Spectral Efficiency Analysis of Mobile Femtocell Based Cellular Systems

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Abstract—In this paper, we propose a new concept called mobile Femtocell (MFemtocell) network, which can be considered as a practical implementation of mobile relays (more precisely, moving networks). MFemtocells can be deployed in moving vehicles, such as trains, buses, or private cars to provide enhanced user throughput, extended coverage, and reduction of the signaling overhead and drop calls. We investigate the spectral efficiency for Mobile Femtocell deployment cellular systems with two resource partitioning schemes. Simulation results demonstrate that with the deployment of MFemtocells, the spectral efficiency and average user throughput can significantly be increased while the signaling overhead is reduced.

I. INTRODUCTION

Cooperative multi-hop communications with relays can greatly improve the spectral efficiency and network coverage and has widely been considered as a major candidate technology in various standards, such as in Long Term Evolution (LTE)-Advanced systems. In relay communications, users do not necessarily communicate directly with the base station (BS). Instead, intermediate nodes are used which relay the data to/from the BS \cite{1}. There are two different types of relays, namely, fixed and mobile relays \cite{2}. Fixed relays are deployed at locations according to cell planning and radio optimization to improve the user throughput or to expand the coverage at the cell edge \cite{3}. Mobile relays \cite{4} are moving wireless nodes which fully support relaying functionalities in cellular systems. Two types of mobile relays can further be distinguished, i.e., mobile user relays and moving networks. Mobile user relays are to use handsets within the close vicinity to relay the information to/from the BS. In moving networks, dedicated relays are mounted on moving vehicles, such as trains, buses, or private cars, to receive data from the BS and forward to the users onboard, and vice versa. In previous works, relay communications mostly focused on scenarios with either fixed relays \cite{5}, \cite{6} or mobile user relays \cite{7}, \cite{8}. There has been little research undertaken for moving networks.

Public vehicles, e.g., trains and buses, are moving hotspots with many people potentially requesting diverse data services, e.g., web browsing, video streaming, and gaming. Users inside a moving vehicle may execute multiple handovers at the same time causing a significant increase in signaling load and drop calls to the network. So, it is worth minimizing the signaling load and drop calls within a fast moving vehicle.

Femtocells, also called home BSs or home evolved NodeB (Home eNodB) \cite{9}, are small, low-power data access points installed by home users to get better indoor coverage or improved user throughput with reduced implementation cost \cite{10}. Femtocells can connect to the operator’s core network via legacy broadband connection such as Digital Subscriber Line (DSL) or optical fiber. The same licensed spectrum of the operator can be utilized by Femtocells and therefore the spectral efficiency can be improved. Also, due to the short transmission range between the Femtocell and its users, the transmission power of users can be reduced resulting in longer battery life.

Motivated by the concepts of mobile relays (moving networks) and Femtocells, in this paper we propose a new concept called Mobile Femtocell (MFemtocell). There are, however, many challenges for researching MFemtocells, e.g., the way resources are shared by macrocell and MFemtocell users, spectrum reuse strategy under a number of MFemtocell deployments, and spectral and energy efficiencies.

A number of studies have been done on spectrum sharing in Femtocell \cite{11}–\cite{13} and multi-hop \cite{6} in Orthogonal Frequency-Division Multiple Access (OFDMA) based cellular systems. The Femtocell may share the same spectrum with macrocell (i.e., non-orthogonal mode) or utilize a dedicated spectrum (i.e., orthogonal mode) \cite{11}. In an orthogonal spectrum-sharing network, the Femtocell uses a separate spectrum band that is not used by macrocell BSs. This mode can avoid interference to/from the macrocell, i.e., intra-cell interference. However, additional spectrum resources are required and hence the spectral efficiency will be reduced.

In this paper we study the impact of two resource partitioning schemes that are mentioned above on the spectral efficiency in MFemtocell based LTE-Advanced cellular systems.

The rest of this paper is organised as follows: Section II
gathers the channel state information (CSI) from all users and MFemtocells. Likewise, the users within a MFemtocell will feed back this information but to the MFemtocell only. The terms backhaul link, access link, and direct link are used to denote eNodB-MFemtocell, MFemtocell-user, and eNodB-user links, respectively. The eNodB will transmit data to MFemtocells over backhaul links. A MFemtocell will then fully decode, buffer, and re-transmit the data to its user (Decode-and-Forward multi-hop strategy). We assume that the backhaul, access, and direct links all experience Non-LOS (NLOS) Rayleigh block fading channels, which are kept constant within a sub-frame and change independently in the following sub-frame. We also assume that the backhaul link has a gain \(G\) over the direct link. This gain can be achieved by using a highly directional antenna pattern as well as pointing MFemtocell’s antenna toward the eNodB. Practically, the multi-hop device cannot transmit and receive data simultaneously on the same frequency. Therefore, a division scheme is required, either in the time or frequency domain, to prevent the self interference. In this paper, time division is assumed.

A. Resource Partitioning Schemes

In an OFDMA-based cellular system, the whole spectrum is split into orthogonal sub-channels. These sub-channels are shared by different users by means of opportunistic resource allocation. By bringing in the MFemtocell, the spectrum has to be allocated (or reused) among different links, i.e. the backhaul, access and direct links. Therefore, it is essential to design an efficient resource partitioning policy in the MFemtocell-enhanced system to improve the performance of the whole system and limit the intra-cell interferences. Two resource partitioning policies can be used and are explained as follows:

1) Orthogonal resource partitioning scheme: In this scheme, the radio resources allocated to the backhaul, direct, and access links are all orthogonal either in the time or frequency domain and hence there is no intra-cell interference from the the eNodB to MFemtocell users and vice versa. Therefore, the Signal-to-Noise Ratios (SNRs) for a direct user, SNR\(_{(a)}\), and an access user, SNR\(_{(o)}\), can be calculated by

\[
\text{SNR}_{(a)} = \frac{P_1|h_{eNB}^A|^2}{2BN_o}\quad \text{and} \quad \text{SNR}_{(o)} = \frac{P_2|h_{eNB}^A|^2}{2BN_o},
\]

where \(h_{eNB}^A\) and \(h_{eNB}^B\) are complex-valued channel gains over the direct link and access link, respectively, and \(P_2\) is the MFemtocell transmission power. \(B\) and \(N_o\) are the system bandwidth and the noise spectral density, respectively.

2) Non-orthogonal resource partitioning scheme: In this scheme, the radio resources are reused by the direct and access links. However, the radio resources are still orthogonally allocated between backhaul and direct and between backhaul and access links. Non-orthogonal mode means that there will be an intra-cell interference to the access and direct users due to the simultaneous transmissions from the MFemtocell and eNodB on the same sub-channels. The advantage of this scheme is the improvement in resource utilization compared to the orthogonal scheme. In addition, this scheme gives
the flexibility to implement Radio Resource Management (RRM) at the eNodB and the MFemtocell independently. The received Signal to Interference-plus-Noise Ratio (SINR) for a direct user, denoted as \( \text{SINR}_{(d)} \), can be calculated by
\[
\text{SINR}_{(d)} = \frac{P_r |h_{m,n}^{eNB}|^2}{|h_{n}^{eNB}|^2 + B N_o}
\]
where \( I \) is the intra-cell interference from the MFemtocell. This type of interference can be reduced significantly by constraining the transmission power within the MFemtocell using a directive antenna. On the other hand, the received SINR for an access link user, \( \text{SINR}_{(a)} \), is given by:
\[
\text{SINR}_{(a)} = \frac{P_r |h_{m,n}^{eNB}|^2}{|h_{n}^{eNB}|^2 + B N_o}
\]

(1)

So, the SINR_{(a)} in (1) can be characterized by SNR received from a MFemtocell and SNR received from the eNodB if the same user was served by eNodB instead. Now, if we assume that the distances from the MFemtocell or its users are the same with respect to the eNodB, we have
\[
\text{SINR}_{(a)} = \frac{\text{SINR}_{(d)} |h_{m,n}^{eNB}|^2}{|h_{n}^{eNB}|^2 + B N_o}
\]

The SINR_{(d)} is the SNR for a backhaul channel for MFemtocell \( j \) which can be calculated for both resource partitioning schemes, by
\[
\text{SINR}_{(d)} = \frac{P_r |h_{j}^{eNB}|^2}{|h_{j,n}^{eNB}|^2 + B N_o}
\]

where \( |h_{j,n}^{eNB}|^2 \) is the channel power gain of the backhaul link for MFemtocell \( j \). The interference that originates from the eNodB can be compromised with good propagation quality between the MFemtocell and its users due to shorter range transmissions.

B. MFemtocell Spectrum Reuse

Another form of spectrum reuse scheme can be applied to MFemtocell scenarios to further improve the spectrum utilization. Hence, multiple MFemtocells can use a common set of sub-channels simultaneously to serve their users. However, this can work only if multiple MFemtocells are located large distances apart or the coverage of each MFemtocell is limited to a small area by using a directive antenna.

C. Spectral Efficiency Analysis

Multiuser scheduling is assumed here where the macrocell users and MFemtocells are served over \( K \) RBs, indexed by \( k=1,...,K \), based on the well-known MAX-SINR and Proportional Fair (PF) scheduling policies. With the MAX-SINR scheduler, the eNodB will assign a RB \( k \) to a user \( n \) having the highest instantaneous SINR at a sub-frame \( t \). Thus, arg max_{\mathcal{N}} \( R_{n}(t,k) \), \( k = 1, ..., K \), where \( R_{n}(t,k) \propto \text{SINR}_{n,t}(t,k) \) (or \( \text{SINR}_{n,t}(t,k) \) in non-orthogonal mode) is the instantaneous achievable rate on RB \( k \) for a user \( n \) and is calculated according to the following Shannon formula. In the PF scheduling case, the scheduler allocates the RB \( k \) to a user \( n \in \mathcal{N} \) according to the following criterion:
\[
\bar{n}_k = \text{arg max}_{n \in \mathcal{N}} \frac{R_{n}(t,k)}{R_{n}} \quad k = 1, ..., K
\]

(2)

where \( \bar{R}_{n} \) is the average delivered rate in the past, measured over a fixed window of observation. It can be calculated using an average filtering [14], which will be updated using the following formula:
\[
\bar{R}_{n}(t) = (1 - \frac{1}{T})\bar{R}_{n}(t - 1) + \frac{1}{T} \sum_{k=1}^{K} R_{n}(k,t) \quad d_{n}(k,t)
\]

(3)

where \( T \) is the time window constant, \( d_{n}(k,t) \) is a binary indicator that is set to 1 if the user \( n \) is scheduled on resource block \( k \) at time \( t \) and to 0 otherwise.

The communication over the eNodB-MFemtocell links takes place over a dedicated time-frequency zone, as shown in Fig. 2(a) and Fig. 2(b). Moreover, a set of MFemtocells is selected based on the same scheduling algorithm that has been used to serve macrocell users. Within the MFemtocell, it is assumed that the users \( (\mathcal{M}_j) \) are served according to round-robin policy. In case of the orthogonal scheme, it is assumed that a fraction of the spectrum \( \beta \), \( 0 < \beta < 1 \), is allocated exclusively for direct transmissions in the second portion of the time, as shown in Fig. 4(a). Whereas in the non-orthogonal scheme, the eNodB and MFemtocells can utilise the whole spectrum to serve their users, as shown in Fig. 4(b).

The achievable capacity (in bps/Hz/cell) on the direct link on time \( t \) can be calculated by
\[
C_d(t) = \begin{cases} \frac{\beta}{2B} \sum_{n=1}^{N} \sum_{k=1}^{K} R_{n}(t,k) \quad d_{n}(k,t) & \text{orthogonal} \\ \frac{1}{2B} \sum_{n=1}^{N} \sum_{k=1}^{K} R_{n}(t,k) \quad d_{n}(k,t) & \text{non-orthogonal}. \end{cases}
\]

(4)

The achievable capacity on the access link can be given by
\[
C_1(t) = \begin{cases} \frac{(1-\beta)}{2B} \sum_{m \in \mathcal{M}_j} \sum_{k=1}^{K} R_{m}(t,k) \quad d_{m}(k,t) & \text{orthogonal} \\ \frac{1}{2B} \sum_{m \in \mathcal{M}_j} \sum_{k=1}^{K} R_{m}(t,k) \quad d_{m}(k,t) & \text{non-orthogonal}. \end{cases}
\]

(5)

Where \( R_{m}(t,k) \propto \text{SINR}_{m,n}(t,k) \) is the instantaneous achievable rate for an access user \( m \). However, the rates on access link between MFemtocells and their users are truncated by the achievable capacity of the backhaul link for MFemtocell \( j \), i.e.,
\[
C_1(t) = \frac{1}{2B} \sum_{k=1}^{K} R_{j}(t,k) \quad d_{j}(k,t).
\]

(6)

where \( R_{j}(t,k) \) instantaneous achievable rate over the backhaul link for an MFemtocell \( j \). As a result, the total system capacity (in bps/Hz/cell) after allocating all RBs to the selected users, including MFemtocell users, can be calculated according to:
\[
C_{sys}(t) = \frac{1}{d} \sum_{j=1}^{J} \text{min}[C_1^j(t-\delta), C_2^j(t)] + C_d(t)
\]

(7)

where \( \delta \) is the time required to decode, buffer, and re-encode the incoming data from the backhaul links. The first term
in (7) stands for the achievable capacity of data flow from eNodB to users via MFemtocell and the second term represents the capacity for direct users. It is worth mentioning that the throughput on the backhaul links is not accounted for system capacity because the data are not delivered to the users, but it still bounds the throughput on the access links. However, to get an efficient resource usage over the multi-hop, the rates over the backhaul and access should be equal, i.e., \( C_1 = C_2 \).

IV. SIMULATION RESULTS AND DISCUSSIONS

The performance of the MFemtocell in the LTE system is evaluated using a dynamic system level simulator which is compliant with 3GPP LTE specification [15]. The simulation consists of several iterations and each of them has 20000 sub-frames. In each iteration, the MFemtocells and mobile users are distributed independently. A frequency-selective fading with 6 taps and a certain power delay profile (PDP) are considered. The number of MFemtocell and macrocell users are assumed to be 10 and 40, respectively. Inside each MFemtocell, it has been assumed that there are two active users. LTE frame structure is considered, which consists of blocks of a 12 contiguous sub-carriers in the frequency domain and 7 OFDM symbols in the time domain. One sub-frame (1 ms) is regarded as scheduling period. The carrier bandwidth is fixed at 10 MHz with 50 RBs. All UEs are equipped with a single antenna while the MFemtocells have two antennas working in diversity mode. The gain, \( G \), is assumed to be 8 dB. A full eNodB buffer is considered where there are always buffered data ready for transmission for each node. The users inside the MFemtocell are assumed to be indoor users with 5 dB penetration loss. Other relevant simulation parameters are summarized in Table 1.

Fig. 3 compares the average spectral efficiency of the orthogonal and non-orthogonal scheme in MFemtocell-enhanced scenario as a function to a percentage of users that associate with MFemtocell. As it is clearly shown, increasing the percentage of users that communicate with an eNodB through the MFemtocell leads to an increase in the spectral efficiency compared with reference system of single-hop. In addition to that, the simulation results demonstrate that the performance of the non-orthogonal scheme is better compared to the orthogonal scheme due to spectrum reuse between the eNodB and the MFemtocells.

The user and MFemtocell average throughput Cumulative Distribution Function (CDF) is presented in Fig. 4, where only non-orthogonal scheme and PF scheduling are assumed. While compared to a system without an MFemtocell, it is shown that the average throughput for macro users increased (from 150 Kbps to 300 Kbps). Furthermore, the MFemtocells themselves have a high throughput (around 500 Kbps) due to additional gain in received SINR \( |D| \) on the backhaul link.

Fig. 5 depicts the system throughput of the two partitioning schemes as function to SNR \( |D| \) of the direct link on different cell positions. Here, it has been assumed that all RBs are allocated to only two users: one connected directly to the eNodB and the other through the MFemtocell. Both schemes provide a better performance, as compared to the reference system of single hop especially in middle and edge of the cell. However, when the MFemtocells are moving near the eNodB after SNR \( |D| \) of 14 dB, the performance of orthogonal scheme lags slightly behind the single hop performance due to the high SNR on the direct link, so it worths to transmit directly to users in this case.

V. CONCLUSIONS

In this paper, we have introduced the architecture of Mobile Femtocell which can be a potential candidate for LTE Advanced system. We studied the performance of two resource partitions schemes which can be used for mobile Femtocell deployed scenario in LTE-Advanced system in presence of opportunistic scheduling. Our system-level simulator shows that performance of system with MFemtocell implementation outperforms a system lacking MFemtocell especially on the middle and edge of the cell. The results demonstrate that by using a non-orthogonal scheme an enhanced performance can be achieved compared with orthogonal scheme.

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REFERENCES

TABLE I
SIMULATION PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>eNodB-MFemto</th>
<th>eNodB-UE</th>
<th>MFemto-UE</th>
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<tr>
<td>Antenna height (m)</td>
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<td>2</td>
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<tr>
<td>Shadowing (dB)</td>
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<td>4</td>
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<tr>
<td>Antenna gain (dBi)</td>
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<td>5</td>
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<tr>
<td>Bandwidth (MHz)</td>
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<tr>
<td>Transmitted power (dBm)</td>
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<td>46</td>
<td>20</td>
</tr>
<tr>
<td>Spectrum sharing (β)</td>
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<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Distance (m)</td>
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<td>≥100</td>
<td>≤15</td>
</tr>
</tbody>
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Fig. 1. System model: a single cell with multiple MFemtocells and users.

Fig. 2. Resource partitioning schemes.

Fig. 3. Spectral efficiency of system-level MFemtocells with multi-user scheduling and resource partitioning schemes.

Fig. 4. The CDFs of user & MFemtocell average throughputs.

Fig. 5. Performance of the cell throughput as a function to SNR(β).