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 → frequency reuse
- Cognitive radios → 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

	Operator		User	
	Adv.	*Disadv.*	*Adv.*	*Disadv.*
Femtocell	• Coverage • Cost opt. • Higher macrocell reliability	• Deployment cost	• Lower power tx. • Longer battery lifetime • Better indoor coverage	• Deployment and operational costs • Burden on backbone connection
CR	• Spectrum opp. for new operators • New business models via spectrum leasing/auctioning • Better spectral capacity	• SU/PU difff. • Resource management and allocation • PU transparent operation	• Autonomous and adaptive operation • Multimode operation • Cheaper services	• Hardware complexity • Spectrum sensing overhead

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

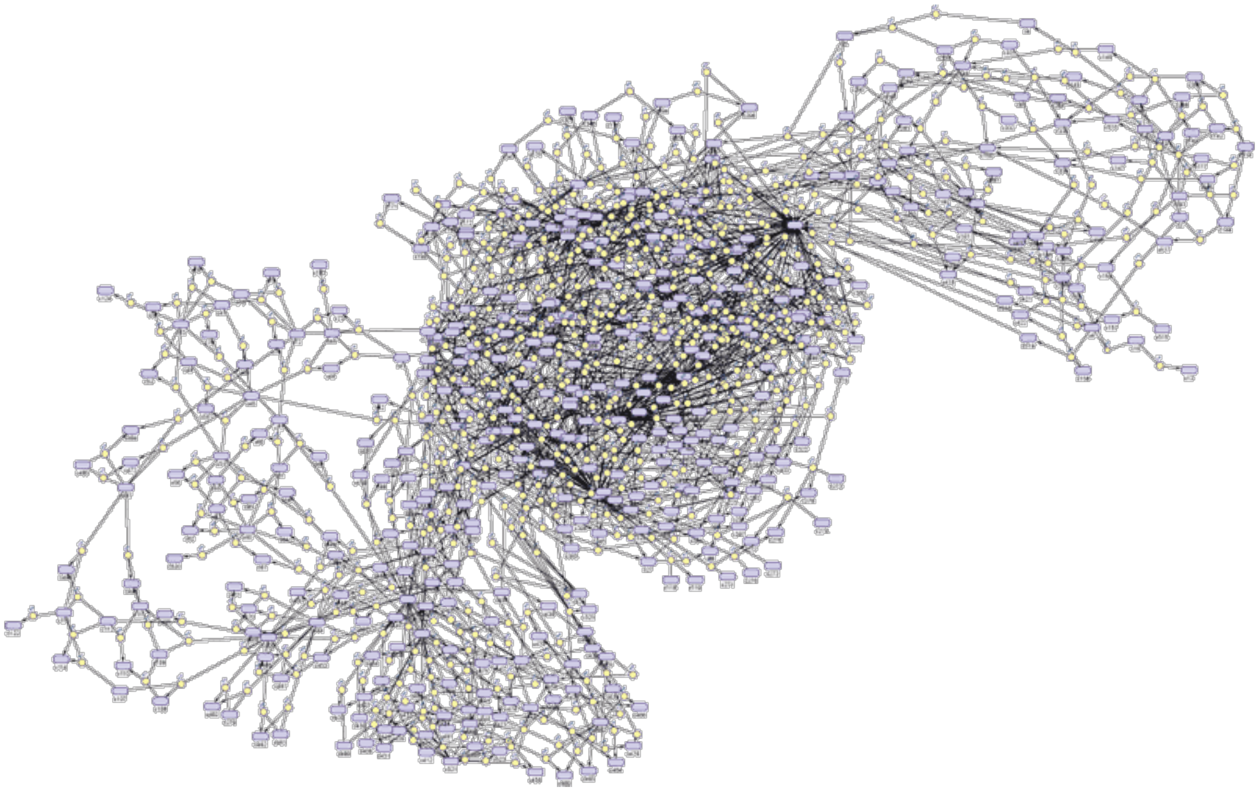
Our contribution

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

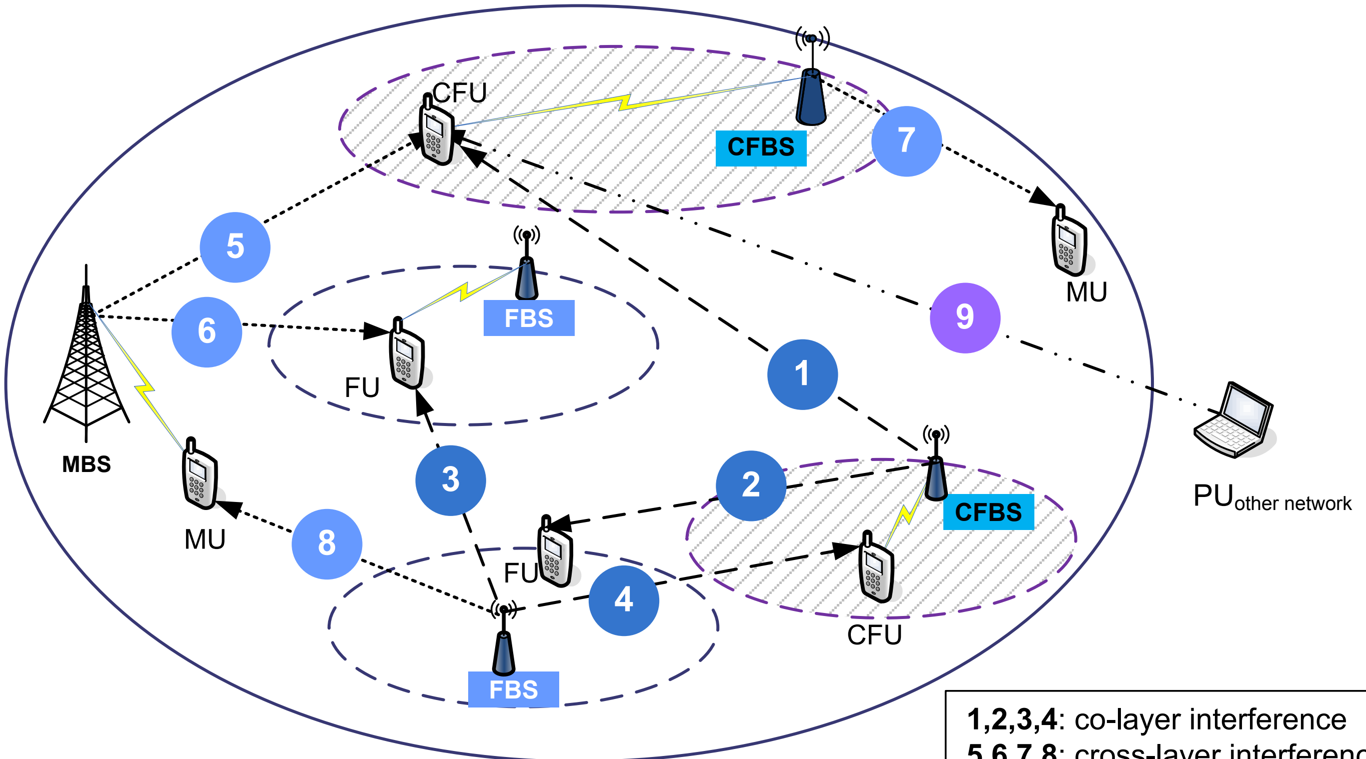
- We will calculate Throughput (C)

  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

Energy Consumption Components

	Tx	Rx	Backhaul	Sensing	Idling
MBS	X				
FBS	X		X		X
CFBS	X		X	X	X
MU		X			X
FU		X			X
CFU		X			X

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_C^s
- 2- Not sensing:
  - Transmission (if traffic for CFUs): E_C^t
  - Idling (If no traffic for CFUs): E_C^i

$$E_C = \frac{E_C^s + (T_s - 1)(\lambda_c E_C^t + (1 - \lambda_c) E_C^i)}{T_s}.$$

Energy Consumption at a CFU

Three states:

- Idling because of CFBS sensing
- Receiving (if some traffic occurs → λ_C)
- Idling (if no traffic)

} reception mode

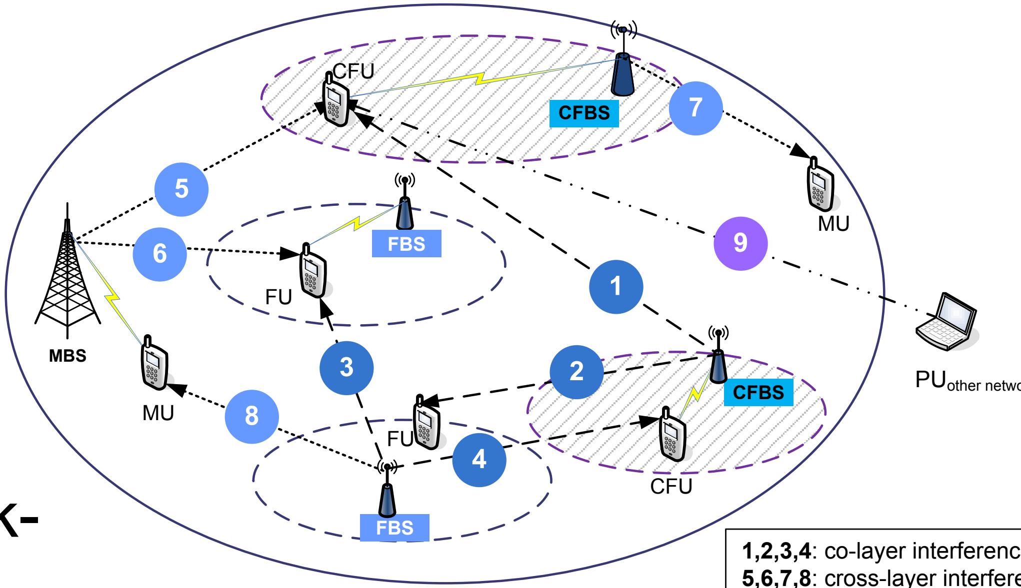
- We include channel switching cost : $P_C^{cs}\delta_F$

$$E_c = \frac{P_c^i + (T_s - 1)(\lambda_c(P_c^{rx} + P_c^{cs}\delta_F) + (1-\lambda_c)P_c^i)}{T_s}$$

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)



1,2,3,4: co-layer interference
5,6,7,8: cross-layer interference
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Total Interference at an Entity

- Number of interferers ($n_{x,y}$: number of interferers of $Type_x$ to $Type_y$)
- Corresponding interference ($I=P_x/d_{(x,y)}{}^{\alpha}$)
- p_d decreases while p_{fa} increases with increasing T_s:

$p_d(T_s)$ and $p_{fa}(T_s)$: $p_d(T_s) = 0.9/(T_s - 1)$

$$p_{fa}(T_s) = 0.1(T_s - 1)$$

$$I_m = n_{C,m}I_{C,m} + n_{F,m}I_{F,m} + N_0$$
$$I_f = n_{C,f}I_{C,f} + n_{F,f}I_{F,f} + n_{M,f}I_{M,f} + N_0$$
$$I_c = n_{C,c}I_{C,c} + n_{F,c}I_{F,c} + n_{M,c}I_{M,c} + n_{P,c}(1 - p_d(T_s))I_{P,c} + N_0.$$

Total Throughput Calculation (C_x's)

$$C_m = \frac{F_M}{n_m} \log_2(1 + \frac{P_M^{out}}{I_m})$$
$$C_c = \frac{T_s - 1}{T_s} \frac{F_C}{n_c} \log_2(1 + \frac{P_C^{out}}{I_c})$$
$$C_f = \frac{F_F}{n_f} \log_2(1 + \frac{P_F^{out}}{I_f}).$$

- 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 (η) ➡ $\eta = \dfrac{C}{E}$

Performance Evaluation

System Parameters

Parameter	Explanation	Value
R	Radius of macrocell	500 m
P_C^{out}, P_F^{out}, P_M^{out}	Transmission power of CFBS, FBS, and MBS	30, 30, 46 dBm
P_C^i, P_C^{bh}, P_C^s	CFBS power of idling, backhaul, and sensing	500, 100, 600 mW
P_m^i,P_m^{rx}	MU idling and receiving power	200, 600 mW
P_c^i,P_c^{rx}	CFU idling and receiving power	200, 300 mW
δ_F	Average number of channel switching	5
F_M, F_{CR}	Number of MBS and CR frequencies	10, 5
p_{idle}	PU probability of being idle	0.6
λ_f, λ_m, λ_c	Traffic probability of FU, MU, and CFU	0.6
$\alpha_{MC}, \alpha_{MF}, \alpha_{PC}$	Path loss exponential (MBS-CFU, MBS-FU, PU-CFU)	2.8
$\alpha_{FC}, \alpha_{CC}, \alpha_{FF}$	Path loss exponential (FBS-CFU, CFBS-CFU, FBS-FU)	2

Effect of Network Population

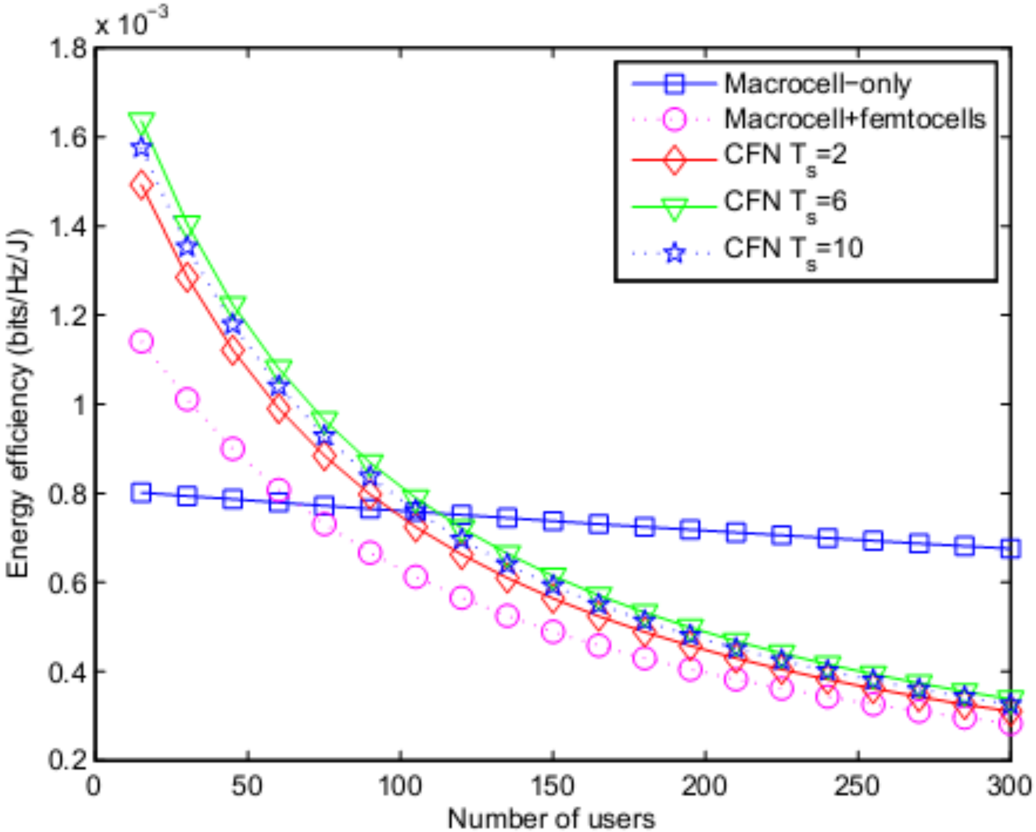
- Varying number of users
- MN, MFN, CFN with various T_s values

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

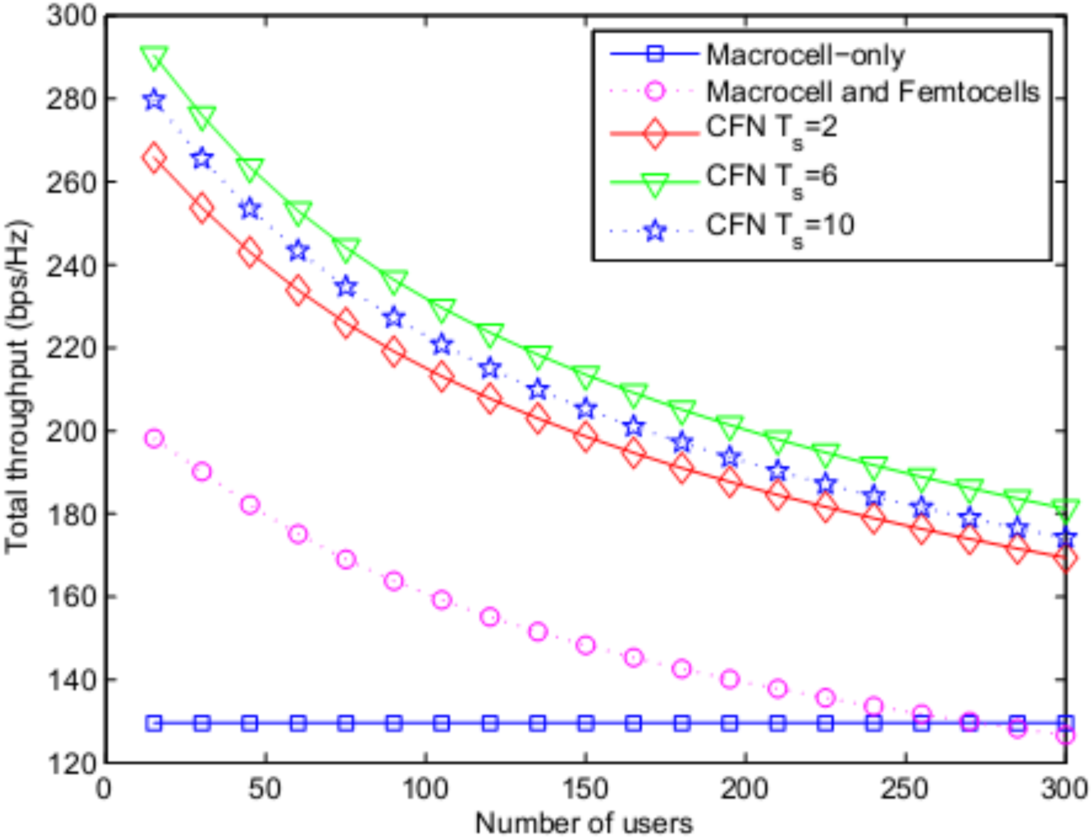
- MN, MFN, CFN with various T_s values
- Energy efficiency (η):



- N ↑ ➡ EE ↓
- T_s = 6 performs as the best one ➡ 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

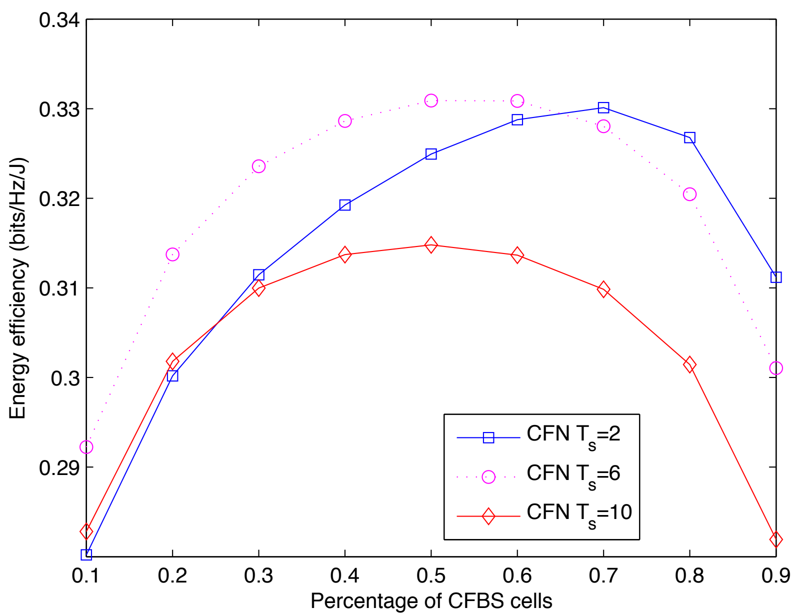
- MN, MFN, CFN with various T_s values
- Total throughput:



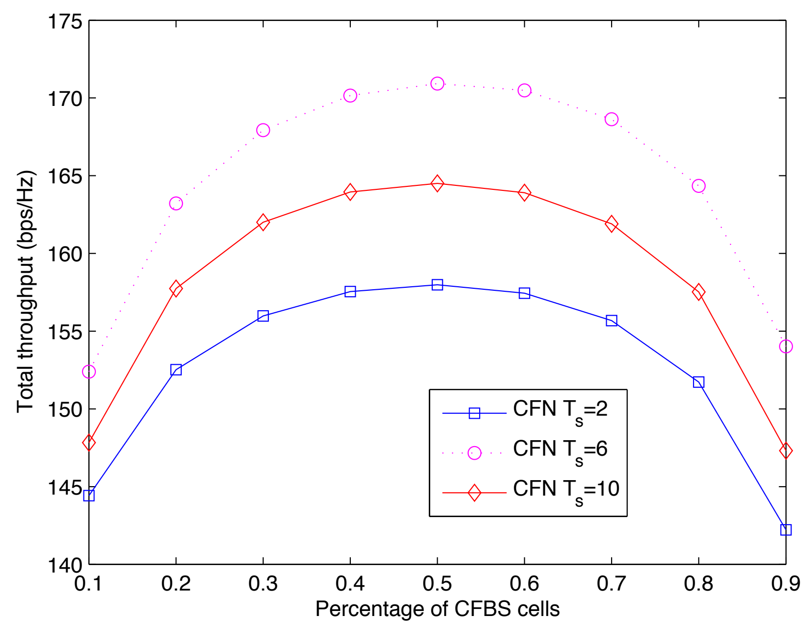
- Similar to EE
- N ↑ ➡ C ↓
- Interference wall resulting in diminished capacity
- T_s = 6 performs as the best case.

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.

Q & A