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Mitigating Inter-Cell and Inter-Tier Interferenceby Covariance Based Zero-Forcing Beamformingin Two-Tier Massive MIMOSystem

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Abstract

In this paper, a covariance based precoding method with R-TDD and time-shifted pilots schemes is proposed to be effective to mitigate inter-cell and intra-cell interference in a two-tier system where a macro cell BSs and overlaid small cells have finite number of antennas. In previous work, the asymptotic behavior of the signal to interference plus noise ratio (SINR) has been obtained when there is only macro cell tier and has an unlimited number of antennas. We exploit these results with small cells and derive the covariance based precoding matrix when a non-orthogonal pilot sequence from other users is received at a base station simultaneously. We propose a scheme to avoid interference by the precoding matrix. Simulation results show that the proposed scheme can significantly minimize the inter-cell and inter-tier interference, and can improve the performance of the cellular network.

1.**Introduction**

The conventional macro cell network system is well-suited for providing wide-area coverage, but cannot handle the rapidly increasing user numbers and increasing mobile traffic. Two approaches have been studied to accommodate the increasing mobile traffic. One is massive MIMO [1], [2] and the other is small cell network [3], [4]. Massive MIMO technology is to deploy large-scale antenna arrays at existing macro base stations (BSs). It has been extensively studied in the recent years with several attractive features. First, the channel capacity can be increased. It means that massive MIMO can be an alternative to traditional way of increasing the network capacity named cell-size shrinking [5]. Second large antenna arrays can reduce uplink and downlink transmit powers [6]-[10]. Moreover, it can focus the radiated energy precisely towards the intended receivers, thereby efficiently reducing intra- and inter-cell interference. Third, if the number of antennas at macro BS is much greater than the number of users, the linear precoders and detectors are optimal and thermal noise and channel estimation errors vanish.

The second approach is to deploy an overlaid layer of small cell access points (SCAs) to offload traffic from macro cell BSs. It can provide capacity enhancements. Since deploying SCs are an efficient way to provide capacity enhancements, researches about how SCs and macro cells can coexist are needed. In [11], a TDD-based two-tier network architecture which incorporates the advantageous features of a massive MIMO macro BS overlaid with small cells has been proposed. The TDD channel reciprocity enables the macro BS to accommodate a large number of antennas without prohibitive channel estimation overhead. This can be used to design downlink precoders which reduce the interference to the SC-tier. The authors have compared two duplexing schemes, TDD and Reverse-TDD (R-TDD), which determine the set of interfering nodes between the two tiers. In R-TDD, while the macro BS is in the downlink, the SCs are in the uplink and vice versa. The choice of the duplexingmode changes the set of interfering nodes between the twotiers. The R-TDD scheme can significantly minimize the aggregate cross-tier interference experienced by SCs at the price of a negligible macro performance loss.

In this paper, we propose a covariance based precoding method with R-TDD and time-shifted pilots schemes to be effective to mitigate inter-cell and intra-cell interference in a two-tier system where a macro cell BSs and overlaid small cells have finite number of antennas. The coexistence of these non-cooperative tiers has several challenges. First, a centralized resource management approach is rendered infeasible due to the large number of SCs [17]. Therefore simultaneous uncoordinated communications cause cross-tier interference and aggravate the overall network performance. To tackle this problem, the TDD protocol is essential as it makes the macro BS to estimate the channels to its intended mobile user equipments (MUEs) and the covariance matrix of the interfering signals from the SCs. Due to the uplink-downlink channel reciprocity, this knowledge can be leveraged to precode the downlink signals orthogonal to the dominating subspace of the interference covariance matrix. Hence, as antennas at the macro BS become a commodity, a fraction of them can be sacrificed to minimize the aggregate interference enforced on the SCs. Moreover, it is notable that the proposed scheme does not induce any explicit form of cooperation or data exchange between the tiers.

The rest of this paper is organized as follows. Section 2 presents our system model and formulate the problem. Section 3 presents the downlink and uplink SINR when macro BS antenna has finite antennas. Section 4 propose the covariance based precoding method with R-TDD and time-shifted pilots schemes. We present the performance evaluation in Section 5 and conclude in Section 6.

2. System Model

In this section, we consider a cellular network composed of L hexagonal macro cells, each consisting of a central finite M-antenna base station to serve its K associated single-antenna MUEs and they are augmented with low range small cell access points(SCAs). Each SCA is equipped with a four antennas and devotes its available resources to its pre-scheduled small cell user equipments (SUEs). It is assumed that transmissions across the tiers are perfectly synchronized. Both tiers share the available bandwidth W with universal frequency reuse. Orthogonal frequency division multiplexing (OFDM) is assumed to be used. Consequently, a flat-fading channel model is considered for each OFDM subcarrier. For a given subcarrier the channel vector between the i-th macro BS and k-th user of the l-th macro cell is denoted by $\mathbf{g}_{ikl} = \sqrt{\beta_{ikl}}\mathbf{h}_{ikl}$. It is assumed that the small-scale fading vectors, $\mathbf{h}_{ikl} \sim \mathcal{C}N(\mathbf{0},\mathbf{I})$, are statistically independent across users. β_{ikl} denotes the large-scale fading coefficients (log normal distribution and geometric decay). These coefficients are constant with respect to frequency and macro BS antenna index. The pilot power of MUE and the transmit power of macro BS are denoted by ρ_{kl} and P_{kl}, respectively. The pilot power of SUE and the transmit power of SCA are denoted by ρ_{rl_q} and P_{rl_q}, respectively. It is assumed that channel vectors $\mathbf{h}_{ikl}$ stay constant during coherence blocks of T OFDM symbols. The channel vectors in different coherence blocks are assumed to be independent. The large-scale fading coefficients are assumed to remain constant as they change more slowly by some orders of magnitude.

3. R-TDD and Time-Shifted Pilots Formulation in Finite Antennas

In this section, we analyze the behavior of the SINR as the number of macro BS antennas M is finite while the number of users per cell remains finite and equal to the length of the pilot sequence K. Also the number of SCA antenna is four while the number of users per small cell is small. If half of the coherence interval is used for reverse-link pilots, then the maximum number of terminals is equal to the coherence-time divided by twice the channel delay-spread. If high radiated energy efficiency (bits/Joule) is required, greater number of service-antennas may be desirable since every doubling of M permits a reduction in total radiated power by a factor of two.

In this asymptotic scenario, we first analyze the case where all users send the pilots simultaneously. Next, we propose and analyze a scheme with time-shifted pilots with R-TDD. In both cases, it is assumed that in all cells the same set of K orthogonal pilots of length K is used. The k-th users in all cells use the same pilot sequence $\psi_k = (\psi_{k1}, \dots, \psi_{kK}),\ |\psi_{kj}| = 1$. Since the pilots are orthogonal, we have $|\psi_{k'}^{\dagger}\psi_k| = K\delta_{k,k'}$.

A. Aligned Pilots with TDD in Macro Cell

In this case, pilots are sent simultaneously by all users in the system. The i-th macro BS receives the signal given by

$$\mathbf{y}_{B_i} = \sum_{j}\sum_{k=1}^{K}\sqrt{\rho\beta_{ikj}}\mathbf{h}_{ikj}\psi_k + \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{\rho\beta_{irj_q}}\mathbf{h}_{irj_q}\psi_{rj_q} + \mathbf{z}_i \quad (1)$$

where $\mathbf{z}_i \in \mathbb{C}^{M\times K}$ is the additive noise. The entries of $\mathbf{z}_i$ are i.i.d. $\mathcal{C}N(\mathbf{0},\mathbf{I})$ random variables. The estimated channel vector $\hat{\mathbf{g}}_{ik'i}$ is given by

$$\hat{\mathbf{g}}_{ik'i} = \frac{\mathbf{y}_{B_i}\psi_{k'}^{\dagger}}{K} = \sqrt{\rho_{ki}\beta_{ik'i}}\mathbf{h}_{ik'i} + \sum_{j=1,\, j\neq i}^{J}\sqrt{\rho_{kj}\beta_{ik'j}}\mathbf{h}_{ik'j} + \mathbf{z}_i{}' \quad (2)$$

where $\mathbf{z}_i' = \frac{\mathbf{z}_i\psi_k^{\dagger}}{K} \sim \square N(\mathbf{0}, \frac{1}{K}\mathbf{I}_M)$ .The beamforming vector $\mathbf{w}_{k'i}$ to the k'-th user is given by

$$\mathbf{w}_{k'i} = \frac{\hat{\mathbf{g}}_{ik'i}}{\left\|\hat{\mathbf{g}}_{ik'i}\right\|}. \tag{3}$$

After pilot sequences are received and the channel vectors are estimated, each macro BS transmit the downlink data to its users. The k'-th user of the i-th cell receives as

$$y_{U_{k'i}} = \sum_{j=1}^{J}\sum_{k=1}^{K}\sqrt{P_{kj}\beta_{jk'i}}\mathbf{h}_{jk'i}^{\dagger}\mathbf{w}_{kj}s_{kj} + \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P_{r'j_q}\beta_{j_qk'i}}\mathbf{h}_{j_qk'i}^{\dagger}\mathbf{w}_{k'j_q}s_{r'j_q} + v_{k'i} \tag{4}$$

where s_{kj} is the signal transmitted to the k-th user in the j-th macro cell and $s_{r'j_q}$ is the signal transmitted to the r'-th user in the j_q-th small cell. $v_{k'i}$ is the unit variance additive white Gaussian noise. Let $S_{kj} = E[\left|Q_{kj}\right|^2]$ be the variance of the received signal s_{kj}. Then the power of the desired signal is given by

$$S_{kj} = E[\left|Q_{kj}\right|^2] = E[P_{kj}\beta_{jki}\left|\mathbf{h}_{jki}^{\dagger}\mathbf{w}_{kj}\right|^2\left|s_{kj}\right|^2].$$

After some manipulations the downlink SINR of the k'-th user in the i-th cell is given by

$$\zeta_{k'i}^{D} = \frac{P_{k'i}\beta_{ik'i}\left\|\mathbf{h}_{ik'i}^{\dagger}\mathbf{w}_{ki}\right\|^2}{\sum_{j=1,\, j\neq i}^{J}P_{k'j}\beta_{ik'j}\left\|\mathbf{h}_{ik'j}^{\dagger}\mathbf{w}_{kj}\right\|^2 + \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}P_{r'j_q}\beta_{j_qk'i}\left\|\mathbf{h}_{j_qk'i}^{\dagger}\mathbf{w}_{k'j_q}\right\|^2 + v_{k'i}^2}. \tag{5}$$

Similar interference caused by the pilot contamination occurs in uplink communication. To obtain the desired signal, users send data to their macro BSs, which then multiply the received signal by the channel estimation. The i-th macro BS receives the signal given by

$$\mathbf{y}_{B_i} = \sum_{j}\sum_{k=1}^{K}\sqrt{P_{kj}^{U}\beta_{ikj}}\mathbf{h}_{ikj}q_{kj} + \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P_{rj_q}^{U}\beta_{irj_q}}\mathbf{h}_{irj_q}q_{rj_q} + \mathbf{v}_i \tag{6}$$

where P_{kj}^{U} is the macro cell uplink transmit power, q_{kj} is the uplink signal sent by the k-th user of the j-th macro cell, $P_{rj_q}^{U}$ is the small cell uplink transmit power, and q_{rj_q} is the uplink signal sent by the r-th user of the j_q-th small cell. After some manipulations the uplink SINR for the i-th macro cell is given by

$$\zeta_{k'i}^{U} = \frac{P_{k'i}^{U}\beta_{ik'i}^{2}\left\|\mathbf{h}_{iki}q_{ki}\right\|^2}{\sum_{j=1,\, j\neq i}^{J}P_{k'j}^{U}\beta_{ik'j}^{2}\left\|\mathbf{h}_{ikj}q_{kj}\right\|^2 \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}P_{rj_q}^{U}\beta_{irj_q}\left\|\mathbf{h}_{irj_q}q_{rj_q}\right\|^2 + \left\|\mathbf{v}_i\right\|^2}. \tag{7}$$

B. Time-shifted pilots with R-TDD in Macro Cell

Let the i-th cell be in the group A_γ. In the first phase, the received signal at the i-thmacro BS is given by

$$\begin{aligned}\mathbf{y}_{B_i} &= \sum_{j\in A_\gamma}\sum_{k=1}^{K}\sqrt{\rho_{kj}\beta_{ikj}}\,\mathbf{h}_{ikj}\psi_k + \sum_{j_q\in A_\gamma}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{\rho_{rj_q}\beta_{ij_q}}\,\mathbf{h}_{irj_q}\psi_{rj_q} + \sum_{l_q\notin A_\gamma}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P^U_{rl_q}\beta_{irl_q}}\,\mathbf{h}_{irl_q}q_{rl_q} \\ &\quad + \sum_{l\notin A_\gamma}\sum_{k=1}^{K}\sqrt{P_{kl}\beta_{il}}\,\mathbf{H}_{il}\mathbf{w}_{kl}s_{kl} + \mathbf{z}_i\end{aligned} \tag{8}$$

where q_{rl_q} is a uplink signal from small cell users in other group, s_{kl} is a downlink signal to the k-th user in the l-th cell, and $\mathbf{H}_{il} \in \square^{M\times M}$ is the channel matrix between antennas of the i-th and the l-th macro base stations. The received signalsat the macro BS are not only pilot signals but also downlink signals transmitted by macro BS and uplink signals transmitted by SUEs from different groups. The estimated channel vector is given by

$$\begin{aligned}\hat{\mathbf{g}}_{ik'i} &= \frac{\mathbf{y}_{B_i}\psi^{\dagger}_{k'}}{K} = \sum_{j\in A_\gamma}\sqrt{\rho\beta_{ik'j}}\,\mathbf{h}_{ik'j} + \frac{1}{K}\sum_{l_q\notin A_\gamma}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P^U_{rl_q}\beta_{irl_q}}\,\mathbf{h}_{irl_q}q_{rl_q}\psi^{\dagger}_{k'} \\ &\quad + \frac{1}{K}\sum_{l\notin A_\gamma}\sum_{k=1}^{K}\sqrt{P_{kl}\beta_{il}}\,\mathbf{H}_{il}\mathbf{w}_{kl}s_{kl}\psi^{\dagger}_{k'} + \mathbf{z}'_i.\end{aligned} \tag{9}$$

The macro BS in all group except $A_{\gamma'}$ transmits downlink data to their respective users after the channel estimation of A_γ and the MUEs in group $A_{\gamma'}$ send the pilot signals to their intended macro BS. In the state of the small cells, the SUEs in all group except $A_{\gamma'}$ transmit uplink data to their intended SCA and the SUEs in group $A_{\gamma'}$ send the pilot signals to their intended SCA. At this phase, the received signal of the k'-th user at the i-th macro BS is given by

$$\begin{aligned}y_{U_{k'i}} &= \sum_{j\in A_\gamma}\sum_{k=1}^{K}\sqrt{P_{kj}\beta_{jk'i}}\,\mathbf{h}^{\dagger}_{jk'i}\mathbf{w}_{kj}s_{kj} + \sum_{l\in A_{\gamma'}}\sum_{k=1}^{K}\sqrt{\rho\beta_{klk'i}}\,h_{klk'i}\psi_k + \sum_{l\notin A_\gamma\cup A_{\gamma'}}\sum_{k=1}^{K}\sqrt{P_{kl}\beta_{lki}}\,\mathbf{h}^{\dagger}_{lki}\mathbf{w}_{lk}s_{lk} \\ &\quad + \sum_{j_q\in A_\gamma}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P^U_{rj_q}\beta_{irj_q}}\,h_{rj_qk'i}q_{rj_q} + \sum_{l_q\in A_{\gamma'}}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{\rho_{rl_q}\beta_{rl_qk'i}}\,h_{rl_qk'i}\psi_{rl_q} \\ &\quad + \sum_{l_q\notin A_\gamma\cup A_{\gamma'}}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P^U_{rl_q}\beta_{irl_q}}\,h_{rl_qk'i}q_{rl_q} + v_{k'i}\end{aligned} \tag{10}$$

where $\beta_{klk'i}$ and $h_{klk'i}$ are slow and fast fading coefficients between k-th user of l-th macro cell and k-th user of the i-th macro cell, respectively, and $v_{k'i}$ is the additive noise term. The received power of the desired signal $s_{k'i}$ is given by

$$S_{k'i} = P_{k'i}\beta_{ik'i}\left|\mathbf{h}^{\dagger}_{ik'i}\mathbf{w}_{k'i}\right|^2. \tag{11}$$

After some manipulations we can obtain the SINR of the downlink given by

$$\zeta^{D}_{k'i} = \frac{P_{k'i}\beta^{2}{}_{ik'i}\left\|\mathbf{h}^{H}_{ik'i}\mathbf{w}_{ki}\right\|^{2}}{\left(\begin{array}{l}\sum\limits_{j\in A_{\gamma},\, j\neq i} P_{k'j}\beta^{2}{}_{jk'i}\left\|\mathbf{h}^{H}_{jk'i}\mathbf{w}_{kj}\right\|^{2} + \sum\limits_{l\in A_{\gamma'}}\sum\limits_{k=1}^{K}\rho\beta_{klk'i} + \sum\limits_{l\notin A_{\gamma}\cup A_{\gamma'}}\sum\limits_{k=1}^{K}P_{kl}\beta_{lki}\left\|\mathbf{h}^{\dagger}_{lki}\mathbf{w}_{lk}\right\|^{2} + \\ \sum\limits_{j_q\in A_{\gamma}}\sum\limits_{q=1}^{Q}\sum\limits_{r=1}^{R}P^{U}_{rj_q}\beta_{irj_q} + \sum\limits_{l_q\in A_{\gamma'}}\sum\limits_{q=1}^{Q}\sum\limits_{r=1}^{R}\rho_{rl_q}\beta_{rl_q k'i} + \sum\limits_{l_q\notin A_{\gamma}\cup A_{\gamma'}}\sum\limits_{q=1}^{Q}\sum\limits_{r=1}^{R}P^{U}_{rl_q}\beta_{irl_q} + v^{2}{}_{k'i}\end{array}\right)}. \tag{12}$$

The similar manipulations can be done for the uplink by using the channel estimates obtained in equation (12) at the receivers. In this scheme, users from all cells transmit to their macro BS simultaneously. The signal received by the i-th macro BS is given by

$$\mathbf{y}_{B_i} = \sum_{j}\sum_{k=1}^{K}\sqrt{P^{U}_{kj}\beta_{ikj}}\,\mathbf{h}_{ikj}q_{kj} + \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P_{rj_q}\beta_{i_q rj_q}}\,\mathbf{H}_{ij_q}\mathbf{w}_{rj_q}s_{rj_q} + \mathbf{v}_i .$$

After some manipulations the uplink SINR is given by

$$\zeta^{U}_{k'i} = \frac{P^{U}_{k'i}\beta^{2}_{ik'i}}{\sum\limits_{j}\sum\limits_{k=1}^{K}P^{U}_{kj}\beta_{ikj} + \sum\limits_{j}\sum\limits_{q=1}^{Q}\sum\limits_{r=1}^{R}P_{rj_q}\beta_{i_q rj_q}\left\|\mathbf{H}_{ij_q}\mathbf{w}_{rj_q}\right\|^{2} + \mathbf{v}^{2}_{i}}. \tag{13}$$

C. Aligned Pilots with TDD in Small Cell

In this case, pilots are sent simultaneously by all users in the system. The received pilot signal at the i_q-th SCAis given by

$$\mathbf{y}_{SCA_{i_q}} = \sum_{j}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{\rho_{rj_q}\beta_{ij_q}}\,\mathbf{h}_{irj_q}\psi_{rj_q} + \sum_{j}\sum_{k=1}^{K}\sqrt{\rho_{kj}\beta_{ikj}}\,\mathbf{h}_{ikj}\psi_{k} + \mathbf{z}_i . \tag{14}$$

The estimated channel vector is given by

$$\hat{\mathbf{g}}_{i_q r'i_q} = \frac{\mathbf{y}_{SCA_i}\psi^{\dagger}_{r'j_q}}{K} = \sqrt{\rho\beta_{i_q r'j_q}}\,\mathbf{h}_{i_q r'i_q} + \sum_{j=1,\, j\neq i}^{J}\sqrt{\rho\beta_{i_q r'j_q}}\,\mathbf{h}_{i_q r'j_q} + \mathbf{z}_{i_q} . \tag{15}$$

The base station computes the beamforming vector to its r'-th user as the normalized version of equation (24) given by

$$\mathbf{w}_{r'i_q} = \frac{\hat{\mathbf{g}}_{i_q r'i_q}}{\left\|\hat{\mathbf{g}}_{i_q r'i_q}\right\|}. \tag{16}$$

After pilot sequences are received and the channel vectors are estimated, each SCA transmits the downlink data to its users. The r'-th user of the i_q-th small cell receives as

$$y_{U_{r'i_q}} = \sum_{j_q}\sum_{q=1}^{Q}\sum_{r=1}^{R}\sqrt{P_{r'j_q}\beta_{j_q r'i_q}}\,\mathbf{h}^{\dagger}_{j_q r'i_q}\mathbf{w}_{r'j_q}s_{r'j_q} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sqrt{P_{kj}\beta_{jk'i}}\,\mathbf{h}^{\dagger}_{jk'i}\mathbf{w}_{kj}s_{kj} + v_{r'i} \tag{17}$$

where $s_{r'j_q}$ is the signal intended to the r'-th user in the j_q-th small cell and s_{kj} is the signal intended to the k-th user in the j-th macro cell. $v_{r'i}$ is the unit variance additive white Gaussian noise.Let $S_{r'i_q} = E[|Q_{r'i_q}|^2]$ be the variance of the received signal $s_{r'i_q}$. The received power of interference signal at SUE is given by

$$S_{r'i_q} = \sum_{j_q, j_q \neq i_q} \sum_{q=1}^{Q} \left| \sqrt{P_{r'j_q} \beta_{i_q r'j_q}} \mathbf{h}_{i_q r'j_q}^{\dagger} \mathbf{w}_{r'j_q} \right|^2 .$$

After some manipulations the downlink SINR of the r'-th user in the i_q-th small cell is given by

$$\zeta_{r'i_q}^{D} = \frac{P_{r'i_q} \beta_{i_q r'i_q} \left\| \mathbf{h}_{i_q r'i_q}^{\dagger} \mathbf{w}_{r'i_q} \right\|^2}{\sum_{j_q} \sum_{q=1}^{Q} \sum_{r=1}^{R} P_{r'j_q} \beta_{j_q r'i_q} \left\| \mathbf{h}_{j_q r'i_q}^{\dagger} \mathbf{w}_{r'j_q} \right\|^2 + \sum_{j=1}^{J} \sum_{k=1}^{K} P_{kj} \beta_{jk'i} \left\| \mathbf{h}_{jk'i}^{\dagger} \mathbf{w}_{kj} \right\|^2 + v_{r'i}^2} . \tag{18}$$

As in equation (8), similar interference caused by the pilot contamination occurs in uplink communication. The signal received by i_q-th SCA is given by

$$\mathbf{y}_{SCA_{i_q}} = \sum_{j} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{P_{rj_q}^{U} \beta_{i_q rj_q}} \mathbf{h}_{i_q rj_q} q_{rj_q} + \sum_{j} \sum_{k=1}^{K} \sqrt{P_{kj}^{U} \beta_{i_q kj}} \mathbf{h}_{ikj} q_{kj} + \mathbf{v}_{i_q} \tag{19}$$

where $P_{rj_q}^{U}$ is the small cell uplink transmit power and q_{rj_q} is the uplink signal sent by the r-th user of the j_q-th cell. P_{kj}^{U} is the macro cell uplink transmit power and q_{kj} is the uplink signal sent by the k-th user of the j-th cell. After some manipulations the uplink SINR for the r'-th user of the i_q-th cell is given by

$$\zeta_{r'i_q}^{U} = \frac{P_{rj_q}^{U} \beta_{i_q rj_q} \left\| \mathbf{h}_{i_q rj_q} q_{rj_q} \right\|^2}{\sum_{j} \sum_{q=1}^{Q} \sum_{r=1}^{R} P_{rj_q}^{U} \beta_{i_q rj_q} \left\| \mathbf{h}_{i_q rj_q} q_{rj_q} \right\|^2 + \sum_{j} \sum_{k=1}^{K} P_{kj}^{U} \beta_{i_q kj} \left\| \mathbf{h}_{ikj} q_{kj} \right\|^2 + \mathbf{v}_{i_q}^2} . \tag{20}$$

D. Time-Shifted Pilots with R-TDD in Small Cell

In this section, we propose a scheme that pilot sequences are sent simultaneously with downlink data from other SCAs.Let the i-th cell be in the group A_γ. The received signal at the i_q-thSCAis given by

$$\begin{aligned} \mathbf{y}_{SCA_{i_q}} = & \sum_{j \in A_\gamma} \sum_{k=1}^{K} \sqrt{\rho_{kj} \beta_{i_q kj}} \mathbf{h}_{i_q rj} \psi_k + \sum_{j_q \in A_\gamma} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{\rho_{rj_q} \beta_{i_q rj_q}} \mathbf{h}_{i_q rj_q} \psi_{rj_q} + \sum_{l_q \notin A_\gamma} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{P_{rl_q}^{U} \beta_{i_q rl_q}} \mathbf{h}_{i_q rl_q} q_{rl_q} \\ & + \sum_{l \notin A_\gamma} \sum_{k=1}^{K} \sqrt{P_{kl} \beta_{i_q kl}} \mathbf{H}_{i_q l} \mathbf{w}_{kl} s_{kl} + \mathbf{z}_{i_q} . \end{aligned} \tag{21}$$

where $\mathbf{H}_{i_q l} \in \square^{N \times M}$ is the channel matrix between antennas of the i_q-th SCA and the l-th macro BS. The estimated channel vector is given by

$$\hat{\mathbf{g}}_{i_q r' i_q} = \frac{\mathbf{y}_{SCA_{i_q}} \psi^{\dagger}_{r' j_q}}{K} = \sum_{j_q \in A_\gamma} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{\rho_{r' j_q} \beta_{i_q r' j_q}} \mathbf{h}_{i_q r' j_q} + \frac{1}{K} \sum_{l_q \notin A_\gamma} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{P^{U}_{r' l_q} \beta_{i_q r' l_q}} \mathbf{h}_{i_q r' l_q} q_{r' l_q} \psi^{\dagger}_{r' j_q}$$
$$+ \frac{1}{K} \sum_{l \notin A_\gamma} \sum_{k=1}^{K} \sqrt{P_{kl} \beta_{i_q kl}} \mathbf{H}_{i_q l} \mathbf{w}_{kl} s_{kl} \psi^{\dagger}_{r' j_q} + \frac{1}{R} \mathbf{z}_{i_q} \psi^{\dagger}_{r' j_q}. \tag{22}$$

The received signal of the r'-th user at the i_q-th is given by

$$y_{U_{r' i_q}} = \sum_{j_q} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{P_{r' j_q} \beta_{i_q r' j_q}} \mathbf{h}^{\dagger}_{i_q r' j_q} \mathbf{w}_{r' j_q} s_{r' j_q} + \sum_{j} \sum_{k=1}^{K} \sqrt{P^{U}_{kj} \beta_{i_q r' j_q}} h_{i_q r' jk} q_{kj}. \tag{23}$$

The received power of the desired signal $s_{r' i_q}$ is

$$S_{r' i_q} = \left| \sqrt{P_{r' i_q} \beta_{i_q r' i_q}} \mathbf{h}^{\dagger}_{i_q r' i_q} \mathbf{w}_{r' i_q} \right|^2.$$

After some manipulations the downlink SINR of the r'-th user in the i_q-th cell is given by

$$\zeta^{D}_{r' i_q} = \frac{P_{r' i_q} \beta_{i_q r' i_q} \left| \mathbf{h}^{\dagger}_{i_q r' i_q} \mathbf{w}_{r' i_q} \right|^2}{\sum_{j_q \neq i_q} \sum_{q=1}^{Q} P_{r' j_q} \beta_{i_q r' j_q} \left| \mathbf{h}^{\dagger}_{i_q r' j_q} \mathbf{w}_{r' j_q} \right|^2 + \sum_{j} \sum_{k=1}^{K} P^{U}_{kj} \beta_{i_q r' j_q}}. \tag{24}$$

In uplink phase, the signal received by i_q-th SCA is given by

$$\mathbf{y}_{SCA_{i_q}} = \sum_{j_q \in A_\gamma} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{P^{U}_{r j_q} \beta_{i r j_q}} \mathbf{h}_{j_q r i_q} q_{r j_q} + \sum_{l \in A_{\gamma'}} \sum_{k=1}^{K} \sqrt{\rho \beta'_{lki_q}} \mathbf{h}_{lki_q} \psi_k + \sum_{l \notin A_\gamma \cup A_{\gamma'}} \sum_{k=1}^{K} \sqrt{P_{kl} \beta_{lki}} \mathbf{H}^{\dagger}_{li_q} \mathbf{w}_{kl} s_{kl}$$
$$+ \sum_{j \in A_\gamma} \sum_{k=1}^{K} \sqrt{P_{kj} \beta_{jk'i}} \mathbf{H}^{\dagger}_{ji_q} \mathbf{w}_{kj} s_{kj} + \sum_{l_q \in A_{\gamma'}} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{\rho_{rl_q} \beta_{l_q r i_q}} \mathbf{h}_{l_q r i_q} \psi_{rl_q} \tag{25}$$
$$+ \sum_{l_q \notin A_\gamma \cup A_{\gamma'}} \sum_{q=1}^{Q} \sum_{r=1}^{R} \sqrt{P^{U}_{rl_q} \beta_{irl_q}} \mathbf{h}_{l_q r i_q} q_{rl_q} + \mathbf{v}_{ri_q}.$$

After some manipulations the uplink SINR for the r'-th user of the i_q-th cell is given by

$$\zeta^{U}_{r' i_q} = \frac{P^{U}_{r' i_q} \beta^{2}_{i_q r' i_q} \left\| \mathbf{h}_{i_q r i_q} q_{r i_q} \right\|^2}{\left(\begin{array}{l} \sum_{j_q \in A_\gamma} \sum_{q=1}^{Q} \sum_{r=1}^{R} P^{U}_{r j_q} \beta_{i_q r j_q} \left\| \mathbf{h}_{j_q r i_q} q_{r j_q} \right\|^2 + \sum_{l \in A_{\gamma'}} \sum_{k=1}^{K} \rho \beta_{lki_q} \left\| \mathbf{h}_{lki_q} \psi_k \right\|^2 + \sum_{l \notin A_\gamma \cup A_{\gamma'}} \sum_{k=1}^{K} P_{kl} \beta_{lki} \left\| \mathbf{H}^{\dagger}_{li_q} \mathbf{w}_{kl} \right\|^2 + \\ \sum_{j \in A_\gamma} \sum_{k=1}^{K} P_{kj} \beta_{jk'i} \left\| \mathbf{H}^{\dagger}_{ji_q} \mathbf{w}_{kj} \right\|^2 + \sum_{l_q \in A_{\gamma'}} \sum_{q=1}^{Q} \sum_{r=1}^{R} \rho_{rl_q} \beta_{l_q r i_q} \left\| \mathbf{h}_{l_q r i_q} \psi_{rl_q} \right\|^2 + \sum_{l_q \notin A_\gamma \cup A_{\gamma'}} \sum_{q=1}^{Q} \sum_{r=1}^{R} P^{U}_{rl_q} \beta_{irl_q} \left\| \mathbf{h}_{l_q r i_q} q_{rl_q} \right\|^2 + \mathbf{v}^{2}_{ri_q} \end{array} \right)}. \tag{26}$$

4. Covariance Based Zero-Forcing Beamforming

After the macro cell uplink phase (under the TDD and the R-TDD protocol), the macro BS decodes its desired signal and subtracts it from the received signal. The remaining part envelops the interference and noise effects which can be exploited to compute the empirical covariance matrix as

$$\begin{aligned}&\frac{1}{\alpha T}\sum_{t=1}^{\alpha T}\tilde{y}_{BS}(t)\tilde{y}_{BS}^{H}(t)=\frac{1}{\alpha T}\sum_{t=1}^{\alpha T}(\sum_{i\in S}\mathbf{f}x_{SCA,i(t)}+\mathbf{n}_{BS}(t))\times\frac{1}{\alpha T}\sum_{t=1}^{\alpha T}(\sum_{i\in S}\mathbf{f}x_{SCA,i(t)}+\mathbf{n}_{BS}(t))^{H}\\&\xrightarrow[T\to\infty]{a.s.}\sum_{i\in S}E[P_{SCA,i}\mathbf{f}_i\mathbf{f}_i^{H}+\mathbf{n}_{BS}(t)\mathbf{n}_{BS}(t)^{H}]=\sum_{i\in S}P_{SCA,i}\mathbf{f}_i\mathbf{f}_i^{H}+\sigma^2\mathbf{I}\triangleq\mathbf{Q}.\end{aligned} \tag{27}$$

Thus, for sufficiently long channel coherence times, the macro BS can estimate $\mathbf{Q}$ with high precision. Furthermore, it is assumed that is known. Let $\mathbf{Q}-\sigma^2\mathbf{I}_N$ be decomposed as $\mathbf{VDV}^H$ where $\mathbf{D}=\mathrm{diag}(\lambda_1,...,\lambda_S)$ contains the eigenvalues of $\mathbf{Q}-\sigma^2\mathbf{I}_N$ in descending order and the k-th column of $\mathbf{V}$ is the eigenvector associated with λ_k. Therefore, given that the macro BS is equipped with M transmit antennas and delivers independent data streams to K users, $m\le M-K$ DoF can be used to spatially reject interference imposed on the SCs. Thus, the precoding matrix is designed as follows

$$\mathbf{W}_{SP}=(\mathbf{I}_N-\mathbf{U}_m\mathbf{U}_m^H)\mathbf{H}^{+}\mathbf{\Gamma}_{SP}^{\frac{1}{2}} \tag{28}$$

where $\mathbf{U}_m$ encompasses the m first columns of $\mathbf{V}$ and $\mathbf{\Gamma}_{\mathrm{SP}}^{\frac{1}{2}}$ normalizes each column of $\mathbf{W}_{\mathrm{SP}}$. Hence, the first term $\mathbf{I}_N-\mathbf{U}_m\mathbf{U}_m^H$ projects the precoding vectors to the subspace orthogonal to the columns of $\mathbf{U}_m$.

5. Performance Evaluation

In this section, we describe the performance evaluation results.A cellular system is organized in hexagonal macro cells with radius 500 m, with 20 users randomly distributed in each macro cells, with 100 small cells who have one user uniformly distributed in each small cells. All the evaluations are performed in MATLAB. The system uses a frequency band of $B=20\mathrm{MHz}$ and a carrier frequency of $1.9\mathrm{GHz}$. It is assumed that the slow fading coefficients β_{ikl} are an average decay of $38\mathrm{dB/decade}$ and log normal shadowing is with a standard deviation of $8\mathrm{dB}$. Time block fading model is assumed here. Each coherence interval T consists of four phases. U is a uplink period and D is a downlink period. The estimation process takes N period and K means the pilot sequence period. We assume $T=12$ and $N=1$. For the aligned pilot scheme we assume $K=5$, $D=3$, and $U=3$. For the time-shifted pilot scheme we assume $K=3$, $D=5$, and $U=3$.

In Figures 1 and 2, we show the downlink rate gains obtained by using the covariance matrix. Time-shifted pilot approach with R-TDD is compared with the aligned pilot approach with TDD, respectively. In both Figures, we plot the fraction of users that can achieve at least a certain rate. First, note in Figure 1 that the downlink rates corresponding to the macro cell time-shifted approach with R-TDD is almost same with the macro cell aligned pilot approach with TDD. Second, Figure 2 is the downlink rates corresponding to the small cell time-shifted approach with R-TDD and the small cell aligned pilot approach with TDD. Note in Figure 2 that the downlink rates corresponding to the small cell time-shifted approach with R-TDD is 2.5 times larger than the small cell aligned pilot approach with TDD.

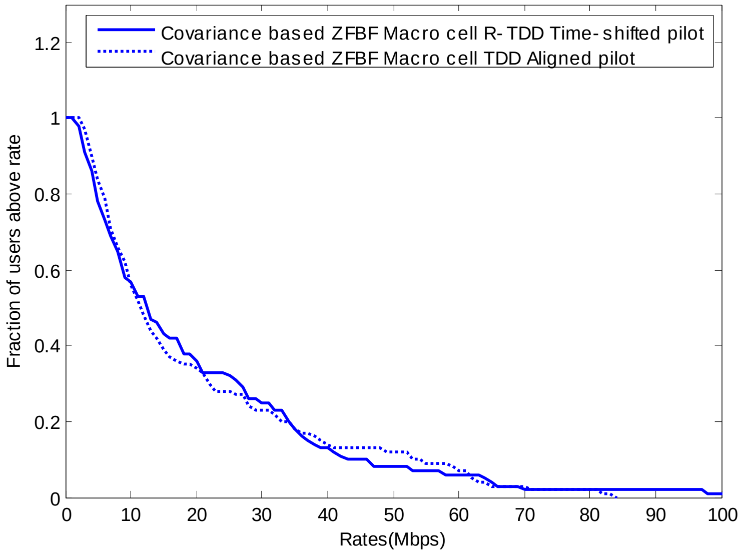

Figure 1: Transmission rate of covariance based macro cell downlink

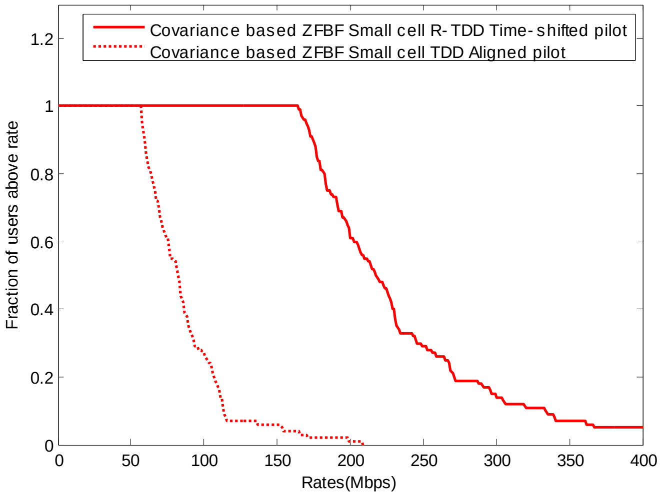

Figure 2: Transmission rate of covariance based small cell downlink

In Figures 3 and 4, we show the uplink rate gains obtained by using the covariance matrix. Time-shifted pilot approach with R-TDD is compared with the aligned pilot approach with TDD, respectively. Figure 3 is the uplink rates corresponding to the macro cell time-shifted approach with R-TDD and the small cell aligned pilot approach with TDD. Note in Figure 3 that the downlink rates corresponding to the macro cell time-shifted approach with R-TDD is almost same with the small cell aligned pilot approach with TDD. Figure 4 is the uplink rates corresponding to the small cell time-shifted approach with R-TDD and the small cell aligned pilot approach with TDD. Note in Figure 4 that the downlink rates corresponding to the small cell time-shifted approach with R-TDD is 2.5 times larger than the small cell aligned pilot approach with TDD.

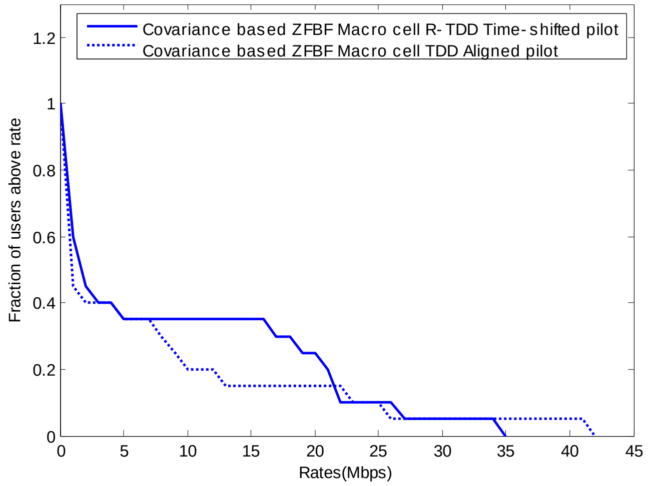

Figure 3: Transmission rate of covariance based macro cell uplink

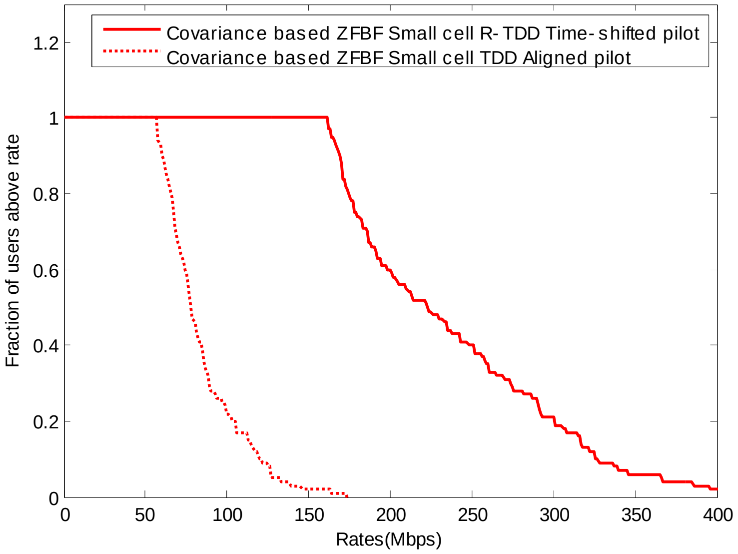

Figure 4: Transmission rate of covariance based small cell uplink

6. Conclusion

In this paper, we have proposed a covariance based precoding method with R-TDD and time-shifted pilots schemes for the behavior of the SINR in the downlink and the uplink of cellular network as the number of macro BS and SCA has finite antennas. We show that the fundamental limitation of such networks is the interference present in thechannel estimation, due to the overlapping of non-orthogonal pilot sequences from adjacent cells. We analyze several cases based on timing of pilot sequences and cell size. First, we consider aligned pilots that all users transmit pilot sequences simultaneously in macro cells and small cells. Second, we analyze time-shifted pilots that transmission of pilot sequences is shifted in time to avoid overlap. As shown in the simulations, the proposed scheme can significantly minimize the inter-tier interference and inter-cell interference. Also it is expected that the proposed schemes are beneficial to cell boundary users who are severely affected by adjacent cells.

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References

[1] F. Rusek, D. Persson, B. Lau, E. Larsson, T. Marzetta, O. Edfors, and F. Tufvesson, “Scaling Up MIMO: Opportunities and Challenges with Very Large Arrays,” *IEEE Signal Process Magazine*, vol. 30, no. 1, pp. 40-60, Jan. 2013.

[2] J. Hoydis, S. ten Brink, and M. Debbah, “Massive MIMO in the UL/DL of Cellular Networks:How Many Antennas Do We Need?” *IEEE Journal on Selected Areas Communications*, vol. 31, no. 2, pp. 160-171, Feb. 2013.

[3] A. Ghoshm N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. A. Thomas, J. G. Andrews, P. Xia, H. S, Jo *et al.*, “Heterogeneous Cellular Networks: From Theory to Practice,” *IEEE Communication Magazine*, vol. 50, no. 6, pp.54-64, Jun. 2012.

[4] A. Adhikary, V. Ntranos, and G. Caire, “Cognitive Femtocells: BreakingtheSpatial Reuse Barrier of Cellular Systems,”in*IEEE Information Theory and Applications Workshop (ITA)*, pp. 1–10, Feb. 2011.

[5] J. G. Andrews, H. Claussen, and M. Dohler, S. Rangan, and M. Reed, “Femtocells: Past, Present, and Future,” *IEEE Journal on Selected Areas Communications*, vol. 30, no. 3, pp. 497-508, Apr. 2012.

[6] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, “Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems,” *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1436-1449, Apr. 2013.

[7] H. Yang and T. L. Marzetta, “Performance of Conjugate and Zero-Forcing Beamforming in Large Scale Antenna Systems,” *IEEE Journal on Selected Areas Communications*, vol. 31, no. 2, pp.172-179, Feb. 2013.

[8] W. Liu, S. Han, C. Yang, C. Sun, “Massive MIMO and Small Cell Network: Who is More Energy Efficient?,” in *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*,pp. 24-29, Apr. 2013.

[9] V. Chandrasekhar and J. G. Andrews, “Uplink Capacity and Interference Avoidance for Two-tier Femtocell Networks,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3498-3509, Jul. 2009.

[10] T. L. Marzetta, “Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas,” *IEEE Transaction on Wireless Communications*, vol. 9, no. 11, pp. 3590-3600, Nov. 2010.

[11] E. Bjornson, M. Kountouris, and M.Debbah, “Massive MIMO and Small Cells: Improving Energy Efficiency by Optimal Soft-Cell Coordination,” in *Proc. International Conference on Telecommunications (ICT)*, pp. 1-5, May. 2013.

[12] J. Hoydis, K. Hosseini, S. t. Brink, and M. Debbah, “Making SmartUse of Excess Antennas: Massive MIMO, Small Cells, and TDD,”*Bell Labs Technical Journal*, vol. 18, no. 2, pp. 5-21, Sep. 2013.

[13] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, “Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems,” *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1436-1449, Apr. 2013.

[14] V. Chandrasekhar and J. G. Andrews, “Uplink Capacity and Interference Avoidance for Two-tier Femtocell Networks,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3498-3509, Jul. 2009.

[15] F. Fernandes A. Ashikhmin, and T. L. Marzetta, “Inter-Cell Interference in Noncooperative TDD Large Scale Antenna Systems,” *IEEE Journal on Selected Areas Communications*, vol. 31, no. 2, pp. 192-201, Feb. 2013.

[16] K. Hosseini, J. Hoydis, S. T. Brink, and M. Debbah, “Massive MIMO and Small Cells: How to Densify Heterogeneous Networks,” in *IEEE International Conference on Communications (ICC)*, pp. 5442-5447, Jun. 2013.