Interference Cancellation With Jointly Optimized Transceivers in Multiuser Multicellular Networks

Refik Fatih Ustok, *Member, IEEE*, Pawel A. Dmochowski, *Senior Member, IEEE*, Peter J. Smith, *Fellow, IEEE*, and Mansoor Shafi, *Life Fellow, IEEE*

***Abstract*—We propose novel jointly optimized transceivers for multiuser multicellular networks for both the uplink and the downlink. The optimization is based on minimizing the total mean square error at each base station given that out-of-cell precoders and the cross-channel information for the weaker interferers are not known. As the transceivers are jointly optimized at the base stations, the proposed schemes do not require multiple feedback iterations between the base stations and the users; thus, significantly reducing the overhead. We also investigate the performance considering a cooperation scheme and propose optimization for noncooperative users. We show that our proposed optimized transceivers outperform the existing schemes even with imperfect channel estimations.**

***Index Terms*—Interference cancellation, MIMO, cellular networks, optimization, transceivers.**

I. Introduction

Mobile and wireless communication technologies have evolved tremendously over the last couple of years. The predictions indicate that this growth will continue exponentially and thus solutions for the increasing demand for higher data rates and larger data volumes are needed. Therefore, the focus is on efficient wireless networks where many users share the same radio resources. Traditional interference management systems such as multiple access techniques do not allow us to use the radio resources efficiently. Interference Alignment (IA) has been shown, under certain conditions, to allow each user to utilize one half of the network resources interference-free, regardless of how many users exist in the network [1], [2]. However, IA requires an impractical number of signalling dimensions to achieve the optimal performance as the number of interferers increases [3], [4].

IA has been applied in Multiple-Input-Multiple-Output (MIMO) networks in [5], [6]. It was shown in [7]–[9] that the uplink-downlink duality theorem states that the degrees of freedom of the downlink (DL) is the same as that of uplink (UL). In [10], the authors proposed a combined receiver for multi-cellular networks in the UL. It was shown that the combined receiver outperforms the minimum-mean-square-error (MMSE) receiver if the number of receive antennas is larger than the number of interfering streams and other cell precoders are unknown. However, because of this antenna requirement, this scheme is only practical for the UL.

The authors of [11] proposed an UL interference alignment and cancellation (IAC) scheme for a heterogeneous network. There, the BSs are connected by wired backhaul links and presented a successive interference cancellation (SIC) method where the picocells communicate with the macrocell BS to cancel the interference from pico users to macro users. [11] also studied an optimization problem to maximize the number of data streams that can be transmitted in the network considering SIC.

It was shown in [12] that collective optimization where the users adapt to optimize an overall system objective function together performs better than individual optimization. In [13], the authors considered a MIMO relay system and proposed an iterative joint source/relay precoding to optimize the overall system performance. The authors of [14] proposed to jointly optimize transmitter and receiver sets for a single-cell multi-user MIMO system in the UL. They showed that the minimizing mean square error (MSE) function is a jointly convex optimization problem given that the constraint set and the Karush-Kuhn-Tucker (KKT) conditions are satisfied. In [15], the authors considered a two-tier cellular system of macro and femto cells in the UL. They proposed to align the intercell interference caused by macrocell users to the femtocell BSs by employing semidefinite programming. However, alignment of the intracell interference was not considered for macrocell users. They proposed an optimization problem which considers minimum achievable Signal-to-Interference-Noise-Ratio (SINR) level for macrocell users as a constraint.

The authors of [16] proposed a joint optimization of transceivers for a system in the DL following a similar approach to [14] also for a single cell system. In [17], an IA technique was proposed for a multicellular system in the DL. The authors proposed the MMSE-like receiver which mimics MMSE and showed that it outperforms zero-forcing (ZF)

Manuscript received July 17, 2017; revised November 15, 2017 and February 18, 2018; accepted March 21, 2018. Date of publication April 24, 2018; date of current version August 13, 2018. The review of this paper was coordinated by Dr. K. Temma. *(Corresponding author: Refik Fatih Ustok.)*

R. F. Ustok is with the School of Engineering and Computer Science, Victoria University of Wellington, Wellington 6012, New Zealand (e-mail: refik.ustok@ecs.vuw.ac.nz).

P. A. Dmochowski and P. J. Smith are with Victoria University of Wellington, Wellington 6012, New Zealand (e-mail: pawel.dmochowski@ecs.vuw.ac.nz; peter.smith@vuw.ac.nz).

M. Shafi is with the Spark New Zealand, Wellington 6011, New Zealand (e-mail: Mansoor.Shafi@spark.co.nz).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2018.2829544

and matched filtering (MF) techniques in systems where there are many interferers with different power levels. They introduced a coloring parameter, which is dependent on the interference levels that the users are exposed to, and used this parameter to unify the extreme cases of these interference levels for the receiver design. They categorized the intercell interference as dominant and remaining and treated the latter interference as noise. ZF precoders were used in [17] in order to cancel intracell interference. The scheme of [17] also includes an iterative technique to improve the performance of the precoding vectors and requiring feedback between the user and the BS for each iteration. This feedback is done via a backhaul link. Therefore the scheme of [17] may not satisfy low-latency requirements of fifth generation (5G) wireless networks [18].

In [19], a partial cooperation scheme for IAC based on received interference powers from adjacent base stations (BSs) was proposed. In [19] we identified the areas in which the coverage of adjacent cells overlap in a 19 cell network. We assumed that the cooperative users were located in these overlapping areas and thus could receive channel information from neighboring BSs to cancel intercell interference, and thus utilized a MMSE-like receiver of [17]. The non-cooperative users utilized the MF receiver due to the lack of channel information from neighboring BSs. Signal-to-leakage-and-noise ratio (SLNR) based precoders were employed in [19] in order to improve performance and relax the condition on the number of transmit-receive antennas in comparison to traditional ZF.

There is considerable ongoing work in IA [20] and interference cancellation with many papers focusing on relaxation methods to allow convex optimisation [21] and various numerical approaches. For example, mixed-integer non-linear programming is used in [22] and an exhaustive search and the golden section are used in [23]. A simpler iterative method for IA with a similar design approach to our work has appeared in [24]. However, the work in [24] is DL only and does not cater for unknown interfering precoders.

In this paper, we propose optimized transceivers for multi-user multi-cell networks in the UL and the DL. The proposed system requires only one-time feedback from the users to the BS, thus significantly reducing the overhead required relative to the schemes in [15]–[17], [25]. The basic idea of this work is to extend the ideas in [14] and [17] to produce high performance transceivers in both the UL and DL. In terms of novelty, first, the basic iterative solution for precoders and decoders in the UL [14] is extended to the DL. Secondly, their iterative schemes are adapted to cater for dominant out-of-cell interference and limited other-cell CSI [17]. The motivation is to obtain the high performance available by an iterative MSE minimization, providing gains over [14], while including the CSI restrictions implicit in [17]. We also consider the partial cooperative scheme where we combine the optimized precoders with the MF receivers for non-cooperative users. The contributions of this paper are as follows.

- We propose a joint optimization of transceivers for multi-user, multi-cellular systems in the UL and the DL. The proposed technique will require less overhead relative to the schemes which require feedback between the users and the BSs for each iteration.
- We consider partial cooperation [19] and combine MF receivers with optimized precoders for non-cooperative users which cannot access the cross-channel state information (CCSI).
- We demonstrate the system performance considering 3GPP scenarios with randomly located and cell-edge users. We also investigate how imperfect channel state information (CSI) and CCSI impact the mean sum rates.

TABLE I
THE MOST COMMONLY USED NOTATION

$\mathbf{H}_{\alpha,i}$	Direct channel In the Uplink: From the user i in cell α to the BS in cell α In the Downlink: From the BS in cell α to the user i in cell α
$\mathbf{G}_{\beta,i}$	Cross channel In the Uplink: From the user i in cell β to the BS in cell α In the Downlink: From the BS in cell β to the user i in cell α
$\mathbf{v}_{\alpha,i}$	Precoding vector for the ith user in cell α
$x_{\alpha,i}$	Transmitted data for the user i in cell α
S	Number of streams per user
K	Number of users in each cell
N_r	Number of receive antennas
N_t	Number of transmit antennas

This article is organized as follows. The system model is given in Section II. Jointly optimized transceiver design for both the UL and the DL is given in Section III. The cooperation of such systems is discussed in Section IV. Performance metrics are given in Section V. Simulation results are provided for the UL and DL, considering imperfect CSI and CCSI in Section VI. We conclude the paper in Section VII.

A. Notation

Bold upper case and lower case letters denote matrices and vectors, respectively, $(\cdot)^*$ denotes the conjugate transpose and $\mathbf{I}$ denotes an identity matrix. $\mathcal{CN}^{a\times b}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ denotes a $a \times b$ size matrix which has complex Gaussian distribution with mean $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}$. Furthermore, max eig.vec.$(\cdot)$ denotes the eigenvector corresponding to the largest eigenvalue of a matrix. The most commonly used notation is summarized in Table I.

II. System Model

We consider a multicell system with K users in each cell utilising S data streams. Each transmitter is equipped with N_t antennas while the number of antennas at the receivers is denoted by N_r. In the UL, each user transmits 1 data stream, therefore total number of data stream per transmitter (user equipment (UE)) is $S = 1$. In the DL, the BS transmits 1 data stream per user, therefore total number of data streams being transmitted from the BS is equal to the number of users, $S = K$. The BS in the DL or the UE in the UL transmits the desired signal for the ith user in cell α, $x_{\alpha,i}$ and $|x_{\alpha,i}| = 1$, using the precoding vectors, $\mathbf{v}_{\alpha,i}$ and $\|\mathbf{v}_{\alpha,i}\| = 1$ through the direct channel

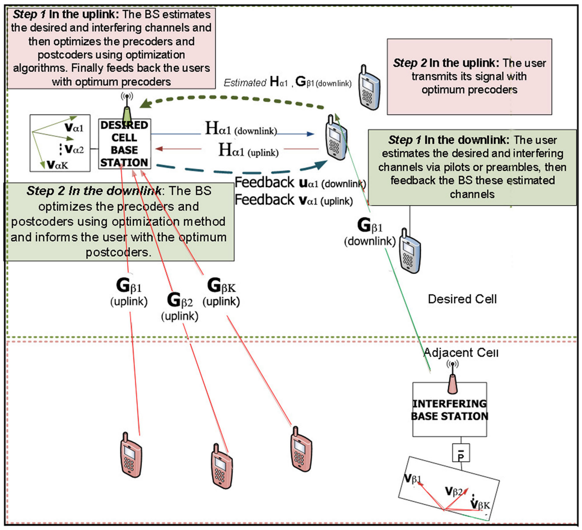


Fig. 1. System model of the proposed optimized transceivers.

$\mathbf{H}_{\alpha,i} \in \mathcal{CN}^{N_r \times N_t}(0, \mathbf{I})$. In the DL, $\mathbf{G}_{\beta,i} \in \mathcal{CN}^{N_r \times N_t}(0, \mathbf{I})$ denotes the cross channel from the BS in cell β to the user i in cell α. In the UL, $\mathbf{G}_{\beta,i} \in \mathcal{CN}^{N_r \times N_t}(0, \mathbf{I})$ denotes the cross channel from the user i in cell β to the BS in cell α. In this paper, all links are assumed to be independent, non-line-of-sight (NLOS) and Rayleigh flat-fading channels in an urban environment. The noise is assumed to be additive white Gaussian noise. We define $\rho_{\alpha,i} = \upsilon \xi_{\alpha,i}$ where υ is the total transmit power of the UE in the UL and the BS in the DL. The variable $\xi_{\alpha,i}$ denotes the attenuation due to path-loss and shadowing. Since we assume noise with unit variance throughout this paper, υ represents the transmit-SNR, as in [17]. We also categorise the intercell interference as *dominant* (interferers with the strongest power) and *remaining*, where full CCSI is assumed for the former and only average power is known for the latter. Thus, remaining interference is treated as noise. Both dominant and remaining interference can be from many transmitters, depending on the system considered.

A. System Model for the UL

The system model for the UL is given in Fig. 1. The BS generates the precoding vectors which are fed back and used for UL transmission by the users.

The received signal intended for user i in cell α is given by

$$\mathbf{y}_\alpha = \sqrt{\frac{\rho_{\alpha,i}}{S}}\mathbf{H}_{\alpha,i}\mathbf{v}_{\alpha,i}x_{\alpha,i} + \underbrace{\sum_{j=1,j\neq i}^{K}\sqrt{\frac{\rho_{\alpha,j}}{S}}\mathbf{H}_{\alpha,j}\mathbf{v}_{\alpha,j}x_{\alpha,j}}_{\text{Intracell Interference}}$$
$$+ \underbrace{\sum_{\beta}\sum_{l=1}^{K}\sqrt{\frac{\rho_{\beta,l}}{S}}\mathbf{G}_{\beta,l}\mathbf{v}_{\beta,l}x_{\beta,l}}_{\text{Dominant Intercell Interference}} + \mathbf{z}_\alpha + \mathbf{n}_\alpha, \quad (1)$$

where $\mathbf{G}_{\beta,l}$ is a dominant intercell interfering channel from a nearby cell, $\mathbf{z}_\alpha$ is the remaining interference and $\mathbf{n}_\alpha$ is the noise with unit variance. Note that β denotes all dominant intercell interferers for which CCSI is available at the BS. The second term in (1) denotes the intracell interference when the BS decodes the signal of the ith user. The transmitter (UE) i in cell α sends data $x_{\alpha,i}$ using a precoding vector, $\mathbf{v}_{\alpha,i}$.

B. System Model for the DL

The system model for the DL is also given in Fig. 1. Each BS generates optimized precoders and postcoders, and feeds back the latter to each user. Each BS transmits its data using K precoding vectors, $\mathbf{B}_\alpha = [\mathbf{v}_{\alpha,1}, \mathbf{v}_{\alpha,2}, \ldots, \mathbf{v}_{\alpha,K}] \in \mathbb{C}^{N_t \times K}$.

The received signal of user i in cell α on the DL is given as

$$\mathbf{y}_{\alpha,i} = \sqrt{\frac{\rho_{\alpha,i}}{S}}\mathbf{H}_{\alpha,i}\mathbf{v}_{\alpha,i}x_{\alpha,i} + \underbrace{\sqrt{\frac{\rho_{\alpha,i}}{S}}\mathbf{H}_{\alpha,i}\sum_{k=1,k\neq i}^{K}\mathbf{v}_{\alpha,k}x_{\alpha,k}}_{\text{Intracell Interference}}$$
$$+ \underbrace{\sum_{\beta}\sqrt{\frac{\rho_{\beta,i}}{S}}\mathbf{G}_{\beta,i}\sum_{l=1}^{K}\mathbf{v}_{\beta,l}x_{\beta,l}}_{\text{Dominant Intercell Interference}} + \mathbf{z}_{\alpha,i} + \mathbf{n}_{\alpha,i}. \quad (2)$$

The received signals, $\mathbf{y}_\alpha$ and $\mathbf{y}_{\alpha,i}$ in the UL and DL, respectively, are processed for each user with $\mathbf{u}_{\alpha,i}$ to give

$$\begin{aligned}\tilde{x}_{\alpha,i} &= \mathbf{u}^*_{\alpha,i}\mathbf{y}_\alpha, \text{(UL)}\\ \tilde{x}_{\alpha,i} &= \mathbf{u}^*_{\alpha,i}\mathbf{y}_{\alpha,i}, \text{(DL)}\end{aligned} \quad (3)$$

where $\tilde{x}_{\alpha,i}$ is the estimated desired signal.

III. Transceiver Design

We present the algorithms for both the UL and DL in Sections III-A and III-B, respectively. In both cases, the optimization process is performed at the BS.

A. Jointly Optimized Transceivers for the UL

We now give the algorithm of IAC in the UL, employing the optimized transceivers which is based on minimizing the total MSE in the BSs. The algorithm steps are as follows.

1) **Initialize the precoders and postcoders:** The BS generates the initial precoding vectors, $\mathbf{v}^{(0)}_{\alpha,i}$, similar to the approach of [17] (MMSE receivers with ZF precoders), that is

$$\mathbf{v}^{(0)}_{\alpha,i} = \text{max eig. vec } (\mathbf{H}^*_{\alpha,i}\bar{\mathbf{\Phi}}^{-1}\mathbf{H}_{\alpha,i}),$$
$$\text{such that } : \|\mathbf{v}^{(0)}_{\alpha,i}I\| = 1, \quad (4)$$

where $\bar{\mathbf{\Phi}}$ is given as

$$\bar{\mathbf{\Phi}} = (1 + \text{INR}_{\text{rem}})\mathbf{I} + \underbrace{\left(\sum_{\beta}\sum_{j=1}^{K} \frac{\rho_{\beta,j}}{S} \mathbf{G}_{\beta,j} \mathbb{E}\{\mathbf{v}_{\beta,j}\mathbf{v}_{\beta,j}^*\} \mathbf{G}_{\beta,j}^*\right)}_{\text{Autocovariance matrix of dominant intercell interference}}, \tag{5}$$

and INR_{rem} is the interference-noise ratio for remaining interference. As the noise is normalized to have unit variance, INR_{rem} is equal to the power of remaining interference. Since the out of cell precoders, $\mathbf{v}_{\beta,j}$, are not known in (5), similarly to the approach in [17] we use $\mathbb{E}\{\mathbf{v}_{\beta,j}\mathbf{v}_{\beta,j}^*\} \approx \frac{1}{N_t}\mathbf{I}$. Similarly to [14], we initialize the postcoder $\mathbf{u}_{\alpha,i}^{(0)}$ using the MMSE principle. In contrast, however, we take into account the dominant and remaining intercell interference, that is

$$\mathbf{u}_{\alpha,i}^{(0)^*} = \mathbf{v}_{\alpha,i}^{(0)*}\mathbf{H}_{\alpha,i}^*\sqrt{\frac{\rho_{\alpha,i}}{S}}\mathbf{T}_{\alpha}^{(0)^{-1}}, \tag{6}$$

where $\mathbf{T}_{\alpha}^{(0)}$ is the autocovariance matrix of the received signal and given by

$$\mathbf{T}_{\alpha}^{(0)} = (1 + \text{INR}_{\text{rem}})\mathbf{I} + \sum_{j=1}^{K} \frac{\rho_{\alpha,j}}{S}\mathbf{H}_{\alpha,j}\mathbf{v}_{\alpha,j}^{(0)}\mathbf{v}_{\alpha,j}^{(0)*}\mathbf{H}_{\alpha,j}^* + \sum_{\beta}\sum_{j=1}^{K} \frac{\rho_{\beta,j}}{S}\mathbf{G}_{\beta,j}\left(\frac{1}{N_t}\mathbf{I}\right)\mathbf{G}_{\beta,j}^*. \tag{7}$$

2) **Optimization:** We find the set of optimum precoders and postcoders that minimize the total MSE. We compute the MSE for each user, which is given by [14]

$$\text{MSE}_{\alpha,i}^{(0)} = 1 - \left(\frac{\rho_{\alpha,i}}{S}\right)\mathbf{v}_{\alpha,i}^{(0)*}\mathbf{H}_{\alpha,i}^*\mathbf{T}_{\alpha,i}^{(0)^{-1}}\mathbf{H}_{\alpha,i}\mathbf{v}_{\alpha,i}^{(0)}, \tag{8}$$

and thus the total MSE_{α} for cell α is

$$\text{MSE}_{\alpha}^{(0)} = \sum_{i=1}^{K}\text{MSE}_{\alpha,i}^{(0)}. \tag{9}$$

The inverse of $\mathbf{T}_{\alpha}^{(0)}$ can be found using matrix inversion lemma as given in [14]

$$\mathbf{T}_{\alpha,i}^{(0)^{-1}} = \mathbf{E}_{\alpha,i}^{(0)^{-1}} - \frac{\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{H}_{\alpha,i}\mathbf{v}_{\alpha,i}^{(0)}\frac{\rho_{\alpha,i}}{S}\mathbf{v}_{\alpha,i}^{(0)*}\mathbf{H}_{\alpha,i}^*\mathbf{E}_{\alpha,i}^{(0)^{-1}}}{1 + \mathbf{v}_{\alpha,i}^{(0)*}\mathbf{H}_{\alpha,i}^*\frac{\rho_{\alpha,i}}{S}\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{H}_{\alpha,i}\mathbf{v}_{\alpha,i}^{(0)}}, \tag{10}$$

where

$$\mathbf{E}_{\alpha,i}^{(0)} = \left(\sum_{k=1,i\neq k}^{K}\frac{\rho_{\alpha,k}}{S}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}\mathbf{v}_{\alpha,k}^{(0)*}\mathbf{H}_{\alpha,k}^*\right) + \left(\sum_{\beta}\sum_{j=1}^{K}\frac{\rho_{\beta,j}}{SN_t}\mathbf{G}_{\beta,j}\mathbf{G}_{\beta,j}^*\right) + (1 + \text{INR}_{\text{rem}})\mathbf{I}. \tag{11}$$

Using (10) and (11), (9) can be written as

$$\text{MSE}_{\alpha}^{(0)} = C_i - \frac{\mathbf{v}_{\alpha,i}^{(0)*}\mathbf{H}_{\alpha,i}^*\frac{\rho_{\alpha,i}}{S}\left(\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{\Xi}_{\alpha,i}^{(0)}\mathbf{E}_{\alpha,i}^{(0)^{-1}}\right)\mathbf{H}_{\alpha,i}\mathbf{v}_{\alpha,i}^{(0)}}{\mathbf{v}_{\alpha,i}^{(0)*}\left(\mathbf{I} + \mathbf{H}_{\alpha,i}^*\frac{\rho_{\alpha,i}}{S}\mathbf{E}_{\alpha,i}^{-1}\mathbf{H}_{\alpha,\mathbf{i}}\right)\mathbf{v}_{\alpha,i}^{(0)}}, \tag{12}$$

where $\mathbf{\Xi}_{\alpha,i}^{(0)} = \mathbf{E}_{\alpha,i}^{(0)} - \sum_{k=1,i\neq k}\frac{\rho_{\alpha,k}}{S}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}\mathbf{v}_{\alpha,k}^{(0)^*}\mathbf{H}_{\alpha,k}^*$ and C_i represents the term independent of the user i. We can find C_i as $C_i = K - \sum_{k\neq i}\mathbf{v}_{\alpha,k}^*\mathbf{H}_{\alpha,k}^*\frac{\rho_{\alpha,k}}{S}\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}$ following [14]. Note that $\mathbf{E}_{\alpha,i}^{(0)}$ does not depend on the precoding vector of the user i, $\mathbf{v}_{\alpha,i}$. For the user i, MSE can be minimized by choosing $\mathbf{v}_{\alpha,i}$ to maximize the second term in (12), which is the term dependent on $\mathbf{v}_{\alpha,i}$. Using the Rayleigh Quotient Theorem [26], the precoding vectors that minimize MSE are given by

$$\mathbf{v}_{\alpha,i}^{(1)} = \text{max eig. vec.}\left(\mathbf{H}_{\alpha,i}^*\frac{\rho_{\alpha,i}}{S}\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{\Xi}_{\alpha,i}^{(0)}\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{H}_{\alpha,i}, \mathbf{I} + \mathbf{H}_{\alpha,i}^*\frac{\rho_{\alpha,i}}{S}\mathbf{E}_{\alpha,i}^{(0)^{-1}}\mathbf{H}_{\alpha,i}\right)$$
$$\text{subject to}: \|\mathbf{v}_{\alpha,i}^{(1)}\| = 1. \tag{13}$$

3) **Iteration:** We update the $\mathbf{E}_{\alpha,i}$ at the lth iteration using the updated precoding vectors

$$\mathbf{E}_{\alpha,i}^{(l)} = \sum_{k=1}^{i-1}\frac{\rho_{\alpha,k}}{S}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(l+1)}\mathbf{v}_{\alpha,k}^{(l+1)*}\mathbf{H}_{\alpha,k}^* + \sum_{j=i+1}^{K}\frac{\rho_{\alpha,j}}{S}\mathbf{H}_{\alpha,j}\mathbf{v}_{\alpha,j}^{(l)}\mathbf{v}_{\alpha,j}^{(l)*}\mathbf{H}_{\alpha,j}^* + \left(\sum_{\beta}\sum_{j=1}^{K}\frac{\rho_{\beta,j}}{SN_t}\mathbf{G}_{\beta,j}\mathbf{G}_{\beta,j}^*\right) + (1 + \text{INR}_{\text{rem}})\mathbf{I}. \tag{14}$$

We update the precoders with updated $\mathbf{E}_{\alpha,i}^{(l)}$,

$$\mathbf{v}_{\alpha,i}^{(l+1)} = \text{max eig. vec.} \left(\mathbf{H}_{\alpha,i}^{*}\frac{\rho_{\alpha,i}}{S}\mathbf{E}_{\alpha,i}^{(l)^{-1}}\mathbf{\Xi}_{\alpha,i}^{(0)}\mathbf{E}_{\alpha,i}^{(l)^{-1}}\mathbf{H}_{\alpha,i}, \mathbf{I} + \mathbf{H}_{\alpha,i}^{*}\frac{\rho_{\alpha,i}}{S}\mathbf{E}_{\alpha,i}^{(l)^{-1}}\mathbf{H}_{\alpha,i}\right)$$
$$\text{subject to} : \|\mathbf{v}_{\alpha,i}^{(l+1)}\| = 1. \tag{15}$$

The iteration continues until the convergence, that is, $\text{MSE}_{\alpha}^{(l+1)} - \text{MSE}_{\alpha}^{(l)} \leq \epsilon$. After finding the optimum precoding vectors, the BS generates the MMSE postcoders,

$$\mathbf{u}_{\alpha,i}^{(l+1)^{*}} = \mathbf{v}_{\alpha,i}^{(l+1)*}\mathbf{H}_{\alpha,i}^{*}\sqrt{\frac{\rho_{\alpha,i}}{S}}\mathbf{T}_{\alpha,i}^{(l+1)^{-1}}$$
$$\text{such that} : \|\mathbf{u}_{\alpha,i}^{(l+1)}\| = 1, \tag{16}$$

where

$$\mathbf{T}_{\alpha}^{(l+1)} = (1 + \text{INR}_{\text{rem}})\mathbf{I} + \left(\sum_{j=1}^{S}\frac{\rho_{\alpha,j}}{S}\mathbf{H}_{\alpha,j}\mathbf{v}_{\alpha,j}^{(l+1)}\mathbf{v}_{\alpha,j}^{(l+1)*}\mathbf{H}_{\alpha,j}^{*}\right) + \left(\sum_{\beta}\sum_{j=1}^{S}\frac{\rho_{\beta,j}}{SN_t}\mathbf{G}_{\beta,j}\mathbf{G}_{\beta,j}^{*}\right). \tag{17}$$

Finally, the BS feeds back the optimum precoders to the user in order to begin transmission.

B. Jointly Optimized Transceivers for the DL

The algorithm of IAC in the DL employing the optimized transceivers is given in this section. As mentioned earlier, we find the trasmitter-receiver set which minimizes the MSE at the BSs assuming the transmitter has no knowledge of other precoders and the remaining intercell interference cross channel. The algorithm steps are given as follows

1) **Initialize the precoders and postcoders:** We first initialize the precoders similar to the UL,

$$\mathbf{v}_{\alpha,k}^{(0)} = \text{ max eig. vec. } (\mathbf{H}_{\alpha,k}^{*}\tilde{\mathbf{\Phi}}_{\alpha,k}\mathbf{H}_{\alpha,k}), \tag{18}$$

where $\tilde{\mathbf{\Phi}}_{\alpha,k} = (1 + \text{INR}_{\text{rem}})\mathbf{I} + \sum_{\beta}\frac{\rho_{\beta,k}}{S}(\mathbf{G}_{\beta,k}\mathbb{E}\{\mathbf{B}_{\beta}\mathbf{B}_{\beta}^{*}\}\mathbf{G}_{\beta,k}^{*})$. It has been shown in [17] that $\mathbb{E}\{\mathbf{B}_{\beta}\mathbf{B}_{\beta}^{*}\} = \frac{S}{N_t}\mathbf{I}$, thus this is used in place of $\mathbf{B}_{\beta}\mathbf{B}_{\beta}^{*}$ in the absence of its estimation. Then, we write the initial value of the MMSE postcoding vector

$$\mathbf{u}_{\alpha,k}^{(0)} = \sqrt{\frac{\rho_{\alpha,k}}{S}}\mathbf{v}_{\alpha,k}^{(0)^{*}}\mathbf{H}_{\alpha,k}^{*}\mathbf{T}_{\alpha,k}^{(0)^{-1}}, \tag{19}$$

where

$$\mathbf{T}_{\alpha,k}^{(0)} = (1 + \text{INR}_{\text{rem}})\mathbf{I} + \frac{\rho_{\alpha,k}}{S}\sum_{j=1}^{K}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,j}^{(0)}\mathbf{v}_{\alpha,j}^{(0)*}\mathbf{H}_{\alpha,i}^{*} + \sum_{\beta}\frac{\rho_{\beta,k}}{S}\mathbf{G}_{\beta,k}\left(\frac{S}{N_t}\mathbf{I}\right)\mathbf{G}_{\beta,k}^{*}. \tag{20}$$

2) **Optimization:** Next, we find the precoders and postcoders that minimize the total MSE for cell α as given

$$\text{MSE}_{\alpha}^{(0)} = \sum_{k=1}^{K}\text{MSE}_{\alpha,k}^{(0)}, \tag{21}$$

where, for each user

$$\text{MSE}_{\alpha,k}^{(0)} = 1 - \mathbf{v}_{\alpha,k}^{(0)*}\mathbf{H}_{\alpha,k}^{*}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{T}_{\alpha,k}^{(0)^{-1}}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}. \tag{22}$$

Next, we note that using the matrix inversion lemma, $\mathbf{T}_{\alpha,k}^{(0)^{-1}}$ can be expressed as

$$\mathbf{T}_{\alpha,k}^{(0)^{-1}} = \mathbf{E}_{\alpha,k}^{(0)^{-1}} - \frac{\mathbf{E}_{\alpha,k}^{(0)^{-1}}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{v}_{\alpha,k}^{(0)^{*}}\mathbf{H}_{\alpha,k}^{*}\mathbf{E}_{\alpha,k}^{(0)^{-1}}}{1 + \mathbf{v}_{\alpha,k}^{(0)^{*}}\mathbf{H}_{\alpha,k}^{*}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{E}_{\alpha,k}^{(0)^{-1}}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}}, \tag{23}$$

where

$$\mathbf{E}_{\alpha,k}^{(0)} = \frac{\rho_{\alpha,k}}{S}\sum_{i=1,i\neq k}^{K}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,i}^{(0)}\mathbf{v}_{\alpha,i}^{(0)*}\mathbf{H}_{\alpha,k}^{*} + \left(\sum_{\beta}\frac{\rho_{\beta,k}}{N_t}\mathbf{G}_{\beta,k}\mathbf{G}_{\beta,k}^{*}\right) + (1 + \text{INR}_{\text{rem}})\mathbf{I}. \tag{24}$$

Then, we can rewrite the total MSE in (21)

$$\text{MSE}_{\alpha}^{(0)} = K - A_{\alpha}, \tag{25}$$

where

$$A_{\alpha} = \sum_{k=1}^{K}\frac{\rho_{\alpha,k}}{S}\mathbf{v}_{\alpha,k}^{(0)^{*}}\mathbf{H}_{\alpha,k}^{*}\left(\mathbf{E}_{\alpha,k}^{(0)^{-1}} - \frac{\mathbf{E}_{\alpha,k}^{(0)^{-1}}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{v}_{\alpha,k}^{(0)^{*}}\mathbf{H}_{\alpha,k}^{*}\mathbf{E}_{\alpha,k}^{(0)^{-1}}}{1 + \mathbf{v}_{\alpha,k}^{(0)^{*}}\mathbf{H}_{\alpha,k}^{*}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{E}_{\alpha,k}^{(0)^{-1}}\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}}\right)\mathbf{H}_{\alpha,k}\mathbf{v}_{\alpha,k}^{(0)}. \tag{26}$$

In order to minimize (25), we need to maximize the second term of (25). Let us rewrite (25)

$$\text{MSE}_{\alpha}^{(0)} = K - \left(\sum_{k=1}^{K}Q_{\alpha,k}^{(0)} - \frac{Q_{\alpha,k}^{(0)^{2}}}{1 + Q_{\alpha,k}^{(0)}}\right), \tag{27}$$

where $Q^{(0)}_{\alpha,k} = \mathbf{v}^{(0)^*}_{\alpha,k}\mathbf{H}^*_{\alpha,k}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{E}^{(0)^{-1}}_{\alpha,k}\mathbf{H}_{\alpha,k}\mathbf{v}^{(0)}_{\alpha,k}$. We note that $Q^{(0)}_{\alpha,k} - \frac{Q^{(0)^2}_{\alpha,k}}{1+Q^{(0)}_{\alpha,k}} = 1 - \frac{1}{1+Q^{(0)}_{\alpha,k}}$, giving

$$\begin{aligned}\mathrm{MSE}^{(0)}_{\alpha} &= K - \sum_{k=1}^{K}\left(1 - \frac{1}{1+Q^{(0)}_{\alpha,k}}\right)\\ &= K - K + \sum_{k=1}^{K}\left(\frac{1}{1+Q^{(0)}_{\alpha,k}}\right)\\ &= \sum_{k=1}^{K}\frac{1}{1+\mathbf{v}^{(0)^*}_{\alpha,k}\mathbf{H}^*_{\alpha,k}\left(\frac{\rho_{\alpha,k}}{S}\right)\mathbf{E}^{(0)^{-1}}_{\alpha,k}\mathbf{H}_{\alpha,k}\mathbf{v}^{(0)}_{\alpha,k}}.\end{aligned} \tag{28}$$

We can minimize (28) by maximising its denominator. Using the Rayleigh Quotient Theorem [26], we find the precoding vectors that minimize the total MSE (28)

$$\mathbf{v}^{(1)}_{\alpha,k} = \text{max eig. vec.}\left(\mathbf{H}^*_{\alpha,k}\frac{\rho_{\alpha,k}}{S}\mathbf{E}^{(0)^{-1}}_{\alpha,k}\mathbf{H}_{\alpha,k}\right)$$
$$\text{such that}: \|\mathbf{v}^{(1)}_{\alpha,k}\| = 1. \tag{29}$$

3) **Iteration:** We can find $\mathbf{E}_{\alpha,k}$ at lth iteration using the updated precoding vectors. The iteration continues until $\mathrm{MSE}^{(l+1)}_{\alpha} - \mathrm{MSE}^{(l)}_{\alpha} \leq \epsilon$. After convergence, the BS finds the optimum precoding vector

$$\mathbf{v}^{(l+1)}_{\alpha,k} = \text{max eig. vec.}\left(\mathbf{H}^*_{\alpha,k}\frac{\rho_{\alpha,k}}{S}\mathbf{E}^{(l)^{-1}}_{\alpha,k}\mathbf{H}_{\alpha,k}\right)$$
$$\text{such that}: \|\mathbf{v}^{(l+1)}_{\alpha,k}\| = 1. \tag{30}$$

After finding the optimum precoders, the postcoders are generated as

$$\mathbf{u}^{(l+1)}_{\alpha,k} = \mathbf{v}^{(l+1)*}_{\alpha,k}\mathbf{H}^*_{\alpha,k}\sqrt{\frac{\rho_{\alpha,k}}{S}}\mathbf{T}^{(l+1)^{-1}}_{\alpha,k},$$
$$\text{such that}: \|\mathbf{u}^{(l+1)}_{\alpha,k}\| = 1, \tag{31}$$

where

$$\begin{aligned}\mathbf{T}^{(l+1)}_{\alpha,k} &= (1+\mathrm{INR}_{\mathrm{rem}})\mathbf{I} + \left(\sum_{\beta}\frac{\rho_{\beta,k}}{N_t}\mathbf{G}_{\beta,k}\mathbf{G}^*_{\beta,k}\right)\\ &\quad + \left(\frac{\rho_{\alpha,k}}{S}\sum_{j=1}^{K_\alpha}\mathbf{H}_{\alpha,k}\mathbf{v}^{(l+1)}_{\alpha,j}\mathbf{v}^{(l+1)*}_{\alpha,j}\mathbf{H}^*_{\alpha,k}\right).\end{aligned} \tag{32}$$

Finally, the transmitter informs each user about the optimum postcoders. Note that the iteration is performed only at the transmitter. There is only one-time feedback of CSI from the user to the BS.

IV. Cooperative IAC

We consider the cooperation scheme of [19] in the DL and discuss the application of the proposed optimized transceivers.

A. Cooperative Users

The users which are located in the cooperation zone have CCSI and thus are able to employ the precoders of (30) and the postcoders of (31). As defined in [19], the cooperative users are decided based on the ratio of the channel strengths

$$r_\beta = 10\log_{10}\left(\frac{\mathrm{tr}(\mathbf{H}_{\alpha,i}\mathbf{H}^*_{\alpha,i})}{\mathrm{tr}(\mathbf{G}_{\beta,i}\mathbf{G}^*_{\beta,i})}\right). \tag{33}$$

For some threshold Λ, a user is considered to be in the cooperation zone if $r_\beta < \Lambda$. Such user receives CCSI from the neighbouring BS(s).[1]

B. Non-Cooperative Users

The users for whom $r_\beta > \Lambda$ are located in the non-cooperation zone and lack CCSI. We thus modify the equations for the optimized transceivers, considering that all intercell interference is added to the remaining interference term and treated as noise. The modified algorithm is as follows.

1) **Initialize the precoders and postcoders:** The initial precoders are found as,

$$\tilde{\mathbf{v}}^{(0)}_{\alpha,k} = \text{max eig. vec.}\ (\mathbf{H}^*_{\alpha,k}\tilde{\tilde{\mathbf{\Phi}}}_{\alpha,k}\mathbf{H}_{\alpha,k}), \tag{34}$$

where $\tilde{\tilde{\mathbf{\Phi}}}_{\alpha,k} = (1+\mathrm{I\tilde{N}R}_{\mathrm{rem}})\mathbf{I}$ and $\mathrm{I\tilde{N}R}_{\mathrm{rem}}$ includes all intercell interference as no CCSI is available from any intercell interferer.

2) **Optimization:** MSE is then computed for each user using (22), with $\mathbf{T}^{(0)}_{\alpha,k}$ replaced by

$$\begin{aligned}\tilde{\mathbf{T}}^{(0)}_{\alpha,k} &= (1+\mathrm{I\tilde{N}R}_{\mathrm{rem}})\mathbf{I}\\ &\quad + \frac{\rho_{\alpha,k}}{S}\sum_{j=1}^{K}\mathbf{H}_{\alpha,k}\tilde{\mathbf{v}}^{(0)}_{\alpha,j}\tilde{\mathbf{v}}^{(0)*}_{\alpha,j}\mathbf{H}^*_{\alpha,i}.\end{aligned} \tag{35}$$

Following the steps given in Section III-B, we find the precoding vectors that minimize the total MSE

$$\tilde{\mathbf{v}}^{(1)}_{\alpha,k} = \text{max eig. vec.}\left(\mathbf{H}^*_{\alpha,k}\left(\frac{\rho_{\alpha,k}}{S}\right)\tilde{\mathbf{E}}^{(0)^{-1}}_{\alpha,k}\mathbf{H}_{\alpha,k}\right)$$
$$\text{such that}: \|\tilde{\mathbf{v}}^{(1)}_{\alpha,k}\| = 1, \tag{36}$$

where

$$\begin{aligned}\tilde{\mathbf{E}}^{(0)}_{\alpha,k} &= \frac{\rho_{\alpha,k}}{S}\sum_{i=1,i\neq k}^{K}H_{\alpha,k}\tilde{\mathbf{v}}^{(0)}_{\alpha,i}\tilde{\mathbf{v}}^{(0)*}_{\alpha,i}\mathbf{H}^*_{\alpha,k}\\ &\quad + (1+\mathrm{I\tilde{N}R}_{\mathrm{rem}})\mathbf{I}.\end{aligned} \tag{37}$$

3) **Iteration:** Following convergence, that is when $\mathrm{M\tilde{S}E}^{(l+1)}_{\alpha} - \mathrm{M\tilde{S}E}^{(l)}_{\alpha} \leq \epsilon$. Then the BS finds the op-

[1] Please note that in Section III-A and III-B, each user is assumed to be able to access CCSI of the dominant interferers, therefore they are regarded as systems with full-cooperation.

timum precoding vector

$$\tilde{\mathbf{v}}_{\alpha,k}^{(l+1)} = \text{max eig. vec.} \left(\mathbf{H}_{\alpha,k}^{*} \left(\frac{\rho_{\alpha,k}}{S}\right) \tilde{\mathbf{E}}_{\alpha,k}^{(l)^{-1}} \mathbf{H}_{\alpha,k}\right)$$
$$\text{such that} : \|\tilde{\mathbf{v}}_{\alpha,k}^{(l+1)}\| = 1. \tag{38}$$

The non-cooperative users then use the MF receivers such that

$$\mathbf{u}_{\alpha,i}^{\text{MF}} = \text{max left singular vector of } (\mathbf{H}_{\alpha,i}). \tag{39}$$

Note that the BS does not need to inform non-cooperative users about the MF postcoding vectors as these can be calculated at the receivers without requiring any information about the other users.

V. Performance Metrics

Note that in this section $\mathbf{u}_{\alpha,k}$ and $\mathbf{v}_{\alpha,k}$ denote the final iteration value of $\mathbf{u}_{\alpha,k}^{(l+1)}$ and $\mathbf{v}_{\alpha,k}^{(l+1)}$ for optimized transceivers, respectively. The SINR for user k in cell α is given by

$$\text{SINR}_{\alpha,k} = \frac{\left(\frac{\rho_{\alpha,k}}{S}\right) \mathbf{u}_{\alpha,k}^{*} \mathbf{H}_{\alpha,k} \mathbf{v}_{\alpha,k} \mathbf{v}_{\alpha,k}^{*} \mathbf{H}_{\alpha,k}^{*} \mathbf{u}_{\alpha,k}}{\Delta_{\alpha,k} + \Omega_{\alpha,k} + \Lambda_{\alpha,k}}, \tag{40}$$

where $\Delta_{\alpha,k}$ is the dominant interference given by

- In the UL:

$$\Delta_{\alpha,k} = \mathbf{u}_{\alpha,k}^{*} \sum_{\beta} \sum_{k=1}^{K} \left(\frac{\rho_{\beta,k}}{S}\right) \mathbf{G}_{\beta,k} \mathbf{v}_{\beta,k} \mathbf{v}_{\beta,k}^{*} \mathbf{G}_{\beta,k}^{*} \mathbf{u}_{\alpha,k}. \tag{41}$$

- In the DL

$$\Delta_{\alpha,k} = \mathbf{u}_{\alpha,k}^{*} \sum_{\beta} \left(\frac{\rho_{\beta,k}}{S}\right) \mathbf{G}_{\beta,k} [\mathbf{v}_{\beta,1} \mathbf{v}_{\beta,2} \cdots \mathbf{v}_{\beta,K}] [\mathbf{v}_{\beta,1} \mathbf{v}_{\beta,2} \ldots \mathbf{v}_{\beta,K}]^{*} \mathbf{G}_{\beta,k}^{*} \mathbf{u}_{\alpha,k}. \tag{42}$$

$\Omega_{\alpha,k}$ is the power of the remaining interference and noise. Note that channels of remaining interference (denoted as $\mathbf{G}_{\beta,k}^{r}$) are independent from those of dominant interference. The expectation of the remaining interference is given by

- In the UL

$$\text{INR}_{\text{rem}} = \mathbb{E}\left\{\text{tr}\left(\sum_{\beta} \sum_{k=1}^{K} \frac{\rho_{\beta,k}^{r}}{S N_t} \mathbf{G}_{\beta,k}^{r} \mathbf{G}_{\beta,k}^{r*}\right)\right\}. \tag{43}$$

- In the DL

$$\text{INR}_{\text{rem}} = \mathbb{E}\left\{\text{tr}\left(\sum_{\beta} \frac{\rho_{\beta,k}^{r}}{N_t} \mathbf{G}_{\beta,k}^{r} \mathbf{G}_{\beta,k}^{r*}\right)\right\}. \tag{44}$$

We assume that remaining interference is simply treated as noise with variance INR_{rem}. We thus calculate the average power of remaining interference and noise using

$$\Omega_{\alpha,k} = \mathbf{u}_{\alpha,k}^{*} (1 + \text{INR}_{\text{rem}}) \mathbf{I} \mathbf{u}_{\alpha,k}. \tag{45}$$

The power of intracell interference, $\Lambda_{\alpha,k}$, is given by

TABLE II
SIMULATION ASSUMPTIONS

Intersite Distance:	2km
Carrier Frequency:	1.9GHz
Log-normal Shadowing standard deviation:	8dB
Path Loss Model (dB):	34.5 + 35$\log_{10}$(distance)

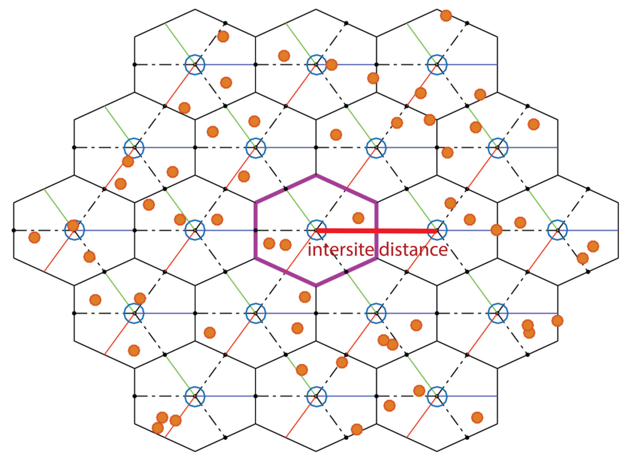


Fig. 2. The cellular layout used for simulations. The snapshot was taken over 1 time-frame.

- In the UL

$$\Lambda_{\alpha,k} = \frac{\rho_{\alpha,k}}{S} \mathbf{u}_{\alpha,k}^{*} \left(\sum_{i=1, i\neq k}^{S} \mathbf{H}_{\alpha,i} \mathbf{v}_{\alpha,i} \mathbf{v}_{\alpha,i}^{*} \mathbf{H}_{\alpha,i}^{*}\right) \mathbf{u}_{\alpha,k}. \tag{46}$$

- In the DL

$$\Lambda_{\alpha,k} = \frac{\rho_{\alpha,k}}{S} \mathbf{u}_{\alpha,k}^{*} \mathbf{H}_{\alpha,k} \left(\sum_{i=1, i\neq k}^{S} \mathbf{v}_{\alpha,i} \mathbf{v}_{\alpha,i}^{*}\right) \mathbf{H}_{\alpha,k}^{*} \mathbf{u}_{\alpha,k}. \tag{47}$$

Substituting (41), (42), (45), (46) and (47) in (40), the corresponding ergodic sum rate per unit bandwidth is

$$\text{R}_{\alpha} = \sum_{k=1}^{K} \mathbb{E}\{\log_2 (1 + \text{SINR}_{\alpha,k})\}. \tag{48}$$

Finally the outage probability for user i in cell α is given by

$$\text{p}_{\alpha,i}^{\text{out}}(R_{\tau}) = \mathbb{P}\{\log_2 (1 + \text{SINR}_{\alpha,i}) < R_{\tau}\}, \tag{49}$$

where R_{τ} is the chosen rate threshold. In [19], we have assumed that the users with received SINR less than -5 dB are in outage, i.e., $R_{\tau} = \log_2(1 + 10^{-0.5}) = 0.3964$.

VI. Simulation Results

Here, we consider the scenarios in [19] for randomly located users and cell-edge users using the same simulation assumptions for urban users as given in Table II. We use a 19-cell hexagonal layout where there are 3 users in each cell as given in Fig. 2, where the orange dots denote the users and the blue circles in the center of each cell denote the BSs.

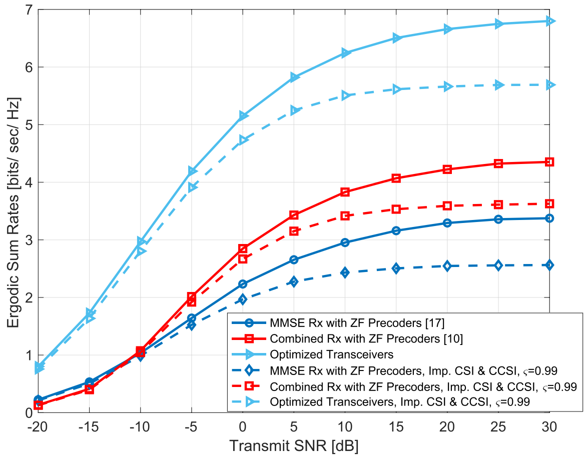


Fig. 3. Ergodic sum rates, random locations (Scen. 1 - UL).

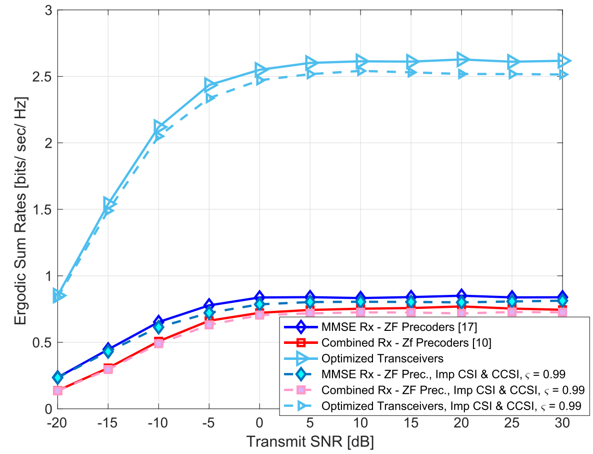


Fig. 4. Ergodic sum rates, cell-edge locations (Scen. 2 - UL).

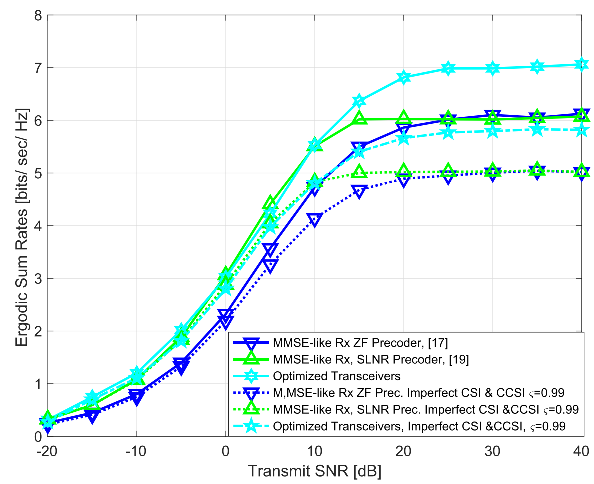


Fig. 5. Ergodic sum rates, random locations (Scen. 1-DL).

We parameterise the system $\gamma = \frac{\text{INR}_{\text{rem}}}{\text{INR}_{\text{dom}}}$, where $\text{INR}_{\text{dom}} = \mathbb{E}\{\Delta_{\alpha,k}\}$ as in [17]. We consider the imperfect CSI and CCSI model in [19] as well as an ideal case where a genie provides all the required channel estimates without cost. In practice, the exchange of the CSI increases the signalling overhead and consequently erodes the gains in throughput. However, it is difficult to precisely estimate the impact on the throughput as it requires a holistic analysis of Radio Resource Control (RRC) procedures that is beyond the scope of this work.

A. The UL

The transmitter power is assumed to be 23 dBm for the UL. We assume that each cell has 3 users, each equipped with $N_t = 3$ antennas. We also assume that CCSI from the users in 3 adjacent cells is available. These interferers are assumed to be dominant while the sum of the other weaker interference is the remaining interference. We set $\gamma \approx 0.14$ for randomly located users and $\gamma \approx 0.44$ for cell-edge users.

Scenario 1: Randomly Located Users: In Fig. 3, we compare the optimized transceiver technique with the MMSE receiver [17] and the combined receiver [10] utilizing ZF precoders. Because we consider the dominant interference from 2 adjacent cell users to be eliminated via ZF in the combined receivers (6 users in total), each BS is equipped with $N_r = 36$ antennas. We calculate the ergodic sum rates using (48). As seen in Fig. 3, the optimized transceivers provide the best ergodic sum rates, where as the MMSE receiver with ZF precoders provide the lowest mean sum rates among all techniques studied. We also observe that the combined receiver performs better than the MMSE-like receiver as the remaining interference and noise level is considerably low. We also consider imperfect CSI and CCSI with $\varsigma = 0.99$ (see (22) in [19]). As seen in Fig. 3, the optimized transceivers with imperfect CSI and CCSI perform better than the other techniques with perfect CSI and CCSI.

Scenario 2: Cell Edge Users: Cell-edge users suffer remaining interference more than other users. At high transmit SNR, the system can be considered noise-limited because the remaining interference is treated as noise. The results in Fig. 4 indicate that the combined receiver does not perform well in noise-limited environments due to ZF noise enhancement. This also supports the findings of [10]. We also consider imperfect CSI and CCSI with $\varsigma = 0.99$. The results demonstrate that the optimized transceivers with imperfect CCSI perform significantly better than the other techniques with perfect CSI and CCSI as the optimized transceivers also deal with the remaining interference with the precoding vectors.

B. The DL

Here, we assume $K = 3$ users in each cell. We also assume that transmitters and receivers are equipped with $N_t = N_r = 4$ antennas as in [17], [19]. The transmitter power is set to be 46 dBm [19]. Considering the existence of 2 dominant interferers, we find $\gamma \approx 0.68$ for randomly located users and $\gamma \approx 1.49$ for cell-edge users [19].

Scenario 1: Random User Locations: We first consider random user locations. Simulation results in Fig. 5 demonstrate that our proposed optimized transceivers outperforms the technique of [17] and [19], i.e., MMSE-like receivers with ZF and SLNR precoders, respectively. Considering 2 dominant interferers, the proposed technique achieves approximately 16% improvement over [17] and [19] with full

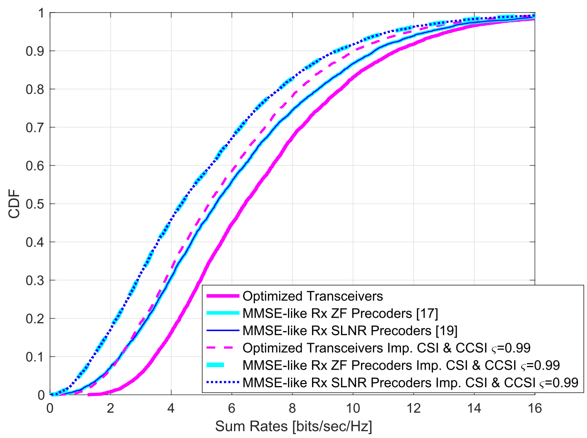


Fig. 6. CDF of sum rates for random locations (Scen. 1-DL).

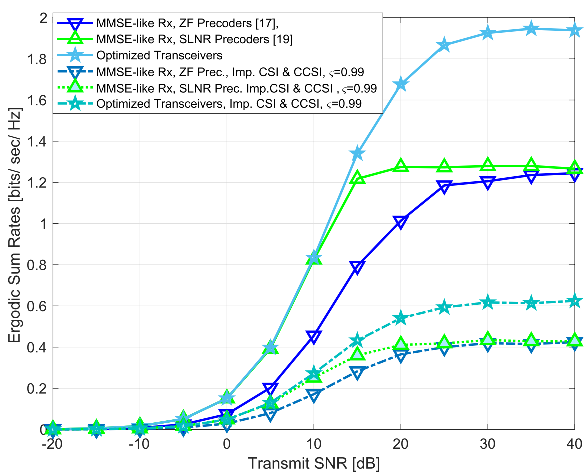


Fig. 7. Ergodic sum rates, cell-edge locations (Scen. 2-DL).

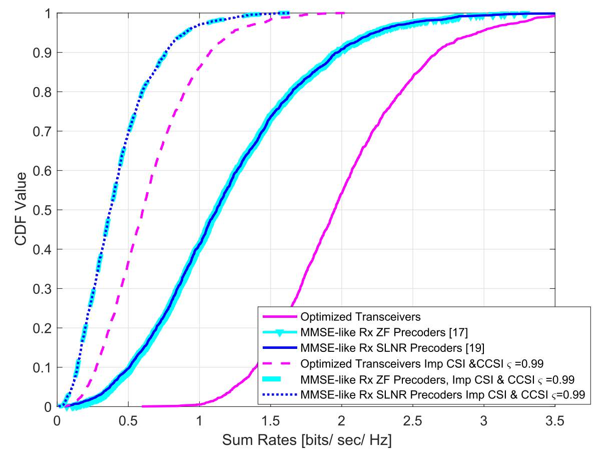


Fig. 8. CDF of sum rates, cell-edge locations (Scen. 2-DL).

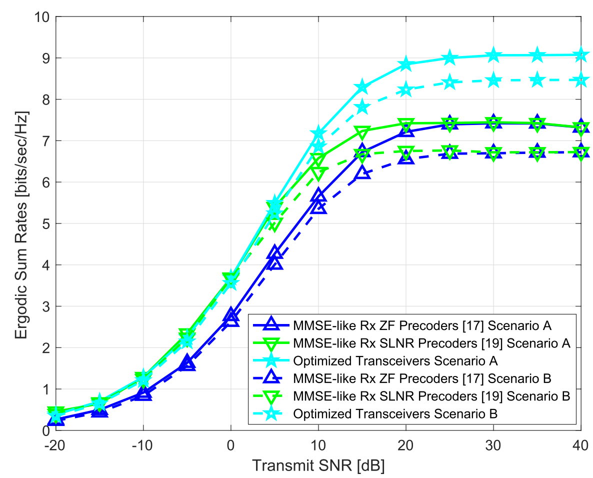


Fig. 9. Ergodic sum rates, random user locations, DL.

cooperation. The same trend is observed for imperfect CSI and CCSI.

We also consider cumulative distribution functions (CDF) of sum rates at 30 dB transmit SNR as in Fig. 6. The results demonstrate that at the median CDF point, there is a 1 bit/sec/Hz difference (approximately an 18% increase) between the optimized transceivers and the techniques of [17] and [19] when CSI and CCSI are perfectly estimated. The results also show a very small gap between the optimized transceivers with imperfect CSI and CCSI and the CDF of [17] and [19] with perfect CSI and CCSI.

Scenario 2: Cell Edge Users: Fig. 7 investigates the performance of cell-edge users. We demonstrate the gain that can be achieved by considering 2 dominant interferers. Simulation results indicate that the proposed optimized transceivers achieve significant gains for cell-edge users. Considering 2 dominant interferers, optimized transceivers achieve approximately 67% improvement in the sum rates over that in [17] and [19]. Furthermore, the optimized transceivers outperform the other techniques with imperfect CSI and CCSI.

In Fig. 8, we demonstrate the CDFs of the sum rates for cell-edge users. At the median cdf point, the results show a significant decrease in ergodic sum rates with imperfect CSI and CCSI. However the optimized transceivers achieve considerably higher ergodic sum rates than [17] and [19].

C. Different Number of Users and Base Stations

We now consider different numbers of users and base stations in our simulations. We first evaluate a four-user-19-cell layout and denote this scenario as Scenario A. Then we change the number of cells (hence base stations) and consider a four-user-37-cell layout and denote this scenario as Scenario B. Note that the intersite distance is assumed as 2 km in both scenarios.

The simulation results for Scenario A and B are given in Fig. 9, where we consider randomly located users in the DL and both transmitters and receivers are equipped with $N_r = N_t = 5$ antennas. The results demonstrate that more cells (therefore more interfering BSs) reduces the ergodic sum rates, as expected. Because the BSs which are added in Scenario B are in the third tier, the additional intercell interference is relatively low. Therefore, the decrease in ergodic sum rates due to the additional cells is not very significant.

TABLE III
OUTAGE PROBABILITY WITH/WITHOUT COOPERATION

Outage probability (%)			
Precoders:	**ZF**	**SLNR**	**Optimized**
Full Cooperation	13.6	13.3	2.6
Partial Cooperation	14.5	13.9	4.7
Partial Coop., Imp. CCSI, $\varsigma = 0.99$	16.1	15.3	5.5
No Cooperation	28.3	27.7	13.6

D. Cooperation

Here, we compare different cooperation levels in our system. In full cooperation, the CCSI from dominant BSs is available for all users. For partial cooperation, only users in the cooperation-zone can access to the CCSI while no-cooperation refers that no CCSI is available to any user [19]. In Table III, we consider the partial cooperation scheme with the cooperation threshold, $\lambda = 8$ dB (see (12) in [19]). We consider the scenarios of [19] in a 19-cell layout given in Fig. 2. We give the outage probabilities for users at 30 dB transmit-SNR and demonstrate that the optimized transceivers provide significant gains over the ZF and SLNR precoders. It is also observed that the optimized transceivers with the partial cooperation and imperfect CCSI can achieve significantly lower outage probabilities than ZF and SLNR precoders with full cooperation and perfect CCSI.[2] This indicates that the optimized transceivers can achieve better performance with less CCSI overhead. This also indicates the optimized transceivers provide higher reliability which will be very important in 5G communications. We note that considering the information of the remaining interference power in the optimized precoders provides significant gains over ZF and SLNR precoders which do not use this information. We also note that the majority of the users which are below the chosen rate threshold (49) are also located in the cooperation-zone. Therefore, the outage probabilities with the partial cooperation scheme are close to the outage probabilities with full cooperation.

E. Computational Complexity and Overhead

Unlike conventional methods such as ZF and SLNR, the proposed method requires an iterative algorithm to derive the optimized precoders which will increase the computational complexity of the transmitter and/or receiver. For simplicity, we neglect the computational complexity of common parts among the techniques. Furthermore, we do not distinguish between real-valued and complex-valued multiplications. Major computational complexity is finding the eigenvectors and matrix inverses. As in (15), (30) and (38), the optimum precoders require to find an eigenvector of an $(N_t \times N_t)$ matrix in each iteration. In [27], it is stated that all computational algorithms to find the eigenvectors are performed at nearly optimal arithmetic cost of $O(\mathbb{M}(N_t)\log(N_t))$ where $\mathbb{M}(N_t)$ is $O(N_t^w)$ and $w < 2.376$ in theory. The matrix of which we find the eigenvectors also requires to find the inverse of $\mathbf{E}_{\alpha,i}$ which approximately has the arithmetic cost of $O(N_r^3)$ using Gauss-Jordan elimination method [26]. Initializing precoding vectors also requires eigenvectors and finding the postcoding vector requires a matrix inverse. Considering l iterations, the proposed method requires $l+1$ eigenvectors and matrix inverses in total. Therefore, the computational complexity is $(l+1)[O(\mathbb{M}(N_t)\log(N_t)) + O(N_r^3)]$.

In contrast, the SLNR precoder would require an eigenvector and a matrix inverse whereas the MMSE-like receiver would require a matrix inverse. The total computational complexity of the proposed scheme will involve additional cost to the non-iterative scheme and this additional cost will be dependent on the number of iterations. The number of iterations required to reach minimum MSE in the proposed method varies for each channel drop. Hence it is difficult to be precise in evaluating the typical number of iterations. In the results presented here we observed that the number of iterations was typically between 6 and 14.

In terms of overheads, [15] requires all the femtocells to share CSI, the centralized version of [16] requires global CSI exchange and [17] has repeated CSI exchange between users and BS. These algorithms all have overheads due to extra CSI exchange. The distributed version of [16] and the non-iterative version of [17] have the same basic CSI exchange as our approach so the overheads are similar. However, [16] is more complex, requiring iterative solutions of semi-definite programming (SDP) problems and is DL only. The non-iterative solution in [17] is not more complex but has lower performance due to its reliance on ZF precoders and maximum beamforming gain receivers. In contrast, our technique allows the precoders and receivers to jointly iterate towards a minimum MSE solution.

VII. CONCLUSION

We have proposed novel optimized transceivers for multicellular networks. For a multicellular UL, we have derived the optimum precoder-postcoder set that minimizes the total MSE at the base station. We have shown that optimized transceivers achieve significantly better results compared to the combined receivers with ZF precoders of [10]. These gains are more prominent for cell-edge users. We have also considered imperfect CSI and CCSI. As cell-edge users suffer from interference, compared to other users, the gain that can be achieved with optimized transceivers is more prominent. In the DL, we have shown that our optimized transceiver outperforms the existing schemes of [17], [19]. Especially for cell-edge users, we have demonstrated that it is possible to get gains more than 60%. Furthermore, we have considered different number of users and cells in our simulations and demonstrate that the additional interfering BSs do not contribute to the intercell interference significantly due to the increased path loss. The computational complexity of the optimized transceivers has been analyzed. We have also considered the partial cooperation scheme of [19] to reduce the required overhead and shown that we can achieve significantly lower outage probabilities

[2] Please note that for all results in Table III, we assume the direct channel estimation is perfect (perfect CSI, thus perfect precoding vectors).

than the MMSE-like receivers with ZF precoders of [17] and SLNR precoders of [19] with full cooperation. Higher mean sum rates for cell-edge users and lower outage probabilities intrinsically improve the reliability which will have key importance in 5G wireless communications.

References

[1] V. Cadambe and S. Jafar, "Interference alignment and the degrees of freedom of the K user interference channel," *IEEE Trans. Inf. Theory*, vol. 54, no. 8, pp. 3425–3441, Aug. 2008.

[2] T. Gou and S. Jafar, "Degrees of freedom of the K user M × N MIMO interference channel," *IEEE Trans. Inf. Theory*, vol. 56, no. 12, pp. 6040–6057, Dec. 2010.

[3] O. El Ayach *et al.*, "The practical challenges of interference alignment," *IEEE Wireless Commun.*, vol. 20, no. 1, pp. 35–42, Feb. 2013.

[4] R. Ustok, "Interference alignment and cancellation in wireless communication systems," Ph.D. dissertation, Victoria Univ. Wellington, Wellington, New Zealand, 2016.

[5] R. Tresch *et al.*, "On the achievability of interference alignment in the K-user constant MIMO interference channel," in *Proc. IEEE Workshop Statist. Signal Process.*, 2009, pp. 277–280.

[6] C. Yetis *et al.*, "On feasibility of interference alignment in MIMO interference networks," *IEEE Trans. Signal Process.*, vol. 58, no. 9, pp. 4771–4782, Jan. 2010.

[7] C. Suh and D. Tse, "Interference alignment for cellular networks," in *Proc. 46th Annu. Allerton Conf. Commun., Control Comput.*, 2008, pp. 1037–1044.

[8] P. Viswanath and D. Tse, "Sum capacity of the multiple antenna Gaussian broadcast channel and uplink–downlink duality," *IEEE Trans. Inf. Theory*, vol. 49, no. 8, pp. 1912–1923, Aug. 2003.

[9] N. Jindal *et al.*, "On the duality of Gaussian multiple access," *IEEE Trans. Inf. Theory*, vol. 50, no. 5, pp. 768–783, May 2004.

[10] R. Ustok *et al.*, "Interference alignment with combined receivers for heterogeneous networks," in *Proc. IEEE Int. Conf. Commun.*, 2014, pp. 35–40.

[11] M. Sheng *et al.*, "Interference alignment and cancellation for the uplink of heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1104–1115, Feb. 2017.

[12] G. S. Rajappan and M. L. Honig, "Signature sequence adaptation for DS-CDMA with multipath," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 2, pp. 384–395, Feb. 2002.

[13] C. Lin *et al.*, "MMSE transceiver design for full-duplex MIMO relay systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 6849–6861, Aug. 2017.

[14] S. Serbetli and A. Yener, "Transceiver optimization for multiuser MIMO systems," *IEEE Trans. Signal Process.*, vol. 52, no. 1, pp. 214–226, Jan. 2004.

[15] B. Guler and A. Yener, "Uplink interference management for coexisting mimo femtocell and macrocell networks: An interference alignment approach," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 2246–2257, Apr. 2014.

[16] T. Bogale *et al.*, "Robust transceiver optimization for downlink coordinated base station systems: Distributed algorithm," *IEEE Trans. Signal Process.*, vol. 60, no. 1, pp. 337–350, Jan. 2012.

[17] C. Suh *et al.*, "Downlink interference alignment," *IEEE Trans. Commun.*, vol. 59, no. 9, pp. 2616–2626, Sep. 2011.

[18] N. Johansson *et al.*, "Radio access for ultra-reliable and low-latency 5G communications," in *Proc. IEEE Int. Conf. Commun. Workshop*, 2015, pp. 1184–1189.

[19] R. Ustok *et al.*, "Cooperative interference cancellation for cellular networks with imperfect CCSI," *IET Commun.*, vol. 10, no. 5, pp. 525–533, 2016.

[20] M. Zhao *et al.*, "Interference alignment and its applications: A survey, research issues, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1779–1803, Jul.–Sep. 2016.

[21] S. Mollaebrahim *et al.*, "Designing precoding and receive matrices for interference alignment in MIMO interference channels," in *Proc. IEEE Int. Global Commun. Conf.*, 2017, pp. 1–6.

[22] M. Sheng *et al.*, "Interference alignment and cancellation for the uplink of Heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1104–1115, Feb. 2017.

[23] J. Ma *et al.*, "Interference alignment and soft-space-reuse based cooperative transmission for multi-cell massive MIMO networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 1907–1922, Mar. 2018.

[24] N. Garg *et al.*, "On the MMSE precoder design for interference alignment in MIMO interfering broadcast channel," in *Proc. IEEE 18th Int. Work. Signal Process. Adv. Wireless Commun.*, 2017, pp. 1–5.

[25] B. Guler and A. Yener, "Selective interference alignment for MIMO cognitive radio femtocell networks," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 3, pp. 439–450, Mar. 2014.

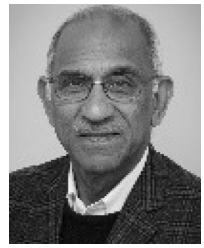
[26] R. Horn and C. Johnson, *Matrix Analysis*. Cambridge, U.K.: Cambridge Univ. Press, 1985.

[27] V. Y. Pan and Z. Q. Chen, "The complexity of the matrix eigenproblem," in *Proc. ACM Symp. Theory Comput.*, pp. 507–516, 1999.

Refik Fatih Ustok (S'12–M'18) was born in Izmir, Turkey. He received the B.Sc. degree in electrical electronics engineering from Istanbul University, Istanbul, Turkey in 2007, the M.Sc. degree in electronics and communications engineering from Izmir Institute of Technology, Izmir, Turkey, in 2010, and the Ph.D. degree from the Victoria University of Wellington, Wellington, New Zealand, in 2016. His research interests include interference alignment and cancellation, cognitive radio networks, fifth-generation wireless communication systems, media applications, and internet of things.

Pawel A. Dmochowski (S'02–M'07–SM'11) was born in Gdansk, Poland. He received the B.A.Sc. degree in engineering physics from The University of British Columbia, Vancouver, Canada, in 1998 and the M.Sc. and Ph.D. degrees from Queens University, Kingston, ON, Canada, in 2001 and 2006, respectively. He is a Senior Lecturer with the School of Engineering and Computer Science, Victoria University of Wellington, Wellington, New Zealand. His current research interests include cognitive radio, millimeter-wave, and massive multiple-input-multiple-output systems. Dr. Dmochowski currently serves as an Editor for the IEEE Communication Letters.

Peter J. Smith (M'93–SM'01–F'15) received the B.Sc. degree in mathematics and the Ph.D. degree in statistics from the University of London, London, U.K., in 1983 and 1988, respectively. From 1983 to 1986, he was with the Telecommunications Laboratories, General Electric Company Hirst Research Centre. From 1988 to 2001, he was a Lecturer in statistics with the Victoria University of Wellington, Wellington, New Zealand. During 2001 to 2015, he was with the Department of Electrical and Computer Engineering, University of Canterbury, Christchurch, New Zealand. In 2015, he joined Victoria University of Wellington as a Professor of statistics. His research interests include the statistical aspects of design, modeling, and analysis for communication systems, cognitive radio, massive MIMO, and millimeter-wave systems.



Mansoor Shafi (S'69–M'82–SM'87–F93–LF'16) received the B.Sc. (Eng.) and Ph.D. degrees in electrical engineering from the University of Engineering and Technology Lahore, Lahore, Pakistan, and The University of Auckland, Auckland, New Zealand, in 1970 and 1979, respectively. From 1975 to 1979, he was a Junior Lecturer with The University of Auckland, he then joined the New Zealand Post Office, that later evolved to Telecom NZ, and recently to Spark New Zealand. He is currently a Telecom Fellow (Wireless at Spark NZ) and an Adjunct Professor with Victoria University. He is a Delegate of NZ to the meetings of ITU-R and APT and has contributed to a large number of wireless communications standards. His research interests include radio propagation, the design and performance analysis for wireless communication systems, especially antenna arrays, MIMO, cognitive radio, and massive MIMO and mmWave systems.