Enhanced Frequency Reuse Schemes for Interference Management in LTE Femtocell Networks

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Abstract— **Femtocells are low power access points that can be deployed by the consumer indoors to alleviate cellular coverage problems, offload traffic from the cellular network and boost user data rates. To enable the widespread of femtocells coexisting with macrocells, smart interference management schemes are required. Interference management by frequency allocation is still a big challenge in hybrid macro/femto cellular networks. Arbitrary frequency allocation schemes may have detrimental effects on the overall system spectral efficiency and coverage. In this paper, we propose soft and partial frequency reuse schemes for interference management in LTE femtocell networks. We analyze the system performance with various frequency allocation schemes via different metrics such as throughput, quality of service (QoS) and fairness. Simulation results show that the proposed soft frequency reuse (SFR) scheme with an optimized interior region radius provides an acceptable tradeoff compared to other allocation schemes.**

Keywords- Femtocells; Frequency Reuse; Resource Allocation; FFR; SFR, PFR, SFFR, Heterogeneous LTE Networks

I. INTRODUCTION

Long Term Evolution (LTE) is currently being evolved by 3GPP into LTE-Advanced to meet the requirements set by ITU-IMT-advanced of affordable mobile broadband systems. LTE characteristics like scalability of bandwidth, orthogonality of subcarriers and immunity against inter-symbol interference makes it the best choice for wideband data services and multimedia transmission. Advantages of LTE over previous 3GPP releases (i.e. WCDMA, UMTS, and HSPA) include its higher spectral efficiency, lower delay and higher peak data rates [1]. LTE exploits OFDMA and SC-FDMA as access schemes for its downlink and uplink respectively. A main feature introduced in LTE-Advanced is its support of heterogeneous cellular networks having macrocells, picocells, femtocells and relays.

Femtocells have been proposed as a solution for poor coverage and unreliable data services that typically occur indoors. Femtocells are low power wireless access points that can be deployed by users indoors to extend the coverage of the cellular network [2]. Femtocells can provide high data services as well as offload traffic from the cellular network air interface to a residential cable broadband connection or DSL. Changing the network topology by deploying smaller cells such as femtocells can alleviate possible problems of scarce resources in LTE [2].

The overlay of a femtocell network over the pre-existing macrocell network represents a major challenge. Inefficient deployment of the femtocell network may lead to a degradation of the overall performance of the cellular system. One example of this performance degradation is coverage holes for indoor macro UEs (MUEs) due to interfering transmissions by nearby femtocells. Efficient frequency allocation for both macrocell and femtocell networks is a major step towards efficient network deployment. Co-channel allocation of frequency resources leads to high spectral efficiency at the expense of quality of service (QoS), while orthogonal channel allocation leads to a high quality of service at the expense of poor spectral efficiency. Hybrid co-channel and orthogonal channel allocations are more efficient frequency allocation schemes.

Many frequency allocation schemes have been studied for macro-cell networks. Increasing the frequency reuse factor (e.g. Reuse-3) can decrease interference from neighboring cells and enhance cell-edge performance compared to Reuse-1, at the expense of spectral efficiency [3]. Soft Frequency Reuse (SFR) has been proposed in [4] as a mix of Reuse -1 and Reuse-3 schemes. The concept of Fractional Frequency Reuse (FFR) has been used for the same purpose. Other variations of FFR as Partial Frequency Reuse (PFR), and Soft Fractional Frequency Reuse (SFFR) have been proposed for macrocell networks [5] [6].

In this paper, we proposed frequency allocation schemes for hybrid macrocell-femtocell networks by exploiting popular macrocell frequency allocation schemes. Our proposed allocations schemes enhance the coexistence of both types of networks. These proposed allocation schemes are assumed to be fixed as they require no coordination, and no signaling between macrocells and femtocells. We compare the different proposed schemes in different femtocell deployment densities using some metrics like throughput, QoS, and fairness. We choose SFR as a suitable frequency allocation scheme that provides an acceptable tradeoff and overall enhanced system performance. Consequently, we optimize the interior region radius of the proposed SFR scheme for better tradeoff between system throughput and fairness performance at different deployment scenarios.

The remaining part of the paper is organized as follows. The system model is described in Section II. The proposed frequency allocation schemes are described in Section III. Our evaluation methodology is described in Section IV, Numerical

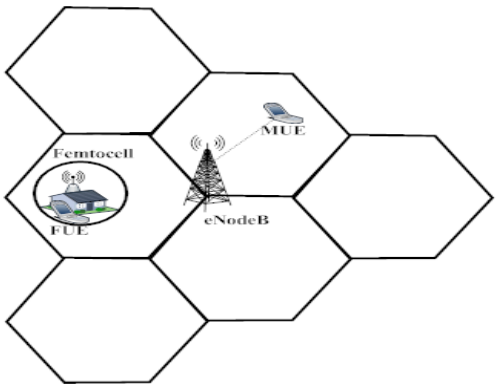

Fig. 1 Cellular Layout

analysis and simulation results are described in Section V. We conclude the paper in Section VI.

II. SYSTEM MODEL

We consider a cellular system model composed of 7 macrocells. Each macrocell consists of 3 hexagonal-sector sites. The macrocell coverage area is classified into two types; outdoor and indoor area. Indoor area is represented by uniformly distributed randomly dropped square houses of size 15 x 15 m. One femtocell is randomly dropped inside each house. The number of active femtocells is set as a variable parameter to evaluate the performance of the network in different femtocell deployment densities. Each femtocell coverage area is defined by a specific radius from the femtocell. MUEs are randomly dropped in the macrocell and classified as outdoor or indoor MUEs. Femto UEs (FUEs) can only be located inside the coverage area of a femtocell, as shown in Fig. 1, as otherwise they will handoff to the macrocell and be a MUE. A femtocell sub-urban deployment model is assumed where the pathloss (PL) model formulas are defined in [7].

Each MUE is interfered by all neighboring macrocells and femtocells that use the same sub-bands assigned to its serving macro BS. Intra-cell interference is eliminated due to the characteristics of OFDMA. The downlink signal to interference and noise ratio (SINR) for any MUE served by a sector S in macrocell B can be formulated as follows

$$SINR_{MUE} = \frac{P_R^{S,B}}{\sigma^2 + \sum_{b=1}^{7}\sum_{\substack{s=1 \\ s\neq S}}^{3} P_R^{s,b} + \sum_{f=1}^{N_f} P_R^f} \quad (1)$$

where $P_R^{S,B}$ is the received power from sector S of serving macrocell B, $P_R^{s,b}$ is the received power from interfering sector s associated with macrocell b using the same sub-bands, and P_R^f is the received power from interfering femtocell f using the same sub-bands, N_f is number of femtocells, and σ^2 is thermal noise power. The power received P_R is directly calculated from the simple formula as follows

$$P_R(dBm) = P_T(dBm) - P_{TL}(dB) \quad (2)$$

where P_T is the macrocell transmission power in dBm and P_{TL} is the total loss encountered by the signal in dBm such that

$$P_{TL}(dB) = P_L(dB) - G_T(dB) \quad (3)$$

where P_L *and* G_T are the macroscopic pathloss and transmitting antenna gain in dB respectively. The antenna gain and Rx noise figure of any UE are assumed to be 0 dB and 9dB respectively.

Similarly, each FUE is also interfered by all neighboring macrocells and femtocells that use the same sub-bands assigned to its serving femto BS. The downlink SINR for a FUE served by a femtocell F is

$$SINR_{FUE} = \frac{P_R^F}{\sigma^2 + \sum_{b=1}^{7}\sum_{s=1}^{3} P_R^{s,b} + \sum_{\substack{f=1 \\ f\neq F}}^{N_f} P_R^f} \quad (4)$$

where P_R^F is the received power from serving femtocell F, and $P_R^{s,b}$ and P_R^f are zero if the corresponding cell is utilizing another sub-band. The theoretical user capacity (bps) for any UE can be formulated as follows (assuming a static AWGN scenario or average SINR in case of fading channels)

$$C_{MUE/FUE} = W \log_2\left(1 + SINR_{\mathrm{MUE/FUE}}\right) \quad (5)$$

where W is the total bandwidth of the sub-carriers available for this UE in Hz. By continuously changing the UE location, we can evaluate the SINR and user capacity at all possible locations within the coverage areas of all macrocells and femtocells. This is justified by fact that fading is averaged out.

III. PROPOSED FREQUENCY ALLOCATION SCHEMES

A. Reuse-3

The entire frequency band is divided equally into 3 sub-bands as shown in Fig. 2a. Each sector is assigned one frequency sub-band. The transmission power level of each sector is set to be 3P where P is the reference power level of Reuse-1 scheme [8]. We propose that femtocells at each sector can use the two remaining frequency sub-bands not used by macrocells. The Reuse-3 scheme provides complete separation in frequency between the macrocell and femtocell networks at the expense of spectral efficiency.

B. Soft Frequency Reuse (SFR)

The SFR scheme divides the coverage area of macrocell into two regions; center (interior) region and edge region as shown in Fig. 2b. The center region is defined by a radius from the macro BS. The optimal radius that maximizes throughput for macrocell networks was found to be 63% of the cell radius [9]. SFR scheme divides the entire frequency band of the system equally into three sub-bands. The entire frequency band is accessed only by center MUEs during first time slot of LTE frame (Reuse-1). The second time slot is reserved for edge MUEs. Edge MUEs at each sector can access one of the three frequency sub-bands (Reuse-3). The transmission power level of the edge region is set to be 3 times the transmission power level of the center region [8].

We propose an allocation scheme for femtocells. Femtocells will be categorized into *center femtocells* and *edge femtocells* according to their location in the macrocell. Femtocells at any sector can only use the sub-bands not allo-

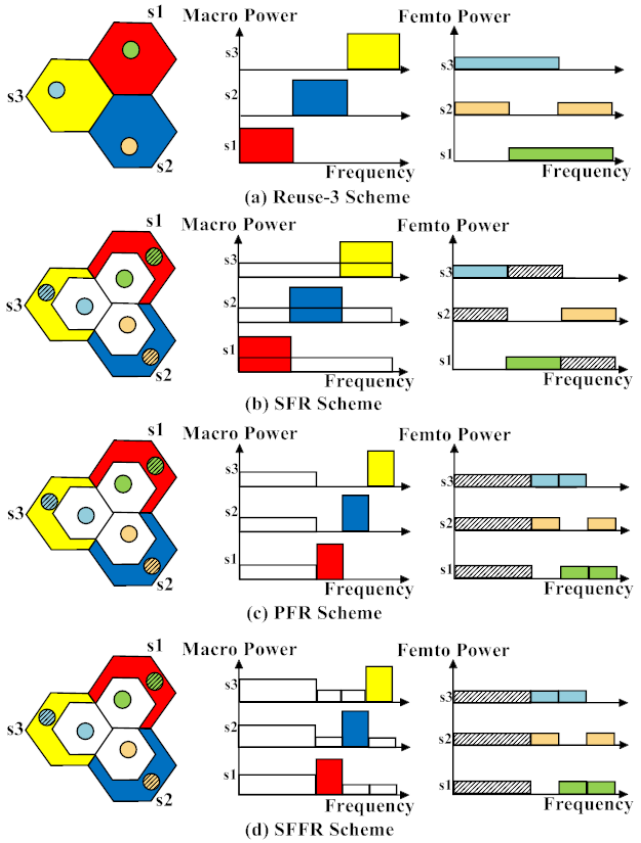

Fig. 2 Proposed Frequency Allocation Schemes

cated to edge MUEs of this sector. Let the entire bandwidth be divided into three sub-bands A, B, and C. *Center femtocells* at each sector will operate only on one sub-band, such that center femtocells in neighboring sectors use different sub-bands. *Edge femtocells* can transmit over the other two frequency sub-bands. For example: if macrocell uses sub-band A to serve edge region at sector 1, then center femtocells will use either sub-band B or C and edge femtocells will use both sub-bands B and C.

This provides efficient femto-macro interference management as

1) Macro-Femto interference in center region only exists in the first time slot instead of all the LTE frame.

2) Femto-Macro interference in center region is attenuated to 1/3 as femtocells only transmit on 1/3 of the allocated BW and can be tolerated by center MUEs as they have a high received power from their serving macro BS.

3) Macro-Femto interference to edge femto UEs is minimized due to distance from the center macro BS.

4) Femto-Macro inteference from edge femtocells is only to center MUEs and is negligible due to low femtocell power.

C. Partial Frequency Reuse (PFR)

Similarly to SFR, PFR divides the coverage area into center and edge regions. PFR scheme divides the entire system bandwidth into 6 sub-bands as shown in Fig. 2c. The first 3 sub-bands are reserved for center MUEs at any sector. These sub-bands are called *Common Sub-bands*. Each of the three remaining sub-bands is reserved for edge MUEs at different sectors. The transmission power level for sub-bands of the edge region is set to be 2/3 of the total transmission power. The transmission power level for sub-bands of center region is set to be 1/3 of total transmission power [10].

Our proposed femtocell allocation scheme also depends on categorizing femtocells into center and edge femtocells. *Center femtocells* at each sector can only operate on the two sub-bands not allocated to the center and edge MUEs of this sector. Edge femtocells at each sector can operate on the same two sub-bands besides the common sub-bands because of limited interference power level received from center BS. For example: if the entire bandwidth is divided into 6 sub-bands A, B, C, D, E, and F. Common sub-bands A, B, and C are reserved for center MUEs at any sector. Sub-bands D, E, and F are reserved for edge MUEs at different sectors. If sub-band D is reserved for edge MUEs at sector 1, center femtocells can operate on sub-bands E, and F. Edge femtocells can operate on the same sub-bands E, and F besides the common sub-bands. PFR provides almost complete separation in frequency between the macrocell and femtocell networks at the expense of spectral efficiency.

D. Soft Fractional Frequency Reuse (SFFR)

SFFR scheme can be considered a generalized case of the PFR scheme, as shown in Fig. 2d. The only difference between PFR and SFFR schemes is the available sub-bands accessed by center MUEs at each sector. Unlike PFR scheme, center MUEs in SFFR scheme can access all available sub-bands except the one reserved for edge MUEs of that sector. The transmission power level of macro BS over the two additional sub-bands accessed by center MUEs is limited to minimize interference. A quarter of total transmission power is reserved for transmission over common sub-bands. The ratio of transmission power level of edge region sub-band to transmission power level of center region additional sub-bands is set to be 10:1 [11]. Our proposed femtocell allocation scheme is the same for the PFR scheme as shown in Fig. 2d.

IV. EVALUATION METHODLOGY

A. Throughput Performance

For a random femtocell deployment, the user capacity of both MUEs and FUEs is calculated using Eq. (5) at all possible locations. Average capacity of MUEs and average capacity of FUEs are then calculated. Overall average UE capacity is calculated using the weighted average formulated as follows

$$C_{overall} = \frac{N_{MUE} C_{avg}^{M} + N_{FUE} C_{avg}^{F}}{N_{MUE} + N_{FUE}} \quad (6)$$

where N_{MUE} and N_{FUE} are the number of MUEs and FUEs respectively. C_{avg}^{M} and C_{avg}^{F} are the average capacities of MUEs and FUEs respectively. The overall average UE capacity can express the average throughput performance of the whole network. This approach is repeated for different femtocell deployment densities to evaluate the performance as the number of deployed femtocells increases.

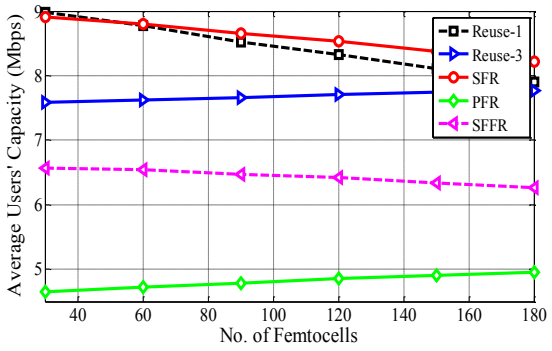

Fig. 3 Average users' capacity vs. number of femtocells

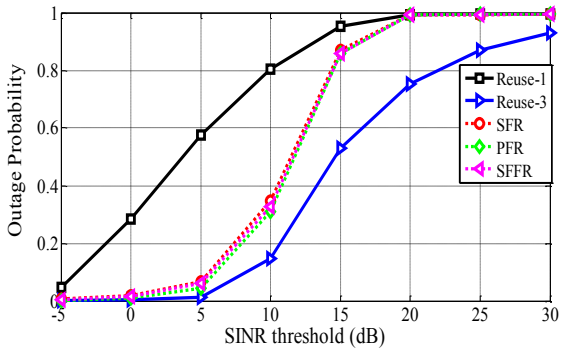

Fig. 4 Outage Probability vs. SINR threshold

B. *QoS Performance*

QoS performance of the network for different allocation schemes is measured by the *outage probability*, defined as the probability of UEs (MUEs + FUEs) having SINR values below a predefined SINR threshold. SINR values usually reflect channel quality indicator (CQI) values. CQI values are sent as feedback by UEs to the serving base station (BS) to determine the modulation and coding scheme (MCS) used in LTE network. The MCS determines the transmission rate and hence QoS in the network.

C. *Fairness Performance*

The fairness of the cellular network is measured using a fairness metric called *fairness ratio*. The fairness ratio is defined here as the ratio of the 5 percentile capacity of all UEs (MUEs + FUEs) to the overall average UEs capacity $C_{overall}$

$$Fair\ Ratio = \frac{5\% - tile\ capacity}{C_{overall}} \quad (7)$$

V. SIMULATION ANALYSIS

A. *Simulation Environment*

We assume in our simulation that one MUE at a time is connected to its serving macro BS using all available resources at this BS. Similarly, one FUE is connected to its serving femto BS. MUE and FUE locations are changed continuously to cover all possible locations within the coverage area of all macrocells and femtocells respectively. We also assume

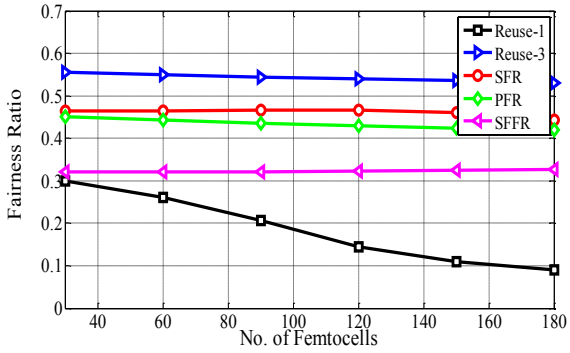

Fig. 5 Fairness Ratio vs. number of femtocells

that all neighboring BSs are always transmitting with full power over all available sub-bands. The heterogeneous LTE cellular system is simulated by modifying the Vienna LTE Simulator [12]. The LTE simulation parameters are summarized in Table 1.

Table 1 System Parameters

Parameter	Value	
	Macro	**Femto**
No. of Cells	7 Cells (3 sectors per cell)	(30 ~ 180) per macrocell
Cell Coverage	Inter-site Distance = 1732 m	Radius = 20 m
Max. transmit power	20 W	20 mW
Antenna Pattern	$A(\theta) = -\min\left[12\left(\frac{\theta}{65^\circ}\right)^2, 20\right]$	Omni-directional
Bandwidth	5 MHz	
FFT Size	512	
Subcarrier spacing	15 KHz	
White Noise power density	-174 dBm/Hz	

B. *Simulation Results*

The average throughput performance is analyzed as explained in Section IV. Fig. 3 shows the overall average users' capacity (Mbps) for different allocation schemes as the number of active femtocells increases. Reuse-1 outperforms all other schemes for only a small number of active femtocells when interference is limited. SFR provides better performance as the number of active femtocells increases. Other schemes like Reuse-3, PFR, and SFFR provide lower throughput performance because of poor spectral efficiency. While total system throughput increases by deploying femtocells, average throughput may decrease by deploying more femtocells due to increased interference and large number of users.

Fig. 4 shows the outage probability of all UEs against a predefined SINR threshold, using 90 active femtocells. The SINR threshold is varied from -5 dB to 30 dB with step of 5 dB. Reuse-1 has very high outage probability compared to other schemes. Reuse-3 is the best in terms of QoS due to full frequency separation. The other schemes (SFR, PFR, and SFFR) provide almost the same acceptable levels of outage

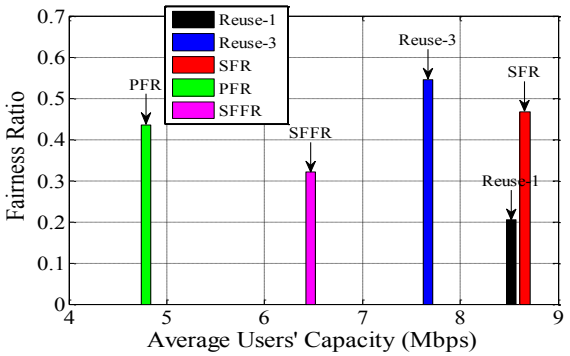

Fig. 6 Fairness/Throughput Tradeoff

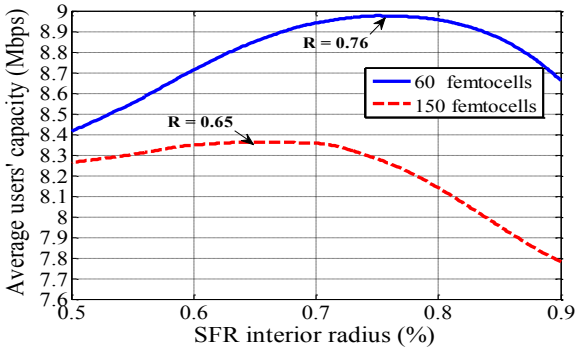

Fig. 7 Average users' capacity vs. SFR interior radius

probability at high SINR thresholds. Fig. 5 shows the fairness ratio against the number of active femtocells for different allocation schemes. Reuse-3 and SFR schemes are the best in terms of fairness with almost flat performance at different femtocell densities. As expected, the fairness of the Reuse-1 is highly degraded at higher femtocell densities due to the unmanaged interference. The tradeoff between average throughput and fairness ratio for different allocation schemes (using 90 active femtocells) is shown in Fig. 6. Reuse-3 and PFR schemes can provide high levels of fairness at the expense of throughput. Reuse-1 can provide high levels of throughput at the expense of poor fairness and QoS. SFR can provide the best throughput with an acceptable level of fairness, which is better than that of the SFFR scheme and slightly lower than the Reuse 3 scheme. Thus, we optimize the proposed SFR scheme for the best possible performance.

The impact of changing the SFR interior region radius on the average throughput performance is shown in Fig. 7. The SFR interior region radius is set as a variable parameter varying from 50% to 90% of the cell radius with 5% steps. Two femtocell deployment scenarios are simulated. The optimal interior region radius that maximized the total femto and macro throughput is found to be 76% of cell radius for medium density deployment of 60 active femtocells and 65% of cell radius for a relatively higher density deployment scenario of 150 active femtocells. We observe that the optimal interior region radius is a factor of the deployment density and decreases with increasing the number of active femtocells. As the radius decreases, more femtocells are considered edge femtocells which are assigned more bandwidth than center femtocells and thus have higher throughput. A slight decrease of fairness by only 5% and 15% occurred at the two optimized interior region radii of 76% and 65% respectively (compared to the 63% interior radius point).

VI. CONCLUSION

We proposed enhanced frequency reuse schemes for macro-femto LTE networks. Reuse-1 is the best scheme in terms of spectral efficiency, but has degraded QoS, and fairness. Although Reuse-3 is the best scheme in terms of QoS, and fairness, its poor spectral efficiency doesn't make it a good choice. Our simulation results show that our proposed SFR scheme achieves the best tradeoff between user capacity and system fairness. We show that the optimal SFR radius that maximizes system throughput and fairness of heterogeneous macro-femto LTE systems is dependent on the femtocell density.

ACKNOWLEDGMENT

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