Interference Mitigation for OFDM-Based Joint Macro-Femto Cellular Networks

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Abstract

Femtocells underlay in macro-cellular network is becoming more popular in order to use spatial frequency reuse gain, extend the coverage and capacity. But interference mitigation is the main challenge for the system designer. Instead of using centralized coordination among base stations to mitigate or reduce interference caused by femtocells to macrocells, this paper investigates the dynamic distributed interference management in femtocells underlay in a macrocell network. The distributed adaptive fractional frequency reuse (FFR) with power control is considered in the proposed approach. Simulation results show that the proposed interference management technique effectively reduces the downlink interference and increases the capacity and improves the outage probability of the macro-cellular network.

Keywords: femtocells, fractional frequency reuse, interference management, power control, macro-cellular network, challenge

1. Introduction

The upcoming next generation (xG) wireless cellular network will provide very high data rate transmission. Due to high path loss, mobile users at the cell edge and indoor environment fail to maintain targeted quality of service (QoS), i.e., data rate and bit error rate. Thus the femtocell concept has been introduced by (Boudreau, 1999; Chandrasekhar, 2008). Femtocell are low powered, low cost, user deployed, self organizing base station that helps the users of macrocellular network to achieve high QoS at the indoor environment and cell edge. It also helps the macrocellular network to achieve spatial frequency reuse gain (Son, 2011) and traffic off-loading in high traffic scenario (Roh, 2011; Calin, 2010).

Interference is the main obstacle in heterogeneous, i.e., a mixture of macro and femto cells, multi-cell environment. A macrocell mobile station (mMS) may receive interference from femto base station (fBS) whereas a femtocell mobile station (fMS) may receive interference from macro and femtocells. It can impair the spatial frequency reuse gain. Since fBSs are user deployed and installed without being planned, this increases the technical difficulties of interference management (Son, 2011).

In this paper we focus on interference mitigation of OFDM based femtocells underlay in macrocellular networks. Many interference mitigation techniques have been reported in the literature. The interference generated by the fBS can not be handled by the macrocell network operator by means of centralized network planning (Boudreau, 1999; Calin, 2010; Galindo, 2010). Thus the interference management in femtocells underlay in macrocellular networks is distributed. Giuliano et al. has proposed fractional frequency reuse (FFR) for wimax and 3GPP LTE in rural environment. In FFR the whole frequency bands were partitioned into sets of sub-channels and orthogonal sub-channels sets are assigned to adjacent users to mitigate interference. Boudreau et al. has discussed Static FFR and Adaptive FFR techniques. Two FFR with frequency hopping have been discussed in (Boudreau, 1999; Juang, 2010). The authors showed that in compared to the static FFR, the dynamic FFR reduced the downlink interference significantly. Performance of macro and co-channel femto has been investigated in (Kim, 2010). Clausseu has also proposed that the transmit power control of fBS based on handoff statistics has reduced the interference considerably.

We would like to extend the work of dynamic interference management with FFR discussed in (Boudreau, 1999).

To the best of our knowledge distributed interference management considering adaptive power control has not been studied for femtocells underlay in macro-cellular network. The throughput and outage probability analysis of the proposed approach has been presented in this paper.

The rest of the paper is organized as follows. Section II discusses the system model, section III includes the power control algorithm and section IV numerical analysis. Finally, we conclude in section V.

2. System and Network Model

Figure 1 shows a hybrid macro-femto cellular network, where femtocells are underlay in a macrocell. There are M macro-mobile stations (mMSs) distributed uniformly and a macro-base station (mBS) is placed at the center of the macrocell. Assume that K is the total number of femto-mobile stations (fMSs), I is the total number of femtocell, ϕ_i is the set of fMSs in the i-th femtocell $\sum_{i=1}^{I}\phi_i = K$, N is total number of OFDM sub-carriers. Femtocells are also distributed uniformly in each femtocell. Figure 2 shows adaptive fractional frequency reuse (FFR) which divides the channel bandwidth into nine sub-channels F1, F2, F3, F4, F5, F6, F7, F8 and F9. We consider adaptive FFR with power control which is the modified version of (Zheng, 2009). It is assumed that channel-state-information (CSI) are available at the receivers, all the nodes use OFDM based transmission using one antenna, user mobility is either static or nomadic. We have only considered the downlink transmission, i.e., from BS to MS for all the cells as shown in Figure 3.

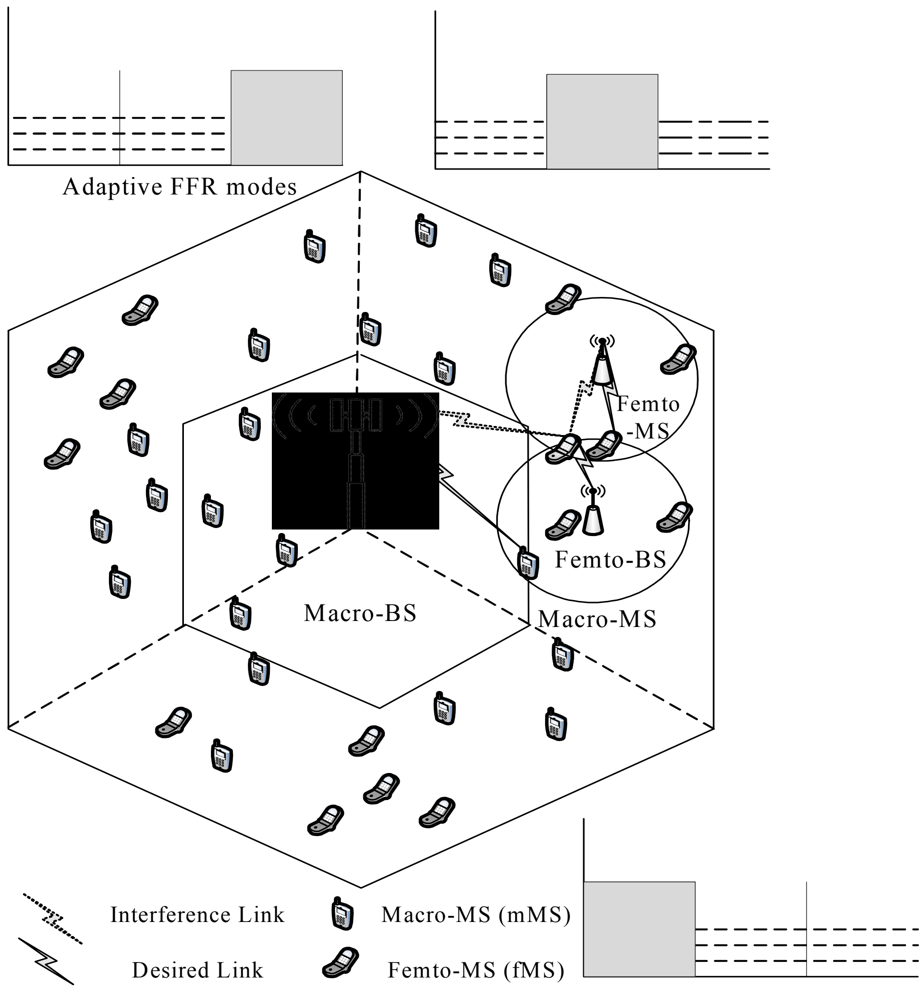

Figure 1. Example Scenario of co-channel interference where fMS share same spectrum with mMS.

There are three sectors which use adaptive Fractional frequency reuse with power control.

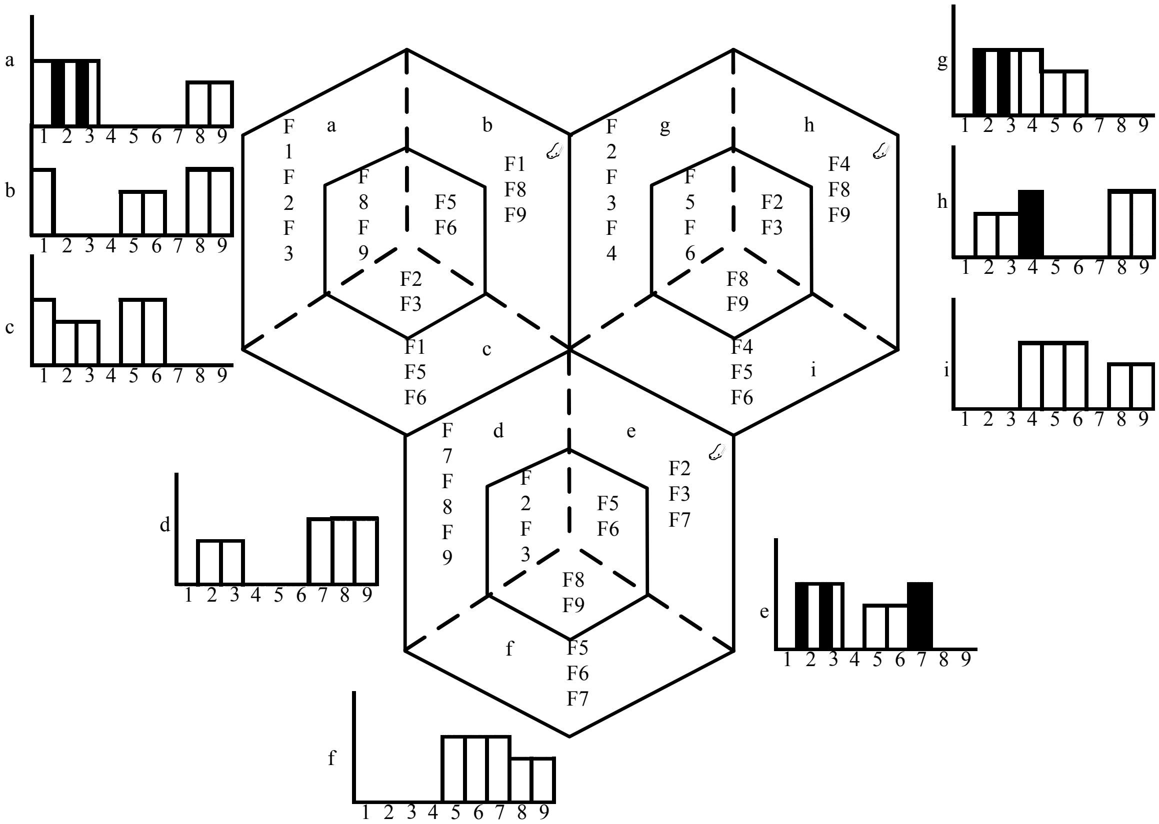

Figure 2. Proposed FFR pattern

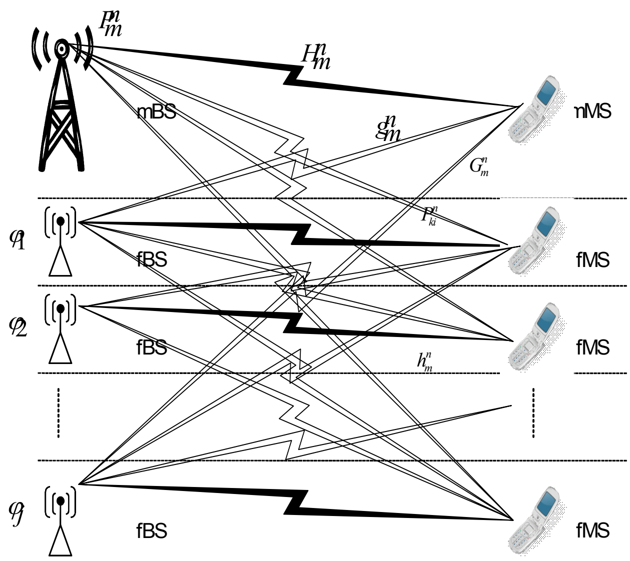

Figure 3. Simplified version of Figure 1

From the Figure 3, the signal to noise and interference ratio (SNIR) for *m*-th mMS on *n*-th subcarrier, denoted by γ_m^n, can be expressed as

$$\gamma_m^n = \frac{P_m^n H_m^n}{\sigma^2 + \sum_{k\in\phi i, i=1}^{I} \eta_{ki}^n p_{ki}^n g_{ki}^n} \tag{1}$$

where P_m^n is the power and H_m^n is the channel gain (including Rayleigh fading and pathloss) of the *m*-th mMS on *n*-th subcarrier, σ^2 is the variance of the additive white Gaussian noise (AWGN), η_{ki}^n is the power control factor, p_{ki}^{n} is the interference power and g_{ki}^{n} is the interfere gain (dominated by path loss) of the *k*-th fMS of the *i*-th femtocell on *n*-th subcarrier.

The SNIR for k-th fMS of i-th femtocell on n-th subcarrier, denoted by γ_{ki}^{n}, can be expressed as

$$\gamma_{ki}^{n} = \frac{\eta_{ki}^{n} p_{ki}^{n} h_{ki}^{n}}{\sigma^2 + \sum_{l \neq ki \in \phi i, i=1}^{I} \eta_{li}^{n} p_{li}^{n} g_{li}^{n} + P_m^n G_m^n} \tag{2}$$

Where, h_{ki}^{n} is the channel gain (pathloss) of *k*-th fMS of *i*-th femtocell on *n*-th subcarrier, G_m^n is the interference channel gain of the *m*-th mMS on *n*-th subcarrier.

The interference management optimization problem can be formulated as follows:

$$\begin{aligned} &\text{maximize } \sum \eta_{ki}^{n} p_{ki}^{n} \\ &\text{subject to } \gamma_m^n \geq 2^{R_m^n} - 1 \\ &\qquad\qquad \gamma_{ki}^{n} \geq 2^{R_{ki}^{n}} - 1 \end{aligned} \tag{3}$$

Where R_m^n and R_{ki}^{n} are the maximum data transmission rate of *m*-th mMS on *n*-th subcarrier and k-th fMS of *i*-th femtocell on *n*-th subcarrier respectively.

3. Power Control Algorithm

The value of η_{li}^{n} should ensure the SNIR of mMS, i.e., γ_m^n be higher than $2^{R_m^n} - 1$, i.e.

$$\begin{aligned} &\gamma_m^n = \frac{P_m^n H_m^n}{\sigma^2 + \sum_{k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n}} \geq 2^{R_m^n} - 1 \\ &\Rightarrow \sigma^2 + \sum_{k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n} \leq \frac{P_m^n H_m^n}{2^{R_m^n} - 1} \\ &\Rightarrow \sum_{k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n} \leq \frac{P_m^n H_m^n}{2^{R_m^n} - 1} - \sigma^2 \\ &\sum_{k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n} \leq \frac{P_m^n H_m^n}{2^{R_m^n} - 1} - \sigma^2 \end{aligned} \tag{4}$$

The value of η_{li}^{n} will be

$$\begin{aligned} &\sum_{k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n} \leq \frac{P_m^n H_m^n}{2^{R_m^n} - 1} - \sigma^2 \\ &\Rightarrow \eta_{li}^{n} \leq \left[\frac{P_m^n H_m^n}{2^{R_m^n} - 1} - \sigma^2 - \sum_{k \neq l, k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n} \right] \frac{1}{p_{li}^{n} g_{li}^{n}} \end{aligned}$$

The fBS adjusts it's transmit power to $\eta_{li}^{n} p_{li}^{n}$ such that

$$\eta_{li}^{n} = \min \left[\left[\frac{P_m^n H_m^n}{2^{R_m^n} - 1} - \sigma^2 - I_f \right] \frac{1}{p_{li}^{n} g_{li}^{n}}, 1 \right] \tag{5}$$

Where $I_f = \sum_{k \neq l, k \in \phi_i, i=1}^{I} \eta_{ki}^{n} p_{ki}^{n} g_{ki}^{n}$ we can write

$$\eta_{li}^{n} = \begin{cases} 1 & 0 < \gamma_m^n < a \\ (b-a)[\gamma_m^n - a] & a \leq \gamma_m^n < b \\ 1 & b \leq \gamma_m^n < \infty \end{cases} \tag{6}$$

Where,

$$a = 2^{R_m^n} - 1$$

$$b = a\left(1 + \frac{P_m^n H_m^n}{\sigma^2 - I_f}\right)$$

The power control curve, shown in Figure 4, can be summarized as follows:

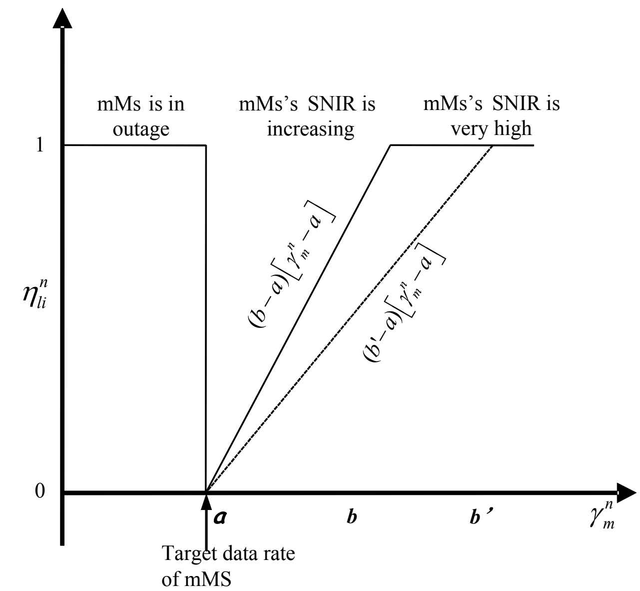

Figure 4. Illustration of the choice of power control parameter with the SNIR of mBS

When $\gamma_m^n < a$, the SNIR of the mMS is in outage. In this case the transmission of fBS to fMS will not have negative influence on mMS transmission. Thus the fBS can transmit with its maximum power p_{ki}^n, here $\eta_{li}^n = 1$.

When $a < \gamma_m^n < b$, the γ_m^n of the mMS is higher than a and the value of the power control factor η increases linearly with the γ_m^n as shown in Figure 4. Thus the fBS can transmit at most $\eta_{li}^n p_{li}^n g_{li}^n$ where $0 < \eta_{li}^n < 1$

When $\gamma_m^n > b$, the γ_m^n of the mBS is very high. If the fBS transmits with its maximum power p_{li}^n it will not affect mMS transmission totally. So, here $\eta_{li}^n = 1$, the γ_m^n will not fall below a

From the constraint of Equation (3), we can write

$$\frac{\eta_{ki}^n p_{ki}^n h_{ki}^n}{\sigma^2 + I_f + P_m^n G_m^n} \geq 2^{R_{ki}^n} - 1 \tag{7}$$

Putting the value of η_{ki}^n found from Equation (6)

$$\frac{\gamma\left[\gamma_m^n - a\right] p_{ki}^n h_{ki}^n}{\sigma^2 + I_f + P_m^n G_m^n} \geq 2^{R_{ki}^n} - 1 \tag{8}$$

Rearranging Equation (8), we can write

$$\gamma\left[\gamma_m^n - a\right] p_{ki}^n h_{ki}^n \geq \left(2^{R_{ki}^n} - 1\right)\left(\sigma^2 + I_f + I_m\right) \tag{9}$$

Where $I_f = \sum_{l \in \phi_i, i=1}^{I} \eta_{li}^n p_{li}^n g_{li}^n$ and $I_m = P_m^n G_m^n$ Finally Equation (9) can be written as

$$\gamma \geq \frac{\left(2^{R_{ki}^{n}}-1\right)\left(\sigma^{2}+I_{f}+I_{m}\right)}{\left[\gamma_{m}^{n}-a\right]p_{ki}^{n}h_{ki}^{n}} \tag{10}$$

If a mMS and a fMS share the same resource n block, A fMS can achieve its target data rate of $2^{R_{ki}^{n}}-1$, If and only if

$$\gamma \geq \frac{\left(2^{R_{ki}^{n}}-1\right)\left(\sigma^{2}+I_{f}+I_{m}\right)}{\left[\gamma_{m}^{n}-a\right]p_{ki}^{n}h_{ki}^{n}}$$

Where γ is the instantaneous SNIR of the mMS and $a<\gamma<b$

4. Numerical Analysis

This section includes Monte Carlo simulation of some numerical results of the femtocell underlay in a macro-cellular network. Table 1 shows simulation parameters. The radius of the femtocell and macrocell are 10 meters and 1000 meters respectively. Femtocells are placed uniformly in the coverage area of the macrocell. If *R* is the distance between *mMS* and *fMS,* the macrocell path loss is expressed as $L_{macro}[dB]=128.1+37.6+10\log(\mathrm{R[km]})$, (Juang, 2010).

Table 1. Simulation parameters

Parameter	Value
Multiplexing	OFDMA
$P_{\max}^{mBS}$, $P_{\max}^{fBS}$	43dBm, 15dBm
Thermal noise density	-174 dBm/Hz
Antenna	SISO; Omni
R, r^{fBS}	0.5 km, 100m
N, M, K	768, 300, 200
Bandwidth	10 MHz
f_C	2.3 GHz
Fading	Rayleigh
σ (outdoor), σ (indoor)	8dB, 4dB
Direction	Downlink

The femtocell pathloss is expressed as $L_{femto}[\mathrm{dB}] = 37 + 3.2\log(\mathrm{R[m]}) + n_w\upsilon_w$ where n_w is the number of walls and υ_w is the attenuation of the indoor wall.

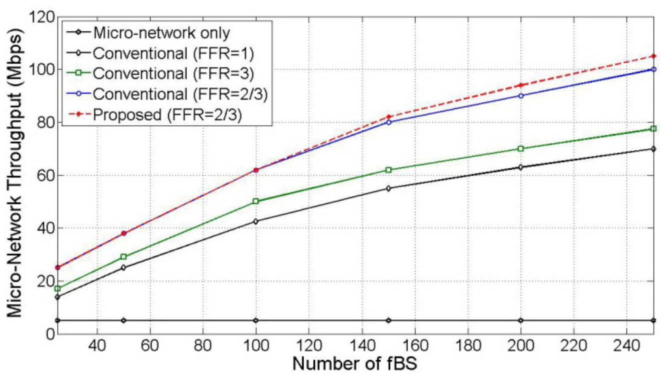

Figure 5. Total throughput, in Mbps, of the Macro-cellular network in the presence of femtocells

The total throughput of macro-cellular network, in Mbps, is shown in Figure 5. The throughput of the proposed method is compared with the conventional methods with FFR re-use pattern of 1, 3, 2/3 discussed in (Boudreau, 1999; Juang, 2010). Since femtocells help the macro cellular network to achieve spatial frequency reuse gain, the throughput of the macro-femto cellular network is higher than that of the macro-cellular network. The performance evaluation also reveals that the proposed adaptive FFR with power control performs better than conventional methods and the macro-cellular network without femtocell. The conventional method with the FFR re-use pattern of 2/3 shows better throughput than all the other conventional methods (Boudreau, 1999; Juang, 2010). The interferences between femtocells and macro cells are reduced through proposed power control. The fBSs throughputs are added to the total throughput of the macro cellular network; this maximizes the capacity of the macro-cellular network.

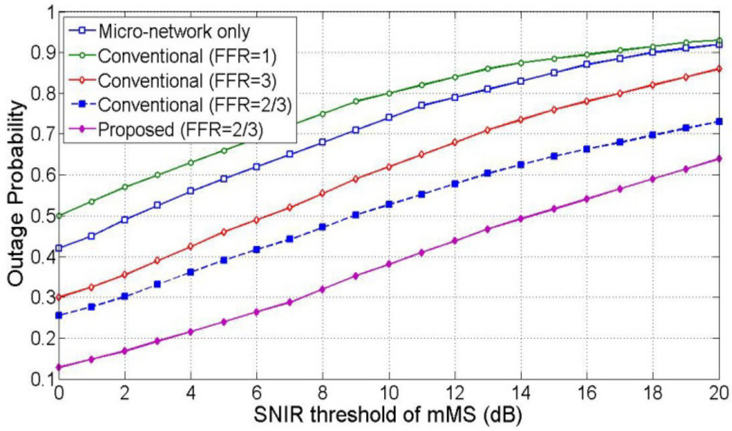

Figure 6. Effect of SNIR threshold of macro cellular network on the outage probability

Figure 6 shows the outage probability analysis of macro network for the different values of SNIR threshold. The performance evaluation shows that the better outage probability can be achieved with the proposed method. The outage probability of the conventional method with FFR of 1 has degraded with respect to macro-cellular network without femtocells.

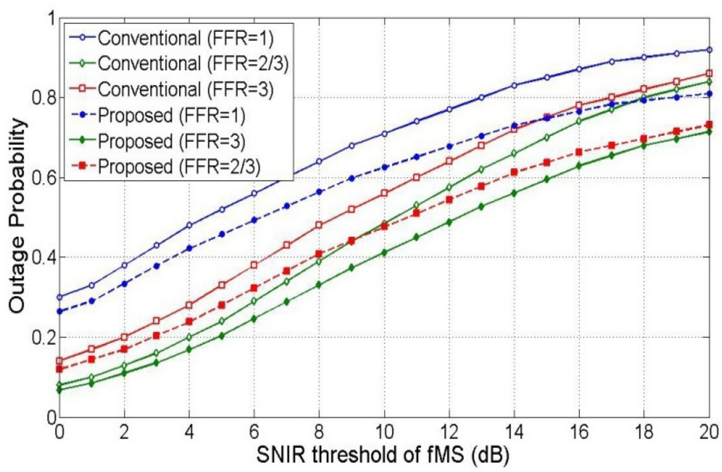

Figure 7. Effect of SNIR threshold of femto network on the outage probability

Figure 7 shows the outage probability performance of femto network. The better SNR benefit can be achieved by using the proposed method with adaptive FFR.

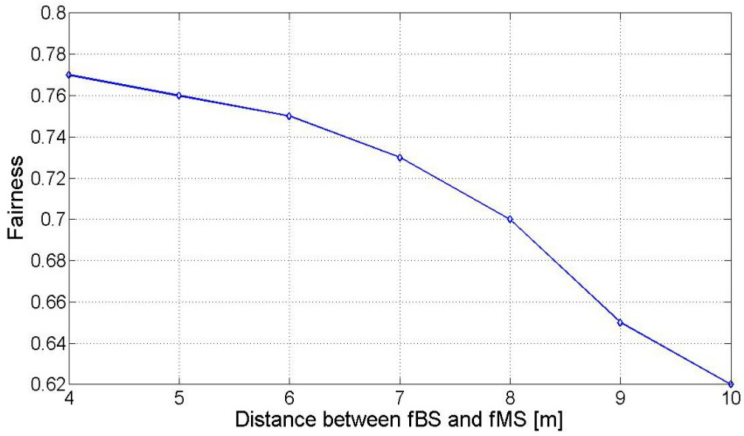

Figure 8. Fairness as a function of distance between fBS and fMS

Figure 8 shows the proportional fairness as a function of distance between fBS and fMS. The fairness of the fMS decreases with increase in the distance between fBS and fMS.

5. Conclusions

We have proposed a decentralized adaptive interference management in femtocell underlay in macro cellular network. Femto to macro interference is minimized by the femtocell power control. Simulation results show that the throughput or capacity of the macro cellular network has been increased and the outage probability has been reduced for the proposed method. This performance improvement is due to the reduction in the downlink interference to the existing macro cellular network. Our future work will focus on close-form expression of outage probability of joint macro-femto cellular network.

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