Energy Efficiency Impact of Cognitive Femtocells in Heterogeneous Wireless Networks

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Motivation

- Huge and increasing volume of wireless traffic
- Need for spectrum
- Small cells $\rightarrow$ frequency reuse
- Cognitive radios $\rightarrow$ opportunistic access to spatio-temporally unused spectrum

**Our research question**

Is Cognitive Femtocell Network (CFN) energy efficient?
What is a Cognitive Femtocell?

- **Femtocell:**
  Home base stations, small-area coverage, short tx-rx distance, plug and play operation

- **Cognitive Femtocell:**
  Femtocell with *CR capabilities* (e.g. dynamic spectrum access, self-organization, environment-awareness)
# Femtocells to Cognitive Femtocells

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Femtocell</td>
<td>Coverage</td>
<td>Deployment cost</td>
<td>Lower power tx.</td>
<td>Deployment and operational costs</td>
</tr>
<tr>
<td></td>
<td>Cost opt.</td>
<td></td>
<td>Longer battery lifetime</td>
<td>Burden on backbone connection</td>
</tr>
<tr>
<td></td>
<td>Higher macrocell reliability</td>
<td></td>
<td>Better indoor coverage</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>Spectrum opp. for new operators</td>
<td>SU/PU diff.</td>
<td>Autonomous and adaptive operation</td>
<td>Hardware complexity</td>
</tr>
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<td></td>
<td>New business models via spectrum leasing/auctioning</td>
<td>Resource management and allocation</td>
<td>Multimode operation</td>
<td>Spectrum sensing overhead</td>
</tr>
<tr>
<td></td>
<td>Better spectral capacity</td>
<td>PU transparent operation</td>
<td>Cheaper services</td>
<td></td>
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</table>

G.Gur et al, EE of Cognitive Femtocells, ACM CRAB 2013
Motivation for EE in CFN

- The expected proliferation of small cells for mobile broadband
  - an emerging energy consumption component

- Traffic offloading from other terrestrial infrastructure
  - an opportunity to decrease the average energy consumption figures

G. Gur et al, EE of Cognitive Femtocells, ACM CRAB 2013
Our contribution

We analyze the impact of deploying cognitive femtocells on downlink energy efficiency of the network:

Three fundamental cases

1. Macrocell-only (MN)
2. Macrocell and femtocells (MFN)
3. Macrocell, femtocells, and cognitive femtocells (CFN)
System Model
Methodology

- Energy efficiency: Throughput/Energy Consumption
- We will calculate Throughput (C) and Shannon’s capacity: \( R = W \log(1 + SINR) \)
- We will calculate energy consumption (E) using a component-based model.
  
  i.e. \( E = \sum_{i} E_i \)
CFN System Model: Interference Links

1, 2, 3, 4: co-layer interference
5, 6, 7, 8: cross-layer interference
9: cognitive-layer interference

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Energy Consumption Components

<table>
<thead>
<tr>
<th></th>
<th>Tx</th>
<th>Rx</th>
<th>Backhaul</th>
<th>Sensing</th>
<th>Idling</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FBS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>CFBS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MU</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FU</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>CFU</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Note the difference between CFBS and FBS.
Energy Consumption at a CFBS

- C, F, M for cognitive femtocell, femtocell, and macrocells
- Capital letters for BS, small letters for user (C, c, F, f, M, m)

Three states:

1. Sensing (periodic sensing with $T_s$): $E^s_C$
2. Not sensing:
   - Transmission (if traffic for CFUs): $E^t_C$
   - Idling (If no traffic for CFUs): $E^i_C$

$$E_C = \frac{E^s_C + (T_s - 1)(\lambda_c E^t_C + (1 - \lambda_c)E^i_C)}{T_s}.$$
Energy Consumption at a CFU

Three states:

- Idling because of CFBS sensing
- Receiving (if some traffic occurs $\rightarrow \lambda_C$)
- Idling (if no traffic)

We include channel switching cost: $P_C^{cs} \delta_F$

$$E_C = \frac{P_c^i + (T_s - 1)\left(\lambda_c (P_c^{rx} + P_c^{cs} \delta_F) + (1 - \lambda_c) P_c^i\right)}{T_s}$$
Interference and Throughput Calculation

Three interference types:
1. Co-layer interference (femto/cogfemto)
2. Cross-layer interference (macro/femto-cogfemto)
3. Cognitive Layer interference (PU network-CFBS at cognitive radio frequencies)
Total Interference at an Entity

- Number of interferers \((n_{x,y} : \text{number of interferers of Type}_x \text{ to Type}_y)\)
- Corresponding interference \((I = P \cdot f d_{(x,y)}^\alpha)\)
- \(p_d\) decreases while \(p_{fa}\) increases with increasing \(T_s\): \(p_d(T_s)\) and \(p_{fa}(T_s)\): 
  \[
  p_d(T_s) = 0.9 / (T_s - 1) \\
  p_{fa}(T_s) = 0.1(T_s - 1)
  \]

\[
\begin{align*}
I_m &= n_{C,m}I_{C,m} + n_{F,m}I_{F,m} + N_0 \\
I_f &= n_{C,f}I_{C,f} + n_{F,f}I_{F,f} + n_{M,f}I_{M,f} + N_0 \\
I_c &= n_{C,c}I_{C,c} + n_{F,c}I_{F,c} + n_{M,c}I_{M,c} + n_P,c(1 - p_d(T_s))I_{P,c} + N_0.
\end{align*}
\]
Total Throughput Calculation ($C_x$'s)

$$C_m = \frac{F_M}{n_m} \log_2(1 + \frac{P_{out}^M}{I_m})$$

$$C_c = \frac{T_s - 1}{T_s} \frac{F_C}{n_c} \log_2(1 + \frac{P_{out}^C}{I_c})$$

$$C_f = \frac{F_F}{n_f} \log_2(1 + \frac{P_{out}^F}{I_f}).$$

- $F_M$: Frequency available for Macrocell’s use
- $F_F$: Frequency available for Femtocell’s use
- $F_C$: Frequency available for CF’s use
Energy Consumption (E) and Throughput of the Network (C)

\[
E = E_M + n_m E_m + N_C E_C + n_c E_c + N_F E_F + n_f E_f
\]

\[
C = n_m C_m + n_c C_c + n_f C_f
\]

- For macrocell-only network (MN): \(N_c = n_c = N_F = n_f = 0\)
- For macrocell+femtocell network (MFN): \(N_c = n_c = 0\)

Energy Efficiency (\(\eta\))

\[
\eta = \frac{C}{E}
\]
Performance Evaluation
## System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Radius of macrocell</td>
<td>500 m</td>
</tr>
<tr>
<td>$P^{out}_C$, $P^{out}_F$, $P^{out}_M$</td>
<td>Transmission power of CFBS, FBS, and MBS</td>
<td>30, 30, 46 dBm</td>
</tr>
<tr>
<td>$P^i_C$, $P^{bh}_C$, $P^s_C$</td>
<td>CFBS power of idling, backhaul, and sensing</td>
<td>500, 100, 600 mW</td>
</tr>
<tr>
<td>$P^i_m$, $P^{rx}_m$</td>
<td>MU idling and receiving power</td>
<td>200, 600 mW</td>
</tr>
<tr>
<td>$P^i_c$, $P^{rx}_c$</td>
<td>CFU idling and receiving power</td>
<td>200, 300 mW</td>
</tr>
<tr>
<td>$\delta_F$</td>
<td>Average number of channel switching</td>
<td>5</td>
</tr>
<tr>
<td>$F_M$, $F_{CR}$</td>
<td>Number of MBS and CR frequencies</td>
<td>10, 5</td>
</tr>
<tr>
<td>$p_{idle}$</td>
<td>PU probability of being idle</td>
<td>0.6</td>
</tr>
<tr>
<td>$\lambda_f$, $\lambda_m$, $\lambda_c$</td>
<td>Traffic probability of FU, MU, and CFU</td>
<td>0.6</td>
</tr>
<tr>
<td>$\alpha_{MC}$, $\alpha_{MF}$, $\alpha_{PC}$</td>
<td>Path loss exponential (MBS-CFU, MBS-FU, PU-CFU)</td>
<td>2.8</td>
</tr>
<tr>
<td>$\alpha_{FC}$, $\alpha_{CC}$, $\alpha_{FF}$</td>
<td>Path loss exponential (FBS-CFU, CFBS-CFU, FBS-FU)</td>
<td>2</td>
</tr>
</tbody>
</table>
Effect of Network Population

- Varying number of users
- MN, MFN, CFN with various $T_s$ values

Comparison of three scenarios:

Scenario I: Macrocell only network, all users are MUs;

Scenario II: FBSs are added to the macrocell network. Half of the users are MUs and the other half are FUs;

Scenario III: MBS, FBS and CFBS are deployed in the macrocell. There are equal number of MUs, FUs, and CFUs in the network.
Effect of Network Population - EE

- MN, MFN, CFN with various $T_s$ values
- Energy efficiency ($\eta$):

- $N \uparrow \Rightarrow EE \downarrow$
- $T_s = 6$ performs as the best one $\Rightarrow$ the tradeoff between energy/throughput consumption of sensing vs. its accuracy.
- After a certain point, CFBS and FBS become so dense that their interference degrades the network performance. Interference management and control schemes are critical.
Effect of Network Population - C

- MN, MFN, CFN with various $T_s$ values
- Total throughput:
  - Similar to EE
  - $N \uparrow \rightarrow C \downarrow$
  - Interference wall resulting in diminished capacity
  - $T_s = 6$ performs as the best case.
What happens if Femtocells become Cognitive Femtocells?

Number of MUs are kept constant and remaining users are served by either FBS or CFBSs. Number of deployed CFBSs is increased from 10% to 90% of the small cells.

(a) Energy efficiency.
(b) Total throughput.

Need for Interference Control and Cooperation under dense CFBS deployment!
Conclusions

- Our analysis illustrates the trade-offs related to the adoption of CFNs from the energy efficiency perspective.
  
  CFNs ➔ EE ↑

- Additional sensing overheads ➔ which may yield higher energy consumption

- Tradeoff between sensing accuracy and EE

- We also observe that under high cognitive femtocell density with uncontrolled cross- and co-layer interference, a macrocell only network performs better. Hence, CFNs have to apply interference management and control schemes to be less sensitive to node density and to be more robust to heavy network load.

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