Fractional Frequency Reuse for Interference Management in LTE-Advanced HetNets

N兹Musz Saqib, Ekram HoSSain, and Dong In Kim

Abstract

Improvement of cell coverage and network capacity are two major challenges for the evolving 4G cellular wireless communication networks such as LTE-Advanced networks. In this context, hierarchical layering of cells with macro base stations coexisting with low-power and short-range base stations (corresponding to picocells or femtocells) in a service area is considered to be an efficient solution to enhance the spectral-efficiency of the network per unit area. Also, such a hierarchical cell deployment, which is referred to as a heterogeneous network, or HetNet, provides significant improvement in the coverage of indoor and cell edge users and ensures better QoS to the users. Interference mitigation between different layers is one of the key issues that needs to be resolved for successful deployment of HetNets. To this end, FFR is considered to be an efficient intercell interference coordination technique for OFDMA-based HetNets. This article focuses on evaluating three state-of-the-art FFR deployment schemes: strict FFR, soft FFR, and FFR-3 schemes for OFDMA-based two-tier HetNets comprising macrocells overlaid with femtocells. Also, a variation of the FFR-3 scheme, which is referred to as the optimal static FFR (OSFFR) scheme, is proposed. A broad comparison among all these FFR schemes is performed by using Monte Carlo simulations considering performance metrics such as outage probability, average network sum rate, and spectral efficiency. Simulation results show that, the average gains in spectral efficiency (b/s/Hz) of the network are significantly higher for the proposed scheme when compared to the strict FFR, soft FFR, and FFR-3 schemes.

Introduction

Conventional cellular systems use a macrocell-based planned homogeneous network architecture, where a network of macrocell base stations (corresponding to as MeNBs) provides coverage to user equipment (UE) in each cell. In such a homogeneous network, the MeNBs have similar transmit power levels, antenna patterns, access schemes, modulation techniques, receiver noise floors, and backhaul connectivity to offer similar quality of service (QoS) to the UE across all cells [1, 2]. However, such a deployment especially degrades the coverage and capacity of the cell edge users. One of the approaches to solving this problem is to make the transmitters and receivers closer to each other. However, this approach may not be economically feasible since it involves deploying more MeNBs within the network, and site acquisition for MeNBs in dense urban areas becomes a difficult proposition for operators [1]. Therefore, the evolving Long Term Evolution Advanced (LTE-Advanced) systems need to adopt a more flexible and scalable deployment approach that is beneficial to both operators and end users. Such an approach is expected to not only increase the coverage and capacity of the cell, but also improve the broadband user experience within the cell in a ubiquitous and cost-effective manner [1]. To this end, cellular heterogeneous networks (HetNets), which correspond to a scalable hierarchical cellular network model, are being deployed to improve spectral efficiency and expand indoor coverage within the network in a cost-effective way [2]. A two-tier HetNet comprises conventional MeNBs in the first tier overlaid with low-power, low-complexity, short-range base stations (corresponding to picocells or femtocells) in the second tier (Fig. 1). Due to the smaller coverage area, the same licensed frequency band can be efficiently reused multiple times within the second-tier elements of a HetNet, thus improving the spectral efficiency per unit area (and hence the capacity) of the network.

Picocells are usually deployed to eliminate coverage holes in a homogeneous system and improve the capacity of the network. The coverage area of picocells usually varies between 40–75 m [2]. Picocells consist of omnidirectional antennas with about 5 dBi antenna gain providing significant indoor coverage to the UE in public places such as airports and shopping malls [2]. On the other hand, short-range (10~30 m) and low-power (10~100 mW) home base stations, commonly known as femtocells or femto access points (FAPs), which operate on the licensed spectrum owned by the mobile operator, enable fixed mobile convergence (FMC) service by connecting to the cellular network via broadband communications links (e.g., digital subscriber line, DSL) [3]. Due to several advantages such as improved indoor coverage, higher...
data rate, better QoS, plug-and-play deployment, and self-organization, a recent study showed that by 2014, 114 million mobile users will be accessing mobile networks through femtocells [4]. In recent years, different types of femtocells have been designed and developed based on various air interface technologies, services, standards, and access control strategies. Due to the flexibility in spectrum allocation, LTE-Advanced femtocells, which are referred to as home evolved Node Bs (HeNBs), will use orthogonal frequency-division multiple access (OFDMA) as the air-interface technology.

In the next section, we describe the interference management problem in HetNets and the basics of the fractional frequency reuse (FFR) method for interference management in OFDMA-based HetNets. After that, different variations of the existing FFR methods in the literature are discussed. Then the optimal static fractional frequency reuse (OSFFR) scheme is presented, which is followed by the comparative performance evaluation results for the different FFR schemes before conclusions are drawn.

**INTERFERENCE MANAGEMENT IN HETNETS AND FRACTIONAL FREQUENCY REUSE**

Figure 1 shows a HetNet where an MeNB is overlaid with one picocell and several 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. From now on, we focus on a two-tier HetNet comprising macrocells and femtocells. Two types of interference occur in such a HetNet.

**Co-tier interference:** This type of interference occurs between neighboring femtocells. For example, a femtocell UE device (aggressor) causes uplink co-tier interference to the neighboring femtocell BSs (victims) (e.g., index 5 in Fig. 1). On the other hand, a femtocell BS acts as a source of downlink co-tier interference to the neighboring femtocell UE (e.g., index 6 in Fig. 1).

**Cross-tier interference:** This type of interference occurs between femtocells and macrocells. For example, femtocell UE (referred to as FUE) and macrocell UE (referred to as MUE) act as sources of uplink cross-tier interference to the serving MeNB (e.g., index 3 in Fig. 1) and nearby HeNBs (e.g., index 1 in Fig. 1), respectively. On the other hand, the serving MeNB and HeNBs cause downlink cross-tier interference to the FUE (e.g., index 2 in Fig. 1) and nearby MUEs (e.g., index 4 in Fig. 1), respectively.

In OFDMA-based femtocell networks, co-tier/cross-tier and uplink/downlink interference occur only when the aggressor (or the source of interference) and the victim use the same sub-channel. Therefore, it is essential to adopt an effective and robust interference management scheme that will mitigate co-tier interference and reduce cross-tier interference considerably in order to enhance the throughput of the overall network. Different techniques such as cooperation among MeNB and HeNBs and collaborative frequency scheduling [5], formation of groups of HeNBs and exchange of information (path loss, geographical location, etc.) among neighboring HeNBs [6], power control [7, 8], and intelligent spectrum access [9] have been considered in the recent literature to reduce co-tier and cross-tier interference. However, in this article we concentrate on an interference avoidance technique, the FFR method (also advocated by Femtoforum in [4]), which requires minimal cooperation among BSs, has a less complex operational mechanism, and is well suited for OFDMA-based LTE-Advanced systems.

The basic mechanism of FFR corresponds to partitioning the macrocell service area into spatial regions, and each subregion is assigned with different frequency subbands. Therefore, cell-edge-zone MUE devices do not interfere with center-zone MUE devices, and with an efficient channel allocation method, the cell-edge-zone MUE may not interfere with neighboring cell-edge-zone MUE. As a result, the cell-edge-zone MUE devices receive an acceptable signal quality, which subsequently reduces the outage probability and increases the network capacity. Note that this type of FFR scheme, when operating on a relatively large timescale, is referred to as a static FFR scheme. In contrast, dynamic FFR schemes [10] can operate on short timescales and can be optimized for system utility with varying network dynamics. However, they are more complex and less scalable than static schemes.

In this article, for OFDMA-based HetNets, we evaluate three different static FFR schemes originally proposed for homogeneous networks, strict FFR, soft FFR, and FFR-3 schemes; also, a new static FFR scheme is proposed in this article, which is referred to as the optimal static FFR (OSFFR) scheme. We provide a broad comparison among all these schemes based on performance metrics such as outage probability.

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1. The MUE devices are considered outdoor users and the FUE devices are considered indoor users.

2. Due to brevity, investigation of dynamic FFR schemes is outside the scope of this article.
average network sum rate, and spectral efficiency in a two-tier HetNet.

**CHANNEL ALLOCATION FOR INTERFERENCE MITIGATION UNDER DIFFERENT FFR DEPLOYMENTS**

**STRICT FFR SCHEME**

The basic mechanism here is to apply a frequency reuse factor (FRF) of 1 to center-zone MUE and an FRF of $N$ to edge-zone MUE. The available frequency band is partitioned in such a way that in a cluster of $N$ cells, the center-zone MUE devices in each macrocell are allocated with a common subband of frequencies, while the rest of the frequencies are equally partitioned into subbands according to the FRF of the edge zone and assigned separately to each cell edge zone of the cluster. Therefore, a total number of $(N + 1)$ subbands are required. Figure 2a (i) illustrates a cellular network with strict FFR deployment. Figure 2a (ii) illustrates a strict FFR deployment scenario with FRF of $N = 3$ to edge-zone MUE. In Fig. 2a (iii), the vertical bar represents the labeling of different subbands that are used by both MeNB(s) and HeNBs in the cluster of cells (i) in Fig. 2a (iii).

In this scheme, the cell-edge MUE devices in a macrocell (e.g., macrocell 1) are not interfered by any other MeNB in tier 1. This significantly reduces the intercell co-tier interference. Also, since the center-zone and edge-zone MUE use different subbands, intracell co-tier interference for the MUE is mitigated. To reduce intracell cross-tier interference, an HeNB located in the center zone needs to choose a subchannel from a subband that is assigned to the MUE in the edge zone. With $N = 3$, since only two subbands are allocated per cell in a cluster, the HeNB situated in the cell edge zone has to select a subchannel from the same subband as used by the MUE in the center-zone (Fig. 2a (ii)). For such an allocation, the cross-tier interference would be significant near the transition areas of the center and edge zones in a macrocell. Under this frequency allocation scenario, the HeNBs are constantly interfered by the omnidirectional transmission from the MUE on the same subband even though the MUE and HeNBs use different subbands in both the center and edge zones. Also, the co-tier interference between HeNBs may become severe, especially in the edge zone since all the neighboring cell-edge-zone HeNBs use limited numbers of subchannels from the same subband.

One of the important design parameters here is the radius of the center zone of the macrocell. Using Monte Carlo simulations, it was shown in [11] that, for uniformly distributed MUE, if the cell-center-zone radius ($r_{\text{center}}$) is 0.65 times the macrocell radius ($R$), the average network throughput is maximized. We consider the same channel allocation and center zone radius for strict FFR in a HetNet where in each cell of a cluster of size $N$, the total subchannels allocated to center zone MUE is given by [11]
where $K_{\text{band}}$ is the total number of available subchannels in a macrocell.

The total subchannels allocated to the edge zone MUE is given by

$$ K_{\text{edge}} = \left[ \left( \frac{K_{\text{band}}}{R} \right) - K_{\text{center}} \right] / N. $$

### Soft FFR Scheme

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 subbands of cell-edge-zone MUE of the neighboring cells within the cluster. For a cluster of $N$ cells, the total number of available subchannels in a cell is divided into $N$ subbands with one subband assigned to each edge zone.

Figure 2b (i) depicts a cellular network with soft FFR deployment. Figure 2b (ii) illustrates the deployment of a soft FFR scheme with FFR of 3 to the edge-zone MUE. The entire frequency is divided into subbands A, B, and C, and assigned to the cell-edge-zone MUE of macrocols 1, 2, and 7, respectively. Now, the center-zone MUE devices of macrocell 1 are allowed to use subbands B and C (i.e., the subbands of cell-edge-zone MUE of macrocells 2 and 7, respectively). Therefore, soft FFR is more bandwidth-efficient than strict FFR.

In this scheme, both center-zone and edge-zone MUE will experience interference from the tier 1 macrocells (Fig. 2b (i)). A power control factor ($\varepsilon$) is therefore introduced for the edge-zone MUE to reduce intercell interference. That is, if MUE device $m$ is located in the center zone, the transmit power from the tagged HeNB is $P_{mk}$ on subchannel $k$, and if the MUE device is located in the edge zone, the transmit power is $\varepsilon P_{mk}$ ($\varepsilon > 1$). The optimal number of subchannels allocated to center-zone MUE is the same as the strict FFR case [11], and the total subchannels allocated to edge-zone MUE is given by $K_{\text{edge}} = \min\{K_{\text{band}}, K_{\text{band}} - K_{\text{center}}\}$.

One of the major advantages of soft FFR is that it has better spectrum efficiency than strict FFR. Similar to strict FFR, an HeNB located in the center zone may select the subband that is used by the MUE in the edge zone, and if the HeNB is located in the edge zone, it chooses the subbands that are used by the MUE in the center zone (Fig. 2b (ii)). Now, the HeNBs in the edge zone have more options from which to choose a subchannel; therefore, the co-tier interference would be reduced. However, the cross-tier interference would be significant for users near the boundary of the center and edge zones.

### FFR-3 Scheme

The macrocell coverage area is partitioned into center and edge zones, including three sectors each (Fig. 2c (i)). The entire frequency band is divided into two parts: one part is solely assigned to the center zone (e.g., subband A in Fig. 2c (ii)), and the other part is partitioned into three subbands (e.g., subbands B, C, and D) and assigned to the three edge zones. An HeNB chooses a subband that is not used in the macrocell sub-area. When the HeNB is located in the center zone, it also excludes the subband that is used by the MUE in the edge zone of the current sector [12].

As an example, when an HeNB is in edge zone $X_1$, it would only use subband A, C, or D and exclude subband B since subband B is used by the MUE in region $X_1$. Similarly, when an HeNB is in center zone $C_1$, it would avoid subband A, which is used by the MUE in the center zone. It would also avoid subband B, which is used by the MUE in edge zone $X_1$, because the received signal power in subband B would be relatively strong for that HeNB and may create severe cross-tier interference [12]. Therefore, the HeNB in center zone $C_1$ would use subband C or D (Fig. 2c (iii)). In this way, the intracell cross-tier interference is minimized significantly.

Due to sectoring, the intercell cross-tier interference would be reduced. For example, when a user is in region $X_1$ of macrocell 1, cross-tier interference is mainly from macrocell 2 and macrocell 7 rather than from all six HeNBs in tier 1 of the network (Fig. 2c (i)). As a result, the overall network sum rate increases in comparison with the strict and soft FFR schemes.

The performance of a sectored FFR scheme such as the FFR-3 scheme can be improved by optimizing the edge-zone FFR, the center-zone radius, and the allocation of frequency resources in center-zone and edge-zone MUE such that the overall network throughput is maximized. Therefore, similar to [13], an optimization problem can be formulated with the objective of maximizing the total network throughput subject to the minimum data rate requirement of MUE in the presence of HeNBs. By solving this optimization problem, we observe that the optimal edge-zone FFR for which the total network throughput is maximized is 6. The resulting FFR scheme is referred to as the optimal static FFR (OSFFR) scheme.

### Optimal Static Fractional Frequency Reuse: An Improved FFR Scheme

#### Channel Allocation

In the OSFFR scheme, the macrocell coverage is partitioned into the center zone and edge zone with six sectors in each zone (Fig. 2d (i)). The center zone MUE devices (i.e., the UE situated within the optimal center-zone radius of the cell) are allocated subband A with the number of subchannels in this subband obtained from the solution of the optimization problem. The rest of the available subchannels are divided into six subbands (B, C, D, E, F, and G), each of which is allocated to one of the edge-zone sectors. The allocation of different frequency subbands to the different areas in the cell is shown in Fig. 2d (ii).

Thus, in OSFFR, FRF of 1 is applied in the center zone, while FRF of 6 is applied to the edge-zone MUE.

Note that in Fig. 2d (i), any MUE in the edge zone would experience intercell interference mainly from one macrocell in tier 1. In other words, the HeNBs in the edge zone have more options from which to choose a subchannel; therefore, the co-tier interference would be reduced. However, the cross-tier interference would be significant for users near the boundary of the center and edge zones.
words, any MUE device $x$ located in edge zone $X_1$ of macrocell 1, which is allocated a subchannel from subband G, will experience interference only from macrocell 4 if any MUE located in edge-zone $X_1$ in this cell is using the same sub-channel as $x$. This substantially reduces the intercell interference among MUE devices. In addition, since center-zone MUE devices do not share spectrum with edge-zone MUE devices, the intracell interference is mitigated. Furthermore, the entire macrocell adopts a FRF of 1. Under such deployment, when an HeNB is turned on, it senses the neighboring macrocell signals, executes Algorithm 1 in a distributed manner, and chooses subbands that are not used in the macrocell sub-area. Likewise in [12], when the HeNB is located in the center zone, it excludes the subband used in the center zone and the subband used by the macrocell in the edge zone of the current sector (Fig. 2d (ii)). The HeNB additionally excludes two subbands that are used by the macrocell in the edge zones just adjacent to the current sector. Note that a low-complexity low-cost implementation of HeNBs for such autonomous operation will be an important issue for successful deployment of this scheme.

As an example, when the HeNB is in edge zone $X_1$, it would use subband A, B, C, D, E, or F and exclude subband G since subband G is used by the macrocell in region $X_1$. Now, when the HeNB is located in center zone $C_1$, it would avoid subband A, which is used by the macrocell in the center zone. It would avoid subband G, which is used by the macrocell in edge zone $X_1$, because the received signal power in subband G would be strong for that HeNB. In addition, it would exclude subbands B and F, two subbands used by the macrocell in the edge zones of the adjacent sectors of the current sector for that HeNB, since the received signal power of subbands B and F would be relatively strong for that HeNB. Therefore, the HeNB located in center zone $C_1$ would use subband C, D, or E.

For the proposed scheme, with a reduced macrocell sub-area, an HeNB has more subbands from which to select. Therefore, the co-tier interference is reduced significantly in comparison with the FFR-3 scheme. Also, the intracell cross-tier interference to FUE may only result from MUE in the same sector in the center zone or near the transition regions of the edge zones of the neighboring sectors within a cell. The intercell cross-tier interference would be from only one neighboring MeNB. For example, an FUE device in region $X_1$ will experience cross-tier interference mainly from the corresponding sector of macrocell 7 (Fig. 2d (i)). In addition, an HeNB in the edge zone would have six from which subbands to select. This reduces the probability of intracell co-tier interference in comparison to other FFR schemes.

**Operational Algorithm**

First, similar to that in [14], the set of usable frequency subbands $J_U$ for the HeNB $f \in F_A$ is initialized to the set of all available frequency subbands $J$. Now, if $f$ is turned on, it senses the neighboring macrocell signals and estimates the received signal strength indication (RSSI) value ($R_f$) for each frequency subband. Let $T$ denote the set of RSSI values for all available frequency subbands in the macrocell, and $R_f^*$ denote the highest RSSI value. If the RSSI value of subband A is the highest, then $f$ is located in the center zone. In this case, $f$ forms $S_f^*$, a set of four subbands (including subband A) the RSSI values of which are comparatively higher than those of other subbands. Now, $S_f^*$ is excluded from $J_U$, the set of usable frequency subbands for $f$ located in any of the center zones $C_1$–$C_6$. However, if the RSSI value of subband A is not the strongest, then $f$ is located in one of the edge zones $X_1$–$X_6$. Then the set $S_f^*$ would consist of only one frequency subband that has the strongest RSSI value (i.e., the frequency subband used by the macrocell in the edge-zone of the current sector). Thus, $S_f^*$ is excluded from $J_U$, the set of usable frequency subbands for HeNB $f$ located in any of the edge zones.

As an example, let us consider that HeNB $f$ is located in center zone $C_1$. From the initialization phase, the set of usable frequency subbands for $f$ would be $J_U = \{A, B, C, D, E, F, G\}$. Since $f$ is in center zone $C_1$, the RSSI value for subband A would be the highest. In addition, since it satisfies the center zone condition, it would form the set $S_f^*$. Now, from Fig. 2d (ii), the RSSI value corresponding to frequency subbands A, B, G, and F would be comparatively higher than the RSSI values corresponding to frequency subbands C, D, and E. Therefore, the set $S_f^*$ in this case would be $S_f^* = \{A, B, G, F\}$. Now, the HeNB would exclude $S_f^*$ from $J_U$. Hence, the set of usable frequency subbands for $f$ located in center zone $C_1$ would be $J_U = \{C, D, E\}$.

**Performance Evaluation**

**Performance Metrics**

We evaluate the performance of the different static FFR schemes in a HetNet scenario by simulations (in MATLAB R2010a) in terms of outage probability, network throughput (or network sum rate), and spectral efficiency.

The signal-to-interference-plus-noise ratio (SINR) for downlink transmission to MUE $x_m$ from MeNB $m$ on subchannel $k$, $\text{SINR}_{x_m,k}$, is given by

$$\text{SINR}_{x_m,k} = \frac{P_x k}{I + N_0}$$

where $P_x$ is the transmit power of the desired signal, $I$ is the total interference power from all other cells, and $N_0$ is the noise power.
\[ p_{k}^{m} + \sum_{m=1}^{N_{0}} f_{k}^{m} h_{k,m}^{m} G_{k,m}^{m} + \sum_{f=1}^{F_{k}} P^{f} G_{k,f}^{f} \]

where \( P_{k}^{m} \) is the transmit power from MeNB \( m \) on subchannel \( k \), \( h_{k,m}^{m} \) is the exponentially distributed channel fading power gain associated with subchannel \( k \), and \( G_{k,m}^{m} \) is the path loss associated with subchannel \( k \) between MUE \( x_{m} \) and MeNB \( m \), which is given as \( G_{k,m}^{m} = 10^{\log_{10}(d)} \). This path loss corresponds to outdoor path loss and is modeled as \( PL_{\text{outdoor}} = 28 + 35\log_{10}(d) \) dB, where \( d \) is the Euclidean distance between a BS and a user in meters. However, \( G_{k,m}^{m} \) is affected by both indoor and outdoor path loss. In this case, \( d \) would be the Euclidean distance between HeNB \( f \) and the edge of the indoor wall in the direction of MUE, \( x_{m} \). After the wall, the path loss will be based on an outdoor path loss model.

In Eq. 1, \( M' \) is the set of interfering MeNBs, which depends on the location of the MUE devices and the specific FFR scheme used. \( F \) is the set of interfering HeNBs. Here, the adjacent HeNBs are defined as those HeNBs that 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 \( \Delta B \) represents subcarrier spacing. The maximum achievable capacity for an MUE \( x_{m} \) on sub-channel \( k \) is then given by \( C_{X_{m},m} = \Delta B \log_{2}(1 + \alpha \text{SINR}_{k,m}) \), where \( \alpha \) is a constant defined by \( \alpha = -1.5/\ln(5 \times \text{BER}) \) [12]. Here, \( \text{BER} \) represents the target bit error rate (e.g., \( 10^{-9} \)) [12].

For FUE \( y_{f} \) communicating with HeNB \( f \) on subchannel \( k \), the downlink SINR, \( \text{SINR}_{y_{f}} \) is

\[ \frac{p_{k}^{y_{f}} G_{k,f}^{f}}{N_{0} \Delta B + \sum_{m=1}^{N_{0}} f_{k}^{m} h_{k,m}^{m} G_{k,m}^{m} + \sum_{f=1}^{F_{k}} P^{f} G_{k,f}^{f}} \]

where \( F' \) is the set of all interfering (or adjacent) HeNBs, and \( M \) is the set of interfering MeNBs. Here, \( G_{k,f}^{f} \) represents indoor path loss gain for distance \( d \) between the FUE and its serving HeNB. On the other hand, \( G_{k,m}^{m} \) corresponds to both indoor and outdoor path loss models. Since the interfering signal is coming from the MeNB, in the denominator we include the channel fading power gain. Due to the fact that the transmission radius of the interfering HeNBs is small, we only assume the indoor path loss model for the channel gain \( G_{k,f}^{f} \). Again, note that the interfering HeNBs are defined as those HeNBs that are within a circular area of radius 60 m centered at FUE \( y_{f} \).

**Outage Probability** — We define the outage probability as the probability that a UE device’s instantaneous SINR on a given subchannel \( k \) falls below the SINR threshold \( \gamma \) given as \( P(\text{outage}) = \mathbb{P}(\text{SINR}_{k,m} < \gamma) \).

**Sum-Rate for FUEs in a Macrocell** — The maximum achievable capacity for FUE \( y_{f} \) is given as \( C_{y_{f}} = \Delta B \cdot \log_{2}(1 + \text{SINR}_{y_{f}}) \).

**Average Network Sum-Rate** — The average network sum rate, \( C_{\text{avg}} \) is

\[ \frac{\sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{f=1}^{F_{k}} G_{k,m}^{m} C_{X_{m},m}^{k} + \sum_{f=1}^{F_{k}} G_{k,f}^{f} C_{y_{f}}}{M_{\text{UE}}} \]

where, in general, \( \gamma_n = 1 \) when a subchannel \( k \) is assigned to a UE device; otherwise, it is set to 0.

**Spectral Efficiency** — We define the spectral efficiency (bits per second per hertz) in terms of average bits per second successfully received by a UE device per unit spectrum. The spectral efficiency of transmission to MUE \( x_{m} \) on subchannel \( k \) is given as \( S_{X_{m},m}^{k} = \log_{2}(1 + \text{SINR}_{k,m}) \) and that for FUE \( y_{f} \) is given as \( S_{y_{f}} = \log_{2}(1 + \text{SINR}_{y_{f}}) \). The average network spectral efficiency, \( \Delta \), is thus given by

### Table 1. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network size</td>
<td>1-tier (7 macrocells)</td>
</tr>
<tr>
<td>Radius of a macrocell</td>
<td>280 m</td>
</tr>
<tr>
<td>Radius of a femtocell</td>
<td>30 m</td>
</tr>
<tr>
<td>SNR at an MUE device</td>
<td>10 dB</td>
</tr>
<tr>
<td>HeNB transmit power</td>
<td>20 mW</td>
</tr>
<tr>
<td>Number of MeNB devices in a macrocell</td>
<td>50</td>
</tr>
<tr>
<td>Number of MUE devices in a femtocell</td>
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</tr>
<tr>
<td>Number of subchannels</td>
<td>50</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>15 kHz</td>
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<tr>
<td>Spectral Efficiency</td>
<td>38.5 + 20\log_{10}(d) + 7dB, 0 &lt; d &lt; 10</td>
</tr>
<tr>
<td></td>
<td>38.5 + 20\log_{10}(d) + 10dB, 10 &lt; d &lt; 20</td>
</tr>
<tr>
<td></td>
<td>38.5 + 20\log_{10}(d) + 15dB, 20 &lt; d &lt; 30</td>
</tr>
</tbody>
</table>
The simulation parameters are shown in Table 1. The network is composed of seven macrocells, and the HeNBs (i.e., femtocells) are randomly deployed over the macrocells. The number of HeNBs is varied up to 40 in one macrocell coverage area. 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 in the network. The MUE and FUE are randomly allocated with available subchannels from the designated frequency bands corresponding to each sub-area for each scheme [12]. We assume a “snapshot” model, where all the network parameters (in Table 1) remain constant during a simulation run.

SIMULATION RESULTS

Figure 3 corresponds to the network throughput vs. fraction of the center zone radius (w.r.t. the macrocell radius) for various cell-edge-zone FRFs. For each cell-edge-zone FRF and fraction of the center zone radius, the optimal number of subchannels for center zone MUE is obtained by enumeration such that the network throughput is maximized.

For the OSFFR scheme, the total network throughput (or spectral efficiency) of the network) is maximized if the center zone radius is 54 percent of the total macrocell radius (Fig. 3), and 36 percent of the total frequency resources are allocated for the center zone MUE (i.e., sub-band A). For FFR-3, the optimal center zone radius is 61 percent of the macrocell radius, and the optimal frequency resources for the center zone MUE is 48 percent of the whole frequency band. The optimal values for OSFFR and FFR-3 are used to obtain the performance evaluation results given below.

Figure 4a shows the variations in outage probability with SINR threshold for different FFR schemes (without HeNBs and with 40 HeNBs per macrocell to demonstrate how the outage probability deteriorates in the presence of a large number of HeNBs). Note that the strict FFR scheme exhibits slightly better outage performance when the SINR targets are low. This is due to the fact that in strict FFR, the edge zone MUE devices of the center MenB (i.e., the MenB under observation) are not interfered by any other MeNBs of the first tier of the network. When the SINR threshold

\[
\sum_{s_k \in S_k} \sum_{m \in m_k} r_{s_k m}^{t_k} + \sum_{y_f \in Y_f} \sum_{s_y \in S_y} r_{s_y f}^{t_y} \leq \gamma_{\text{band}} 
\]

\[
\sum_{s_k \in S_k} \sum_{m \in m_k} r_{s_k m}^{t_k} + \sum_{y_f \in Y_f} \sum_{s_y \in S_y} r_{s_y f}^{t_y} \leq \gamma_{\text{band}} 
\]

SIMULATION PARAMETERS

The simulation parameters are shown in Table 1. The network is composed of seven macrocells, and the HeNBs (i.e., femtocells) are randomly deployed over the macrocells. The number of HeNBs is varied up to 40 in one macrocell coverage area. We assume that the HeNBs operate in closed access mode (i.e., only registered FUE devices will be able to access the HeNBs). The

\[
\sum_{s_k \in S_k} \sum_{m \in m_k} r_{s_k m}^{t_k} + \sum_{y_f \in Y_f} \sum_{s_y \in S_y} r_{s_y f}^{t_y} \leq \gamma_{\text{band}} 
\]

\[
\sum_{s_k \in S_k} \sum_{m \in m_k} r_{s_k m}^{t_k} + \sum_{y_f \in Y_f} \sum_{s_y \in S_y} r_{s_y f}^{t_y} \leq \gamma_{\text{band}} 
\]

**Figure 4.** a) Outage probability of MUE with signal-to-noise ratio (SNR) = 10 dB for different FFR schemes as the SINR threshold varies; b) average network sum rate of MUE for different FFR schemes.
increases (e.g., > 11.5 dB), the outage probability of the strict FFR scheme (in the presence of HeNBs) becomes higher than the proposed scheme and reaches close to that of the soft FFR scheme.

For the proposed scheme, intercell interference to the edge zone MUE is caused by only one HeNB, whereas for the FFR-3 and soft FFR schemes, intercell interference is caused by two and six HeNBs, respectively. As a result, the outage probability is higher for these two FFR schemes. In comparison with the other FFR schemes, in the proposed scheme, the usable subbands for femtocells are increased in the edge and center zones of a cell. As a result, the probability that two neighboring HeNBs would use the same subband and the same subchannel is greatly reduced compared to the other FFR schemes. Therefore, the inter-HeNB interference is significantly reduced. Also, with the proposed scheme, due to the increased number of subbands for HeNBs in both the center and edge zones, the number of subchannels for FUE per unit area increases. This corresponds to a smaller probability of causing cross-tier interference with the MUE in comparison with the other FFR schemes. As a result, the outage probability is comparatively low for the MUE.

Figure 4b shows the variation in average network sum rate as the number of HeNBs varies within the cell. We observe that the average network sum rate for the proposed scheme is higher than that for each of the other FFR schemes. Again, this is due to the reduced co-tier and cross-tier interference and hence higher SINR offered by the proposed scheme. Also, with the proposed scheme, the usable number of subchannels per unit area increases when compared with the other FFR schemes, and consequently the spectral efficiency increases. Figure 5 shows variations in the spectral efficiency of the network as the number of HeNBs varies. Note that for the proposed scheme, with only 25 HeNBs per macrocell service area, the target spectral-efficiency for LTE-A systems (i.e., 30 b/s/Hz [15]) is well satisfied. Also, from Fig. 5, we observe that for the edge zone UE, the average gains in spectral efficiency for the proposed scheme are 27, 41, and 49 percent, compared to the FFR-3, strict FFR, and soft FFR schemes, respectively. With the proposed scheme, for the UE in both the center and edge zones, the average gains in spectral efficiency are 23, 43, and 51 percent, compared to the FFR-3, strict FFR, and soft FFR schemes, respectively.

**CONCLUSION**

FFR is a simple and effective mechanism for interference management in OFDMA-based HetNets. We have presented a broad comparison among four different FFR schemes — strict FFR, soft FFR, FFR-3, and OSFFR schemes for two-tier HetNets in LTE-Advanced systems. Simulation results have shown that the proposed OSFFR scheme offers superior performance than the three other state-of-the-art FFR schemes.

The FFR schemes described in this article correspond to partitioning and allocation of spectrum into different spatial regions of the macrocell service area in a static manner. Such static allocations may not be optimal under dynamic traffic load variation (e.g., due to the mobility of UE) and may increase the blocking probability. Note that an open access mode can reduce this blocking probability resulting from static resource partitioning. Optimal FFR schemes in the presence of mass deployment of HeNBs that satisfy the data rates for UE as well as the target blocking probabilities need to be developed. In this context, self-organizing and autonomous FFR frameworks will be desirable from the scalability point of view. In addition, dynamic power control methods can be developed to use in conjunction with FFR schemes to improve the capacity of HetNets. Such a hybrid scheme based on resource partitioning through FFR as well as power control is currently being considered for LTE-Advanced systems.

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