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# Massive MIMO and Small Cells: How to Densify Heterogeneous Networks

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***Abstract*—We propose a time division duplex (TDD) based network architecture where a macrocell tier with a "massive" multiple-input multiple-output (MIMO) base station (BS) is overlaid with a dense tier of small cells (SCs). In this context, the TDD protocol and the resulting channel reciprocity have two compelling advantages. First, a large number of BS antennas can be deployed without incurring a prohibitive overhead for channel training. Second, the BS can estimate the interference covariance matrix from the SC tier which can be leveraged for downlink precoding. In particular, the BS designs its precoding vectors to transmit independent data streams to its users while being orthogonal to the subspace spanned by the strongest interference directions; thereby minimizing the sum interference imposed on the SCs. In other words, the BS "sacrifices" some of its antennas for interference cancellation while the TDD protocol allows for an implicit coordination across both tiers. Simulation results suggest that, given a sufficiently large number of BS antennas, the proposed scheme can significantly improve the sum-rate of the SC tier at the price of a small macro performance loss.**

## I. Introduction

It is widely acknowledged that the future capacity needs of wireless cellular networks can only be satisfied by a significant network densification through the deployment of small cells (SCs) [1], [2]. While SCs are an efficient means to provide local capacity enhancements (e.g., hotspots in urban areas), they can not replace macro cells which ensure area coverage and support highly mobile terminals. Hence, a two-tier architecture for cellular systems naturally emerges which poses the challenge of how SCs and macro cells can coexist.

Another way of network densification relies on increasing the number of antennas deployed at each cell site to form a "massive MIMO" network [3]. Massive MIMO exploits the additional spatial degrees of freedom (DoF) to multiplex messages for several terminals on the same time-frequency resource. Moreover, large antenna arrays can focus the radiated energy precisely towards the intended receivers, thereby efficiently reducing intra- and intercell interference. Nonetheless, unless the channel structure is available at the BS [4], the prohibitive downlink channel training and feedback in frequency division duplex (FDD) systems constrain the number of BS antennas. In contrast, a time division duplex (TDD) system exploits the channel reciprocity to considerably reduce the related signaling overhead. Hence, employing a TDD scheme is indispensable for massive MIMO. For an overview of related work, we refer to [5] and the references therein.

This paper proposes a TDD-based network architecture to integrate a massive MIMO network augmented with a dense layer of SCs to attain the benefits of both schemes. Nonetheless, the coexistence of these *non-cooperative* tiers raises several challenges that need to be tackled [6], [7], [8], [9]. In particular, due to the large number of SCs, any centralized resource management approach is rendered infeasible. Therefore, simultaneous, uncoordinated, communications cause cross-tier interference and exacerbate the overall network performance. To tackle this problem, the TDD protocol is crucial as it does not only enable the BS to estimate the channels to its intended mobile user equipments (MUEs), but also to estimate 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 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 authors of [10], [11] propose covariance-based transmission schemes to maximize the sum rate in a two-cell network operating at high signal-to-noise power ratio and a cognitive network, respectively.

We also consider a variant of the TDD protocol called *reversed* TDD (R-TDD). In contrast to TDD, the order of the uplink and downlink periods in one of the tiers is reversed, i.e., while the macro BS is in the downlink, the SCs are in the uplink and vice versa. The choice of the duplexing mode changes the set of interfering nodes between the two tiers. Hence, depending on the network topology, R-TDD may outperform TDD or vice versa. An advantage of the R-TDD protocol is that the interference subspace can be accurately estimated as both the SCs and the BS have fixed locations, i.e., the interference channels between the SCs and the BS are quasi-static. The work in [12] considers a time-shifted TDD protocol to reduce the negative effects of pilot contamination. In [13], building upon the uplink-downlink duality established in [14], a distributed power allocation algorithm is proposed to ensure symmetric uplink-downlink rates in both tiers.

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We compare our proposed architecture to several baseline systems and the scheme in [13]. Our simulation results indicate that the proposed architecture can entirely eliminate the BS-to-SC interference, while achieving non-negligible macro rates. Moreover, our scheme could be concatenated with power control or other interference reduction techniques (e.g., the scheme in [13]) to further boost the performance.

The rest of this paper is organized as follows. Section II presents the system model and explains both TDD and R-TDD communication modes in a two tier network. Section III studies the covariance-based precoding design at the macro BS to minimize the aggregate interference experienced by SCs. Finally, Section V presents our simulation results and Section VI concludes the paper.

*Notation:* Matrices are presented in bold capital letters $\mathbf{A}$, column vectors are denoted in bold letters $\mathbf{a}$, and scalars are symbolized by lowercase letters $a$. $\mathbf{I}_N$ is the $N \times N$ identity matrix. The trace, transpose, and Hermitian transpose are respectively denoted by $\mathrm{tr}\,(\cdot)$, $(\cdot)^{\mathsf{T}}$, and $(\cdot)^{\mathsf{H}}$. The $k^{\mathrm{th}}$ column of $\mathbf{A}$ is expressed as $\mathbf{a}_k$. Moreover, $\mathbf{A}_k$ is matrix $\mathbf{A}$ with its $k^{\mathrm{th}}$ column removed.

## II. System Model

We consider a single-cell network where a macro tier is augmented with $S$ low range small-cell access points (SCAs), as schematically shown in Fig. 1. The BS employs $N$ transmit antennas to serve its $K$ associated single-antenna MUEs. Each SCA is equipped with a single antenna and devotes its available resources to its pre-scheduled small-cell user equipment (SUE).[1] We assume that transmissions across the tiers are perfectly synchronized. Both tiers share the available bandwidth $W$ with universal frequency reuse. All transmissions are assumed to take place over flat fading channels. Moreover, the maximum power of each transmitting node during the uplink and downlink is limited. Linear zero-force beamforming (ZFBF) and minimum mean square error (MMSE) detection are employed during the downlink and uplink, respectively.

### A. TDD Scheme

Fig. 2 depicts a two-tier network operating via the TDD protocol. During the downlink transmission, the BS and the SCAs transmit to their associated users over the first $\alpha T$, $\alpha \in [0,1]$, time slots of the channel coherence time $T$. Hence, the received signals at the MUEs are interfered by the transmission from the SCAs. Similarly, each SUE receives interfering signals from the BS and other SCAs. Therefore, the received base-band signal at MUE $k$ $y_{\mathrm{MUE},k}(t)$ and SUE $i$ $y_{\mathrm{SUE},i}(t)$ at a given time $t$ are, respectively, modeled as

$$y_{\mathrm{MUE},k}(t) = \mathbf{h}_k^{\mathsf{H}} \mathbf{W} \mathbf{x}_{\mathrm{BS}}(t) + z_{\mathrm{MUE},k}(t) \tag{1}$$

$$y_{\mathrm{SUE},i}(t) = g_{ii}^{*} x_{\mathrm{SCA},i}(t) + z_{\mathrm{SUE},i}(t) \tag{2}$$

where $\mathbf{h}_k$ is the channel vector between MUE $k$ and the BS, $\mathbf{x}_{\mathrm{BS}}(t) \sim \mathcal{CN}\left(\mathbf{0}, P_{\mathrm{BS}}\mathbf{I}_K\right)$ is the vector of transmitted symbols

[1]Extensions to different numbers of antennas at SCAs, MUEs, and SUEs are straightforward.

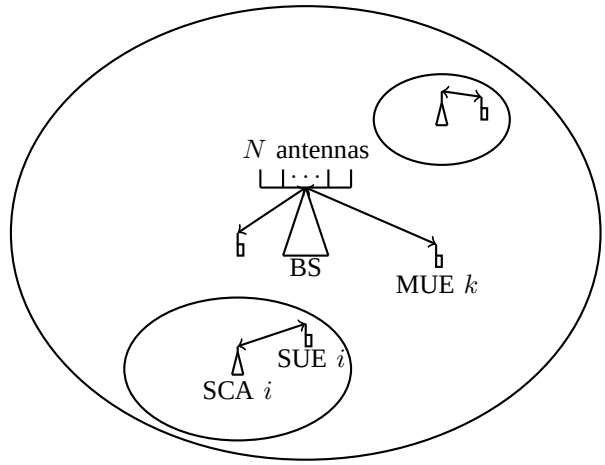


Fig. 1. A macrocellular network overlaid with small cells. The BS is equipped with $N$ antennas and serves $K$ MUEs, while each of the $S$ SCAs employs a single antenna to serve its associated SUE.

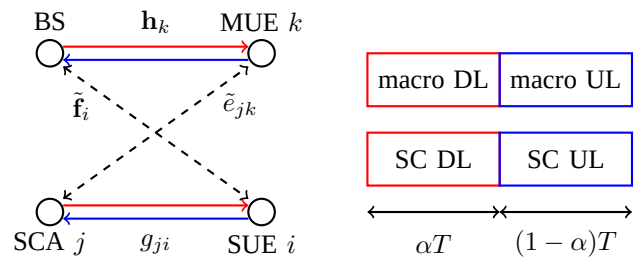


Fig. 2. A two-tier network employing TDD protocol; solid arrows denote direct links and dashed arrows denote interfering links.

from the BS to the MUEs, $g_{ji}$ expresses the channel gain between SCA $j$ and SUE $i$, and $x_{\mathrm{SCA},i}(t) \sim \mathcal{CN}\left(0, P_{\mathrm{SCA},i}\right)$ is the data symbol transmitted to the $i^{\mathrm{th}}$ SUE from its associated SCA. Assuming ZFBF precoding at the BS, $\mathbf{W} = [\mathbf{w}_1, \ldots, \mathbf{w}_K]$ is an $N \times K$ downlink precoding matrix normalized to allocate equal transmit power across MUEs. Let $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_K]$ be the $N \times K$ channel matrix between the MUEs and the BS and $\mathbf{H}^{+} = \mathbf{H}\left(\mathbf{H}^{\mathsf{H}}\mathbf{H}\right)^{-1}$ be the Moore-Penrose pseudo-inverse of $\mathbf{H}$. Therefore, $\mathbf{W}$ is given as

$$\mathbf{W} = \mathbf{H}^{+}\mathbf{\Gamma}^{\frac{1}{2}}$$

where $\mathbf{\Gamma}$ is a diagonal matrix whose $n^{\mathrm{th}}$ entry normalizes the corresponding column of $\mathbf{H}^{+}$ so that $||\mathbf{w}_n||^2 = 1/K$. Furthermore, interference and noise terms are lumped into $z_{\mathrm{MUE},k}(t)$ and $z_{\mathrm{SUE},i}(t)$ terms as

$$z_{\mathrm{MUE},k}(t) = \sum_{i \in \mathcal{S}} \tilde{e}_{ik}^{*} x_{\mathrm{SCA},i}(t) + n_{\mathrm{MUE},k}(t)$$

$$z_{\mathrm{SUE},i}(t) = \sum_{j \in \mathcal{S}\setminus\{i\}} g_{ji}^{*} x_{\mathrm{SCA},j}(t) + \tilde{\mathbf{f}}_i^{\mathsf{H}} \mathbf{W} \mathbf{x}_{\mathrm{BS}}(t) + n_{\mathrm{SUE},i}(t)$$

where $\tilde{e}_{ik}$ is the channel from MUE $k$ to the $i^{\mathrm{th}}$ SCA, $\mathcal{S} = \{1, 2, \ldots S\}$ is the set of SCAs' indices, and $\tilde{\mathbf{f}}_i$ denotes the $N$-dimensional channel vector between the BS and SUE $i$. Furthermore, $n_{\mathrm{MUE},k}(t)$ and $n_{\mathrm{SUE},i}(t)$ denote, in order, the

additive white Gaussian noise (AWGN) with variance $\sigma^2$ at MUE $k$ and SUE $i$; for simplicity, we assume that the noise powers at all antennas are identical. Therefore, the spectral efficiency of the $k^{\text{th}}$ MUE and the $i^{\text{th}}$ SUE are stated as

$$R^{\text{DL}}_{\text{MUE},k} = \alpha \log_2\left(1 + \text{SINR}^{\text{DL}}_{\text{MUE},k}\right)$$
$$R^{\text{DL}}_{\text{SUE},i} = \alpha \log_2\left(1 + \text{SINR}^{\text{DL}}_{\text{SUE},i}\right)$$

with the signal-to-interference-plus-noise ratios (SINRs)

$$\text{SINR}^{\text{DL}}_{\text{MUE},k} = \frac{P_{\text{BS}}|\mathbf{h}_k^{\mathsf{H}}\mathbf{w}_k|^2}{\sum_{j\in\mathcal{S}} P_{\text{SCA},j}|\tilde{e}_{jk}|^2 + \sigma^2}$$
$$\text{SINR}^{\text{DL}}_{\text{SUE},i} = \frac{P_{\text{SCA},i}|g_{ii}|^2}{\sum_{j\in\mathcal{S}\setminus\{i\}} P_{\text{SCA},j}|g_{ji}|^2 + P_{\text{BS}}\tilde{\mathbf{f}}_i^{\mathsf{H}}\mathbf{W}\mathbf{W}^{\mathsf{H}}\tilde{\mathbf{f}}_i + \sigma^2}.$$

During the remaining $(1-\alpha)T$ time slots, both tiers operate in the uplink mode. Hence, the received base-band signals at the BS $\mathbf{y}_{\text{BS}}(t)$ and SCA $i$ $y_{\text{SCA},i}(t)$ are expressed as

$$\mathbf{y}_{\text{BS}}(t) = \mathbf{H}\mathbf{x}_{\text{MUE}}(t) + \mathbf{z}_{\text{BS}}(t) \tag{3}$$
$$y_{\text{SCA},i}(t) = g_{ii}x_{\text{SUE},i}(t) + z_{\text{SCA},i}(t) \tag{4}$$

where $\mathbf{x}_{\text{MUE}}(t) \sim \mathcal{CN}(\mathbf{0}, P_{\text{MUE}}\mathbf{I}_K)$ is the transmitted signal vector from the MUEs to the BS and $x_{\text{SUE},i}(t) \sim \mathcal{CN}(0, P_{\text{SUE},i})$ denotes the transmitted signal from the $i^{\text{th}}$ SUE to its SCA. Similar to the expressions in (1)-(2), $\mathbf{z}_{\text{BS}}(t)$ and $z_{\text{SCA},i}(t)$ include the noise plus interference terms and are given as follows

$$\mathbf{z}_{\text{BS}}(t) = \sum_{i\in\mathcal{S}} \tilde{\mathbf{f}}_i x_{\text{SUE},i}(t) + \mathbf{n}_{\text{BS}}(t)$$
$$z_{\text{SCA},i}(t) = \sum_{j\in\mathcal{S}\setminus\{i\}} g_{ij}x_{\text{SUE},j}(t) + \tilde{\mathbf{e}}_i^{\mathsf{H}}\mathbf{x}_{\text{MUE}}(t) + n_{\text{SCA},i}(t)$$

where $\tilde{\mathbf{e}}_i = [\tilde{\mathbf{e}}_{i1}, \ldots, \tilde{\mathbf{e}}_{iK}]^{\mathsf{T}}$ and $\mathbf{n}_{\text{BS}}(t)$ and $n_{\text{SCA},i}(t)$ represent noise at the BS and SCA $i$. Assuming MMSE detection at the BS, the SINR of MUE $k$ and SUE $i$ are stated, respectively, as follows

$$\text{SINR}^{\text{UL}}_{\text{MUE},k} = P_{\text{MUE}}\mathbf{h}_k^{\mathsf{H}}\mathbf{\Sigma}^{-1}\mathbf{h}_k$$
$$\text{SINR}^{\text{UL}}_{\text{SUE},i} = \frac{P_{\text{SUE},i}|g_{ii}|^2}{\sum_{j\in\mathcal{S}\setminus\{i\}} P_{\text{SUE},j}|g_{ij}|^2 + P_{\text{MUE}}\tilde{\mathbf{e}}_i^{\mathsf{H}}\tilde{\mathbf{e}}_i + \sigma^2}$$

where

$$\mathbf{\Sigma} = P_{\text{MUE}}\mathbf{H}_k\mathbf{H}_k^{\mathsf{H}} + \sum_{i\in\mathcal{S}} P_{\text{SUE},i}\tilde{\mathbf{f}}_i\tilde{\mathbf{f}}_i^{\mathsf{H}} + \sigma^2\mathbf{I}_N.$$

The resulting uplink spectral efficiencies are given as

$$R^{\text{UL}}_{\text{MUE},k} = (1-\alpha)\log_2\left(1 + \text{SINR}^{\text{UL}}_{\text{MUE},k}\right)$$
$$R^{\text{UL}}_{\text{SUE},i} = (1-\alpha)\log_2\left(1 + \text{SINR}^{\text{UL}}_{\text{SUE},k}\right).$$

### *B. Reverse TDD scheme*

A two-tier network employing the R-TDD protocol is shown schematically in Fig. 3. In contrast to the TDD protocol, uplink and downlink transmissions in one tier are reversed, i.e., during the first $\alpha T$ time slots, the macro and SC tiers operate in the downlink and uplink mode, respectively. The transmission directions are reversed during the remaining time slots. Hence,

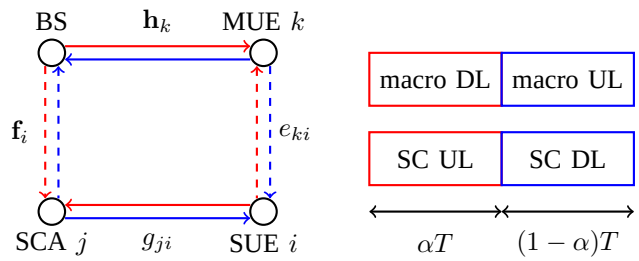


Fig. 3. A two-tier network employing R-TDD protocol; solid arrows denote direct links and dashed arrows denote interfering links.

downlink base-band signal models are equivalent to the expressions summarized in (1)-(2) wherein the interference plus noise terms are determined as

$$z_{\text{MUE},k}(t) = \sum_{i\in\mathcal{S}} e_{ki}^* x_{\text{SUE},i}(t) + n_{\text{MUE},k}(t)$$
$$z_{\text{SUE},i}(t) = \sum_{j\in\mathcal{S}\setminus\{i\}} g_{ji}^* x_{\text{SCA},j}(t) + \mathbf{e}_i^{\mathsf{H}}\mathbf{x}_{\text{MUE}}(t) + n_{\text{SUE},i}(t)$$

where $\mathbf{e}_i = [e_{1i}, \ldots e_{Ki}]^{\mathsf{T}}$ is the channel vector from SUE $i$ to the MUEs. Hence, the downlink SINR of MUE $k$ and SUE $i$ are formulated as

$$\text{SINR}^{\text{DL}}_{\text{MUE},k} = \frac{P_{\text{BS}}|\mathbf{h}_k^{\mathsf{H}}\mathbf{w}_k|^2}{\sum_{i\in\mathcal{S}} P_{\text{SUE},i}|e_{ki}|^2 + \sigma^2}$$
$$\text{SINR}^{\text{DL}}_{\text{SUE},i} = \frac{P_{\text{SCA},i}|g_{ii}|^2}{\sum_{i\in\mathcal{S}\setminus\{i\}} P_{\text{SCA},j}|g_{ji}|^2 + P_{\text{MUE}}\mathbf{e}_i^{\mathsf{H}}\mathbf{e}_i + \sigma^2}.$$

Note that in a R-TDD system, the downlink rate pre-log factors of the macro and SC tiers are $\alpha$ and $1-\alpha$, respectively.

Likewise, uplink signals are equivalent to expressions in (3)-(4), where the interference plus noise terms are expressed as

$$\mathbf{z}_{\text{BS}}(t) = \sum_{i\in\mathcal{S}} \mathbf{f}_i x_{\text{SCA},i}(t) + \mathbf{n}_{\text{BS}}(t)$$
$$z_{\text{SCA},i}(t) = \sum_{j\in\mathcal{S}\setminus\{i\}} g_{ij}x_{\text{SUE},j}(t) + \mathbf{f}_i^{\mathsf{H}}\mathbf{W}\mathbf{x}_{\text{BS}}(t) + n_{\text{SCA},i}(t). \tag{5}$$

Accordingly, the uplink SINRs are calculated as

$$\text{SINR}^{\text{UL}}_{\text{MUE},k} = P_{\text{MUE},k}\mathbf{h}_k^{\mathsf{H}}\mathbf{\Omega}^{-1}\mathbf{h}_k$$
$$\text{SINR}^{\text{UL}}_{\text{SCA},i} = \frac{P_{\text{SUE},i}|g_{ii}|^2}{\sum_{j\in\mathcal{S}\setminus\{i\}} P_{\text{SUE},j}|g_{ij}|^2 + P_{\text{BS}}\mathbf{f}_i^{\mathsf{H}}\mathbf{W}\mathbf{W}^{\mathsf{H}}\mathbf{f}_i + \sigma^2}$$

where

$$\mathbf{\Omega} = P_{\text{BS}}\mathbf{H}_k\mathbf{H}_k^{\mathsf{H}} + \sum_{i\in\mathcal{S}} P_{\text{SCA},i}\mathbf{f}_i\mathbf{f}_i^{\mathsf{H}} + \sigma^2\mathbf{I}_N.$$

Moreover, uplink rate pre-log factors are $1-\alpha$ and $\alpha$ for the macro and SC tiers. It is worth emphasizing that unlike a TDD system, the macro uplink duration is coupled with that of the SC downlink and vice versa. Thus, improving the uplink or downlink rates of each tier reduces, respectively, the downlink and uplink rates of the other.

## III. Covariance Based ZFBF

Upon completion of the macro cell uplink phase (under the TDD and the R-TDD protocol), the BS decodes its desired signal $\mathbf{x}_{\mathrm{MUE}}(t)$, and subtracts it from the received signal $\mathbf{y}_{\mathrm{BS}}(t)$. The remaining part $\tilde{\mathbf{y}}_{\mathrm{BS}}(t)$ envelops the interference and noise effects from SCs' transmissions which can be exploited to compute the empirical covariance matrix as[2]

$$\begin{aligned}
&\frac{1}{\alpha T}\sum_{t=1}^{\alpha T}\tilde{\mathbf{y}}_{\mathrm{BS}}(t)\tilde{\mathbf{y}}_{\mathrm{BS}}^{\mathsf{H}}(t)\\
&= \frac{1}{\alpha T}\sum_{t=1}^{\alpha T}\left(\sum_{i\in\mathcal{S}}\mathbf{f}_i x_{\mathrm{SCA},i}(t)+\mathbf{n}_{\mathrm{BS}}(t)\right)\\
&\qquad\times\left(\sum_{j\in\mathcal{S}}\mathbf{f}_j x_{\mathrm{SCA},j}(t)+\mathbf{n}_{\mathrm{BS}}(t)\right)^{\mathsf{H}}\\
&\xrightarrow[T\to\infty]{\text{a.s.}}\sum_{i\in\mathcal{S}}\mathbb{E}\left[P_{\mathrm{SCA},i}\mathbf{f}_i\mathbf{f}_i^{\mathsf{H}}+\mathbf{n}_{\mathrm{BS}}(t)\mathbf{n}_{\mathrm{BS}}(t)^{\mathsf{H}}\right]\\
&= \sum_{i\in\mathcal{S}}P_{\mathrm{SCA},i}\mathbf{f}_i\mathbf{f}_i^{\mathsf{H}}+\sigma^2\mathbf{I}\\
&\triangleq \mathbf{Q}
\end{aligned}\tag{6}$$

where "$\xrightarrow[T\to\infty]{\text{a.s.}}$" denotes almost sure convergence. Thus, for sufficiently long channel coherence times, the BS can estimate $\mathbf{Q}$ with high precision. Furthermore, it is assumed that $\sigma^2$ is known. The essential question to address is *how can the BS leverage this information to reduce sum cross-tier interference?* Let $\mathcal{I}_{\mathrm{sum}}$ denote the sum interference imposed on SCAs. From (5), one concludes that $\mathcal{I}_{\mathrm{sum}}$ is calculated as

$$\mathcal{I}_{\mathrm{sum}}=\sum_{i\in\mathcal{S}}\mathbf{f}_i^{\mathsf{H}}\mathbf{W}\mathbf{W}^{\mathsf{H}}\mathbf{f}_i=\mathrm{tr}\left[\mathbf{W}^{\mathsf{H}}\left(\sum_{i\in\mathcal{S}}\mathbf{f}_i\mathbf{f}_i^{\mathsf{H}}\right)\mathbf{W}\right].\tag{7}$$

Let $\mathbf{Q}-\sigma^2\mathbf{I}_N$ be decomposed as $\mathbf{V}\mathbf{D}\mathbf{V}^{\mathsf{H}}$ where $\mathbf{D}=\mathrm{diag}(\lambda_1,\ldots,\lambda_S)$ contains the eigenvalues of $\mathbf{Q}-\sigma^2\mathbf{I}_N$ in descending order and the $k^{\mathrm{th}}$ column of $\mathbf{V}$ is the eigenvector associated with $\lambda_k$. One can conclude from (7) that in order to minimize $\mathcal{I}_{\mathrm{sum}}$, the beamforming vectors must be orthogonal to the subspace spanned by $\sum_{i\in\mathcal{S}}\mathbf{f}_i\mathbf{f}_i^{\mathsf{H}}$. Therefore, given that the BS is equipped with $N$ transmit antennas and delivers independent data streams to $K$ users, $m\leq N-K$ DoF can be used to spatially reject interference imposed on the SCs. Thus, the precoding matrix is designed as follows

$$\mathbf{W}_{\mathrm{SP}}=\left(\mathbf{I}_N-\mathbf{U}_m\mathbf{U}_m^{\mathsf{H}}\right)\mathbf{H}^{+}\mathbf{\Gamma}_{\mathrm{SP}}^{\frac{1}{2}}$$

where $\mathbf{U}_m$ encompasses the $m$ first columns of $\mathbf{V}$ and $\mathbf{\Gamma}_{\mathrm{SP}}^{\frac{1}{2}}$ normalizes each column of $\mathbf{W}_{\mathrm{SP}}$ so that $||\mathbf{w}_{\mathrm{SP},k}||^2=1/K$. Hence, the first term $\mathbf{I}_N-\mathbf{U}_m\mathbf{U}_m^{\mathsf{H}}$ projects the precoding vectors to the subspace orthogonal to the columns of $\mathbf{U}_m$. Furthermore, the maximum dimension of the interference subspace $\sum_{i\in\mathcal{S}}\mathbf{f}_i\mathbf{f}_i^{\mathsf{H}}$ is $S$. Therefore, even with a small number of antennas, i.e., $N$ is not much larger than $K$, a significant gain can be obtained by only suppressing the strongest interference directions.

The proposed precoding scheme can similarly be employed in a TDD network to guarantee the coexistence of the two tiers. Nonetheless, it is remarkable that the quality of the interference covariance estimation is not identical. In a R-TDD network, the SCAs' downlink transmissions interfere with the received signal at the BS during its uplink mode. Since the SCAs are assumed to be stationary, the SCA-to-BS channels are quasi-static; the covariance estimation is not susceptible to the instantaneous channel variations and is stable over long time scales. On the other hand, in a TDD network, the uplink transmission of the *mobile* SUEs interfere with the uplink transmission of the macro tier. The SUE-to-BS channels potentially fluctuate at a higher rate. Therefore, less samples are available to approximate the time-averaged interference covariance and the estimation error may degrade the system performance.

## IV. Benchmark Architectures

We compare our proposed architectures with two existing schemes in the literature, namely frequency division multiple access (FDMA) with TDD or FDD (FDMA-TDD/FDD) and R-TDD via uplink-downlink duality (R-TDD-UD) [15], [14]. In a FDMA-TDD/FDD, the transmissions of the two tiers are orthogonal in frequency. Therefore, cross-tier interference does not exist. Although FDD suffers from the aforementioned issues summarized in Section I, the rate regions of both schemes are identical since we do not account for channel training.

R-TDD-UD is proposed in [13]. During the first $\alpha T$ time slots, the macro BS employs ZFBF and transmits to its associated users. Furthermore, the SUEs transmit in the uplink direction with a constant power. Given that the uplink-downlink duality conditions hold during the remaining $(1-\alpha)T$ time slots, it is assured that each user achieves the same SINR as that of its first stage. An iterative power allocation algorithm based on Yates distributed scheme [16] is employed to assign powers during the second stage.

## V. Simulation Results

We consider a circular cell of radius $R=500$ meters where the BS is located at the center, $K=20$ MUEs and $S=100$ SCAs are uniformly scattered within the cell region, and share the available bandwidth of $W=5$ MHz. Each individual SUE is randomly placed within 5 to 15 meters from its associated SCA. We furthermore consider two different network setups; indoor SCs and outdoor SCs, where in the former case, SCAs and SUEs are isolated from the rest of the network via internal and external walls. Therefore, the distance dependent path loss between two nodes at positions $x$ and $y$ is defined as

$$a(x,y)=\frac{L_e^{n(x,y)}L_i^{p(x,y)}}{1+d(x,y)^{\beta}}$$

[2]We present the derivations for R-TDD scheme in this paper. The same approach can be used for TDD. Furthermore, we assume that channels are stationary and ergodic.

TABLE I
NETWORK PARAMETERS

| | |
|---|---|
| $R = 500$ meters | cell radius |
| $W = 5$ MHz | total bandwidth |
| $N_0 = -174$ dBm | noise power spectral density |
| $K = 20$ | number of MUEs |
| $S = 100$ | number of SCAs/SUEs |
| $P_{\mathrm{BS}} = 43$ dBm | BS power |
| $P_{\mathrm{SCA}} = 23$ dBm | SCA power |
| $P_{\mathrm{MUE}} = P_{\mathrm{SUE}} = 23$ dBm | MUE and SUE powers |
| $L_e = 15$ dB | external wall loss |
| $L_i = 7$ dB | internal wall loss |
| $\alpha = 0.5$ | pre-log factor |

where the external and internal wall losses are, respectively, presented by $L_e$ and $L_i$. The functions $n(x, y)$ and $p(x, y)$ count the number of external and internal walls between the communication ends in order. Moreover, $d(x, y)$ denotes the distance between two points and $\beta$ is a path loss exponent. It is assumed that, one internal wall blocks the indoor communication way, one external wall exists between indoor and outdoor nodes, and two external walls are located between any SCA-to-SCA links. $\beta$ is set to 3.7 for BS-to-all-other-node channels and $\beta$ is 4 for the remaining links. The simulation results are averaged over node positions and Rayleigh fading channel realizations. Table I summarizes the network parameters.

Fig. 4 and 5 compare, respectively, the achievable downlink (DL) rates of the mentioned schemes for the indoor and outdoor scenarios where $m$ DoF (or antennas) have been used to spatially reject the interference enforced from the BS on the SC-tier.[3] As can be seen, increasing the number of antennas at the BS provides a power gain and, consequently, boosts the aggregate downlink rate of the macro tier. Moreover, exploiting the interference covariance information in a R-TDD network only degrades the macro tier performance, while it has no effect on the downlink rates of the SCs. However, our simulation results show that the TDD scheme concatenated with the covariance based precoding at the BS can boost the SC's DL rates by $42\,\%$ and $75\,\%$ with $N = 100$ and $N = 200$ antennas compared to the achievable rates with $m = 0$ in the indoor scenario. In particular, given the number of MUEs and SCs in the cell region, the BS employing $N = 200$ antennas can completely remove the cross-tier interference imposed on SCs. Therefore, an interference-free operating point is achievable and the sum rate of the SC tier is the same as that of the FDMA-TDD/FDD where the entire band is assigned to the SC tier. In addition, our proposed scheme outperforms the R-TDD-UD scheme and provides considerably higher downlink rates for SCs. However, the R-TDD-UD scheme provides symmetric uplink and downlink rates (at the cost of violating the individual per-node power constraints) which is not the case for our scheme.

The obtainable gain of the TDD scheme with covariance based precoding is less considerable in the outdoor scenario. In essence, given the lack of coordination among the SCs,

[3]Note that the dimension of the cross-tier interference is equal to 100 in our setup.

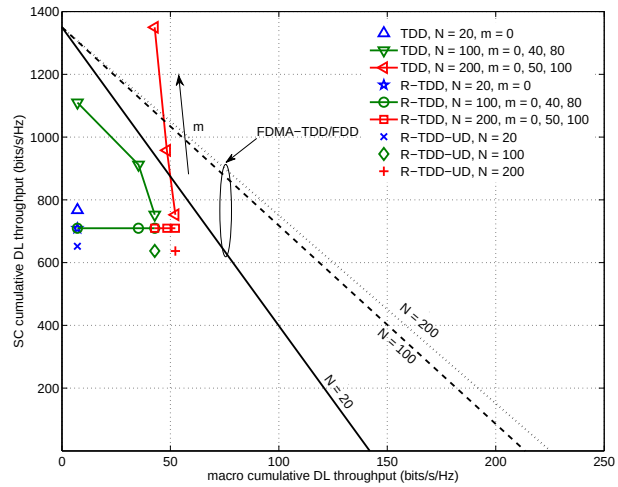


Fig. 4. Achievable DL rates of indoor scenario. The connected points denote the achievable spectral efficiency of each scheme with increasing $m$ from right to left.

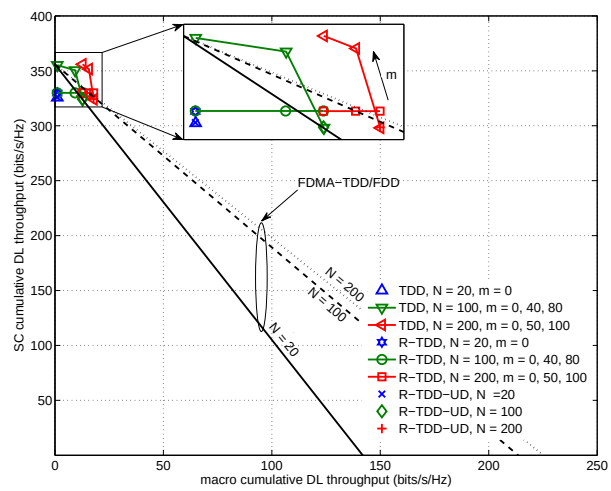


Fig. 5. Achievable DL rates of outdoor scenario. The connected points denote the achievable spectral efficiency of each scheme with increasing $m$ from right to left.

co-tier interference, i.e., interference between SCs, dominates the cross-tier interference. Nonetheless, the proposed scheme improves SCs' rates by $8\,\%$ while the performance loss of the macro rate is indistinguishable.

In a similar fashion, Fig. 6 and 7 compare the uplink (UL) achievable rates for both indoor and outdoor setups in order. Unlike the previous case, the SC uplink rates can be improved using the R-TDD scheme combined with the covariance based precoding by $61\,\%$ with $N = 100$ and $117\,\%$ with $N = 200$. However, sacrificing the available DoF in the TDD approach does not improve the uplink rates of the SCs. In addition, compared to R-TDD-UD, our proposed approach provides significant gains for both tiers.

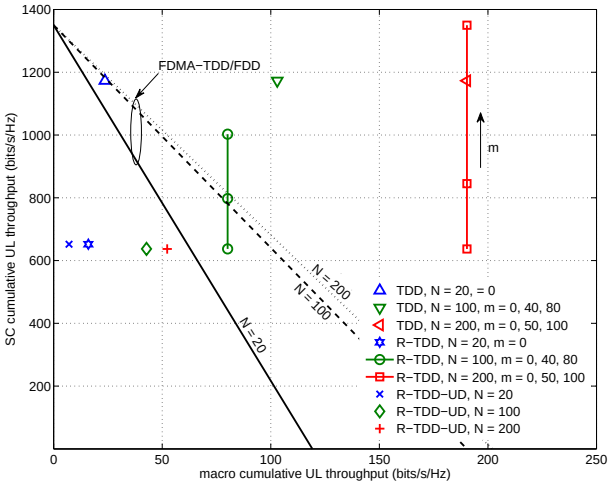


Fig. 6. Achievable UL rates of indoor scenario. The connected points denote the achievable spectral efficiency of each scheme with increasing $m$ from bottom to top.

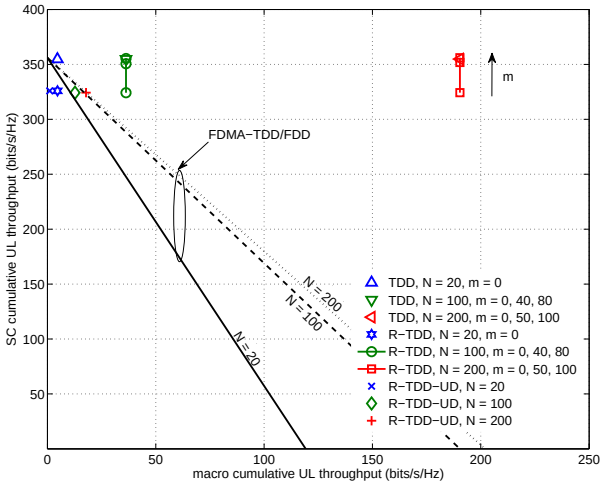


Fig. 7. Achievable UL rates of outdoor scenario. The connected points denote the achievable spectral efficiency of each scheme with increasing $m$ from bottom to top.

## VI. Conclusion

We have considered a TDD-based two-tier network architecture which incorporates the advantageous features of a massive MIMO macro BS overlaid with small cells. The TDD channel reciprocity not only enables the BS to accommodate a large number of antennas without prohibitive channel estimation overhead, but also allows it to estimate the interfering subspace from its received uplink signal. This knowledge can be used to design downlink precoders which reduce the interference to the SC-tier. We have compared two duplexing schemes, TDD and R-TDD, which determine the set of interfering nodes between the two tiers. Our simulation results indicate that the proposed scheme can significantly minimize the aggregate cross-tier interference experienced by SCs at the price of a negligible macro performance loss. Most importantly, our scheme could be combined with power control or other interference reduction techniques (e.g., the scheme in [13]) for a further performance increase. Future work evaluates the performance gains of the proposed scheme in a more realistic multi-cell setting where also the SCs are equipped with mutiple antennas and employ a similar precoding scheme to cancel inter- and intra-tier interference.

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