Mitigation of Macro-Femto Co-channel Interference by Spatial Channel Separation

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Abstract—Interference mitigation between macro-cell and femto-cells are studied in this paper. Via demonstrating the communications between various transmitter-receiver pairs on different spatial channels could be insulated via proper channel de-correlation at receivers, we propose to separate the transmissions of macro-cell and of femto-cell in spatial domain. Induced challenges such as spatial channel estimation and codeword-to-channel mappings are investigated, and we further adopt the Gibbs sampler to achieve co-channel selection of femto-cells. The proposed solutions can be realized without macro-femto coordinations and additional feedback, and are demonstrated aligned with current 3GPP LTE standardization status. We evaluate the proposed schemes by sophisticated simulations based on the dual-strip model in 3GPP femto-cell evaluation scenarios. It has been shown the SINR of users attached to macro-cell can be improved 60 dB while the SINR of users attached to femto-cells can be maintained about 10 dB. Both the significant performance improvements and backward compatibility implies the proposed scheme is valuable and could be contributed to 3GPP instantly.

Index Terms—Femtocell, HetNet, Co-channel Interference, Spatial, MIMO.

I. INTRODUCTION

Femto-cell is a low-power, lower-cost indoor base station (referred to as Home base station or HBS) which can be easily installed by users and utilizes wire broadband connection (e.g. Digital Subscriber Line, DSL) as backhaul [1]. It has been proposed to next generation wireless systems such as IEEE 802.16m [2] and 3GPP LTE [3] to enhance cell-coverage and user-throughput, to result a network with many femto-cells overlaid on a macro-cell. By introducing femto-cells, indoor users can enjoy high data rate due to the short distance from HBS and operators can reduce the cost to deploy macro-cell base station (MBS) since many users can be served by HBS.

To maximize area spectrum efficiency, it is common to allow macro-cell and femto-cell to share the same spectrum. Theoretically, co-channel deployments benefit both the indoor and outdoor users since more bandwidth are available for each of them. But in fact, such benefits can be realized only when the inter-cell interference can be properly controlled. At the first glance, there shall be two kinds of interference in downlink, one is from MBS to user equipment (UE) attached to HBS (denoted as HUE), another is from HBS to UE attached to MBS (denoted as MUE). There are many researches have been proposed to mitigate the interference by power control [4] - [5] and spectrum allocation [6] - [8]. The concept of power control is to dynamically adjust the transmission power of femto-cell to avoid large interference to MUE while keep acceptable link quality of HUE. And the concept of spectrum allocation is to assign spectrum without interference to HUE and MUE. In additions, the time domain approaches which either configure some frames as blank or shift frames by symbol level to avoid interference has also been proposed to 3GPP standard meetings (e.g. [9]).

In this paper, we mitigate the macro-femto co-channel interference in a different way from all the existing approaches. The propose solution is pioneer to investigate the spatial channel separation which assumes multiple antennas at MBS, HBS and UE. The fundamental idea is to un-correlate the MIMO (Multiple Input Multiple Output) channels between each transmission-receiver pair and let the transmissions of MBS-MUE and HBS-HUE happen on different spatial channels. Since different spatial channels have been un-correlated, no interference would occur. It is worth to mention that, the proposed solution can be implemented without macro-femto coordination and no more feedback information is needed. It is due to the number of spatial channels between each Tx-Rx pair is quite limited, the spatial channel which has not been utilized can be easily detected autonomously. Such detection can be realized by the channel quality indicator (CQI) in current systems and thus no more feedback is necessary. The coordination-free feature of the proposed solution is important in 3GPP scenario since it has been agreed that there is no backhaul coordinations between macro-cell and femto-cells in Rel 10 baseline solutions. And the feedback-free feature is also critical for practical systems since every additional control bit would induce unwanted capacity loss.

In current standardization such as 3GPP LTE and IEEE 802.16m, it has been shown that the interference from HBS to MUE which is in proximity of HBS is more critical than the interference from MBS to HUE. It is due to the penetration loss of the wall can effectively reduce the signal strength, and thus insulate the outdoor and indoor transmissions. This phenomenon make the integration of femto-cell into current systems easier since the current specification of MBS can be reused, and only the transmission schemes of HBS shall be addressed. In this paper, we particularly focus on this
special case and numerically demonstrate 60 db SNR gain from baseline systems of the proposed solution.

II. SYSTEM MODEL

Fig. 1 depicts our system model including two transmitter-receiver pairs as MBS-MUE and HBS-HUE. The transmitted signal vector of HBS and MBS are denoted as $x_1 \in \mathbb{C}^m$ and $x_2 \in \mathbb{C}^n$, where $m$ and $n$ are antenna number of HBS and MBS. Both of $x_1$ and $x_2$ are generated by multiplying the data vector $s_1 \in \mathbb{C}^p$ and $s_2 \in \mathbb{C}^q$ with the pre-coding matrix $\Phi_1 \in \mathbb{C}^{m \times p}$ and $\Phi_2 \in \mathbb{C}^{n \times q}$. The $H_{11} \in \mathbb{C}^{d \times m}$, $H_{21} \in \mathbb{C}^{d \times m}$, $H_{12} \in \mathbb{C}^{d \times n}$ and $H_{22} \in \mathbb{C}^{d \times n}$ are channel matrices from HBS to HUE, from HBS to MUE, from MBS to HUE and from MBS to MUE, where $d$ is antenna number of UE. The received signal vector at HUE and MUE can be represented as follows, where $n_1 \in \mathbb{C}^d$ and $n_2 \in \mathbb{C}^d$ are noise vector.

$$\begin{align*}
\mathbf{r}_1 &= \mathbf{H}_{11}\mathbf{x}_1 + \mathbf{H}_{12}\mathbf{x}_2 + \mathbf{n}_1 \\
\mathbf{r}_2 &= \mathbf{H}_{22}\mathbf{x}_2 + \mathbf{H}_{21}\mathbf{x}_1 + \mathbf{n}_2
\end{align*}$$

(1)

For the receive vector $\mathbf{r}_1$ at HUE the $\mathbf{H}_{12}\mathbf{x}_2$ is interference from MBS, and for the receive vector $\mathbf{r}_2$ at MUE the $\mathbf{H}_{21}\mathbf{x}_1$ is interference from HBS. We then introduce the spatial channel separation to avoid both interference at HUE and MUE.

III. SPATIAL CHANNEL SEPARATION

As we mentioned in section I, the idea of spatial channel separation is to let the MBS and HBS transmit at different spatial channels. In this section, we use an example to clarify this idea and discuss induced implementation challenges.

A. Concept Description by Example

Under the assumption that $m = n = d = 2$, we write the data vector of HBS and MBS as follows.

$$\begin{align*}
\mathbf{s}_1 &= \begin{bmatrix} \alpha \\ 0 \end{bmatrix} \\
\mathbf{s}_2 &= \begin{bmatrix} 0 \\ \beta \end{bmatrix}
\end{align*}$$

(2)

Its the HBS and MBS load their data symbols on spatial channel 1 and 2 respectively. Via this way, the received signal vector at MUE can be represented as follows, where $\mathbf{H}_{22} = \mathbf{H}_{22}\mathbf{\Phi}_2$ and $\mathbf{H}_{21} = \mathbf{H}_{21}\mathbf{\Phi}_1$.

$$\begin{align*}
\mathbf{r}_2 &= \mathbf{H}_{22}\mathbf{\Phi}_2 \begin{bmatrix} 0 \\ \beta \end{bmatrix} + \mathbf{H}_{21}\mathbf{\Phi}_1 \begin{bmatrix} \alpha \\ 0 \end{bmatrix} + \mathbf{n}_2 \\
&= \mathbf{H}_{22} \begin{bmatrix} 0 \\ \beta \end{bmatrix} + \mathbf{H}_{21} \begin{bmatrix} \alpha \\ 0 \end{bmatrix} + \mathbf{n}_2
\end{align*}$$

(3)

If both the $\mathbf{H}_{22}$ and $\mathbf{H}_{21}$ can be estimated at MUE, the received vector $\mathbf{r}_2$ can be transformed to $\mathbf{r}_2'$ as follows.

$$\mathbf{r}_2' = \mathbf{H}_{21}^\dagger \mathbf{r}_2 = \mathbf{H}_{21}^\dagger \mathbf{H}_{22} \begin{bmatrix} 0 \\ \beta \end{bmatrix} + \begin{bmatrix} \alpha \\ 0 \end{bmatrix} + \mathbf{n}_2'$$

(4)

As we observe, the second element of $\mathbf{r}_2'$ can be written as follows, and thus can be detected without interference.

$$\mathbf{r}_2'_{21} = h_2\beta + n$$

(5)

Similarly, the desired signal $\alpha$ at HUE can also be detected without interference as follows.

$$\mathbf{r}_2'_{11} = h_1\alpha + n$$

(6)

By this example, we demonstrate both the MUE and HUE can detect desired signal without interference by spatial channel separation. In the following, we consider implementation issues for applying to practical systems such as 3GPP LTE.

B. Codeword-to-Channel Mapping

As we introduced in section III-A, to utilize spatial channel separation the MBS and HBS shall upload their data symbols on only parts of spatial channels. However, it is not supported by the codeword-to-channel mapping in current 3GPP LTE specifications. Therefore, we propose that the elements of Table I shall be integrated into Table 6.3.3.2-1 in 3GPP Technical Specification 36.211 [10] for femto-cells.

<table>
<thead>
<tr>
<th>Channels</th>
<th>Codewords</th>
<th>Mappings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>$s^{0}(i) = \mu^{(0)}(i), s^{1}(i) = 0$</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>$s^{0}(i) = \mu^{(0)}(i), s^{1}(i) = 0, s^{2}(i) = s^{3}(i) = 0$</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>$s^{0}(i) = \mu^{(0)}(i), s^{1}(i) = \mu^{(1)}(i), s^{2}(i) = s^{3}(i) = 0$</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>$s^{0}(i) = \mu^{(0)}(i), s^{1}(i) = \mu^{(1)}(i), s^{2}(i) = \mu^{(2)}(i), s^{3}(i) = 0$</td>
</tr>
</tbody>
</table>

The notation $\mu$ in Table I denotes the data symbol needed to be uploaded to spatial channel $s$, and the $i$ is symbol index. As observed, we propose to add new mappings to allow MBS and HBS can upload zero symbols to spatial channels (or uploading symbols to only parts of spatial channels).

C. Backward Compatibility

In view of Table I, one backward compatible challenge arises due to it may not be possible to modify current codeword-to-Channel mapping of MBS. It means MBS still have to upload its data symbols to all spatial channels instead of partial. For this case, the interference from MBS to HUE can not be avoided since the signal of MBS occupies all spatial channels. However, as we inferred in section I, due to the penetration loss of the wall the interference from MBS to HUE may not be critical. To confirm this point, we conduct practical simulations in section V to demonstrate that, even the...
MBS utilizes all spatial channels the SINR of HUE can still be maintained acceptable. Therefore, the proposed scheme can be applied to current systems trying to integrating femto-cells without modifying existing codeword-to-channel mapping.

D. Channel State Information

As we introduce the concept of spatial channel separation in section III-A, we assume both the H₂₂ and H₂₁ are known at MUE when detecting desired signal. It means all the H₂₂, Φ₂, H₂₁ and Φ₁ shall be estimated reliably at MUE, and all the H₁₁, Φ₁, H₁₂ and Φ₂ shall be available at HUE. Obviously, it may not be reasonable assumptions unless special attention is paid. In this subsection, we take 3GPP LTE as example to demonstrate the proposed spatial channel separation is compatible with current standardization status of femto-cell.

Two kinds of baseline solutions for macro-femto interference mitigation are agreed in 3GPP [11] until now, one is power setting and another is time domain approach. The time domain approaches fall into two classes as blank frame configuration and symbol-level shifting. The idea of blank frame configuration is to mute femto-cell transmissions in some frames to reduce the interference to macro-cell transmissions on both control and data channels. On the other hand, the idea of symbol level shift is to shift the frame transmission time of femto-cell to avoid interference to control channels of macro-cell. Fig. 2 depicts one example of symbol level shift proposed to 3GPP LTE. In this case, the control channels occupies the first three OFDM symbols (pink part) of one sub-frame, and thus shift the frame transmission time of HBS by 2 OFDM symbols can avoid most control channel interference between macro-cell and femto-cell. As we mentioned above, to apply the proposed spatial channel separation to further cancel data channel interference, MUE need to estimate all the H₂₂, Φ₂, H₂₁ and Φ₁. Obviously, MUE can obtain H₂₂ and Φ₂ in regular way since it is attached to MBS. To obtain H₂₁ and Φ₁, MUE need to decode the control message (pink part) and reference signal (blue part) of HBS. Since from Fig. 2 we can observe that both the control message and reference signal of MBS and HBS are transmitted at different time, theoretically MUE can detect H₂₁ and Φ₁ reliably.

IV. FEMTO-CELL CO-SPATIAL-CHANNEL SELECTION BY GIBBS SAMPLER

To separate transmissions of MBS and HBS to different spatial channels, we need all femto-cells to select the same spatial channel. Since the backhaul coordination among femto-cells may not practically be possible, distributed co-spatial-channel selection become critical. In this section, we introduce Gibbs sampler [12] to conquer this challenge.

A. Review of Gibbs Sampler

Consider an undirected graph with K nodes, in which two nodes are neighbor if they are connected by an edge. Each node k is with a state s_k ∈ S, and we define the state vector for the graph as s = [s₁ s₂ ... sₖ]ᵀ. In our case, the node k denotes the femto-cell k and the state s_k is the spatial channel that femto-cell k selected. A clique of order n is defined as a set having n nodes in which every pair of nodes are neighbor, while the set of all cliques with order n is represented as C(n). A global energy function E(s) is then defined as follows.

\[
E(s) = \sum_{n} \sum_{\mathcal{B} \in \mathcal{C}(n)} V(\mathcal{B}) \tag{7}
\]

where V(\mathcal{B}) is potential function which associates non-negative real number to all subsets of nodes in \mathcal{B}. Another local energy function of node k can be derived from global energy function as follows.

\[
E_k(s_k, s_i \neq k) = \sum_{n} \sum_{\mathcal{B} \in \mathcal{C}(n)} V(\mathcal{B}) \tag{8}
\]

Given the global and local energy function, Gibbs sampler provides a procedure to minimize global energy. In which every node updates its state by sampling a random variable over the state set S according to the following probability distribution p(s) which depends only on local energy (and thus is distributed approach).

\[
p(s) = \frac{e^{-\frac{E_k(s_k, s_i \neq k)}{T}}}{\sum_{s' \in S} e^{-\frac{E_k(s', s_i \neq k)}{T}}} \tag{9}
\]

In our cases, the global energy can be defined as minus of total interference that all femto-cells experienced from all other femto-cells. Since Gibbs sampler can minimize global energy (and thus maximize total interference), all femto-cell are selecting the same spatial channel.

B. Co-Spatial-Channel Selection by Gibbs Sampler

Since our target is to maximize total interference (and thus minimize global energy), by slightly modifying the potential function proposed in [13], we use the following definitions.

\[
V(\mathcal{B}) = 0, \quad \text{for } \mathcal{B} \in \{k\}
\]

\[
V(\mathcal{B}) = -I(k, k'), \quad \text{for } \mathcal{B} \in \{k, k'\} \tag{10}
\]

\[
V(\mathcal{B}) = 0, \quad \text{for } |\mathcal{B}| \geq 3
\]
In the proposed potential function, the $I(k, k')$ is the interference from femto-cell $k'$ to $k$ if both of them are using the same spatial channel. The local energy function can then be specified as follows.

$$E_k = -\sum_{k' \neq k} I(k, k')$$

(11)

As we mentioned above, we use $-I(k, k')$ instead of $I(k, k')$ since the target of Gibbs sampler is to minimize global energy but our target is to maximize interference. Following this way, we provide an algorithm based on the one proposed in [13] for femto-cells to select the same spatial channels.

**Algorithm 1** FEMTO-CELL SPATIAL CHANNEL SELECTION

1: Compute the temperature parameter: $T = \frac{T_0}{\log_2(2+t)}$.
2: Each femto-cell compute local energy $E_k$ for each spatial channel.
3: For every spatial channel, compute $p(s)$ for each spatial channel.
4: Sample a random variable over $S$ by $p(s)$ and update its spatial channel accordingly.

In this algorithm, $t$ is age variable representing system time of each femto-cell. $T_0$ is the parameter determining the speed of convergence (the speed that all femto-cells converge to the same spatial channel).

**V. SIMULATION**

In this section, we conduct a sophisticated simulation completely based on 3GPP dual strip model for femto-cell evaluation to evaluate the proposed spatial channel separation. We start from introducing the simulation environment and parameters, and then demonstrating the numerical results.

**A. Environment and Parameters**

Fig. 3 depicts our simulation environment including one macro-cell with three sectors and each sector embraces one apartment block. There is one floor in every apartment block and each apartment block includes two strips. Total of 40 apartments are included in one apartment block (the wall inside the apartment block) and outer wall (the wall of the apartment block) can effectively reduce the macro-femto interference. Therefore, practically simulate the penetration loss is critical in femto-cell evaluations. The minimum distance between MBS and UE, HBS and UE and MBS and HBS are set to 35 m, 3 m and 75 m. The antenna pattern of HBS is assumed to be Omni-directional with 5 dB gain, but the antenna pattern of MBS is assumed as follows with 14 dB antenna gain. Both of the antenna setups are strictly following the appendix B in [14].

$$A(\phi) = -\min\{12(\phi/\phi_{\text{max}})^2, A_m\}.$$  

$$\phi_{\text{max}} = 70\,\text{degrees},\, A_m = 25\,\text{dB}.$$  

(12)

Based on the dual-strip model and simulation parameters, we can evaluate the proposed spatial channel separation under a practical scenario and obtain valuable results applicable to advanced systems such as 3GPP LTE and WiMAX.

**B. Numerical Results**

We evaluate the performance of the proposed scheme by showing the signal to interference and noise ratio (SINR) of MUE and HUE with and without spatial channel separation in Fig. 4 and Fig. 5. In both of the figures, the scheme “baseline” means there is no interference control mechanism applied while the scheme “spatial channel separation” denotes the approach proposed in section III. The parameter $\alpha$ denotes the percentage of active femto-cell in one apartment block. From Fig. 4, we first observe that in baseline the SINR of HUE under $\alpha = 25\%$ and $\alpha = 50\%$ differs about 3 dB, it is due

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>2 GHZ</td>
</tr>
<tr>
<td>Transmission Bandwidth</td>
<td>10 MHZ</td>
</tr>
<tr>
<td>Number of Antenna</td>
<td>2</td>
</tr>
<tr>
<td>Macro Transmission Power</td>
<td>46 dBm</td>
</tr>
<tr>
<td>Femto Transmission Power</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Femto Active Ratio</td>
<td>$\alpha = 25%$ or $50%$</td>
</tr>
<tr>
<td>Indoor MUE Ratio</td>
<td>$\beta = 35%$ or $80%$</td>
</tr>
<tr>
<td>Path Loss and Shadowing</td>
<td>Table A.2.1.1.2-8 in [14]</td>
</tr>
<tr>
<td>Penetration loss</td>
<td>Table A.2.1.1.2-8 in [14]</td>
</tr>
<tr>
<td>Channel Model</td>
<td>Rayleigh fading</td>
</tr>
<tr>
<td>Min. Macro-to-UE distance</td>
<td>35 m</td>
</tr>
<tr>
<td>Min. Femto-to-UE distance</td>
<td>3 m</td>
</tr>
<tr>
<td>Min. Macro-to-Femto distance</td>
<td>75 m</td>
</tr>
<tr>
<td>Antenna Pattern of HBS</td>
<td>Omni with 5 dB gain</td>
</tr>
<tr>
<td>Antenna Pattern of MBS</td>
<td>Table A.2.1.1-2 in [14]</td>
</tr>
</tbody>
</table>

**TABLE II: Simulation Parameters**

In Table II we list parameters used in our simulation, where transmission power of MBS and HBS are set as 46 dBm and 20 dBm, and the number of antennas at MBS, HBS and users are assumed as 2. The femto active ratio

denotes the fraction of active HBS in one apartment block, while the indoor MUE ratio denotes the fraction of MUE located inside apartment blocks. Path loss, shadowing and penetration loss are generated according to 3GPP setup in table A.2.1.1.2-8 of [14]. Among the three effects, penetration loss plays a critical role in femto-cell evaluations. It is due to the signal strength degradation due to the inner wall (the wall inside the apartment block) and outer wall (the wall of the apartment block) can effectively reduce the macro-femto and femto-femto interference. Therefore, practically simulate the penetration loss is critical in femto-cell evaluations. The minimum distance between MBS and UE, HBS and UE and MBS and HBS are set to 35 m, 3 m and 75 m. The antenna pattern of HBS is assumed to be Omni-directional with 5 dB gain, but the antenna pattern of MBS is assumed as follows with 14 dB antenna gain. Both of the antenna setups are strictly following the appendix B in [14].

In Fig. 4, we first observe that in baseline the SINR of HUE under $\alpha = 25\%$ and $\alpha = 50\%$ differs about 3 dB, it is due

![3GPP Dual-Strip Model for Femto-cell Evaluation](image-url)  

Fig. 3: 3GPP Dual-Strip Model for Femto-cell Evaluation.
to the more active femto-cells implies the higher interference to HUE. For SINR of MUE under baseline, the curve appears ‘S’ shape due to the 35% MUE inside the apartment block suffer severer interference from HBS than the other 65% MUE outside the apartment block. Considering the curves under spatial channel separation, it can be easily observed that significant MUE SINR improvement (about 60 dB) is achieved while slight SINR improvement (about 3dB) for HUE. It is because for MUE the only interference sources are from femto-cell, and thus can achieve very high SINR when insulating the MBS transmissions from HBS transmissions. But for femto-cells, it suffer interference from both macro-cell and femto-cells. It means even one HUE is free of interference from macro-cell due to spatial channel separation, it also experience interference from other femto-cells using the same spatial channel. However, it may not be a trouble for HUE since its SINR is still quite high (more than 80% HUE are with SINR higher than 10 dB). Since the interference from macro-cell to HUE is not serious due to the outer wall penetration loss, applying spatial channel separation to macro-cell may not be necessary. It undoubtedly supports our inference of backward compatibility in section III-C.

In Fig. 5, we further demonstrate the SINR of MUE and HUE when β = 80% MUE are inside apartment blocks. The transmissions from macro-BS to macro-UE are insulated from the transmissions from femto-BS to femto-UE by using orthogonal spatial channels. The induced challenges of codeword-to-channel mapping, backward compatibility and spatial channel estimations are studied under 3GPP LTE scenario. Gibbs sampler is further introduced to conquer the challenge of femto-cell distributed co-channel-selection. The evaluation of the proposed scheme is by sophisticated simulations based on 3GPP femto-cell evaluation scenario. We demonstrate the SINR of macro-UE can be significantly improved more than 60 dB to 30 dB and the SINR of femto-UE can be improved to 10 dB. All the results show that the proposed scheme is good at performance and can be proposed to the standardization of advanced systems such as 3GPP LTE without much specification impact.

VI. CONCLUSION
In this paper we propose spatial channel separation to mitigate the interference between macro-cell and femto-cells. The transmissions from macro-BS to macro-UE are insulated from the transmissions from femto-BS to femto-UE by using orthogonal spatial channels. The induced challenges of codeword-to-channel mapping, backward compatibility and spatial channel estimations are studied under 3GPP LTE scenario. Gibbs sampler is further introduced to conquer the challenge of femto-cell distributed co-channel-selection. The evaluation of the proposed scheme is by sophisticated simulations based on 3GPP femto-cell evaluation scenario. We demonstrate the SINR of macro-UE can be significantly improved more than 60 dB to 30 dB and the SINR of femto-UE can be improved to 10 dB. All the results show that the proposed scheme is good at performance and can be proposed to the standardization of advanced systems such as 3GPP LTE without much specification impact.

REFERENCES