# Decentralized Precoding for Multicell MIMO Downlink

Winston W. L. Ho, *Member, IEEE,* Tony Q. S. Quek, *Member, IEEE,* Sumei Sun, *Member, IEEE,* and Robert W. Heath, Jr., *Fellow, IEEE*

***Abstract*—Interference is a performance limiting factor in dense cellular networks with aggressive frequency reuse. Cooperation among base stations (BSs) is a promising approach for improving data rates by eliminating or mitigating interference. For the downlink, the highest spectral efficiency gains are achieved through precoding with full coordination, which requires complete channel state information (CSI) and data be shared among BSs at the cost of significant utilization of the backhaul. In this paper, we propose distributed precoding techniques for the multicell MIMO downlink. Unlike prior work, our proposed precoders are both decentralized with respect to the BSs as well as capable of enabling multiple users to share the same frequency carrier spatially within each cell. Specifically, each BS designs its own precoder without requiring data or downlink CSI of links from other BSs. Since CSI is unlikely to be perfect, we study the effect of imperfect CSI on our proposed precoders and propose a robust precoder in the presence of CSI uncertainty. Simulations show that our proposed methods enjoy a rate increase with SNR similar to multicell joint dirty paper coding in the high SNR regime due to effective interference mitigation. Numerical results reflect the sensitivity of each proposed precoder with respect to the imperfectness in the available CSI.**

***Index Terms*—Multicell, network MIMO, interference mitigation, decentralized precoder, inter-cell interference, dirty paper coding, CSI uncertainty.**

## I. Introduction

MULTIPLE-INPUT multiple-output (MIMO) systems where multiple antennas are deployed at both the transmitter and the receiver has emerged as one of the most significant technological breakthroughs in modern wireless communications [1], [2]. Recently, important information theoretic results have established that the capacity of the multiuser MIMO downlink is achievable by dirty paper coding (DPC) [3]–[6]. In next generation cellular networks, the increased density of base stations (BSs) and the aggressive reuse of frequencies are seen as the solution to the pressing problem of scarce frequency spectrum. As a result, cellular systems are going to be interference limited. Multicell or network MIMO promises to reduce or eliminate the interference problem through cooperation or coordination between BSs [7]–[14].

Joint encoding with DPC among cooperating BSs has been shown to achieve the (maximum theoretical) capacity of the multicell MIMO downlink. Joint encoding is hard to achieve in practical systems due to the requirement of precise time and phase synchronization of the transmitted signals from involved BSs [9]. Besides DPC, zero-forcing beamforming [15] and game theoretic optimization for scheduling across frequency and time [16], [17] have also been proposed. Linear block diagonalization methods null out inter-cell interference using linear zero-forcing (ZF) techniques to create a block diagonal effective channel from the BSs to the users [18], [19]. The authors in [20] proposed linear algorithms for full and clustered broadcast channel scenarios that approach the sum capacity of multicell DPC. In [21], the authors proposed a feedback-bit partitioning algorithm to ensure a manageable load on the finite-capacity backhaul.[1]

In [24], the multicell downlink is interpreted as a factor graph with local message passing between neighboring BSs. They proposed a downlink beamforming algorithm based on belief propagation. The authors in [25] analyzed the effect of the coordination cluster size through cellular system simulations. In [26], the authors proposed a framework for optimizing the downlink where multicell joint transmission is possible but constrained by a limited backhaul infrastructure between sites. In [27], the authors considered single-class and double-class networks and analyzed schemes involving cell-breathing, cophasing, superposition coding, as well as other hybrid strategies.

We found that most techniques assume a high level of cooperation among BSs in which (processed) data for an intended user needs to be available at multiple BSs. In such a scenario, multiple cooperating BSs act as a large virtual antenna array to beamform to a particular user. Clearly, system performance is improved at the cost of significant system overhead related to channel state information (CSI) feedback to the central processor and data exchange among the BSs. The concept of maximizing the signal-to-leakage-plus-noise ratio (SLNR) has been used in [28]–[30] to reduce the complexity of the transmitter processing. The authors in [28] applied it in the single-cell multiuser MIMO downlink. In [29], the authors

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W. W. L. Ho, T. Q. S. Quek, and S. Sun are with the Modulation and Coding Department, Institute for Infocomm Research, 1 Fusionopolis Way, #21-01 Connexis, South Tower, Singapore 138632 (e-mail: {wlho, qsquek, sunsm}@i2r.a-star.edu.sg).

R. W. Heath is with the Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX, 78712-0240 USA (e-mail: rheath@ece.utexas.edu). R. Heath was supported in part by the National Science Foundation through grant NSF-CCF-0830615.

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[1]For related work on the uplink, see [22], [23].

extended it to the multicell scenario using joint transmission. The authors in [30] considered a single user per cell and applied the SLNR concept for decentralized precoding. SLNR-based precoding can be seen as a balance between the altruistic and egoistic beamforming strategies in the game theory of interference channels [31]–[37].

In this paper, we propose two decentralized precoding methods for network MIMO downlink channels, where multi-antenna BSs serve multiple users equipped with one or more antennas. Each BS performs coordinated processing in a distributed fashion with only the CSI of links originating from itself and only the data intended for users in its own coverage region (intra-cell users). If time division duplex (TDD) is used, the CSI of the channels from the BS to the intra-cell and out-of-cell users can be obtained implicitly during the uplink phase using channel reciprocity without the need for explicit feedback.[2] With frequency division duplex (FDD), the user may need to feedback the downlink CSI from the neighboring BS via backhaul to the said BS.

These distributed precoders tackle both intra-cell and out-of-cell interference. In particular, we propose a nonlinear precoder called the leakage-DPC and a linear precoder called the multicell leakage suppression. The leakage-DPC obtains a higher sum rate than the multicell leakage suppression, while the later has lower complexity because it is a linear technique. Our leakage-DPC method performs a channel precoding based on maximizing a cell-based SLNR followed by DPC for intra-cell users. To enhance the robustness of the leakage-DPC method with respect to CSI uncertainty, we propose a robust variation of the leakage-DPC strategy. The multicell leakage suppression method is a linear precoding method based on the SLNR.

Unlike prior work, both our precoders handle multiple intra-cell and out-of-cell users in a decentralized manner. In other words, a central processor among the BSs is not required. We examine the performance of our proposed precoders with respect to the amount of out-of-cell interference, SNR, numbers of antennas and users as well as CSI uncertainty. With sufficient number of transmit antennas, the proposed methods enjoy a rate growth with SNR similar to multicell joint DPC in the high SNR regime, due to the interference mitigation. For our proposed methods, at high out-of-cell channel gains, increasing the out-of-cell channel gain has diminishing negative effects on the sum rate performances because our precoders are able to mitigate the out-of-cell interference.

This paper is organized as follows. In Section II, we describe the multicell downlink system model. In Sections III and IV, we introduce our nonlinear and linear precoders respectively. Numerical simulations are given in Section V. Finally, we give a discussion and a conclusion in Sections VI and VII respectively. The following notation is used. Bold lowercase letters, e.g. $\mathbf{a}$, are used to denote column vectors, bold uppercase letters, e.g. $\mathbf{A}$, are used to denote matrices, and non-bold letters in italics, e.g. $a$ or $A$, are used to denote scalar values. $\min(a, b)$ is the minimum of two real numbers $a$ and $b$. $(\cdot)^T$ and $(\cdot)^H$ denote the matrix transpose and conjugate transpose operations respectively. $\mathbb{E}[\cdot]$ stands for statistical expectation. $\mathbb{C}^{P\times Q}$ denotes the space of complex $P \times Q$ matrices. The distribution of a circularly symmetric complex Gaussian (CSCG) vector with mean vector $\mathbf{m}$ and covariance matrix $\mathbf{R}$ is denoted by $\mathcal{CN}(\mathbf{m}, \mathbf{R})$, and $\sim$ means "distributed as". $\mathbf{R}_{\mathbf{x}} = \mathbb{E}[\mathbf{x}\mathbf{x}^H]$ is the covariance matrix of a vector $\mathbf{x}$. $\|\cdot\|_2$ denotes the vector Euclidean norm, while $\mathbf{I}_N$ denotes the $N \times N$ identity matrix. $\mathrm{Tr}(\mathbf{A})$ stands for the trace of a matrix $\mathbf{A}$. $\det(\mathbf{A})$ denotes the determinant of $\mathbf{A}$. $[\mathbf{A}]_{i,j}$ is the scalar entry of $\mathbf{A}$ in the $i$-th row and $j$-th column. $\mathrm{vec}(\mathbf{A})$ is a column vector composed of the entries of $\mathbf{A}$ taken column-wise. $\mathrm{diag}(\mathbf{A})$ represents the diagonal matrix with the same diagonal as the matrix $\mathbf{A}$. $\mathrm{blkdiag}(\mathbf{A}_1, \mathbf{A}_2, \ldots, \mathbf{A}_U)$ denotes a block diagonal matrix whose block diagonal elements are $\mathbf{A}_u, u = 1, ..., U$.

## II. System Model

We consider a downlink cellular network with $M$ cells of $N_{\mathrm{T}}$ transmit antennas each, serving $U$ users with $N_{\mathrm{R}}$ receive antennas each. For notational simplicity, we assume a synchronous multicell system. To facilitate the rate analysis later, the received signal vector of all users in the system is written in a block system format as

$$\mathbf{y}_{\mathrm{sys}} = \mathbf{H}_{\mathrm{sys}}\mathbf{x}_{\mathrm{sys}} + \mathbf{z}_{\mathrm{sys}} \tag{1}$$

where $\mathbf{y}_{\mathrm{sys}} = \mathrm{vec}([\mathbf{y}_1, \mathbf{y}_2, \ldots, \mathbf{y}_M]) \in \mathbb{C}^{MUN_{\mathrm{R}}\times 1}$ is the system receive signal vector such that $\mathbf{y}_m \in \mathbb{C}^{UN_{\mathrm{R}}\times 1}$ is the received signal vector at the $m$-th cell. $\mathbf{x}_{\mathrm{sys}} = \mathrm{vec}([\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_M]) \in \mathbb{C}^{MN_{\mathrm{T}}\times 1}$ is the system transmit signal vector such that $\mathbf{x}_m \in \mathbb{C}^{N_{\mathrm{T}}\times 1}$ is the transmit signal vector from the $m$-th BS with average power constraint $P_m = \mathbb{E}[\mathrm{Tr}(\mathbf{x}_m\mathbf{x}_m^H)]$. $\mathbf{z}_{\mathrm{sys}} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{MUN_{\mathrm{R}}})$ is the additive CSCG noise vector. The instantaneous downlink channel matrix $\mathbf{H}_{\mathrm{sys}} \in \mathbb{C}^{MUN_{\mathrm{R}}\times MN_{\mathrm{T}}}$ is given by

$$\mathbf{H}_{\mathrm{sys}} = \begin{bmatrix} \mathbf{H}_1 & \mathbf{H}_{2\to 1} & \cdots & \mathbf{H}_{M\to 1} \\ \mathbf{H}_{1\to 2} & \mathbf{H}_2 & \cdots & \mathbf{H}_{M\to 2} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}_{1\to M} & \mathbf{H}_{2\to M} & \cdots & \mathbf{H}_M \end{bmatrix} \tag{2}$$

where $\mathbf{H}_m = \mathbf{H}_{m\to m} \in \mathbb{C}^{UN_{\mathrm{R}}\times N_{\mathrm{T}}}$ denotes the channel matrix from the $m$-th BS to all its served users and $\mathbf{H}_{m\to n}$ denotes the channel matrix from the $m$-th BS to all the $U$ users in the $n$-th cell. For our proposed precoders, the $m$-th BS would only require at most the CSI of $\mathbf{H}_{m\to n}, 1 \le n \le M$. By denoting $\mathbf{y}_m = \mathrm{vec}([\mathbf{y}_{m,1}, \mathbf{y}_{m,2}, \ldots, \mathbf{y}_{m,U}]) \in \mathbb{C}^{UN_{\mathrm{R}}\times 1}$, the received signal of the $u$-th user at the $m$-th cell is given by

$$\mathbf{y}_{m,u} = \mathbf{H}_{m,u}\mathbf{x}_m + \sum_{n\neq m}^{M} \mathbf{H}_{n\to m,u}\mathbf{x}_n + \mathbf{z}_{m,u} \tag{3}$$

where $\mathbf{H}_{m,u} \in \mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{T}}}$ is the channel matrix from the $m$-th BS to the $u$-th intra-cell user such that $\mathbf{H}_m = [\mathbf{H}_{m,1}^T, \mathbf{H}_{m,2}^T, \ldots, \mathbf{H}_{m,U}^T]^T \in \mathbb{C}^{UN_{\mathrm{R}}\times N_{\mathrm{T}}}$ in (2). $\mathbf{H}_{n\to m,u} \in \mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{T}}}$ is the channel matrix from the $n$-th BS to the $u$-th user in the $m$-th cell such that $\mathbf{H}_{n\to m} = [\mathbf{H}_{n\to m,1}^T, \mathbf{H}_{n\to m,2}^T, \ldots, \mathbf{H}_{n\to m,U}^T]^T$ in (2). $\mathbf{z}_{m,u} \sim$

[2]Neighbouring BSs may need to coordinate their served users to perform channel sounding at different times for the training to be orthogonal.

$\mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{N_\mathrm{R}})$ is the additive noise. To accommodate the transmission of multiple data streams, we allow each user to receive $d$ data streams from its own serving BS where $d \le N_\mathrm{R}$.

For the $m$-th BS, if an out-of-cell channel $\mathbf{H}_{m\to n,u}$ for some cell $n \neq m$ and some user $u$ has small path gains compared to $\mathbf{H}_{m\to m}$, as in the small co-channel interference scenario, this channel need not be known because the interference effect is negligible.[3] The benefit is that in TDD systems, the BS would only need to perform uplink channel estimations for users with significant path gains. Suppose there are $\bar{U}$ such out-of-cell users. Let $\bar{\mathbf{H}}_m \in \mathbb{C}^{\bar{U}N_\mathrm{R}\times N_\mathrm{T}}$ represent the channel towards these $\bar{U}$ users. Also, define $\bar{\mathbf{H}}_{m,u} = [\mathbf{H}_{m,1}^T, \ldots, \mathbf{H}_{m,u-1}^T, \mathbf{H}_{m,u+1}^T, \ldots, \mathbf{H}_{m,U}^T, \bar{\mathbf{H}}_m^T]^T \in \mathbb{C}^{(U-1+\bar{U})N_\mathrm{R}\times N_\mathrm{T}}$ as the channel from this BS to its $U-1$ intra-cell users other than the $u$-th user as well as those $\bar{U}$ out-of-cell users. In the following sections, we design precoding matrices for each BS by taking into account both intra-cell and out-of-cell interference.

The following channel model shall be used to incorporate CSI uncertainty [38]

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E} \tag{4}$$

where $\mathbf{E}$ is the probabilistic additive error component with independent and identically distributed (i.i.d.) elements $[\mathbf{E}]_{i,j} \sim \mathcal{CN}(0, \sigma_\mathrm{e}^2)$. $\sigma_\mathrm{e}^2$ is a parameter that captures the quality of the channel estimation and is assumed to be known at the transmitter. $\hat{\mathbf{H}}$ is the estimate of the channel available at the transmitter with elements distributed as $\mathcal{CN}(0, 1-\sigma_\mathrm{e}^2)$ and $\mathbf{H}$ is the actual channel with elements distributed as $\mathcal{CN}(0,1)$.

## III. Leakage-DPC Strategy

In this section, we propose a nonlinear technique called leakage-DPC. Unlike prior work, our approach ensures no interference between the signals to different users by applying a block diagonal DPC processing. For this to work, a projection operation is applied beforehand as though the base station is transmitting on multiple eigenmodes to the users collectively, not individually as in the approach in [28]. The cell index subscript $m$ is sometimes dropped for notational simplicity because the BS processing is decentralized. The $m$-th BS requires at most the CSI of $\mathbf{H}_{m\to n}, 1 \le n \le M$.

### A. Algorithm Description

The objective is to find an orthogonal precoder that maximizes the intra-cell signal strength and minimizes the out-of-cell leakage. It should also have sufficient rank to support multiple intra-cell users. Consider the hypothetical case in which the BS performs beamforming via a semi-unitary matrix $\mathbf{V} \in \mathbb{C}^{N_\mathrm{T}\times N_\mathrm{V}}$ where $\mathbf{V}^H\mathbf{V} = \mathbf{I}_{N_\mathrm{V}}$ (which does not change the transmit power). $\mathbf{V}$ and $N_\mathrm{V}$ are to be determined. The stacked desired signal vector received by the intra-cell users is given by $\mathbf{y}^{\mathrm{sig}} \in \mathbb{C}^{UN_\mathrm{R}\times 1}$ where

$$\mathbf{y}^{\mathrm{sig}} = \sqrt{P/N_\mathrm{V}}\mathbf{H}_m\mathbf{V}\mathbf{s} \tag{5}$$

and $\mathbf{s}$ is the (uncoded) data symbol vector. Assume the stacked noise vector received by these users is $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{UN_\mathrm{R}})$. The leakage to the out-of-cell users is given by $\mathbf{y}^{\mathrm{leak}} \in \mathbb{C}^{\bar{U}N_\mathrm{R}\times 1}$ where

$$\mathbf{y}^{\mathrm{leak}} = \sqrt{P/N_\mathrm{V}}\bar{\mathbf{H}}_m\mathbf{V}\mathbf{s}. \tag{6}$$

The covariance matrices of the desired signal, leakage, and noise are given respectively by

$$\begin{aligned}
\mathbf{R}_{\mathbf{y}^{\mathrm{sig}}} &= (P/N_\mathrm{V})\,\mathbf{H}_m\mathbf{V}\mathbf{V}^H\mathbf{H}_m^H \\
\mathbf{R}_{\mathbf{y}^{\mathrm{leak}}} &= (P/N_\mathrm{V})\,\bar{\mathbf{H}}_m\mathbf{V}\mathbf{V}^H\bar{\mathbf{H}}_m^H \\
\mathbf{R}_{\mathbf{z}} &= N_0\mathbf{I}_{UN_\mathrm{R}}.
\end{aligned}$$

The cell SLNR $\zeta_\mathrm{C}$ is defined as

$$\begin{aligned}
\zeta_\mathrm{C} &= \frac{\mathrm{Tr}\left(\mathbf{R}_{\mathbf{y}^{\mathrm{sig}}}\right)}{\mathrm{Tr}\left(\mathbf{R}_{\mathbf{y}^{\mathrm{leak}}}\right) + \mathrm{Tr}\left(\mathbf{R}_{\mathbf{z}}\right)} \\
&= \frac{\sum_{i=1}^{N_\mathrm{V}} \mathbf{v}_i^H\mathbf{G}_\mathrm{A}\mathbf{v}_i}{\sum_{i=1}^{N_\mathrm{V}} \mathbf{v}_i^H\mathbf{G}_\mathrm{B}\mathbf{v}_i}
\end{aligned} \tag{7}$$

where $\mathbf{G}_\mathrm{A} = \rho\mathbf{H}_m^H\mathbf{H}_m$, $\mathbf{G}_\mathrm{B} = \rho\bar{\mathbf{H}}_m^H\bar{\mathbf{H}}_m + UN_\mathrm{R}\mathbf{I}_{N_\mathrm{T}}$, and $\rho = P/N_0$. For a given $N_\mathrm{V}$, finding the optimal $\mathbf{V}$ to maximize $\zeta_\mathrm{C}$ is analytically challenging. Therefore, we maximize a lower bound $\zeta_\mathrm{L}$ of the cell SLNR given by [29]

$$\zeta_\mathrm{L} = \min_{i=1,\ldots,N_\mathrm{V}} \frac{\mathbf{v}_i^H\mathbf{G}_\mathrm{A}\mathbf{v}_i}{\mathbf{v}_i^H\mathbf{G}_\mathrm{B}\mathbf{v}_i}. \tag{8}$$

Maximizing the lower bound in (8) maximizes the smallest generalized Rayleigh quotient $\frac{\mathbf{v}_i^H\mathbf{G}_\mathrm{A}\mathbf{v}_i}{\mathbf{v}_i^H\mathbf{G}_\mathrm{B}\mathbf{v}_i}$ among all the BS's transmission eigenmodes. Consequently,

$$\begin{aligned}
\zeta_{\mathrm{L,max}} &= \max_{\mathbf{V}^H\mathbf{V}=\mathbf{I}_{N_\mathrm{V}}} \min_{i=1,\ldots,N_\mathrm{V}} \frac{\mathbf{v}_i^H\mathbf{G}_\mathrm{A}\mathbf{v}_i}{\mathbf{v}_i^H\mathbf{G}_\mathrm{B}\mathbf{v}_i} \\
&= \max_{\mathcal{V}:\dim(\mathcal{V})=N_\mathrm{V}} \min_{\mathbf{v}\in\mathcal{V}} \frac{\mathbf{v}^H\mathbf{G}_\mathrm{A}\mathbf{v}}{\mathbf{v}^H\mathbf{G}_\mathrm{B}\mathbf{v}}.
\end{aligned} \tag{9}$$

According to the generalized Courant-Fischer max-min theorem [39, Chap. 4], $\zeta_{\mathrm{L,max}}$ is equal to the $N_\mathrm{V}$-th largest eigenvalue of $\mathbf{G}_\mathrm{S}$ where $\mathbf{G}_\mathrm{S} = \mathbf{G}_\mathrm{B}^{-1}\mathbf{G}_\mathrm{A}$. $\mathbf{V}$ is then given by the $N_\mathrm{V}$ orthonormal basis vectors of the space spanned by the $N_\mathrm{V}$ dominant eigenvectors of $\mathbf{G}_\mathrm{S}$ as follows from [29] assuming $\mathrm{rank}(\mathbf{G}_\mathrm{S}) \ge N_\mathrm{V}$. This solution maximizes $\zeta_\mathrm{L}$.[4] After obtaining $\mathbf{V}$, apply an initial precoding via a projection matrix $\mathbf{V}\mathbf{V}^H$ to the intra-cell channel $\mathbf{H}_m$ to get $\mathbf{H}_{m,\perp} = \mathbf{H}_m\mathbf{V}\mathbf{V}^H$. This precoding step increases the desired signal power directed to the intra-cell users and reduces the interference power towards the out-of-cell users. The reason is due to the objective of maximizing the cell SLNR in (7). The overall effect is an altruistic cooperation among BSs that serves to increase the overall system rate.

The second step of the leakage-DPC method involves block diagonal DPC processing on $\mathbf{H}_{m,\perp}$ to transmit to the intra-cell users. By multiplying $\mathbf{H}_{m,\perp}$ by $\mathbf{W}_m$ and $\mathbf{Q}_m$ where $\mathbf{W}_m$ and $\mathbf{Q}_m$ have orthonormal columns, it is possible to create a lower triangular equivalent channel $\mathbf{L}_m$ in which users employing multiple data streams can have equal channel gain per stream. The block diagonal geometric mean decomposition

[3] Calibration of the isolation of the out-of-cell users from the $m$-th BS may be required [26].

[4] By the generalized Rayleigh-Ritz theorem [39, Chap. 4], for the case where $\mathbf{G}_\mathrm{B} = \mathbf{I}$ the proposed $\mathbf{V}$ maximizes $\zeta_\mathrm{C}$.

(BD-GMD) introduced in [40] provides the required matrices $\mathbf{W}_m$, $\mathbf{L}_m$, and $\mathbf{Q}_m$ such that

$$\mathbf{W}_m^H \mathbf{H}_{m,\perp} \mathbf{Q}_m = \mathbf{L}_m. \quad (10)$$

$\mathbf{W}_m$ is the receive equalization matrix, $\mathbf{Q}_m$ is the transmit pre-equalization matrix, and $\mathbf{L}_m$ is the resultant lower triangular channel matrix for the $m$-th cell. The BD-GMD is a nonlinear ZF technique for the single-cell multiuser MIMO broadcast channel. Its MMSE variant, the BD-UCD, achieves the single-cell broadcast channel capacity. The BD-GMD has a lower complexity of $\mathcal{O}(UN_T^3)$ [41]. The advantage of the BD-GMD processing is that all the users' data streams are decoupled, making it amenable to efficient power control techniques to satisfy user quality of service (QoS). For example, to ensure QoS for the users' real-time traffic, power allocation can be performed to minimize the BS transmit power subject to users' rate requirements [42]. In this way, the receive power of the users are adjusted based on their channel gains to compensate for different transmission distances from the BS. When users have a single antenna each, the BD-GMD is equivalent to ZF-DPC. As there is some residual inter-cell interference after the leakage-based precoding, a performance margin for co-channel interference effects should be considered just as in conventional cellular network planning.

From (10), $\mathbf{W}_m^H \mathbf{H}_m \mathbf{Q}_m = \mathbf{L}_m$ follows directly from $\mathbf{H}_{m,\perp}\mathbf{Q}_m = \mathbf{H}_m\mathbf{Q}_m$ [43]. The transmit pre-equalization matrix is $\mathbf{F}_m = \mathbf{Q}_m\mathbf{\Omega}_m$ where $\mathbf{\Omega}_m$ is the diagonal power allocation matrix for the intra-cell users. The block diagonal receive beamforming matrix is $\mathbf{W}_m = \mathrm{blkdiag}(\mathbf{W}_{m,1}, \mathbf{W}_{m,2}, \ldots, \mathbf{W}_{m,U})$. The block diagram for the transceiver that uses the leakage-DPC is shown in Fig. 1. Tomlinson-Harashima precoding (THP) is used as a low-complexity suboptimal implementation of DPC, where $\mathbf{B}_m = \mathbf{\Omega}_m^{-1}\mathrm{diag}(\mathbf{L}_m)^{-1}\mathbf{L}_m\mathbf{\Omega}_m$ is the monic lower triangular matrix for THP interference pre-subtraction. $\mathbf{\Gamma}_m = \frac{1}{N_0}\mathrm{diag}(\mathbf{L}_m)\mathbf{\Omega}_m$ is the diagonal matrix of SNRs for each data stream in the $m$-th cell.

The question of what value of $N_\mathrm{V}$ to use will now be addressed. It is clear that $N_\mathrm{V} \geq Ud$ in order to support the $U$ users. Also, $N_\mathrm{V} \leq \min(N_\mathrm{T}, UN_\mathrm{R})$ due to the dimensions of the system. As $N_\mathrm{T}$ increases, it is better to use a larger value of $N_\mathrm{V}$. For example, $N_\mathrm{V}$ may be chosen to be $N_\mathrm{T} - \bar{U}N_\mathrm{R}$ in order to have sufficient degrees of freedom (DoF) for suppressing the interference to the $\bar{U}N_\mathrm{R}$ antennas of the out-of-cell users. A heuristic value of $N_\mathrm{V}$ is thus given by

$$N_\mathrm{Q} = \min\left(\max\left(Ud, N_\mathrm{T} - \bar{U}N_\mathrm{R}\right), UN_\mathrm{R}, N_\mathrm{T}\right). \quad (11)$$

This value of $N_\mathrm{V} = N_\mathrm{Q}$ has been shown to work well in the simulations. The leakage-DPC method works best when the BS has sufficient transmit antennas, i.e. $\phi_\mathrm{a} = N_\mathrm{T} - Ud \geq \phi_\mathrm{r}$, where $\phi_\mathrm{r}$ is the rank of $\bar{\mathbf{H}}_m$. Algorithm 1 summarizes the leakage-DPC strategy.

### B. User Rates with Perfect CSI

Assuming $N_\mathrm{T} \geq U$ for data transmission to the $U$ intra-cell users, we denote $\tilde{\mathbf{y}}_m = \mathbf{W}_m^H\mathbf{y}_m$ as the (stacked) signal vector received by the users inside the $m$-th cell after equalization.[5]

[5]The length of $\tilde{\mathbf{y}}_m$ is given by the total number of data streams of the intra-cell users, whereby each user can have multiple data streams.

**Algorithm 1** Leakage-DPC

1: Calculate $\mathbf{G}_\mathrm{S} = \left(\rho\bar{\mathbf{H}}_m^H\bar{\mathbf{H}}_m + UN_\mathrm{R}\mathbf{I}_{N_\mathrm{T}}\right)^{-1}\rho\mathbf{H}_m^H\mathbf{H}_m$.
2: Form the matrix $\mathbf{V} \in \mathbb{C}^{N_\mathrm{T}\times N_\mathrm{V}}$ in which the columns are the orthonormal basis vectors of the space spanned by the first $N_\mathrm{V}$ dominant eigenvectors of $\mathbf{G}_\mathrm{S}$.
3: Pre-multiply the channel: $\mathbf{H}_{m,\perp} = \mathbf{H}_m\mathbf{V}\mathbf{V}^H$.
4: Apply the block diagonal processing on $\mathbf{H}_{m,\perp}$ to get $\mathbf{W}_m^H\mathbf{H}_{m,\perp}\mathbf{Q}_m = \mathbf{L}_m$ as in (10).
5: Perform DPC on the equivalent channel $\mathbf{L}_m$ with pre-equalization matrix $\mathbf{F}_m = \mathbf{Q}_m\mathbf{\Omega}_m$ and receive beamforming matrices $\mathbf{W}_{m,u}^H$ as in Fig. 1.

We can express $\tilde{\mathbf{y}}_m$ as a sum of the signal, interference, and noise terms

$$\tilde{\mathbf{y}}_m = \tilde{\mathbf{y}}_m^{\mathrm{sig}} + \tilde{\mathbf{y}}_m^{\mathrm{int}} + \tilde{\mathbf{z}}_m \quad (12)$$

where

$$\tilde{\mathbf{y}}_m^{\mathrm{sig}} = \mathbf{W}_m^H\mathbf{H}_m\mathbf{F}_m\tilde{\mathbf{x}}_m$$
$$\tilde{\mathbf{y}}_m^{\mathrm{int}} = \sum_{n\neq m}^{M}\tilde{\mathbf{y}}_{n\to m}, \qquad \tilde{\mathbf{y}}_{n\to m} = \mathbf{W}_m^H\mathbf{H}_{n\to m}\mathbf{F}_n\tilde{\mathbf{x}}_n$$
$$\tilde{\mathbf{z}}_m = \mathbf{W}_m^H\mathbf{z}_m.$$

$\tilde{\mathbf{x}}_m$ is the Tomlinson-Harashima precoded data symbol vector for the $m$-th BS. Due to independence of transmit signals from different BSs, the covariance matrix of the interference after equalization is

$$\mathbf{R}_{\tilde{\mathbf{y}}_m^{\mathrm{int}}} = \sum_{n\neq m}^{M}\mathbf{R}_{\tilde{\mathbf{y}}_{n\to m}}. \quad (13)$$

After applying the leakage-DPC, the rate for each data stream is given by

$$r_i = \log_2\left(1 + \frac{N_0\left[\mathbf{\Gamma}_m\right]_{i,i}}{\left[\mathbf{R}_{\tilde{\mathbf{y}}_m^{\mathrm{int}}}\right]_{i,i} + N_0}\right) \quad (14)$$

assuming that the transmitted signals and noise are Gaussian. The rate for each user can be obtained by summing up over the data streams of the user.

### C. User Rates with Imperfect CSI

In this subsection, we wish to analyze the effect of CSI uncertainty on the sum rate for the leakage-DPC method introduced earlier. The transmit and receive beamforming matrices $\mathbf{Q}_m$ and $\mathbf{P}_m$ are derived from $\hat{\mathbf{H}}_m$ because the BS processing is based on the CSI estimate. A signal model for THP with channel uncertainty and without out-of-cell interference can be found in [44]. Consider the case where there is out-of-cell interference as in a cellular system. The received signal in the $m$-th cell can be expressed as the sum of desired signal, error, interference, and noise components as follows:

$$\tilde{\mathbf{y}}_m = \tilde{\mathbf{y}}_m^{\mathrm{sig}} + \tilde{\mathbf{y}}_m^{\mathrm{err}} + \tilde{\mathbf{y}}_m^{\mathrm{int}} + \tilde{\mathbf{z}}_m \quad (15)$$

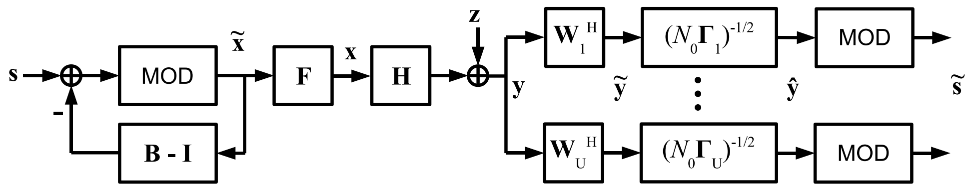


Fig. 1. Block diagram of the leakage-DPC MIMO downlink transmission that implements THP for a cell with $U$ users.

where

$$\begin{aligned}\tilde{\mathbf{y}}_m^{\text{sig}} &= \mathbf{W}_m^H \hat{\mathbf{H}}_m \mathbf{F}_m \tilde{\mathbf{x}}_m \\ \tilde{\mathbf{y}}_m^{\text{err}} &= \mathbf{W}_m^H \mathbf{E}_m \mathbf{F}_m \tilde{\mathbf{x}}_m \\ \tilde{\mathbf{y}}_m^{\text{int}} &= \sum_{n \neq m}^{M} \tilde{\mathbf{y}}_{n \to m}, \qquad \tilde{\mathbf{y}}_{n \to m} = \mathbf{W}_m^H \mathbf{H}_{n \to m} \mathbf{F}_n \tilde{\mathbf{x}}_n \\ \tilde{\mathbf{z}}_m &= \mathbf{W}_m^H \mathbf{z}_m.\end{aligned}$$

In (15), $\mathbf{H}_{n \to m} \in \mathbb{C}^{UN_{\text{R}} \times N_{\text{T}}}$ is the actual[6] channel matrix from the $n$-th BS to the users in the $m$-th cell. Due to the independence and zero mean of transmit signals from different BSs, $\mathbf{E}_m$, and $\tilde{\mathbf{z}}_m$,

$$\mathbf{R}_{\tilde{\mathbf{y}}_m} = \mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{sig}}} + \mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{err}}} + \mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{int}}} + \mathbf{R}_{\tilde{\mathbf{z}}_m}. \tag{16}$$

The covariance matrix of the error component, $\tilde{\mathbf{y}}_m^{\text{err}}$, is given by

$$\begin{aligned}\mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{err}}} &= \mathbb{E}_{\mathbf{E}} \mathbb{E}_{\tilde{\mathbf{x}}} \left[ \mathbf{P}_m^H \mathbf{E}_m \mathbf{Q}_m \mathbf{\Omega}_m \tilde{\mathbf{x}}_m \tilde{\mathbf{x}}_m^H \mathbf{\Omega}_m \mathbf{Q}_m^H \mathbf{E}_m^H \mathbf{P}_m \right] \\ &= \mathbb{E}_{\mathbf{E}} \left[ \mathbf{P}_m^H \mathbf{E}_m \mathbf{Q}_m \mathbf{\Omega}_m \mathbf{R}_{\tilde{\mathbf{x}}_m} \mathbf{\Omega}_m \mathbf{Q}_m^H \mathbf{E}_m^H \mathbf{P}_m \right] \\ &= \mathbf{P}_m^H \sigma_{\text{e}}^2 \text{Tr} \left( \mathbf{Q}_m \mathbf{\Omega}_m \mathbf{R}_{\tilde{\mathbf{x}}_m} \mathbf{\Omega}_m \mathbf{Q}_m^H \right) \mathbf{I}_{UN_{\text{R}}} \mathbf{P}_m \\ &= \sigma_{\text{e}}^2 P_m \mathbf{I}_{Ud}.\end{aligned} \tag{17}$$

A lower bound on the achievable rate for each data stream is given by

$$\begin{aligned}r_{\text{L},i} &= \log_2 \left( 1 + \frac{N_0 \left[ \mathbf{\Gamma}_m \right]_{i,i}}{\left[ \mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{err}}} \right]_{i,i} + \left[ \mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{int}}} \right]_{i,i} + \left[ \mathbf{R}_{\tilde{\mathbf{z}}_m} \right]_{i,i}} \right) \\ &= \log_2 \left( 1 + \frac{N_0 \left[ \mathbf{\Gamma}_m \right]_{i,i}}{\sigma_{\text{e}}^2 P_m + \left[ \mathbf{R}_{\tilde{\mathbf{y}}_m^{\text{int}}} \right]_{i,i} + N_0} \right)\end{aligned} \tag{18}$$

assuming that the transmitted signals and noise are Gaussian [45].[7] The lower bound rate for each user can be obtained by summing up over the data streams of the user.

### D. Robust Version

The leakage-DPC is sensitive to channel uncertainty, thus we also present an extension called the robust leakage-DPC that incorporates the variance of the uncertainty. Assume $\sigma_{\text{e}}^2$ is known at the transmitter. The effective additive noise due to the receiver noise and the CSI error is $\bar{N}_0 = N_0 + \sigma_{\text{e}}^2 P$. Accounting for the CSI error, the following value of $\rho$ is used.

$$\rho = P / \bar{N}_0. \tag{19}$$

[6]This is the actual as opposed to estimated channel matrix.

[7]Assuming Gaussian input, the worst case noise is Gaussian [45]. The rate per stream is calculated as in (18) due to the decoupling of the data streams by the block diagonal processing in (10).

Algorithm 1 is applied using the estimated values of $\mathbf{H}_m$, $\bar{\mathbf{H}}_m$, and the $\rho$ given above. The lower bound rate can be calculated as in Section III-C.

## IV. Multicell Leakage Suppression

If low complexity is essential, it may be practical to use linear transmission techniques. In this section, a linear precoding method called multicell leakage suppression is introduced. Unlike [28], our approach allows for an arbitrary number of data streams per user and mitigates out-of-cell interference to boost the cell-edge users' rates.

### A. Algorithm Description

First consider a single data stream per user. Let the transmit power to each intra-cell user be $P_m/U$. The signal component transmitted by the $m$-th BS intended for its $u$-th user is given by $\mathbf{q}_{m,u} \sqrt{P_m/U} s_{m,u}$, where $\mathbf{q}_{m,u}$ is a unit norm beamforming vector. Considering this transmission alone, the desired signal received by this user is

$$\mathbf{y}_{m,u}^{\text{sig}} = \mathbf{H}_{m,u} \mathbf{q}_{m,u} \sqrt{P_m/U} s_{m,u}. \tag{20}$$

The *leakage* directed away from this user is given by

$$\mathbf{y}_{m,u}^{\text{leak}} = \bar{\mathbf{H}}_{m,u} \mathbf{q}_{m,u} \sqrt{P_m/U} s_{m,u}. \tag{21}$$

Recall from Section II that $\bar{\mathbf{H}}_{m,u}$ is the matrix concatenation of the intra-cell and out-of-cell channel gains. The signal-to-leakage-plus-noise ratio (SLNR) $\zeta_{m,u}$ is defined as

$$\begin{aligned}\zeta_{m,u} &= \frac{\left\| \mathbf{y}_{m,u}^{\text{sig}} \right\|_2^2}{\left\| \mathbf{y}_{m,u}^{\text{leak}} \right\|_2^2 + N_{\text{R}} N_0} \\ &= \frac{\mathbf{q}_{m,u}^H \mathbf{H}_{m,u}^H \mathbf{H}_{m,u} \mathbf{q}_{m,u}}{\mathbf{q}_{m,u}^H \left( \bar{\mathbf{H}}_{m,u}^H \bar{\mathbf{H}}_{m,u} + \left( UN_{\text{R}} N_0 / P_m \right) \mathbf{I}_{N_{\text{T}}} \right) \mathbf{q}_{m,u}}.\end{aligned} \tag{22}$$

The generalized Rayleigh quotient $\zeta_{m,u}$ is maximized when $\mathbf{q}_{m,u}$ is the generalized eigenvector corresponding to the maximum generalized eigenvalue of the matrix pencil

$$\left( \mathbf{H}_{m,u}^H \mathbf{H}_{m,u}, \bar{\mathbf{H}}_{m,u}^H \bar{\mathbf{H}}_{m,u} + \left( UN_{\text{R}} N_0 / P_m \right) \mathbf{I}_{N_{\text{T}}} \right). \tag{23}$$

Since the second matrix argument is invertible, the solution is given by $\mathbf{q}_{m,u} = \mathbf{q}_{m,u}^o$, where $\mathbf{q}_{m,u}^o$ is the unit norm eigenvector corresponding to the maximum eigenvalue of the matrix

$$\left( \bar{\mathbf{H}}_{m,u}^H \bar{\mathbf{H}}_{m,u} + \left( UN_{\text{R}} N_0 / P_m \right) \mathbf{I}_{N_{\text{T}}} \right)^{-1} \mathbf{H}_{m,u}^H \mathbf{H}_{m,u}. \tag{24}$$

The resulting beamforming vectors to each user reduce the total interference leakage to other intra-cell users as well as out-of-cell users. The extension to the case of multiple data streams per user can be obtained by applying a similar approach as described in Section III-A. Algorithm 2 summarizes the multicell leakage suppression strategy.

**Algorithm 2** Multicell Leakage Suppression

**for** each intra-cell user i.e. $u = 1$ to $U$ **do**
  Form the matrix $\mathbf{G}_{m,u} = \left(\bar{\mathbf{H}}_{m,u}^{H}\bar{\mathbf{H}}_{m,u} + (UN_{\mathrm{R}}N_0/P_m)\,\mathbf{I}_{N_{\mathrm{T}}}\right)^{-1}\mathbf{H}_{m,u}^{H}\mathbf{H}_{m,u}$.
  Obtain $\mathbf{q}_{m,u} = \mathbf{q}_{m,u}^{o}$, the unit norm eigenvector corresponding to the maximum eigenvalue of $\mathbf{G}_{m,u}$.
**end for**
BS transmits $\mathbf{x} = \sum_{u=1}^{U}\mathbf{q}_{m,u}\sqrt{P_m/U}s_{m,u}$.

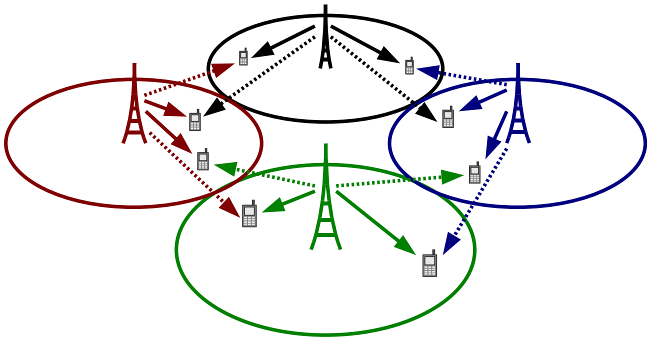

Fig. 2. Circular Wyner model used in the simulations with $M = 4$ cells and $U = 2$ users per cell.

### B. User Rates with Perfect CSI

We shall calculate the achievable rate for each user when applying the multicell leakage suppression. The signal received by the $u$-th user in the $m$-th cell is given by

$$\mathbf{y}_{m,u} = \mathbf{y}_{m,u}^{\mathrm{sig}} + \mathbf{y}_{m,u}^{\mathrm{int}} + \mathbf{z}_{m,u} \quad (25)$$

where $\mathbf{y}_{m,u}^{\mathrm{sig}}$ is the desired signal (20) and $\mathbf{z}_{m,u} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{N_{\mathrm{R}}})$ is the noise. The received interference is

$$\mathbf{y}_{m,u}^{\mathrm{int}} = \mathbf{H}_{m,u}\sum_{k\neq u}^{U}\mathbf{q}_{m,k}\sqrt{P_m/U}s_{m,k} + \sum_{n\neq m}^{M}\mathbf{H}_{n\to m,u}\sum_{k=1}^{U}\mathbf{q}_{n,k}\sqrt{P_n/U}s_{n,k}. \quad (26)$$

The first summand is the intra-cell interference while the second summand is the out-of-cell interference. The achievable rate for the $u$-th user in the $m$-th cell is given by

$$\begin{aligned} r_{m,u} &= \log_2\det\left(\mathbf{R}_{\mathbf{y}_{m,u}}\left(\mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{int}}} + \mathbf{R}_{\mathbf{z}_{m,u}}\right)^{-1}\right) \\ &= \log_2\det\left(\mathbf{R}_{\mathbf{y}_{m,u}}\left(\mathbf{R}_{\mathbf{y}_{m,u}} - \mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{sig}}}\right)^{-1}\right). \end{aligned} \quad (27)$$

### C. User Rates with Imperfect CSI

In this subsection, we derive the rate for the multicell leakage suppression method in the presence of CSI errors. Following the same channel uncertainty model in (4), the received signal of the $u$-th user in the $m$-th cell is given by

$$\mathbf{y}_{m,u} = \mathbf{y}_{m,u}^{\mathrm{sig}} + \mathbf{y}_{m,u}^{\mathrm{err}} + \mathbf{y}_{m,u}^{\mathrm{int}} + \mathbf{z}_{m,u} \quad (28)$$

where

$$\begin{aligned} \mathbf{y}_{m,u}^{\mathrm{sig}} &= \hat{\mathbf{H}}_{m,u}\mathbf{q}_{m,u}\sqrt{P_m/U}s_{m,u} \\ \mathbf{y}_{m,u}^{\mathrm{err}} &= \mathbf{E}_{m,u}\mathbf{q}_{m,u}\sqrt{P_m/U}s_{m,u} \\ \mathbf{y}_{m,u}^{\mathrm{int}} &= \mathbf{H}_{m,u}\sum_{k\neq u}^{U}\mathbf{q}_{m,k}\sqrt{P_m/U}s_{m,k} \\ &\quad + \sum_{n\neq m}^{M}\mathbf{H}_{n\to m,u}\sum_{k=1}^{U}\mathbf{q}_{n,k}\sqrt{P_n/U}s_{n,k} \end{aligned}$$

and $\mathbf{z}_{m,u} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_{N_{\mathrm{R}}})$ is the noise. The desired signal is $\mathbf{y}_{m,u}^{\mathrm{sig}}$, the error component is $\mathbf{y}_{m,u}^{\mathrm{err}}$, and the received interference is $\mathbf{y}_{m,u}^{\mathrm{int}}$. $\mathbf{H}_{n\to m,u}$ is the actual channel from the $n$-th BS to the $u$-th user in the $m$-th cell. Due to the independence and zero mean of the transmit signals from different BSs, $\mathbf{E}_m$, and $\tilde{\mathbf{z}}_m$,

$$\mathbf{R}_{\mathbf{y}_{m,u}} = \mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{sig}}} + \mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{err}}} + \mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{int}}} + \mathbf{R}_{\mathbf{z}_{m,u}}. \quad (29)$$

The covariance matrix of the error component $\mathbf{y}_{m,u}^{\mathrm{err}}$ is given by

$$\begin{aligned} \mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{err}}} &= \mathbb{E}_{\mathbf{E}}\mathbb{E}_{s_{m,u}}\left[(P_m/U)\,|s_{m,u}|^2\,\mathbf{E}_{m,u}\mathbf{q}_{m,u}\mathbf{q}_{m,u}^{H}\mathbf{E}_{m,u}^{H}\right] \\ &= \mathbb{E}_{\mathbf{E}}\left[(P_m/U)\,\mathbf{E}_{m,u}\mathbf{q}_{m,u}\mathbf{q}_{m,u}^{H}\mathbf{E}_{m,u}^{H}\right] \\ &= \left(\sigma_{\mathrm{e}}^2 P_m/U\right)\mathbf{I}_{N_{\mathrm{R}}}. \end{aligned} \quad (30)$$

A lower bound on the achievable rate for the $u$-th user in the $m$-th cell is obtained as

$$r_{\mathrm{L},m,u} = \log_2\det\left(\mathbf{R}_{\mathbf{y}_{m,u}}\left(\mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{err}}} + \mathbf{R}_{\mathbf{y}_{m,u}^{\mathrm{int}}} + \mathbf{R}_{\mathbf{z}_{m,u}}\right)^{-1}\right) \quad (31)$$

assuming that the transmitted signals and noise are Gaussian [45].[8]

## V. SIMULATIONS

We consider a circular variant of the linear Wyner model [46] depicted in Fig. 2, in which $M = 4$ cells are arranged in a circle. The circular setup is homogenous and provides symmetry between the BSs. For a large number of cells, the circular setup and the more conventional linear setup are equivalent [15], [27]. By using a 4-cell simulation and adjusting the parameters of interest, we are able to concisely demonstrate the effect that physical phenomena such as relative channel gains have on our proposed precoders.

For each BS, the channel towards the intra-cell users is represented by the solid arrows and each element of the channel matrix $\mathbf{H}_m$ is i.i.d. as $\mathcal{CN}(0,1)$. The channel towards the out-of-cell users is represented by the dashed arrows. Each element of the channel matrix $\bar{\mathbf{H}}_m$ to these out-of-cell users is i.i.d. $\mathcal{CN}(0,\alpha^2)$ where $\alpha$ is the co-channel interference factor [27], [47]. Each BS has $N_{\mathrm{T}}$ transmit antennas and each cell has $U$ intra-cell users and $\bar{U} = U$ out-of-cell users. All users have $N_{\mathrm{R}}$ receive antennas each. The input-output relationship for the system is given in (1).

[8] Assuming Gaussian input, the worst case noise is Gaussian.

On the one hand, channel inversion power control enforces user fairness but may not be desirable from the service provider's point of view as it reduces the system sum rate. On the other hand, maximizing the sum rate via water-filling by loading even higher powers for the users with good channels may adversely affect the data rates for users with poor channel conditions. Therefore, in the simulations, equal power loading is utilized for all the downlink methods. For the purpose of comparison, ignore the THP precoding loss $\bar{M}/(\bar{M}-1)$ for $\bar{M}$-QAM constellations. This will result in $\mathbf{R}_{\tilde{\mathbf{x}}} = \mathbf{I}_{Ud}$. In practice, $\mathbf{R}_{\tilde{\mathbf{x}}} \approx \mathbf{I}_{Ud}$ for large $\bar{M}$.

The simulation graphs include the curve for 'no cooperation' which is the non-cooperative BD-GMD scenario with single-cell processing. The curve for 'orthogonal transmission' refers to single-cell processing with a frequency reuse factor of $f_{\text{reuse}} = 1/2$. For our 4-cell topology, 2 orthogonal channels are sufficient to create the idealized scenario of zero inter-cell interference. In frequency reuse, the rate becomes scaled by $f_{\text{reuse}}$. The graphs also show the curves for 'projected channel DPC' [43], which is a multiuser extension of the projected channel SVD [48]. The BS performs ZF nulling towards the out-of-cell users and applies block diagonal DPC to transmit to the intra-cell users [43]. This precoding strategy is also decentralized. Unless otherwise indicated, the default system settings for the simulations are as follows. $N_{\text{T}} = 8$, SNR $P/N_0 = 15$dB, $\alpha = 0.5$, and $U = 4$. 1000 Monte Carlo runs are used. Table I compares the complexities of the schemes tested.

The BD-GMD is an efficient ZF-DPC technique with low complexity [41]. However, multicell joint BD-GMD processing requires CSI of all the inter-cell links which may make it difficult for implementation due to the backhaul requirement. Except for the multicell scheme, all other approaches are distributed so the CSI matrix sizes are reasonable, at most $(U+\bar{U})N_{\text{R}}$ or $N_{\text{T}}$ per dimension. Therefore all proposed techniques can be considered of low complexity.

In Fig. 3, the sum rate per cell is plotted against the number of BS antennas $N_{\text{T}}$. When $N_{\text{T}} = 4$, the projected channel DPC and the leakage-DPC coincide with the case of no cooperation. This is because there are insufficient transmit antennas to do any projection of the channel. As $N_{\text{T}}$ increases, all three methods as well as the no cooperation case improve. The rate improvement of the three methods over the no cooperation case also increases with $N_{\text{T}}$ due to the increase in the DoF. Although orthogonal transmission has the highest sum rate for $N_{\text{T}} = 4$, the proposed methods obtain significantly higher rates for $N_{\text{T}} \geq 6$.

The effect of SNR on the sum rate is shown in Fig. 4. As long as there are sufficient transmit antennas, i.e. $N_{\text{T}} \geq Ud + \bar{U}N_{\text{R}}$, the sum rates per cell for the projected channel DPC and leakage-DPC are shown to increase linearly with SNR for high SNR. For the multicell leakage suppression, $N_{\text{T}} \geq (U-1+\bar{U})N_{\text{R}} + d$ is required for sum rate to increase linearly at high SNR. Otherwise, the sum rates will plateau due to insufficient DoF. The rate with no cooperation plateaus at about 12 bps/Hz. At low SNR, the system is noise-limited so the projected channel DPC performs poorly due to unnecessary channel projections. The multicell leakage suppression has a high sum rate as it takes noise variance

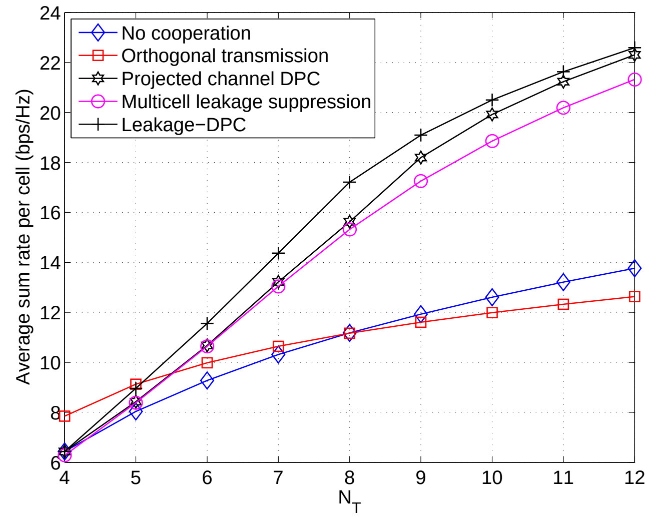


Fig. 3. Sum rate per cell vs number of BS transmit antennas $N_{\text{T}}$ for $U = 4$, $N_{\text{R}} = d = 1$, SNR=15dB, and $\alpha = 0.5$.

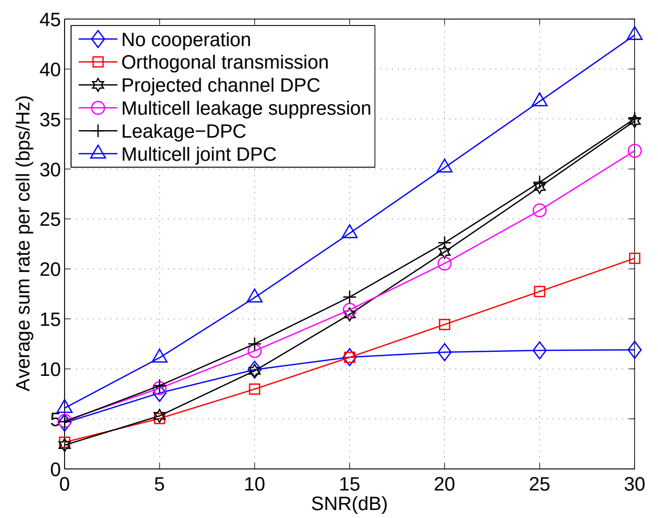


Fig. 4. Sum rate as a function of SNR $P/N_0$ for $N_{\text{T}} = 8$, $\alpha = 0.5$, $U = 2$, and $N_{\text{R}} = d = 2$. A similar trend can be seen for $U = 4$, and $N_{\text{R}} = d = 1$.

into account when designing the beamforming vectors. The leakage-DPC approaches this curve at low SNR due to the precoding based on the SLNR. At high SNR, the system is interference-limited so the multicell leakage suppression has a relatively lower sum rate due to the linear processing. The leakage-DPC approaches the curve for the projected channel DPC at high SNR because the best strategy is to eliminate all interference and the leakage-DPC method tends to eliminate all the interference in that regime. Therefore, we see that the leakage-DPC method obtains the benefits of both the multicell leakage suppression and the projected channel DPC. There is an SNR gap of 7dB between multicell joint DPC and leakage-DPC at high SNR because multicell joint DPC makes use of out-of-cell channel gains by sharing data and CSI among BSs.

Next, in Fig. 5, the performance of the three techniques are compared when the interference factor $\alpha$ is varied. As expected, increasing $\alpha$ does not degrade the performance of orthogonal transmission. The rate for projected channel DPC is also invariant to $\alpha$ because of the channel projection that

TABLE I
COMPLEXITIES OF THE VARIOUS SCHEMES

| | Processing per cell excluding BD-GMD | | | BD-GMD processing |
|---|---|---|---|---|
| | Matrix multiplications | Matrix inversions | Other | |
| No cooperation | 0 | 0 | - | single-cell |
| Orthogonal transmission | 0 | 0 | - | single-cell |
| Projected channel DPC | 2 | 0 | 1 SVD | single-cell |
| Multicell leakage suppression | $3U$ | $U$ | $U$ eigenvector evaluations | none |
| (Robust) Leakage-DPC | 5 | 1 | 1 eigenvector matrix evaluation, 1 SVD | single-cell |
| Multicell joint DPC | 0 | 0 | - | multicell |

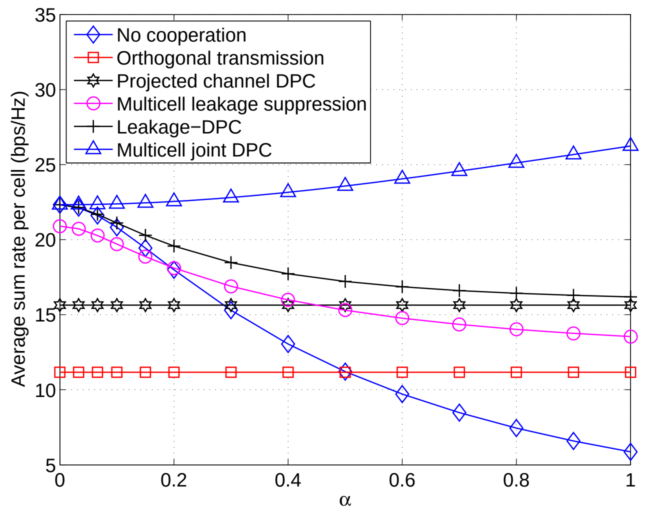


Fig. 5. Effect of the interference factor $\alpha$ on the sum rate for $N_{\mathrm{T}} = 8$, $U = 4$, $N_{\mathrm{R}} = d = 1$, and SNR=15dB.

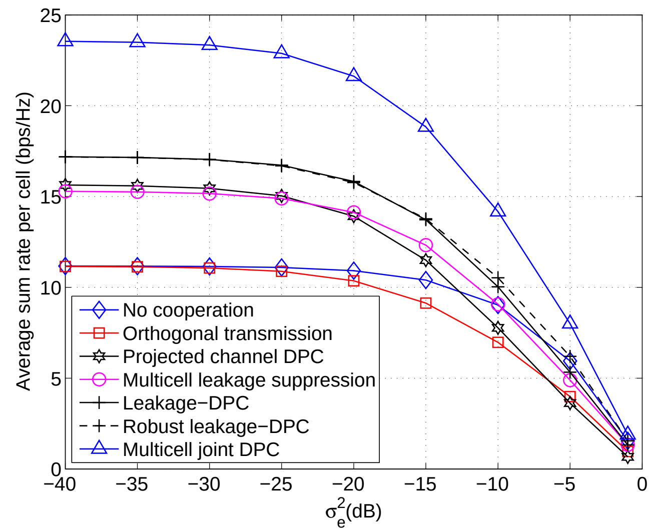


Fig. 6. Effect of channel uncertainty on the sum rates of various methods for $N_{\mathrm{T}} = 8$, $U = 4$, $N_{\mathrm{R}} = d = 1$, $\alpha = 0.5$, and SNR=15dB.

completely nulls the interference to the out-of-cell users. All the other methods suffer rate loss as $\alpha$ increases. If the number of transmit antennas are not enough, the projected channel DPC will also suffer considerable rate loss. The multicell leakage suppression suffers more rate loss for high $\alpha$ as the system is interference-limited. The leakage-DPC strategy consistently performs better than all the other methods. When $\alpha = 0$, the leakage-DPC method is as good as the case with no cooperation. The reason is that the leakage term in the cell SLNR expression (7) is zero. Consequently, the channel after projection $\mathbf{H}_{\perp} = \mathbf{H}\mathbf{V}\mathbf{V}^{H}$ is identical to $\mathbf{H}$. As the interference factor $\alpha$ increases, the degradation due to interference becomes small for the decentralized precoders because the number of antennas at the BS is sufficient. Eventually, marginal increases in $\alpha$ have negligible effects on the decentralized strategies. The rate for multicell joint DPC is observed to increase without bounds as the interference factor increases because multicell joint DPC always benefits from increasing channel gains across cells. These gains may be unrealistic because joint processing demands exchange of data and CSI among BSs.

The effect of channel uncertainty on the sum rates of the proposed methods are examined in Fig. 6. To model the CSI uncertainty [38], the following is used to generate the channels:

$$[\hat{\mathbf{H}}]_{i,j} = \sqrt{[\mathbf{C}_{\mathrm{V}}]_{i,j}(1-\sigma_{\mathrm{e}}^2)}[\mathbf{H}_{\mathrm{w}}]_{i,j}$$
$$[\mathbf{E}]_{i,j} = \sqrt{[\mathbf{C}_{\mathrm{V}}]_{i,j}\sigma_{\mathrm{e}}^2}[\mathbf{E}_{\mathrm{w}}]_{i,j}$$
$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E} \tag{32}$$

where $[\mathbf{H}_{\mathrm{w}}]_{i,j} \sim \mathcal{CN}(0,1)$ and $[\mathbf{E}_{\mathrm{w}}]_{i,j} \sim \mathcal{CN}(0,1)$. For the curve of the robust leakage-DPC, the CSI error variance $\sigma_{\mathrm{e}}^2$ is assumed to be available at the transmitter. It can be seen that the projected channel DPC is more sensitive to CSI error than the multicell leakage suppression due to the sensitivity of eigenspace projections. As the precoding of the leakage-DPC is based on the cell SLNR metric, it obtains a higher rate than these two methods. Also, it performs better than all other strategies for $\sigma_{\mathrm{e}}^2 \leq -7$dB. The robust leakage-DPC is observed to recover some of the rate loss of the leakage-DPC method as $\sigma_{\mathrm{e}}^2$ increases. The robust leakage-DPC provides 1 bps/Hz improvement over the leakage-DPC at high estimation errors $\sigma_{\mathrm{e}}^2 = -5$dB. It would be interesting to look at ways to find precoders that are more robust to CSI uncertainty.

The circular Wyner model had been used to illustrate the effects of a few parameters. We provide here a more comprehensive $M = 19$ cell simulation using the "Urban Macro NLOS" model in [49]. The cells are arranged as in Fig. 7 with inter-site distance of 500m. A log-distance path loss model with Rayleigh fading is used, with the path loss exponent $\eta = 3.9$. The path loss at the reference distance of 10m is 58.7dB. The minimum separation of the users from the BS is also 10m. The noise power density is taken to be

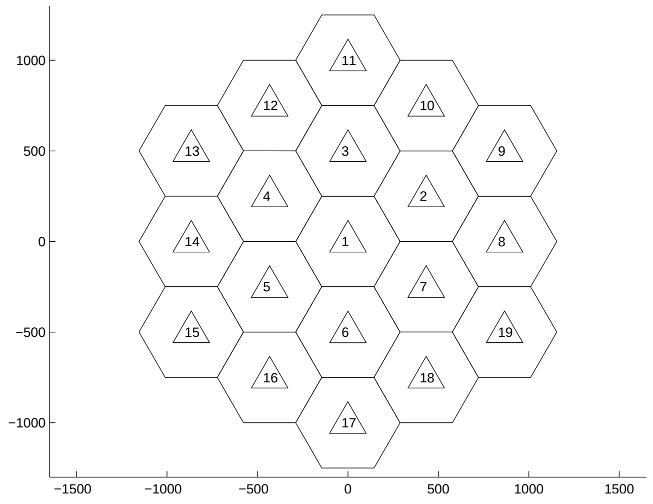


Fig. 7. Cellular simulation with $M = 19$ cells with inter-site distance of 500m where a log-distance path loss model with Rayleigh fading was used.

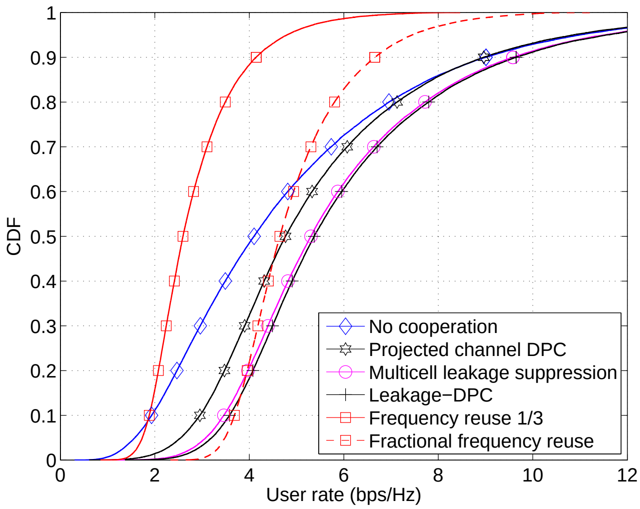


Fig. 8. Cumulative distribution function (CDF) of user rates for $N_{\mathrm{T}} = 8$, $U = 2$, $N_{\mathrm{R}} = d = 1$.

-174dBm/Hz. Shadow fading is not considered. The transmit power of each BS is -24dBm/Hz. We also simulate a fully loaded hard fractional frequency reuse (FFR) system with 16 subcarriers, 7 of which are used for the inner band and 3 are used for the outer band in each cell [50]. The radius for the inner band is set as 150m. In all the schemes compared, there are $U = 2$ users per subcarrier per cell. Fig. 8 shows the cumulative distribution function (CDF) of the user rates for a system with $N_{\mathrm{T}} = 8$ and $N_{\mathrm{R}} = d = 1$. The plot is obtained by evaluating user rates over 25000 independent channel sets. For the 50-th percentile rate, the leakage-DPC performs the best, followed by multicell leakage suppression, projected channel DPC [43] with $\phi = 3$ dominant eigenmodes used for projection, FFR, 'no cooperation', 'frequency reuse 1/3', in this order. The 10-th percentile rate for FFR is 0.1bps/Hz higher than the leakage-DPC, indicating greater isolation of the cell-edge users from interference. The 90-th percentile rate for leakage-DPC is 3bps/Hz higher than FFR due to universal frequency reuse of the proposed method. The leakage-DPC has a higher rate than the projected channel DPC because the latter nulls the interference even though the out-of-cell channel may be very weak, but the leakage-DPC balances the projection according to the out-of-cell channel gains. The difference in rates between the 'no cooperation' and projected channel DPC decreases as the CDF increases from 10% to 90% because the rates are dominated by the cell-center users which observe minimal benefit of the interference avoidance technique.

## VI. Discussion

Multicell or network MIMO is also known as coordinated multi-point transmission/reception (CoMP) [49], which has been identified as one of the potential technologies for satisfying the quality of service (QoS) and rate requirements of the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) Release 10 / "LTE-Advanced" or future wireless standards [51]. In this paper, we proposed the leakage-DPC which is a nonlinear method that mitigates out-of-cell interference by applying a precoding based on the cell SLNR and block diagonal DPC for the intra-cell users. Our multicell leakage suppression is a linear method which performs beamforming to each user to maximize its SLNR. The leakage-DPC strategy attains higher sum rates than the multicell leakage suppression over varying SNR, interference conditions, and channel imperfectness. The higher spectral efficiency is because of the use of DPC. On the other hand, the multicell leakage suppression has a lower complexity than the leakage-DPC due to the use of linear transmit and receive processing.

The number of the BS antennas required for our proposed methods is expected to be larger than for conventional cellular systems because additional BS antennas are required for transmission to intra-cell users and interference mitigation for out-of-cell users. We see this requirement as reasonable due to the relaxed hardware and processing power constraints at the BSs. $\bar{U}$ out-of-cell users impose a requirement of $\bar{U}N_{\mathrm{R}}$ more transmit antennas at the BS for interference suppression. However, this requirement can be reduced by considering the aggregate of the channel matrix and the out-of-cell users' receive beamforming. Thus, only $\bar{U}d$ additional transmit antennas would be required for interference mitigation. This method is beyond the scope of this paper, as we assume that the receive matrices of out-of-cell users are unknown to the BS. It would be good to examine the practicality of such an implementation, with respect to feedback, channel estimation, and oscillation issues.

In this paper, the techniques for uplink channel estimation or channel state feedback was not considered. Multi-user detection or limited feedback [21] to reduce uplink overhead are also interesting topics for future work. While the precoders proposed in this paper are suitable for same/single frequency networks, they are also applicable to cellular systems employing frequency reuse, especially those with smaller cell sizes which indicate high co-channel interference. In this case, each BS only needs to consider the users in the co-channel cells.

Conventional frequency reuse requires careful frequency planning to ensure reliable service. In FFR, further planning is also required to demarcate the handover regions. The FFR scheme is transparent to the standards and can be considered as an implementation issue [52]. It involves the division of the spectrum to provide full frequency reuse for cell-center users and isolation of the cell-edge users from interference. According to the localized topology of each cell, the division of the spectrum, the power allocations, and the physical boundary between the inner and outer bands for hard/soft FFR is evaluated.

Our proposed methods are able to work with single frequency networks, thereby alleviating the need for frequency planning. The 3GPP LTE-Advanced has specified to support as many as eight antennas at the BS, where our proposed methods have already shown significant capacity gain. Furthermore, with even higher number of antennas, more gains can be achieved. In cases of insufficient transmit antennas, user scheduling can always be implemented together with our proposed methods.

## VII. Conclusion

To improve cellular system throughput, there is a trend towards a more aggressive reuse of frequencies and higher cell densities. Due to increased inter-cell interference, network MIMO or BS cooperation becomes an appealing solution to handle interference and raise spectral efficiencies. Most existing techniques involve coordination with heavy exchange of CSI or data over backhaul links. In this paper, we have proposed a nonlinear and a linear distributed precoder for the multicell multiuser MIMO downlink. Unlike existing work, our precoders are designed to tackle both out-of-cell and intra-cell interference in a decentralized manner. Each BS constructs its own precoder without requiring downlink CSI from other BSs or data of out-of-cell users. This paper studied the general scenario where each cell contains a multi-antenna BS that serves multiple users equipped with one or more antennas.

Simulations show that with sufficient transmit antennas, the proposed precoders enjoy a linear rate growth with SNR similar to multicell joint DPC in the high SNR regime due to the interference mitigation. The proposed methods also show significant improvements over orthogonal transmission for various interference scenarios provided there are sufficient transmit antennas at each BS relative to the number of users per cell. With high channel gains between cells, an increase in the co-channel interference factor $\alpha$ has diminishing negative effect on the sum rate performances of the proposed precoders as they are able to mitigate the out-of-cell interference. The leakage-DPC has the benefits of both multicell leakage suppression and projected channel DPC. Furthermore, we analyzed the rate of our precoders in the presence of CSI error. The robust version of the leakage-DPC was observed to retrieve some of the rate loss due to the CSI uncertainty.

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**Winston W. L. Ho** (S'06-M'08) received the B.Eng (Hons.) degree in electrical engineering from the National University of Singapore (NUS) in 2004. He obtained the Ph.D. degree from the NUS in 2009, also in electrical engineering, under a scholarship from the Agency for Science, Technology and Research (A*STAR). He has been with the Institute for Infocomm Research ($I^2R$) since 2008. In 2003, during his half year industrial attachment, he had also worked at the $I^2R$, formerly Institute for Communications Research.

Dr. W. W. L. Ho was the Secretary of the IEEE Vehicular Technology Society Singapore Chapter from 2009 to 2010 and organized the IEEE International Conference on Communication Systems in 2010. His research interests include multiple-antenna wireless transmission, cooperative networks, multiuser space-time systems, green communications, application of information and optimization theories for resource allocation, signal processing, compressed sensing, and broadband communications.

**Tony Q. S. Quek** (S'98-M'08) received the B.E. and M.E. degrees in Electrical and Electronics Engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1998 and 2000, respectively. At Massachusetts Institute of Technology (MIT), Cambridge, MA, he earned the Ph.D. in Electrical Engineering and Computer Science in Feb. 2008.

Since 2008, he has been with the Institute for Infocomm Research, A*STAR, where he is currently a Principal Investigator and Senior Research Engineer. He is also an Adjunct Assistant Professor with the Division of Communication Engineering, Nanyang Technological University. His main research interests are the application of mathematical, optimization, and statistical theories to communication, detection, signal processing, information theoretic and resource allocation problems. Specific current research topics include cooperative networks, interference networks, heterogeneous networks, green communications, wireless security, and cognitive radio.

Dr. Quek has been actively involved in organizing and chairing sessions, and has served as a member of the Technical Program Committee (TPC) in a number of international conferences. He served as the Technical Program Chair for the Services & Applications Track for the IEEE Wireless Communications and Networking Conference (WCNC) in 2009, the Cognitive Radio & Cooperative Communications Track for the IEEE Vehicular Technology Conference (VTC) in Spring 2011, and the Wireless Communications Symposium for the IEEE Globecom in 2011; as Technical Program Vice-Chair for the IEEE Conference on Ultra Wideband in 2011; and as the Workshop Chair for the IEEE Globecom 2010 Workshop on Femtocell Networks and the IEEE ICC 2011 Workshop on Heterogeneous Networks. Dr. Quek is currently an Editor for the Wiley Journal on Security and Communication Networks. He was Guest Editor for the Journal of Communications and Networks (Special Issue on Heterogeneous Networks) in 2011.

Dr. Quek received the Singapore Government Scholarship in 1993, Tokyu Foundation Fellowship in 1998, and the A*STAR National Science Scholarship in 2002. He was honored with the 2008 Philip Yeo Prize for Outstanding Achievement in Research and the IEEE Globecom 2010 Best Paper Award.

**Sumei Sun** obtained the B.Sc.(Honours) degree from Peking University, China, the M.Eng degree from Nanyang Technological University, and the Ph.D. degree from the National University of Singapore. She's been with the Institute for Infocomm Research (formerly Centre for Wireless Communications) since 1995 and she is currently Head of the Modulation and Coding Department, developing physical layer-related solutions for next-generation communication systems. She is the co-recipient of the IEEE PIMRC'2005 Best Paper Award.

**Robert W. Heath Jr.** (S'96-M'01-SM'06-F'11) received the B.S. and M.S. degrees from the University of Virginia, Charlottesville, VA, in 1996 and 1997 respectively, and the Ph.D. from Stanford University, Stanford, CA, in 2002, all in electrical engineering. From 1998 to 2001, he was a Senior Member of the Technical Staff then a Senior Consultant at Iospan Wireless Inc, San Jose, CA where he worked on the design and implementation of the physical and link layers of the first commercial MIMO-OFDM communication system. Since January 2002, he has been with the Department of Electrical and Computer Engineering at The University of Texas at Austin where he is currently an Associate Professor and Associate Director of the Wireless Networking and Communications Group. He is also President and CEO of MIMO Wireless Inc. and VP of Innovation at Kuma Signals LLC. His research interests include several aspects of wireless communication and signal processing including limited feedback techniques, multihop networking, multiuser and multicell MIMO, adaptive video transmission, manifold signal processing, and 60GHz communication techniques.

Dr. Heath has been an Editor for the IEEE Transactions on Communication, an Associate Editor for the IEEE Transactions on Vehicular Technology, lead guest editor for an IEEE Journal on Selected Areas in Communications special issue on limited feedback communication, and lead guest editor for an IEEE Journal on Selected Topics in Signal Processing special issue on Heterogenous Networks. He was a member of the Signal Processing for Communications Technical Committee in the IEEE Signal Processing Society and is currently Chair of the IEEE COMSOC Communications Technical Theory Committee. He was a technical co-chair for the 2007 Fall Vehicular Technology Conference, general chair of the 2008 Communication Theory Workshop, general co-chair, technical co-chair and co-organizer of the 2009 IEEE Signal Processing for Wireless Communications Workshop, local co-organizer for the 2009 IEEE CAMSAP Conference, technical co-chair for the 2010 IEEE International Symposium on Information Theory, and is technical co-chair for the 2014 IEEE GLOBECOM conference.

Dr. Heath was a co-author of best student paper awards at IEEE VTC 2006 Spring, WPMC 2006, IEEE GLOBECOM 2006, IEEE VTC 2007 Spring, and IEEE RWS 2009, as well as co-recipient of the Grand Prize in the 2008 WinTech WinCool Demo Contest. He co-authored a Gold Prize in the 2007 Humantech Paper Contest. He was a 2003 Frontiers in Education New Faculty Fellow. He is the recipient of the David and Doris Lybarger Endowed Faculty Fellowship in Engineering. He is a licensed Amateur Radio Operator and is a registered Professional Engineer in Texas.