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

More capacity @hotspot

To fill coverage holes

55-698 MHz
TV White Space

3.55-3.7 GHz
3.5 GHz Shared band

5.15-5.835 GHz
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

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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
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

   \[ R_i = \alpha_i (\text{channel rate}_i), \quad i = 1, \ldots, N \]

   with

   $\alpha_i = \text{Fraction of time to transmit payload at Wi-Fi } i$
   
   $= f(N, \text{random back-off, successful transmission, packet collision})$

   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

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

where

- \(E_c\) = received channel energy
- \(\lambda_c\) = CCA threshold (typically, 62 dBm)

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Date Rate (Mbps)</th>
<th>Link SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.5</td>
<td>9.3</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>11.3</td>
</tr>
<tr>
<td>2</td>
<td>19.5</td>
<td>13.3</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>17.3</td>
</tr>
<tr>
<td>4</td>
<td>39</td>
<td>21.3</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>24.3</td>
</tr>
<tr>
<td>6</td>
<td>58.5</td>
<td>26.3</td>
</tr>
<tr>
<td>7</td>
<td>65</td>
<td>27.3</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE</td>
<td>OFDMA FDD</td>
</tr>
<tr>
<td>Block error rate</td>
<td>10%</td>
</tr>
<tr>
<td>Transmission mode</td>
<td>1 (SISO)</td>
</tr>
<tr>
<td>Channel</td>
<td>Flat Rayleigh</td>
</tr>
<tr>
<td>Channel overhead (controlling)</td>
<td>30%</td>
</tr>
</tbody>
</table>

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

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

\[\begin{align*}
\text{If No LTE then} & \quad C_w = f \left( \frac{P_w G_w}{N_0} \right) \\
R_w &= \alpha C_w \\
\text{else when LTE is present} & \\
\text{If } E_c > \lambda_c & \quad \text{No Wi-Fi Transmission, } R_w = 0 \\
\text{else} & \\
C_w &= f \left( \frac{P_w G_w}{P_l G_{wl} + N_0} \right) \\
R_w &= \alpha C_w \\
\end{align*}\]

Notation and definition:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>{w,l}</td>
<td>WiFi and LTE indices, respectively</td>
</tr>
<tr>
<td>R_w</td>
<td>WiFi Throughput</td>
</tr>
<tr>
<td>C_w</td>
<td>Wi-Fi channel rate</td>
</tr>
<tr>
<td>\alpha</td>
<td>Fraction of time for Wi-Fi payload transmission</td>
</tr>
<tr>
<td>P_i</td>
<td>Transmission power, (i \in {w,l})</td>
</tr>
<tr>
<td>G_w</td>
<td>Channel gain of Wi-Fi link</td>
</tr>
<tr>
<td>G_{wl}</td>
<td>Channel gain(LTE HeNB Wi-Fi UE)</td>
</tr>
<tr>
<td>N_0</td>
<td>Noise power</td>
</tr>
<tr>
<td>E_c</td>
<td>Channel energy at Wi-Fi AP</td>
</tr>
<tr>
<td>\lambda_c</td>
<td>CCA Threshold</td>
</tr>
</tbody>
</table>
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

\[ R_{lw}^{nw} = f \left( \frac{P_i G_l}{N_0} \right) \]

else when Wi-Fi is present

If \( E_c > \lambda_c \) then

No Wi-Fi interference

\[ R_w = R_{lw}^{nw} \]

else

\[ R_{lw}^{w} = f \left( \frac{P_i G_l}{P_w G_{lw} + N_0} \right) \]

\[ R_l = \eta_E R_{lw}^{nw} + \eta_S R_{lw}^{w} \]

end

end

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<tr>
<td>{w,l}</td>
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<tr>
<td>( R_l )</td>
<td>LTE Throughput</td>
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<td>( P_i )</td>
<td>Transmission power, ( i \in {w,l} )</td>
</tr>
<tr>
<td>( G_l )</td>
<td>Channel gain of LTE link</td>
</tr>
<tr>
<td>( G_{lw} )</td>
<td>Channel gain(Wi-Fi AP, LTE UE)</td>
</tr>
<tr>
<td>( N_0 )</td>
<td>Noise power</td>
</tr>
<tr>
<td>( E_c )</td>
<td>Channel energy at Wi-Fi AP</td>
</tr>
<tr>
<td>( \lambda_c )</td>
<td>CCA Threshold</td>
</tr>
<tr>
<td>( \eta_E, \eta_S )</td>
<td>Fraction of time of Wi-Fi random backoff and successful transmission, respectively</td>
</tr>
</tbody>
</table>
Evaluation

Inter-AP Distance (variable)

Distance [m] | Throughput [Mbps]
---|---
< 21 | $R_w = 0$ (CCA threshold)
< 56 | $R_w = 0$ (SINR < min SINR)
56 | $R_w + R_L = \text{lowest (} \approx 20\text{)}$
≥ 133 | $R_w = \text{highest (} \approx 60\text{)}$
< 56, ≥ 104 | $R_L = \text{highest (} \approx 63\text{)}$

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 $= f(\text{network topology, Wi-Fi CSMA and CCA})$
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 $i$

\[
C_i = f(SNR),
\beta_i = \frac{\text{no. of MIS}_i \text{ belongs}}{\text{total no. of MIS}},
\]
\[
R_i = f(\beta_i C_i)
\]


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Dense Wi-Fi/LTE Throughput

Wi-Fi Throughput

\textbf{If No LTE then}

\begin{itemize}
  \item Compute $M$ MIS for Wi-Fi
  \item Calculate $R_i, i \in W$
\end{itemize}

\textbf{else when LTE is present}

\begin{itemize}
  \item CCA: Identify $W'$ shut-off Wi-Fi
    \hspace{1cm} $R_i = 0, i \in W'$
  \item Compute $M'$ MIS for ON Wi-Fi
  \item Calculate $R_i, i \in (W - W')$
    \hspace{1cm} considering LTE interference
\end{itemize}

\textbf{end}

LTE Throughput

\textbf{If No Wi-Fi then}

\begin{itemize}
  \item Calculate $R_i, i \in L$ considering interference from other LTE links
\end{itemize}

\textbf{else when Wi-Fi is present}

\begin{itemize}
  \item For each $M'$ MIS
    \hspace{1cm} \textbf{end}
    \hspace{1cm} \textbf{end}
    \hspace{1cm} \hspace{1cm} \textbf{end}
    \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} \textbf{end}
\end{itemize}

\begin{itemize}
  \item Consider Wi-Fis active in that
    \hspace{1cm} MIS only
  \item Calculate LTE throughput
    \hspace{1cm} considering Wi-Fi interference
\end{itemize}

\begin{itemize}
  \item Compute avg. $R_i, i \in L$, over $M'$ MIS
\end{itemize}
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
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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