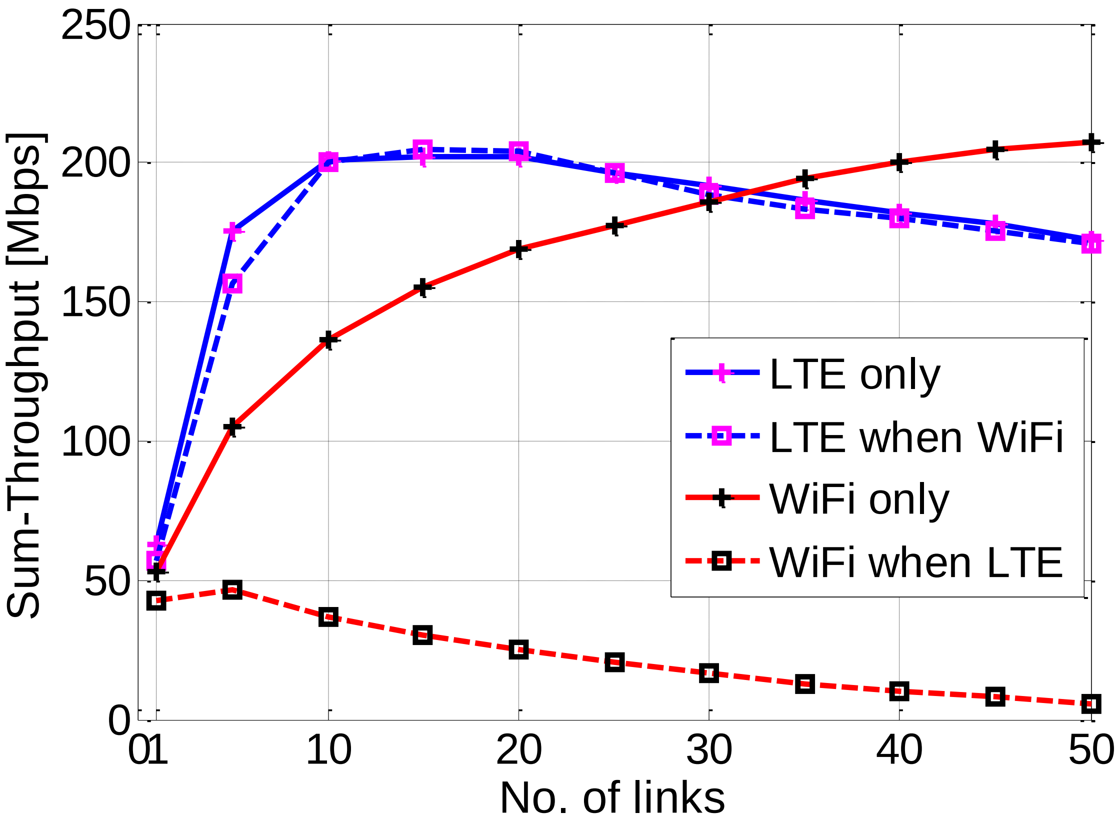
- Consider Wi-Fis active in that MIS only
  - Calculate LTE throughput considering Wi-Fi interference

end

- Compute avg. $R_i, i \in L,$ over *M'* MIS

end

Evaluation



In coexistence, degradation:
WiFi: 20 – 97%
LTE: 1 – 10%

Aggregated throughput over each technology
No. of (Wi-Fi links = LTE links), equal Tx Power (at maximum = 20 dBm)

Key Observations

Upper-bound throughput approximation due to
1) Wi-Fi: No consideration of packet collision
2)LTE: simultaneous transmission at Wi-Fis in a MIS

97% Wi-Fi throughput degradation
vs.
1% LTE throughput degradation

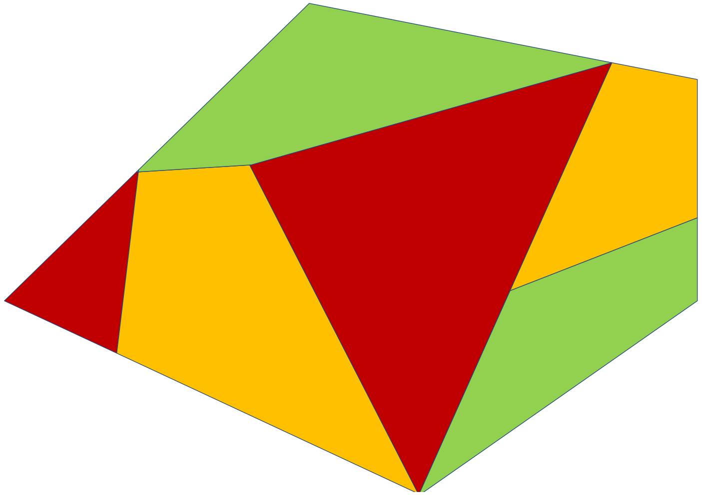
Need a coordination for fair throughput allocation!!

Frequency (Channel) Diversity

Frequency Diversity

Evaluation of Wi-Fi-LTE inter-network coordination in frequency domain under channel allocation schemes:

- Random channel assignment
- Intra-RAT coordination
  - GMCA across APs of same (Wi-Fi/LTE) technology
- Inter-RAT coordination
  - Joint GMCA across APs of both Wi-Fi and LTE



Graph multi-coloring like channel assignment (**GMCA**)
(no two neighboring APs on the same channel)

Key Observations

Normalized Throughput gain per channel- random assignment: 3x, Intra/Inter RAT coordination: 4-5x

Similar sum-throughput of Intra & Inter RAT coordination, in Inter:

LTE throughput gain: elimination of dominant interference

Wi-Fi throughput drop: inefficient channel assignment at Wi-Fi in CSMA range

Need a optimized joint resource allocation!

Conclusion

- Proposed an analytical interference model for Wi-Fi-LTE coexistence
- High Wi-Fi throughput drop compared to minimal LTE throughput drop for dense network
- 4-5x throughput gain due to frequency diversity

Future Work:

- Validation interference characterization model through experiments
- Inter-network coordination based on optimization

Thank You!

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