

Throughput Performance of Interference Mitigation Techniques in Cognitive Femtocell Networks

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Abstract. The exponential growth in demand for higher data rates and other services in wireless networks require a more dense deployment of base stations which results in more demand of the radio spectrum. Due to the scarcity of radio spectrum and the under-utilization of assigned spectrum, government regulatory bodies have started to review their spectrum allocation policies so as to implement opportunistic spectrum access (sharing) through cognitive femtocells. The cognitive femtocell technique is however challenging due to uncertainties associated with co-tier and cross-tier interference, adjacent channel fading, path loss, and other environment dependent conditions that bring about a progressive degradation of the signal coverage. In this paper, we review the different interference solutions and prioritize the Optimal Static Fractional Frequency Re-use (OSFFR) approach. We analyze the system performance with different metrics such as throughput, number of free channels and Bit Error Rate. Simulation results show that the proposed OSFFR shows an improved result compared to other frequency reuse schemes.

Keywords: Cognitive femtocell · Interference mitigation · Hetnet · Optimal static fractional frequency Re-use (OSFFR) · Soft fractional frequency reuse (SFFR)

1 Introduction

With the advent of LTE, big data era and the emergence of new hand-held devices such as tablet PC and smart phones, data intensive applications like online video streaming and network gaming have inexorably occupied many users' focus. LTE-A calls for higher data rates to provide quality services and better user experience. Studies have suggested that this rapidly increasing demand for high data rate is chiefly generated from indoor environments in urban and sub-urban areas [1]. In an effort to meet increasing data traffic demand and enhance network spectral efficiency, cellular network operators can densify their existing networks using cognitive-capable femtocell access points in a cognitive femtocell architecture. In addition, joint deployments of

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femtocells and macrocells can enhance the energy efficiency of cellular networks by hugely boosting data rates at a small energy cost [2]. Cognitive radio is an intelligent and adaptive wireless communication system that enables more efficient utilization of the radio spectrum [3]. The use of cognitive radio technology requires frequent sensing of the radio spectrum and processing of the sensor data which would require additional power with a proportional increase in co-tier interference.

However, efficient spectrum usage is not the only concern of cognitive radio. Actually, in the original definition of cognitive radio by J. Mitola, every possible parameter measurable by a wireless node or network is taken into account (Cognition) so that the network intelligently modifies its functionality to meet a certain objective [4]. It has been shown in recent works that structures and techniques based on cognitive radio reduce the energy consumption, while maintaining the required quality-of-service (QoS), under various channel conditions [5]. There are a number of other technologies and techniques which have been developed so as to quantify energy savings in cognitive femtocells through mitigation of interference which include; defining the interference [3], interference cartography [6], frequency overlay, frequency under lay, cognitive femtocell power control, contention schemes [7], adaptive uplink algorithm, frequency bandwidth dynamic division, clustering algorithm, interference signature, and cognitive femtocell network controller. Hence, a roadway to the future would be striving for more feasible, less complex, and less expensive schemes of mitigating interference within the scope of cognitive radio. The remaining part of the paper is organized as follows: The system model is described in Sect. 2. Section 3 presents the Het-net interference mitigation techniques. Our evaluation methodology is described in Sect. 4, and the analysis and simulation results presented in Sect. 5. We conclude the paper in Sect. 6.

2 System Model

Figure 1 shows a Heterogeneous Network (HetNet) where a Master enhanced Node B (MeNB) is overlaid with one Picocell and several Home enhanced Node B (HeNBs). In this network, each UE device usually communicates on a specific subchannel corresponding to the base station (BS) from which it receives the strongest signal strength, while the signals received from other BSs on the same subchannel are considered as interference. We focus on a two-tier HetNet comprising macrocells and femtocells. Two types of interference occur in such a HetNet. Co-tier interference occurs between neighboring femtocells. For example, a femtocell UE device (aggressor) causes uplink co-tier interference to the neighboring femtocell BSs (victims). Each MUE is interfered by all neighboring macrocells and femtocells that use the same sub-bands assigned to its serving macro BS.

The signal-to-interference-plus-noise-ratio (SINR) for downlink transmission to MUE x_m from MeNB m on sub-channel k , SINR is given by

$$SINR_{x_m,m}^k = \frac{P_m^k h_{x_m,m}^k G_{x_m,m}^k}{N_0 \Delta B + \sum_{m' \in M'} P_{m'}^k h_{x_m,m'}^k G_{x_m,m'}^k + \sum_{f \in F} P_f^k G_{x_m,f}^k} \quad (1)$$

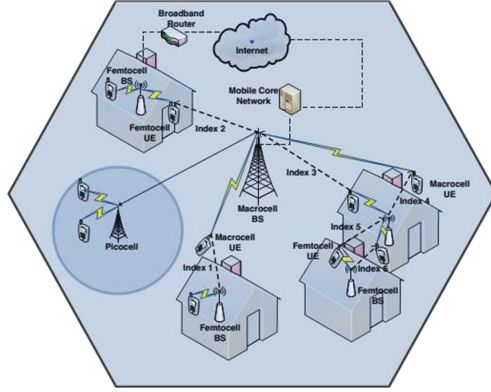


Fig. 1. Cognitive femtocell interference scenario

where; P_m^k is the transmit power from MeNB m on sub-channel k . $h_{x_m,m}^k$ is the exponentially distributed channel fading power gain associated with sub-channel k , $G_{x_m,m}^k$ is the path loss associated with sub-channel k between MUE x_m and MeNB which is given as

$$G_{x_m,m}^k = 10^{-PL_{outdoor}/10} \quad (2)$$

where $PL_{outdoor}$ is the outdoor pathloss modeled as [8];

$$PL_{outdoor} = 28 + 35 \log_{10}(d) \text{ dB}$$

with d as the Euclidean distance between a base-station and a user in meters. However, $G_{x_m,f}^k$ is affected by both indoor and outdoor path-loss. In this case, d would be the Euclidean distance between a HeNB f and the edge of the indoor wall in the direction of MUE x_m . After the wall, the pathloss is based on an outdoor path loss model. In (1), \mathcal{M} is the set of interfering MeNBs, which depends on the location of the MUEs and the specific FFR scheme used. \mathcal{F} is the set of interfering HeNBs. Here, the adjacent HeNBs are defined as those HeNBs which are inside a circular area of radius 60 m centered at the location of MUE x_m . N_0 represents noise power spectral density and ΔB represents sub-carrier spacing. The maximum achievable capacity for a MUE x_m on sub-channel k is then given by;

$$C_{y_m,m}^k = (\Delta B \cdot \log_2(1 + \alpha SINR_{y_m,m}^k)) \quad (3)$$

Where α is a constant defined by;

$$\alpha = \frac{-1.5}{\ln(5XBER)} \quad (4)$$

Here, BER represents the target Bit Error Rate (e.g., 10^{-6}). For an FUE y_f communicating with the HeNB f on sub-channel k , the downlink $SINR$,

$$SINR_{y_f,f}^k = \frac{P_f^k G_{y_f,f}^k}{N_0 \Delta B + \sum_{m \in M} P_m^k h_{y_f,m}^k G_{y_f,m}^k + \sum_{f' \in F'} P_{f'}^k G_{y_f,f'}^k} \quad (5)$$

where F' is the set of all interfering (or adjacent) HeNBs, M is the set of interfering MeNBs, $G_{y_f,f}^k$ represents indoor path loss gain for distance d between the FUE and its serving HeNB and $G_{y_f,m}^k$ corresponds to both indoor and outdoor path loss model. The maximum achievable capacity for an FUE $_{y_f}$ is given as;

$$C_{y_f,f}^k = (\Delta B. \log_2(1 + \alpha SINR_{y_f,f}^k)) \quad (6)$$

The average network capacity, C_{avg} is given as:

$$C_{avg} = \frac{\sum_{x_m \in X_m} \sum_{k \in K} \Gamma_{x_m,m}^k C_{x_m,m}^k}{MUE_{total}} + \frac{\sum_{f \in F_A} \sum_{y_f \in Y_f} \sum_{k \in K} \Gamma_{y_f,f}^k C_{y_f,f}^k}{FUE_{total}} \quad (7)$$

Where, in general, $\Gamma^k = 1$ when a sub-channel k is assigned to a UE, otherwise it is set to zero. The spectral efficiency η in digital communication systems is defined as;

$$\eta = \frac{C}{W} \quad (8)$$

Where C is the channel capacity (in bits/second) and W is the channel bandwidth in Hz. Shannon showed there is a fundamental tradeoff between energy efficiency and bandwidth efficiency for reliable communications [9]. If we let $\eta = C/W$ (the spectral efficiency), then we can re-express in terms of $\frac{E_b}{N_o}$ as;

$$\frac{E_b}{N_o} = \frac{2^\eta - 1}{\eta} \quad (9)$$

3 Conventional HetNet Interference Mitigation Techniques

A. Interference Avoidance Techniques: Interference avoidance techniques include; power control, Game Based Resource Allocation in Cognitive Environment (GRACE), Coverage Adaption, Frequency Bandwidth Dynamic Division and Clustering Algorithm. Q-Based Learning algorithm [10], cognitive sniffing, and contention control [7].

B. Interference Cancellation: Interference cancellation refers to a class of techniques that demodulate/decode desired information, and then use this information along with channel estimates to cancel received interference from the received signal. It aims at demodulating and canceling interferences through multi-user detection methods so as reduce and cancel interference at the receiver end [11]. Interference cancellation schemes include; successive interference cancellation (SIC), and parallel interference cancellation (PIC).

C. Interference Randomization: These techniques aim at randomizing the interfering signals and thus allowing interference suppression. Randomization averages the interference on user equipment by randomly hopping between channels [12]. Interference randomization policy therefore spreads the user's transmission over a distributed set of subcarriers in order to randomize the interference scenario and achieve frequency diversity gain. Such schemes include IDMA and interference averaging [13].

D. Interference Alignment: Interference alignment (IA) is a linear beam forming technique used to align beam forming matrices at the transmitters such that the interference at each receiver is aligned in an interference subspace. This leaves the desired signal to transmit in an interference-free subspace whereas at the receivers, a simple zero-forcing (ZF) receiving vector to project the desired signal onto the interference-free subspace, which is sufficient for signal detection is employed [14]. This includes; Distributed Algorithm Interference Alignment [15], Opportunistic Interference alignment, Lattice Alignment, Blind Interference Alignment, Retrospective Interference alignment, Asymptotic Interference Alignment, Linear Interference alignment [16].

E. Interference Suppression: This scheme employs signal noise projection and conventional maximum likelihood techniques to decode both the interference and desired signals at the receiver using the euclidean and hamming distances between the code words received.

F. Interference Coordination: This approach capitalizes on efficient radio resource management techniques to coordinate the channel allocation in nearby cells and minimize the interference level. Interference co-ordination techniques include; Fractional Frequency Reuse, Soft Frequency Reuse, Optimal Fractional Frequency reuse [17], and Coordinated Frequency Reuse Table 1.

Table 1. Summarized comparison of key interference techniques

	Complexity	Mitigation efficiency	Channel State Information	User capacity	Spectral efficiency
Avoidance	Low	High	Not Required	High	High
Cancellation	High	High	Required	Low	Medium
Coordination	Low	High	Not Required	High	Low
Alignment	High	High	Required	Low	Low
Randomization	Low	Medium	Not Required	Medium	Medium

We now consider various interference mitigation techniques based on complexity, mitigation efficiency, channel state information, user capacity and spectrum efficiency. Interference avoidance combined with interference coordination techniques such as fractional frequency reuse with power control show a high performance with regard to co-channel interference mitigation, spectrum efficiency and capacity, compared to other techniques reviewed above.

- 1) **Soft Fractional Frequency Reuse:** This uses a cell partitioning technique similar to that of the strict FFR scheme. However, the center-zone MUE devices of any

cell are allowed to use the sub bands of cell-edge-zone MUE of the neighboring cells within the cluster. For a cluster of N cells, the total number of available sub channels in a cell is divided into N sub bands with one sub band assigned to each edge zone. One of the major advantages of soft FFR is that it has better spectrum efficiency than strict FFR. Similar to strict FFR, a HeNB located in the center zone may select the sub band that is used by the MUE in the edge zone, and if the HeNB is located in the edge zone, it chooses the sub bands that are used by the MUE in the center zone [17].

- Optimal Static Fractional Frequency Reuse:** The macrocell coverage is partitioned into the center zone and edge zone with six sectors in each zone, the center zone MUE devices (i.e., the UE situated within the optimal center-zone radius of the cell) are allocated sub band A with the number of sub-channels in this sub band obtained from the solution of the optimization problem. The rest of the available sub channels are divided into six sub-bands (B, C, D, E, F, and G), each of which is allocated to one of the edge-zone sectors [17]. Figure 2 shows the OSSFR channel allocation mechanisms.

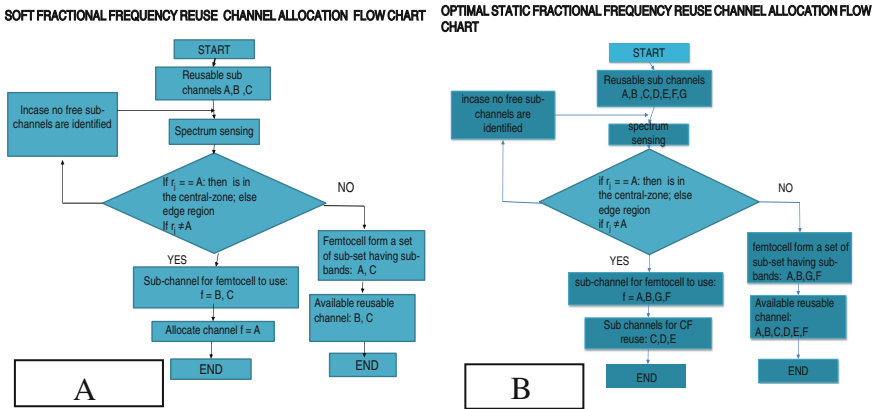


Fig. 2. SFFR and OSFFR channel allocation schemes

4 Evaluation Methodology

A. Number of free channels (local sensing at CFAP): Due to random deployment of the cognitive FAP, local sensing is performed based on Monte Carlo simulations using energy detection spectrum sensing technique. This approach is repeated for different fractional frequency reuse schemes to evaluate the performance as the number of deployed femtocells increases with increase in center radius.

B. User capacity performance: By continuously changing the FUE location, we evaluate the SINR and user capacity at all possible locations within the coverage areas of all macrocells and femtocells. This is justified by the fact that fading is averaged out and an AWGN channel is assumed. Using Monte Carlo Simulations, we simulate the

available user capacity to the HeNB as the location of the Femtocell varies from the center-zone to the edge-zone. FAP distance is varied within the MeNB for three schemes while the user capacity is obtained.

C. Throughput performance: For a random femtocell deployment, the user capacity of both MUEs and FUEs is calculated using (7) at all possible locations. Average capacity of MUEs and average capacity of FUEs are then calculated. The overall average FUE capacity can express the average throughput performance of the whole network. This is repeated for all the respective schemes.

D. Bit Error Rate performance: BER performance is evaluated based on the Shannon bandwidth-energy efficiency relationship in (9). This shows the quality of radio signal received per cognitive femtocell user.

5 Simulation Analysis

5.1 Simulation Environment

We assume that the HeNBs operate in closed access mode (i.e. only registered FUE devices will be able to access the HeNBs). The MUE devices are uniformly distributed while FUE are randomly distributed in the network. The MUE and FUE are randomly allocated with available sub-channels from the designated frequency bands corresponding to each sub-area for each scheme and also continuously change positions. A FUE is considered as a cell-edge one if its distance from the center is more than 70 % of the cell radius. The numbers of HeNBs are varied up to 40 in one Macrocell coverage area but we take a sample of 4 FUEs in the network. We also assume that all the neighboring macrocell base stations always transmit at full power over all the available sub bands.

5.2 Simulation Parameters

We take two scenarios into account to compare the performance of OFDMA based communication networks using the proposed OSFFR scheme with those using other frequency reuse techniques such as the SFR scheme, and the classical reuse-1 scheme. 4G LTE-Advanced wireless standard is simulated with the parameters shown in Table 2.

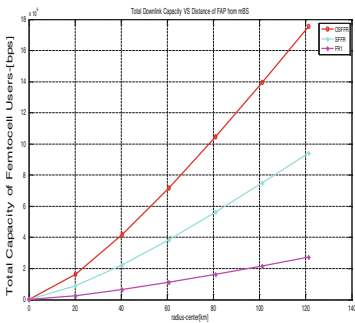
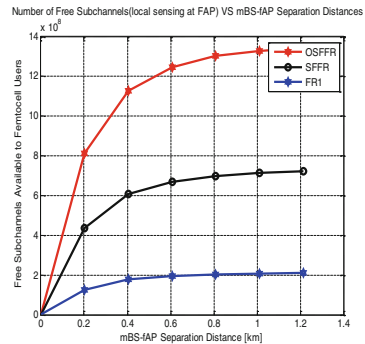
5.3 Simulation Results

Figure 5 shows that at low SINR values such as 5 dB, the throughput is well below 1Mbps but increases with a greater SINR value for the OSFFR scheme. In addition, OSFFR energy efficiency is 73.33 % and SFR energy efficiency is 25.93 %. This is due to the fact that the edge-zone secondary users of the FAP, the FAP under observation, are not interfered with by any other MeNB of the first-tier network. Figures 3 and 4 show that OSSFR gives a better performance, compared to SFR. At a given distance of

Table 2. Simulation parameters

Parameters	Value used
Bandwidth	10 MHz
FDD-LTE	OFDMA
Number of sub-channels	512
Carrier Frequency	800 MHz
Number of thin walls	4
Sub-carrier Spacing	15 kHz
Radius of the femtocell	30 m
Radius of the MeNB	280 m
CR Threshold	-111.6 dB
Noise Spectral Density	-174 dBm/Hz
Indoor penetration loss	20 dB
FAP TX Power	20 dBm
Number of subcarriers	600
Number of FUEs	4
Antenna Gains	MeNB: 14 dBi, FAP: 5 dBi, Users: 0 dBi
Target SNR	20 dB
Noise spectral density Shadowing standard deviation	Macro: 10 dB, Femto: 4 dB
Modulation	QPSK

0.4 km from the centre-zone (Fig. 4), OSFFR shows 80 % increment in number of free channels while SFFR indicates a 62.5 % increment. In Fig. 6, we note that at higher E_b/N_0 , the probability of error reduces for all schemes hence higher data rates for the femtocells in the network. For example at a $E_b/N_0 = 9$ dB, we observe a lower probability of error at 10^{-5} for the OSFFR scheme. It can also be observed that SFFR possesses a higher bit error rate performance. This is accounted for by the increased number of sub-channel division it has as compared to FFR 1.

**Fig. 3.** Total capacity**Fig. 4.** Number of free channels

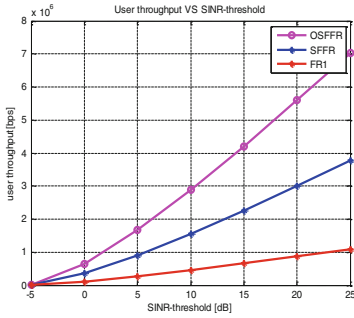


Fig. 5. Throughput performance

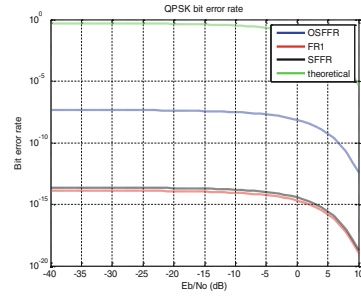


Fig. 6. BER performance

6 Conclusion

We have compared different cognitive femtocell interference mitigation techniques. Results show that the ICIC schemes offer superior performance to other state-of-the-art interference mitigation schemes. Based on Shannon's energy-bandwidth efficiency relationship, a performance evaluation by means of event driven Monte Carlo simulations was presented, and OSFFR compared with SFFR. The proposed OSFFR scheme achieves the best tradeoff between user capacity, downlink throughput, and number of free channels obtained after local sensing. Furthermore, OSFFR can provide more flexibility, improved BER performance and robustness than the SFFR scheme. Our results demonstrate that the OSFFR radius that maximizes system throughput and the number of free channels obtained after local sensing, is a more efficient mechanism to realize energy savings in cognitive femtocell under heterogeneous LTE-A systems.

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