A Precoder for Reducing Downlink Interference from Femtocells to Macro Users Based on Cognitive Radio

Xueying Hou, Wei Ling, Zhikun Xu and Chenyang Yang
School of Electronics and Information Engineering, Beihang University, Beijing, P. R. China
e-mail: hxymr@ee.buaa.edu.cn

Abstract—**This paper proposes a preprocessor for femtocell base stations to avoid the downlink interference to the macro users, where both systems are multicarrier systems. By using the concept of cognitive radio, we design a low complexity transmitter including a precoder followed by a power allocation. With the judicious design of the interference tolerant constraints, the performance degradation of the macro user is controlled to be less than a predetermined value. Simulation results show that the spectrum efficiency of the femtocell system with the presented transmitter is improved significantly.**

Keywords-precoding; femtocell; interference; cognitive radio

I. INTRODUCTION

To increase system throughput and eliminate dead zones in traditional homogeneous networks, femtocells are introduced recently which include low-power Home enhanced node B (HeNB) for providing cellular services within home or enterprise environments [1]. A femtocell can devote a large portion of its resources (i.e., transmit power and bandwidth) to its subscriber. However, due to the co-channel deployments with the macrocells, the femtocells act as interferers to the macro users (MUEs) in the downlink transmission, especially when the femtocells only serve the close subscriber groups [2]. Thereby the interference management between femtocells and macrocells should be carefully considered.

If the femtocell and the macrocell systems access the spectrum orthogonally either in a static [2] or in a dynamic way [3], the interference from HeNB to MUE will vanish. However, this is not optimal and will reduce the spectral efficiency. With power control the interference from the femtocells to the macrocell is reduced effectively [4], but the potential of the femtocells is not fully exploited.

In practice, HeNBs are installed and turned on or off by customers. As a result, there may be many HeNBs in a macrocell and these HeNBs are located in an ad hoc manner. Furthermore, the topology of the HeNBs may be dynamic, which is hard to be controlled by the operators. This leads to the difficulty of the interference management. In fact, the co-existence of the macrocell and the femtocells is quite similar to the co-existence of the primary and secondary systems in cognitive radio systems [6,7]. Consequently, we can regard the macrocell as a primary system whereas regard the femtocells as the secondary systems, i.e., the femtocells should adjust their transmit strategy to minimize the interference to the MUE.

In this paper, we propose a preprocessor for the HeNBs with the principle of cognitive radio to reduce the downlink interference from the HeNBs to the MUE. After formulating the transceiver design as an optimization problem that minimizing the mean square error (MSE), we resort a heuristic method to reduce the complexity. To ensure the interference to the MUE to be less than a predetermined threshold, we provide a feasible approach for multiple HeNBs to obtain their respective interference tolerant constraints.

Notations: Boldface upper and lower case letters $\mathbf{X}$ and $\mathbf{x}$ represent matrices and vectors and standard lower case letters x denote scalars. $\mathbf{X}^T$, $\mathbf{X}^H$, $\mathbf{X}^{-1}$ and $\mathrm{Tr}(\mathbf{X})$ denote the transpose, the Hermitian conjugate transpose, the inverse and the trace of $\mathbf{X}$. $\mathrm{diag}\{\mathbf{x}\}$ is a diagonal matrix with the elements of $\mathbf{x}$. $\mathrm{E}(x)$ represents the expectation of a random variable x. $\mathbf{I}_N$ denotes an $N \times N$ identity matrix.

II. SYSTEM AND SIGNAL MODELS

A. System Model

We consider a scenario where a macrocell contains a Macro enhanced node B (MeNB) and K MUEs. M HeNBs are also located in the macrocell and each HeNB serves one home user (HUE). An example topology with one macrocell and two femtocells is illustrated in Fig. 1.

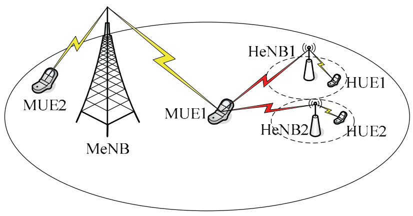

Fig. 1. Topology of a HetNet, where MeNB is the Macro base station

Orthogonal frequency division multiple access (OFDMA) is considered for downlink transmission in the macrocells, where the entire spectral band with N_s subcarriers is divided into M groups and each group with N_p subcarriers is allocated to a MUE. Universal frequency reuse is considered, so that both macro cell and femtocells operate on the same spectral band. We assume that the femtocells transmit to their HUEs with whole bandwidth using OFDM modulation, whose subcarrier spacing is the same as the macro system. Such an assumption is realistic which complies with the existing or forthcoming systems such as LTE Advanced systems [8]. Time division duplexing (TDD) system is considered, where the channels of the uplink and downlink are reciprocal.

B. Signal Model of Femtocells

Denote the frequency domain signal vector transmitted from the ith HeNB to its user as $\mathbf{d}_i = [d_i(0), \cdots, d_i(N_s-1)]^T$. After preprocessed by a matrix $\mathbf{B}_i$, the transmit OFDM symbol in time domain of the ith HeNB can be expressed as

$$\mathbf{x}_i^t = \mathbf{F}^H \mathbf{x}_i^f = \mathbf{F}^H \mathbf{B}_i \mathbf{d}_i, \quad (1)$$

where $\mathbf{F}$ is the $N_s \times N_s$ Fourier transform matrix.

Assume that the cyclic prefix (CP) of the OFDM symbol is long enough such that there is no inter-symbol interference. We further assume that the HUE and the HeNB are synchronous in both symbol timing and carrier frequency. Then the received signal of the ith HUE after removing CP is

$$\mathbf{y}_i^t = \mathbf{H}_i^{hh} \mathbf{x}_i^t + \mathbf{z}_i, \quad (2)$$

where $\mathbf{H}_i^{hh}$ is a $N_s \times N_s$ circulant matrix whose first column is $\mathbf{h}_i^{hh} = [h_i^{hh}(0), \cdots, h_i^{hh}(L_i^{hh}-1), 0, \cdots, 0]^T$, which is the channel impulse response (CIR) between the ith HeNB and its serving HUE, L_i^{hh} is the number of resolvable paths, $\mathbf{z}_i$ represents the interference plus noise at the ith HUE.

$\mathbf{H}_i^{hh}$ can be decomposed as $\mathbf{H}_i^{hh} = \mathbf{F}^H \mathbf{\Lambda}_i^{hh} \mathbf{F}$ [9], where $\mathbf{\Lambda}_i^{hh} = \mathrm{diag}\{[\lambda_i^{hh}(0), \cdots, \lambda_i^{hh}(N_s-1)]\}$ is the diagonalized channel frequency response (CFR) between the ith HeNB and its serving HUE, the kth diagonal entry $\lambda_i^{hh}(k)$ is the CFR at the kth subcarrier.

The HUE firstly transforms the received signal to the frequency domain, and then uses a linear processor $\mathbf{G}_i$ to estimate the transmitted signal vector, i.e.,

$$\hat{\mathbf{d}}_i = \mathbf{G}_i \mathbf{F} \mathbf{y}_i^t. \quad (3)$$

C. Signal Model of Macrocell

Assume that the jth MUE is located near the femtocells, and denote the set of subcarriers used by the jth MUE as Γ_j. In the following, we omit the index of the MUE for brevity.

Although symbol timing synchronization may be possible in practice, carrier frequency synchronization is hard to achieve between the HeNB and the MUE when the femtocells and the macrocell are non-cooperative. We assume that a frequency offset δ_f^i exists between the ith HeNB and the victim MUE, which can be estimated by HeNB via overhearing the training signal from the MUE [7].

Denote the CIR between the ith HeNB and the MUE as $\mathbf{h}_i^{hm} = [h_i^{hm}(0), \cdots, h_i^{hm}(L_i^{hm}-1), 0, \cdots, 0]^T$, then the interference signal vector received by the MUE in time domain can be expressed as

$$\mathbf{u}_i^t = \mathbf{\Delta}_i^f \mathbf{H}_i^{hm} \mathbf{F}^H \mathbf{B}_i \mathbf{d}_i = \mathbf{\Delta}_i^f \mathbf{F}^H \mathbf{\Lambda}_i^{hm} \mathbf{B}_i \mathbf{d}_i, \quad (4)$$

where $\mathbf{\Delta}_i^f = \mathrm{diag}\{[1, e^{j2\pi\frac{\delta_i^f}{N_s f_s}}, \cdots, e^{j2\pi\frac{(N_s-1)\delta_i^f}{N_s f_s}}]\}$ represents the diagonalized frequency offset vector, f_s denotes the subcarrier spacing, $\mathbf{H}_i^{hm} = \mathbf{F}^H \mathbf{\Lambda}_i^{hm} \mathbf{F}$ is a $N_s \times N_s$ circulant matrix whose first column is $\mathbf{h}_i^{hm}$, $\mathbf{\Lambda}_i^{hm} = \mathrm{diag}\{\lambda_i^{hm}(0), \cdots, \lambda_i^{hm}(N_s-1)\}$ is the diagonalized CFR between the ith HeNB and the victim MUE.

We assume that the interference channel matrix $\mathbf{H}_i^{hm}$ can also be estimated by HeNB via overhearing the training signal transmitted from the MUE.

Then the interference signal from the ith HeNB to the victim MUE at the kth subcarrier is

$$u_i^f(k) = \mathbf{a}_k^H \mathbf{F} \mathbf{u}_i^t = \mathbf{a}_k^H \mathbf{F} \mathbf{\Delta}_i^f \mathbf{F}^H \mathbf{\Lambda}_i^{hm} \mathbf{B}_i \mathbf{d}_i, \ k \in \Gamma \quad (5)$$

where Γ is the set of subcarrier positions used by the MUE and $\mathbf{a}_k$ denotes a column vector with 1 at the kth position and 0 in other positions.

The received signal at the kth subcarrier of MUE is

$$r^f(k) = \lambda^{mm}(k) s(k) + \sum_{i=1}^{M} u_i^f(k) + u_{out}(k) + n(k), k \in \Gamma \quad (6)$$

where $s(k)$ is the frequency domain transmit signal for MUE, $\lambda^{mm}(k)$ is the CFR at the kth subcarrier between the MeNB and the MUE, $u_{out}(k)$ denotes the interference signal from other MeNBs, $n(k)$ is the additive white Gaussian noise with zero mean and variance σ_n^2.

III. A PREPROCESSOR AT THE HENB

In this section, we will design the transceiver of each femtocell which ensures the performance of the MUE meanwhile improves the performance of the femtocell.

A. Problem Formulation

The pre-processing matrix $\mathbf{B}_i$ and the post-processing matrix $\mathbf{G}_i$ for the ith HeNB and its serving HUE can be jointly designed by minimizing the MSE of the receive signal [7]. From (3), the estimation error of the data symbol of the ith HUE can be obtained as

$$\mathbf{e}_i = \hat{\mathbf{d}}_i - \mathbf{d}_i = (\mathbf{G}_i \mathbf{F} \mathbf{H}_i^{hh} \mathbf{F}^H \mathbf{B}_i - \mathbf{I}_{N_s}) \mathbf{d}_i + \mathbf{G}_i \mathbf{F} \mathbf{z}_i. \quad (7)$$

Then, the MSE is $\mathrm{Tr}(\mathrm{E}(\mathbf{e}_i \mathbf{e}_i^H))$. Given $\mathbf{B}_i$, it is not hard to derive $\mathbf{G}_i$ as [7],

$$\mathbf{G}_i = \mathbf{B}_i^H \mathbf{F} (\mathbf{H}_i^{hh})^H \mathbf{T}_i^{-1} \mathbf{F}^H, \quad (8)$$

where $\mathbf{T}_i = \mathbf{H}_i^{hh} \mathbf{F}^H \mathbf{B}_i \mathbf{B}_i^H \mathbf{F} (\mathbf{H}_i^{hh})^H + \mathbf{R}_i^{\mathbf{z}}$, $\mathbf{R}_i^{\mathbf{z}} = \mathrm{E}[\mathbf{z}_i \mathbf{z}_i^H]$ is the covariance matrix of the interference plus noise experienced by the ith HUE.

Now the problem of minimizing the MSE only involves $\mathbf{B}_i$.

To ensure the performance of the MUE when femtocells are active, the interference energy from the ith HeNB to the MUE at each subcarrier should be lower than an interference threshold, $P_{th}^i(k)$, i.e.,

$$\mathrm{E}(|u_i^f(k)|^2) \le P_{th}^i(k), \quad k \in \Gamma, i = 1, \cdots, M. \quad (9)$$

Consider that the transmit power of the ith HeNB should satisfy its maximal transmission power constraint $P_{\max}^i$, then the optimization problem can be formulated as

$$\begin{aligned} \min_{\mathbf{B}_i} \quad & \mathrm{Tr}(\mathrm{E}(\mathbf{e}_i \mathbf{e}_i^H)) \\ s.t. \quad & \mathrm{Tr}(\mathbf{B}_i \mathbf{B}_i^H) \le P_{\max}^i \\ & \mathrm{E}(|u_i^f(k)|^2) \le P_{th}^i(k), \ k \in \Gamma \end{aligned} \quad (10)$$

This is a convex problem, which can be solved by using the primal-dual interior point method [7]. However, the computational complexity is prohibited for practical use. In the sequel, we propose a heuristic solution to design the preprocessing matrix $\mathbf{B}_i$.

B. Low Complexity Preprocessor

In order to reduce the complexity, we decouple the preprocessing matrix into a power allocation matrix and a precoding matrix as

$$\mathbf{B}_i = \mathbf{B}_i^{'}\mathbf{P}_i , \tag{11}$$

where $\mathbf{P}_i = \text{diag}\{[\sqrt{p_0^i},\cdots,\sqrt{p_{N_s-1}^i}]\}$ is the power allocation matrix, $p_k^i, k = 0,1,\cdots,N_s-1$, is the transmit power of the *i*th HeNB for the *k*th symbol $d_i(k)$, and $\mathbf{B}_i^{'}$ is a unitary matrix.

Consider that the frequency offset between the HeNB and the MUE will lead to inter-subcarrier interference, we design the precoding matrix $\mathbf{B}_i^{'}$ to map the interference channel $\mathbf{H}_i^{hm}$ into multiple orthogonal subspaces. Then we design the power allocation matrix $\mathbf{P}_i$ to meet the interference tolerant constraints on the subspaces used by the MUE.

To this end, we rearrange the channel matrix between the HeNB and the MUE as

$$\overline{\mathbf{H}}_i^{hm} = [\overline{\mathbf{H}}_{Pi}^H \quad \overline{\mathbf{H}}_{NPi}^H] , \tag{12}$$

where $\overline{\mathbf{H}}_{Pi} = \mathbf{F}_M \boldsymbol{\Delta}_i^f \mathbf{H}_i^{hm}$, $\mathbf{F}_M \in \mathbb{C}^{N_p \times N_s}$ is the N_p rows of $\mathbf{F}$ with indexes as the subcarrier indexes used by the MUE, $\overline{\mathbf{H}}_{NPi} = \mathbf{F}_{NM} \boldsymbol{\Delta}_i^f \mathbf{H}_i^{hm}$, $\mathbf{F}_{NM} \in \mathbb{C}^{(N_s-N_p)\times N_s}$ is the rest rows of the matrix $\mathbf{F}$ with $\mathbf{F}_M$ being removed.

To obtain an orthogonal subspace of the interference channel, we apply QR decomposition to the rearranged channel matrix

$$\overline{\mathbf{H}}_i^{hm} = \mathbf{U}_i \mathbf{R}_i , \tag{13}$$

where $\mathbf{U}_i$ is a unitary matrix, and $\mathbf{R}_i$ is an upper triangular matrix. Then we obtain the frequency domain precoding matrix as $\mathbf{B}_i^{'} = \mathbf{F}\mathbf{U}_i$.

In typical settings, the bandwidth used by femtocell systems will be larger than that of the victim MUE in macrocell system. This is especially true when the femtocell is located at the cell edge of the macrocell. In this case, we only need to control the transmit power of the HeNBs on the subcarriers occupied by MUE to be lower than a threshold. We can improve the transmission performance of femtocells by power allocation to transmit more power on the subcarriers which are not used by MUE. The optimal power allocation $\mathbf{P}_i$ matrix can be obtained by the well known multilevel water-filling method [10]. It is worth to note that the power constraints are on account of the subcarriers rather than the transmit symbol. We can observe from (5) and (9) that even when the interference tolerant constraints to different carriers are all equal, the equivalent interference tolerant constraints to different symbol, $d_i(n)$, differ.

C. Interference Threshold

In practice, the distance between the MUE and the HeNB will vary due to the movement of MUE. Moreover, the HeNBs can be either placed far from the MeNB or near the MeNB, thereby the allowed maximal transmit power of HeNBs $P_{\max}^i$ will also depends. We need to judiciously design the interference threshold P_{th}^i to guarantee the performance of the MUE for all possible scenarios.

We propose the following criterion to design the interference threshold in an adaptive way. We let the normalized performance reduction of MUE at each subcarrier be no larger than a predetermined value, i.e,

$$\frac{r_0(k) - r_I(k)}{r_0(k)} \le \eta , \; k \in \Gamma \tag{14}$$

where $r_0(k)$ is the data rate that the MUE can achieve at the *k*th subcarrier when there are no interference from the HeNBs, and $r_I(k)$ is the rate when there are interference from the HeNBs.

Since we consider that *M* HeNBs act as interference to the MUE, $r_0(k)$ and $r_I(k)$ can be respectively expressed as

$$r_0(k) = \log_2[1 + S(k)/N(k)] , \tag{15}$$

$$r_I(k) = \log_2[1 + S(k)/(N(k) + I_{sum}(k))] , \tag{16}$$

where $S(k) = |\lambda^{mm}(k)|^2$ is the received signal power of the MUE from the MeNB, $N(k) = |u_{out}(k)|^2 + |n(k)|^2$ is the thermal noise power plus the total interference power from other MeNBs, and $I_{sum}(k)$ is the sum interference power from all HeNBs. $I_j(k) = |u_i^f(k)|^2$

When $S(k)$ and $N(k)$ are known, the allowed maximal sum interference power $I_{sum}(k)$ can be obtained by substituting (15) and (16) into (14) as

$$I_{sum}^{\max}(k) = \frac{S(k)}{(1 + \frac{S(k)}{N(k)})^{1-\eta} - 1} - N(k) . \tag{17}$$

Then the interference threshold of the *i*th HeNB can be calculated as

$$P_{th}^i(k) = \frac{I_i(k)}{\sum_{i=1}^{M} I_i(k)} I_{sum}^{\max}(k) , \tag{18}$$

where $I_j(k) = |u_i^f(k)|^2$ is the interference power from the *j*th HeNB to the victim MUE when no interference coordination is employed.

To compute $P_{th}^i(k)$, both $I_{sum}^{\max}(k)$ and $I_j(k)$, *j*=1,…,*M*, should be known as a priori. Considering that there could be some signaling exchange between the MeNB and the HeNBs, we suggest that the MeNB first collects all the needed information and computes the interference threshold for each HeNB, then send them to each HeNB through backhaul link.

In practice, considering the feedback delay, it is impossible for the MeNB to obtain the instant information on the subcarriers used by MUE. Thus we use the long term average information to take the place of the instant information required by the computation of $P_{th}^i(k)$. Specifically, we assume that each HeNB can firstly sense the average interference power from itself to the victim MUE, i.e., $\overline{I}_i$, and then transmit it to the MeNB through backhaul link. We further assume that the MeNB can obtain the average signal power and average SINR of the MUE, i.e., $\overline{S}$ and $\overline{\text{SINR}}$, which is realistic because these can be acquired in practical system through the feedback of the received power of the reference signal and the wideband channel quality indicator. The average noise power can be calculated as follows when $\overline{S}$, $\overline{\text{SINR}}$ and $\overline{I}_i$ are known as a priori,

$$\overline{N} = \frac{\overline{S}}{\overline{SINR}} - \sum_{i=1}^{M} \overline{I}_i \quad . \tag{19}$$

Substituting $\overline{S}$, $\overline{\text{SINR}}$, $\overline{I}_i$ and $\overline{N}$ into (18), we can obtain a unified interference threshold of the *i*th HeNB for all the subcarriers occupied by the MUE.

IV. Simulation Results

Now we evaluate the performance of the proposed method. A topology with 7 macrocells and 3 sectors in each cell is considered. The inter-site distance is 500m. We consider that two HeNBs are located in each sector. The line between the two HeNBs is perpendicular to the line between the MeNB and the midpoint of two HeNBs, and the distance between MeNB and the midpoint is d=150m. The HUE is 3 meter away from its HeNB and the location of MUE is along the line between MeNB and the midpoint of the two HeNBs.

The transmit power of MeNB and HeNB are 46dBm and 20dBm respectively, and the terminal noise power is -95dBm. The carrier frequency is 2G Hz, the subcarrier spacing is 15k Hz, $N_s = 128$ and $N_P = 32$. The pathloss model is the same as that in [8]. The frequency offsets between all HeNBs and MUE are uniformly distributed between 0 ppm and 0.3 ppm [11]. The performance degradation value of MUE, i.e., η, is set as 5%.

We compare the performance of the proposed method with the case using orthogonal frequency splitting between the macrocell and femtocell systems as well as the case without any interference coordination. In Fig. 2 and Fig. 3, we present the spectrum efficiency of the MUE and the HUE versus d^{hm}, which represents the distance between the MUE and the midpoint of two HeNBs. It is observed that the performance degradation of the MUE over the orthogonal transmission scheme is about 0.2bps/Hz, while the performance increase of the HUE improves from 1.7 bps/Hz to 2.7 bps/Hz when the MUE moves away from the HeNBs.

V. Conclusions

In this paper we proposed a low complexity transmit strategy for HeNBs, which includes a precoder and a power allocation satisfying specific interference tolerant constraints. We provided an adaptive interference constraints calculation method for each HeNB, where only limited coordination is required between the MeNB and HeNBs. The HeNBs are able to operate in a distributed manner. It was shown by simulation results that our preprocessor improves the spectrum efficiency of the femtocell systems significantly with a permitted performance degradation of the MUE.

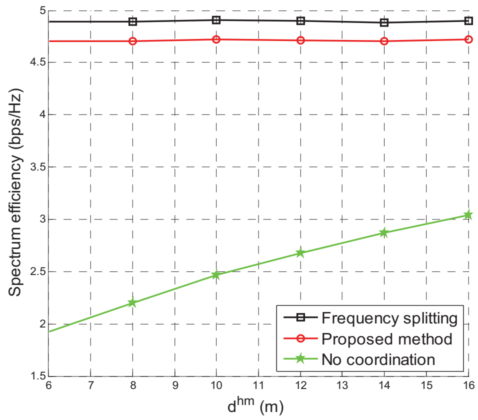

Fig. 2. Performance of the MUE versus d^{hm}

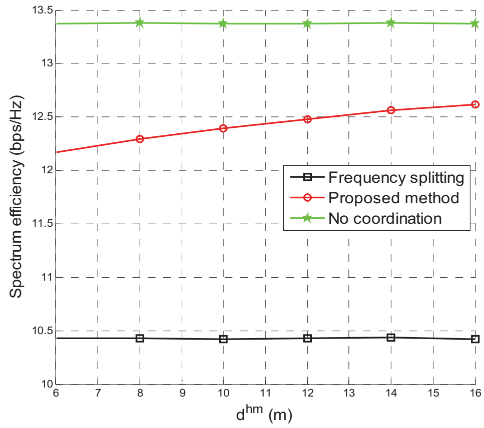

Fig. 3. Performance of the HUE versus d^{hm}

References

[1] V. Chandransekhar, J. Andrews and A. Gatherer, "Femtocell network: a surery," *IEEE Commun. Mag.*, vol. 46, pp. 59–67, Sep. 2008.

[2] J. D. Hobby and H. Claussen, "Deployment options for femtocells and their impact on existing Mmacrocellular networks," *Bell Labs Technical Journal*, vol. 13, no. 4, pp. 145–160, Feb. 2009.

[3] Z. Bharucha, H. Haas, G. Auer and I. Cosovic, "Femto-cell resource partitioning," *IEEE GLOBECOM Workshops*, 2009.

[4] V. Chandrasekhar, J.G Andrews, T. Muharemovic, Z. Shen and A. Gatherer, "Power control in two-tier femtocell networks," *IEEE Trans. on Wireless Commun.*, vol. 8, no. 8, pp. 4316–4328, Aug. 2009.

[5] X. Li, L. Qian and D. Kataria, "Downlink power control in co-channel macrocell femtocell overlay," *IEEE CISS*, 2009.

[6] J. Ma, G. Y. Li, and B. Juang, "Signal processing in cognitive radio," *IEEE Proceedings*, vol. 97, no. 5, pp. 805–823, May 2009.

[7] Z. Xu and C. Yang, "Secondary transeiver design in the presence of frequency offset between OFDM-based primary and secondary systems," *IEEE ICC*, 2010.

[8] 3GPP TR36.814 v.1.7.0, "Further advancements for E-UTRA physical layer aspects (Release 9)," Feb. 2010.

[9] Y. G. Li and G. L. Stuber, *Orthogonal Frequency Division Multiplexing for Wireless Communications*. Springer, 2006.

[10] F. Boccardi and H. Huang, "Zero-forcing precoding for the MIMO broadcast channel under per-antenna power constraints," *IEEE 7th Workshop on SPAWC*, 2006.

[11] 3GPP TS 25.105 v.10.0.0,"Base station (BS) radio transmission and reception (TDD) (Release 10)," June 2010.