Optimal Precoder Design Maximizing the Worst-Case Average Received SNR for Massive Distributed MIMO Systems

Xiang-Chuan Gao, Jian-Kang Zhang, *Senior Member, IEEE*, Zhong-Yong Wang, *Member, IEEE*, and Jin Jin, *Member, IEEE*

***Abstract*—In this letter, we consider a distributed multiple-input multiple-output (D-MIMO) system, where the channel is flat fading and may be correlated, and experiences both small and large-scale fading. We assume that the full knowledge of channel state information (CSI) is available at the receiver and only the first-and second-order statistics of the channel are available at the transmitter. For such a system employing the linear zero-forcing (ZF) receiver, an efficient linear precoding technique is proposed to optimize the worst-case performance of average signal-to-noise ratio (SNR) at the receiver and a simple closed-form optimal precoder is derived. In addition, under some realistic assumptions, some significant asymptotic properties are established for the massive D-MIMO system designed in this letter. Computer simulations verify our theoretic analysis and show that our presented optimal system attains significant performance gains over the currently available equal power-loading system.**

***Index Terms*—Distributed MIMO, large scale fading, zero-forcing, worst-case average received signal to noise ratio.**

I. Introduction

THE distributed MIMO system has become a promising candidate for future mobile communication systems because of its open architecture and flexible resource management. Many research activities on D-MIMO system have been intensified in the past few years owing to the fast growing demand for high data-rate services [1]–[7]. The scenario in [8]–[12], has been investigated under various assumptions on the availability of channel state information at the transmitters (CSIT), global or local CSIT. In practice, however, it is not easy to be implemented due to the high cost to acquire full CSIT at all transmitters and signal processing overhead, even the local CSIT [11], [12] especially for the massive MIMO system setting in which each terminal is equipped with a large number of antennas [13], [14]. Therefore, the works in [15], [16] assumed no CSIT and proposed distributed space-time coding for transmission. Unfortunately, they are not efficiently incorporated to make use of the available partial CSIT. All these aforementioned factors motivates us to investigate the design of transmission strategies with relatively-low implementation complexity when partial CSIT such as only the first-and second-order statistics of the channel is available at all the transmitter. Contrasted with conventional point-to-point MIMO systems, since many radio-antenna ports (RPs) in D-MIMO systems are geographically distributed over a large area, each link experiences different path-loss and large-scale fading (a.k.a. shadowing) effects. It is these two composite fading (small and large scale) effects that make the development of a novel transmission technique which is efficient in exploiting the advantage of partial CSIT of the D-MIMO systems a more challenging problem. In this letter, we propose an efficient and effective linear precoding method to maximize the worst-case average received SNR for the D-MIMO systems with composite fading MIMO channels employing the ZF receiver. By fully taking advantage of information on the channel and receiver structures, and probabilistic density of individual random subchannel for each user, a nice closed-form optimal solution is obtained. One of main advantages of the proposed optimal system is that it naturally leads us to making some important and realistic assumptions for successfully revealing the significant asymptotic behaviors of the massive D-MIMO system.

Notation: Matrices are denoted by uppercase boldface characters (e.g., $\mathbf{A}$), while column vectors are denoted by lowercase boldface characters (e.g., $\mathbf{b}$). The i-th entry of $\mathbf{b}$ is denoted by b_i. The (i,j)-th entry of $\mathbf{A}$ is denoted by $a_{i,j}$, and also denoted by $[\mathbf{A}]_{i,j}$. The columns of a $P\times K$ matrix $\mathbf{A}$ are denoted by $\mathbf{a}_1,\mathbf{a}_2,\ldots,\mathbf{a}_N$. The transpose of $\mathbf{A}$ is denoted by $\mathbf{A}^T$. The Hermitian transpose of $\mathbf{A}$ (i.e., the conjugate and transpose of $\mathbf{A}$) is denoted by $\mathbf{A}^H$. An $L\times L$ identity matrix is denoted by $\mathbf{I}_L$.

II. System Model

In this section, we consider the same model as that in [17], i.e., a single-cell D-MIMO communication system equipped with N receiver antennas at the base station (BS) and K RPs with each having M transmitter antennas and also require that $N\geq KM$. For such a system, we assume that the BS has perfect CSI and only the first-and second-order statistics of the channel are available at the transmitter. We also assume that all RPs transmit their data streams to the BS simultaneously. Therefore, an input-output relationship can be written as

$$\mathbf{y}=\mathbf{Ts}+\mathbf{n}=\mathbf{H}\mathbf{R}_T^{\frac{1}{2}}\Xi^{\frac{1}{2}}\mathbf{Fs}+\mathbf{n}, \tag{1}$$

where $\mathbf{y}$ is an $N\times 1$ received signal vector, $\mathbf{s}$ is a $KM\times 1$ transmitted symbol vector with unit average power per element and $\mathbf{n}$ is an $N\times 1$ circularly symmetric complex Gaussian noise vector with zero-mean and covariance matrix $\mathrm{E}[\mathbf{nn}^H]=N_0\mathbf{I}_N$. Here, the composite channel matrix $\mathbf{T}$ is composed of four parts. The first part is small-scale fading captured by an $N\times KM$

Manuscript received July 6, 2014; revised December 20, 2014; accepted December 23, 2014. Date of publication January 9, 2015; date of current version April 8, 2015. The work of X.-C. Gao was supported by the National High Technology Research and Development Program 863 of China (2014AA01A705) and National Natural Science Foundation of China (U1204607, 61172086, 61401401). The work of J.-K. Zhang was funded in part by NSERC. The associate editor coordinating the review of this paper and approving it for publication was S. Jin.

X.-C. Gao, Z.-Y. Wang, and J. Jin are with the School of Information and Engineering, Zhengzhou University, Zhengzhou 450 002, China (e-mail: iexcgao@zzu.edu.cn).

J.-K. Zhang is with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON L8S 4K1, Canada (e-mail: jkzhang@mail.ece.mcmaster.ca).

Digital Object Identifier 10.1109/LCOMM.2015.2389803

random matrix $\mathbf{H}$, whose entries are modelled as i.i.d $CN(0,1)$ random variables. The second part is the $KM \times KM$ transmitted positive definite covariance matrix $\mathbf{R}_T$. Note that small-scale fading correlation occurs only between the transmitter antennas of the one RP, since the different users are, in general, geographically separated. Such a scenario may occur when several users, with multiple spatially correlated antennas, transmit to a common multiple-antennas BS. Hence, the transmitted correlation matrix is a $KM \times KM$ block-diagonal matrix, with each block being an $M \times M$ matrix, i.e., $\mathbf{R}_T = \mathrm{diag}(\mathbf{R}_{T1}, \mathbf{R}_{T2}, \ldots, \mathbf{R}_{TK})$, where $\mathbf{R}_{Tk}$ is the correlation matrix between the transmitter antennas of the k-th RP for $k = 1, 2, \ldots, K$ and its entries are modeled via the common exponential correlation model [18], i.e., $[\mathbf{R}_{Tk}]_{i,j} = \rho_k^{|i-j|}$ for $i, j = 1, 2, \ldots, M$, where $|\rho_k| \in [0,1]$ is the transmitter correlation coefficient. The third part is large scale effects, which is captured by the $KM \times KM$ diagonal matrix Ξ, i.e., $\Xi = \mathrm{diag}(\Xi_1/D_1^v \mathbf{I}_M, \Xi_2/D_2^v \mathbf{I}_M, \ldots, \Xi_K/D_K^v \mathbf{I}_M)$, where each D_k for $k = 1, 2, \ldots, K$ denotes the distance between the k-th user and the BS and v is the path-loss exponent. We consider the lognormal shadowing model, which is the commonly-used model in the characterization of shadowing effects in various radar, optical and RF wireless channels. In this case, the probability density function (PDF) of the large-scale fading coefficients Ξ_k for $k = 1, 2, \cdots, K$ is given by

$$f(\xi_k) = \frac{\eta}{\xi_k \sqrt{2\pi}\delta_k} e^{-\frac{(\eta \ln \xi_k - \mu_k)^2}{2\delta_k^2}} \quad \text{for } \xi_k \geq 0, \tag{2}$$

where $\eta = 10/\ln 10$, μ_k and δ_k are the mean and standard deviation (both in dB) of the variable's natural logarithm, respectively. The last part is the $KM \times KM$ block-diagonal linear precoding matrix $\mathbf{F}$ to be determined, i.e., $\mathbf{F} = \mathrm{diag}(\mathbf{F}_1, \mathbf{F}_2, \ldots, \mathbf{F}_K)$, with each $\mathbf{F}_k$ being an $M \times M$ matrix. The D-MIMO channel model (1) looks almost the same as the MIMO multi-access channel model. However, one of major differences between them, is that in addition to small-scale fading, there is large-scale fading at each RP linking to the BS, which is independent of the other RPs. At the receiver, we use ZF equalization, i.e., $\mathbf{G} = (\mathbf{T}^H\mathbf{T})^{-1}\mathbf{T}^H$. Then, after the ZF equalizer, (1) becomes

$$\widehat{\mathbf{y}} = \mathbf{G}\mathbf{y} = \mathbf{s} + \mathbf{G}\mathbf{n}. \tag{3}$$

III. Precoder Design via Worst-Case Performance Optimization of Average Received SNR

A. Optimization Analysis

Our main purpose in this section is to optimize the worst-case of the average received SNR subject to a total transmission power constraint. To this end, we first notice that the received signals in (3) are decomposed into KM parallel data streams with the instantaneous received SNR for the m-th subchannel of k-th RP given by

$$\gamma_{km} = \frac{[\Xi]_{km,km}}{N_0 \left[(\mathbf{H}^H\mathbf{F}^H\mathbf{R}_T\mathbf{F}\mathbf{H})^{-1}\right]_{km,km}}, \tag{4}$$

where the equality in (4) follows from the fact that Ξ is the diagonal matrix. It is known [19] that $X_{km} = \frac{1}{[(\mathbf{H}^H\mathbf{H})^{-1}]_{km,km}}$ follows a complex Chi-square distribution with its PDF given by $g(x_{km}) = \frac{1}{\Gamma(N-KM+1)} x_{km}^{N-KM} e^{-x_{km}} x_{km} > 0$. Thus, we have $\mathrm{E}\left[\frac{1}{[(\mathbf{H}^H\mathbf{H})^{-1}]_{km,km}}\right] = N - KM + 1$. Similarly, utilizing (2) yields

$$\mathrm{E}[\Xi_k] = \frac{e^{\frac{\delta_k^2 + 2\eta\mu_k}{2\eta^2}}}{D_k^v} = B_k. \tag{5}$$

Therefore, the average received SNR is determined by

$$\mathrm{E}[\gamma_{km}] = \frac{C_k}{\left[\left(\mathbf{F}^H\mathbf{R}_T\mathbf{F}\right)^{-1}\right]_{km,km}}, \tag{6}$$

where C_k is defined by

$$C_k = B_k(N - KM + 1)/N_0. \tag{7}$$

Now, our primary task in this letter is to solve the following optimization problem.

Problem 1: Find the block-diagonal precoding matrix $\mathbf{F}$ such that

$$\max_{\mathbf{F}} \left\{ \min_{1 \leq k \leq K, 1 \leq m \leq M} \{\mathrm{E}[\gamma_{km}]\} \right\}$$
$$\text{subject to } \mathrm{tr}(\mathbf{F}^H\mathbf{F}) = P_T. \tag{8}$$

■

To solve this problem, we first notice that both $\mathbf{R}_T$ and $\mathbf{F}$ are block-diagonal matrices. Hence, from (6) we have $\mathrm{E}[\gamma_{km}] = \frac{C_k}{[(\mathbf{F}_k^H\mathbf{R}_{Tk}\mathbf{F}_k)^{-1}]_{m,m}}$. By taking advantage of this separable structure of the objective function, we can split Problem 1 into the following two subproblems.

Subproblem 1: For any fixed power P_k of the k-th user, find a precoding matrix $\mathbf{F}_k$ such that

$$\max_{\mathbf{F}_k} \min_{1 \leq m \leq M} \{\mathrm{E}[\gamma_{km}]\}$$
$$\text{subject to } \mathrm{tr}\left(\mathbf{F}_k\mathbf{F}_k^H\right) = P_k.$$

■

Subproblem 2: For the kth RP: $1 \leq k \leq K$, let the optimum in Subproblem 1 be denoted by $\bar{\gamma}_k = \max_{\mathbf{F}_k} \min_{1 \leq m \leq M} \{\mathrm{E}[\gamma_{km}]\}$. Then, find a power loading matrix $\mathbf{P} = \mathrm{diag}(P_1, P_2, \cdots, P_K)$ such that

$$\max_{\mathbf{P}} \min_{1 \leq k \leq K} \{\bar{\gamma}_k\}$$
$$\text{subject to } \sum_{k=1}^{K} P_k = P_T.$$

■

First, let us consider how to solve Subproblem 1. Note that

$$\begin{aligned}
\min_{1 \leq m \leq M} \{\mathrm{E}[\gamma_{km}]\} &= \min_{1 \leq m \leq M} \left\{ \frac{C_k}{\left[(\mathbf{F}_k^H\mathbf{R}_{Tk}\mathbf{F}_k)^{-1}\right]_{m,m}} \right\} \\
&= \frac{C_k}{\max_{1 \leq m \leq M} \left\{ \left[\left(\mathbf{F}_k^H\mathbf{R}_{Tk}\mathbf{F}_k\right)^{-1}\right]_{m,m} \right\}} \\
&\leq \frac{MC_k}{\mathrm{tr}\left(\left(\mathbf{F}_k^H\mathbf{R}_{Tk}\mathbf{F}_k\right)^{-1}\right)}
\end{aligned}$$

Therefore, we obtain

$$\max_{\mathbf{F}_k} \min_{1 \leq m \leq M} \{\mathrm{E}[\gamma_{km}]\} \leq \frac{MC_k}{\min_{\mathbf{F}_k} \mathrm{tr}\left(\left(\mathbf{F}_k^H\mathbf{R}_{Tk}\mathbf{F}_k\right)^{-1}\right)} \tag{9}$$

Now, following the way similar to that in [20], a solution to the optimization problem $\min_{\mathbf{F}_k} \mathrm{tr}((\mathbf{F}_k^H \mathbf{R}_{Tk} \mathbf{F}_k)^{-1})$ in (9) can be obtained as follows: $\mathbf{F}_k = \mathbf{V}_k \mathbf{P}_k^{\frac{1}{2}} \mathbf{U}$, where $\mathbf{U}$ is an arbitrarily given $M \times M$ unitary matrix, $\mathbf{V}_k$ is the eigenvector matrix of $\mathbf{R}_{Tk}$, i.e., $\mathbf{R}_{Tk} = \mathbf{V}_k \Lambda_k \mathbf{V}_k^H = \mathbf{V}_k \mathrm{diag}(\lambda_{k1}, \lambda_{k2}, \ldots, \lambda_{kM}) \mathbf{V}_k^H$ and $\mathbf{P}_k = \mathrm{diag}(p_{k1}, p_{k2}, \ldots, p_{kM})$, with p_{km} determined by $p_{km} = \frac{P_k \lambda_{km}^{-\frac{1}{2}}}{\sum_{i=1}^M \lambda_{ki}^{-\frac{1}{2}}} = \frac{P_k \lambda_{km}^{-\frac{1}{2}}}{M \overline{A}_{kM}}$, where $\overline{A}_{kM} = \frac{1}{M} \sum_{m=1}^M \lambda_{km}^{-\frac{1}{2}}$. In this case, we have $(\mathbf{F}_k^H \mathbf{R}_{Tk} \mathbf{F}_k)^{-1} = \mathbf{U}^H \mathbf{P}_k^{-1} \Lambda_k^{-1} \mathbf{U}$. Therefore, by specifically choosing $\mathbf{U}$ to be the $M \times M$ normalized DFT matrix $\mathcal{W}$, we can attain that $[(\mathbf{F}_k^H \mathbf{R}_{Tk} \mathbf{F}_k)^{-1}]_{1,1} = [(\mathbf{F}_k^H \mathbf{R}_{Tk} \mathbf{F}_k)^{-1}]_{2,2} = \cdots = [(\mathbf{F}_k^H \mathbf{R}_{Tk} \mathbf{F}_k)^{-1}]_{M,M}$, i.e., the equality in (9) holds, thus, leading to the optimal solution to Subproblem 1.

We are now in a position to solve Subproblem 2. We first notice that with the optimal solution given in Subproblem 1, the objective function in Subproblem 2 becomes $\overline{\gamma}_k = C_k P_k / (M \overline{A}_{kM}^2)$ and thus, we aim at $\max_{\mathbf{P}} \min_{1 \le k \le K} \frac{C_k P_k}{M \overline{A}_{kM}^2}$. If for some i: $1 \le i \le K$, $\min_{1 \le k \le K} \frac{C_k P_k}{M \overline{A}_{kM}^2} = \frac{C_i P_i}{M \overline{A}_{iM}^2}$, then, we have $\frac{C_k P_k}{M \overline{A}_{kM}^2} \ge \frac{C_i P_i}{M \overline{A}_{iM}^2}$. For notational simplicity, let $W = \sum_{k=1}^K \overline{A}_{kM}^2 / C_k$. Then, we can attain

$$\begin{aligned} \frac{C_i P_i}{M \overline{A}_{iM}^2} &= \frac{1}{\sum_{k=1}^K \frac{\overline{A}_{kM}^2}{C_k}} \left(\frac{P_i}{M} + \sum_{k \ne i}^K \frac{C_i P_i \overline{A}_{kM}^2}{M \overline{A}_{iM}^2 C_k} \right) \\ &\le \frac{1}{\sum_{k=1}^K \frac{\overline{A}_{kM}^2}{C_k}} \left(\frac{P_i}{M} + \sum_{k \ne i}^K \frac{P_k}{M} \right) = \frac{P_T}{MW} \end{aligned} \tag{10}$$

where the equality in (10) holds if and only if

$$\frac{C_1 P_1}{M \overline{A}_1^2} = \frac{C_2 P_2}{M \overline{A}_2^2} = \cdots = \frac{C_K P_K}{M \overline{A}_K^2} \tag{11}$$

Combining (11) with the total transmission power constraint yields $P_k = \frac{P_T \overline{A}_{kM}^2 / C_k}{W}$.

After having solved Subproblems 1 and 2, we now show how to make use of these two optimal solutions to solve Problem 1. Since $\min_{1 \le k \le K, 1 \le m \le M} \mathrm{E}[\gamma_{km}] \le \min_{1 \le m \le M} \mathrm{E}[\gamma_{\ell m}] \le \max_{\mathrm{tr}(\mathbf{F}_\ell^H \mathbf{F}_\ell) \le P_\ell} \min_{1 \le m \le M} \mathrm{E}[\gamma_{\ell m}]$ for any ℓ: $1 \le \ell \le K$ and for any fixed P_ℓ: $0 \le P_\ell \le P_T$, we have $\min_{1 \le k \le K, 1 \le m \le M} \mathrm{E}[\gamma_{km}] \le \min_{1 \le \ell \le K} \overline{\gamma}_\ell$ and thus, $\max_{\mathbf{F}} \min_{1 \le k \le K, 1 \le m \le M} \mathrm{E}[\gamma_{km}] \le \max_{\mathbf{P}} \min_{1 \le \ell \le K} \overline{\gamma}_\ell$. Very fortunately, the two suboptimal solutions of Subproblems 1 and 2 together make all the equalities here hold simutaneously, hence, resulting in an optimal solution to the original Problem 1. Finally, all the above discussions can be summarized as the following theorem.

Theorem 1: Let the eigenvalue decomposition of $\mathbf{R}_{Tk}$ be given by $\mathbf{R}_{Tk} = \mathbf{V}_k \Lambda_k \mathbf{V}_k^H = \mathbf{V}_k \mathrm{diag}(\lambda_{k1}, \lambda_{k2}, \cdots, \lambda_{kM}) \mathbf{V}_k^H$. If we let $\overline{A}_{kM} = \frac{1}{M} \sum_{m=1}^M \lambda_{km}^{-1/2}$ and $\overline{W}_{KM} = \frac{1}{K} \sum_{k=1}^K \overline{A}_{kM} / B_k$, with B_k defined in (5), then, the optimal solution to Problem 1 are determined as follows: $\widetilde{\mathbf{F}} = \mathrm{diag}(\widetilde{\mathbf{F}}_1, \widetilde{\mathbf{F}}_2, \ldots, \widetilde{\mathbf{F}}_K)$, where $\widetilde{\mathbf{F}}_k = \mathbf{V}_k \widetilde{\mathbf{P}}_k^{\frac{1}{2}} \mathcal{W}$, with $\mathcal{W}$ being the normalized $M \times M$ DFT matrix, and $\widetilde{p}_{km} = \frac{\lambda_{km}^{-\frac{1}{2}} \overline{A}_k P_T}{M \overline{W}_{KM}}$. In addition, the optimum of the worst case average received SNR is given by $\widetilde{\gamma}_{KM} = \frac{(N - KM + 1) P_T}{KM \overline{W}_{KM} N_0}$. ■

We would like to make the following three comments on Theorem 1:

(a) Theorem 1 tells us that the worst average SNR is optimized when the SNR of each subchannel is equal each other and optimized.
(b) Since the covariance matrix $\mathbf{R}_T$ is block-diagonal, each RP can obtain ρ_k and p_{km} through its feedback channel from the receiver and then, by Theorem 1, design the optimal precoder independently and simultaneously.
(c) Because of Comment (b) and the Toeplitz structure of each $\mathbf{R}_{Tk}$, the complexity of the optimal precoder design for each RP using Theorem 1 is $O(M^2)$

B. Massive D-MIMO

One of main advantages of our optimal system designed by Theorem 1 is that it exposes some nice structures naturally leading us to study its asymptotic behavior when the following situations occur:

Case 1: M grows to infinity while K is kept fixed;
Case 2: K grows to infinity while M is kept fixed;
Case 3: K and M grow to infinity simultaneously.

Let us assume that the ratio of the number of receiver antennas to that of the transmitter antennas, β is fixed, i.e., $\beta = \frac{N}{KM}$ is a constant independent of K and M. By Theorem 1, we have $\widetilde{\gamma}_{KM} = \frac{((\beta - 1) KM + 1) P_T}{KM \overline{W}_{KM} N_0}$. Therefore, we can directly attain the following proposition.

Proposition 1: Let notations $\overline{A}_{kM}$, $\overline{W}_{KM}$, and $\widetilde{\gamma}_{KM}$ are defined in Theorem 1. Then, the following three statements are true for massive D-MIMO systems:

1) If $\lim_{M \to \infty} \overline{A}_{kM} = \overline{A}_k$ exists for each k: $1 \le k \le K$, then, $\overline{W}_{K\infty} = \lim_{M \to \infty} \overline{W}_{KM} = \frac{1}{K} \sum_{k=1}^K \overline{A}_k / B_k$ and thus, $\widetilde{\gamma}_{K\infty} = \lim_{M \to \infty} \widetilde{\gamma}_{KM} = (\beta - 1) P_T / (N_0 \overline{W}_{K\infty})$.
2) If $\overline{W}_{\infty M} = \lim_{K \to \infty} \overline{W}_{KM}$ exists, then, $\widetilde{\gamma}_{\infty M} = \lim_{K \to \infty} \widetilde{\gamma}_{KM} = (\beta - 1) P_T / (N_0 \overline{W}_{\infty M})$.
3) If $\overline{W}_{\infty\infty} = \lim_{K \to \infty} \overline{W}_{K\infty}$ exists, then, $\widetilde{\gamma}_{\infty\infty} = \lim_{K \to \infty} \widetilde{\gamma}_{K\infty} = (\beta - 1) P_T / (N_0 \overline{W}_{\infty\infty})$. ■

Fig. 1 verifies that the optimal worst case average received SNR is indeed convergent, which implies that the assumptions on Proposition 1 are reasonable.

IV. Simulation Results

In this section, we carry out some computer simulations to compare our proposed optimal precoding scheme with the equal power-loading scheme considered in literature [17]. For simulation simplicity, some parameters of the small and large-scale fading are fixed throughout our experiments.

To show superiority of our proposed optimal power-loading scheme, we compare the SER performance of the proposed system with that of the system using the equal power allocation. All numerical results are shown in Figs. 2 and 3. From these results, we can see that the efficient utilization of the statistics of the channels at the transmitter leads to significant performance enhancement, particularly for the high correlation and the massive MIMO system.

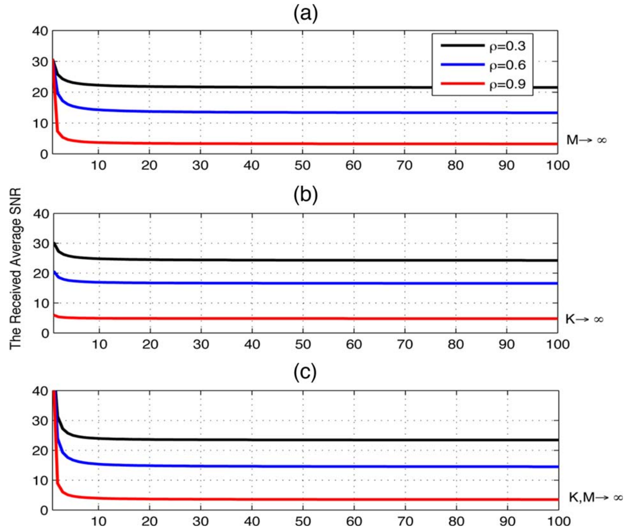

Fig. 1. Analytical received average SNR against the M or K (SNR = 20 dB, $\beta = 2$, $\rho = [0.1, 0.6, 0.9]$, $v = 4$, $\mu_k = 4$, $\delta_k = 2$).

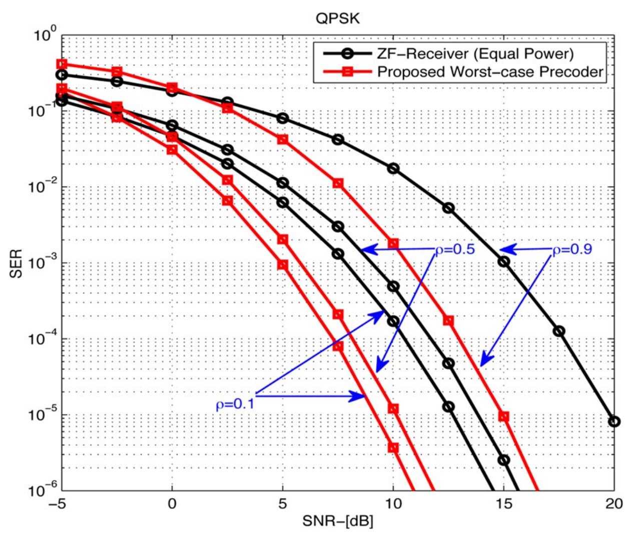

Fig. 2. Simulated average SER against the SNR (QPSK, $\beta = 2$, $K = 4$, $M = 2$, $\rho = [0.1, 0.5, 0.9]$, $v = 4$, $\mu_k = 4$, $\delta_k = 2$, $D_1 = 0.5$ km, $D_2 = 1$ km, $D_3 = 1.5$ km, $D_4 = 2$ km).

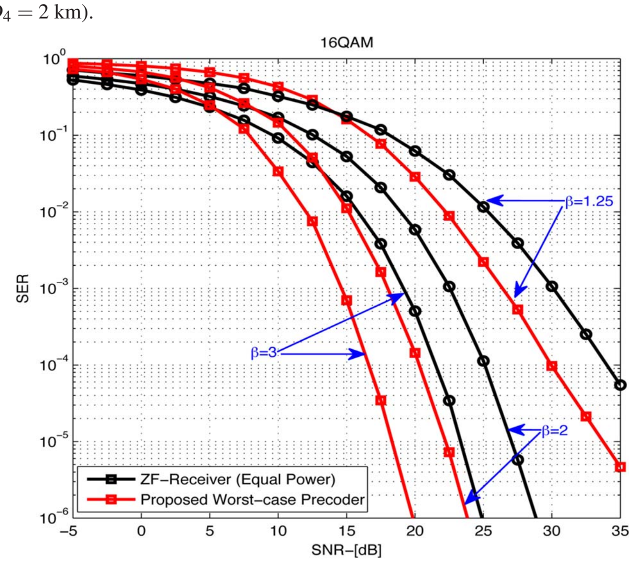

Fig. 3. Simulated average SER against the SNR (16QAM, $\beta = [1.25, 2, 3]$, $K = 4$, $M = 2$, $\rho = 0.9$, $v = 4$, $\mu_k = 4$, $\delta_k = 2$, $D_1 = 0.5$ km, $D_2 = 1$ km, $D_3 = 1.5$ km, $D_4 = 2$ km).

V. Conclusion

In this letter, we have considered the D-MIMO system, in which the channel experiences both small and large-scale fading. For such a system equipped with the ZF receiver, we have developed an optimal precoder optimizing the worst-case of the received average SNR subject to a total transmission power constraint, where only the first-and second-order statistics of the channel are needed at the transmitter. A simple closed-form optimal solution has been attained. In addition, some interesting asymptotic properties of the optimum of the worst case received SNR for the massive D-MIMO systems proposed in this letter have been revealed under some realistic assumptions. Comprehensive computer simulations have verified our theoretic analysis and demonstrated that our presented optimal system attains significant performance gains over the currently available equal power-loading system.

References

[1] H. Zhang and H. Dai, "On the capacity of distributed MIMO systems," in *Proc. CISS*, Mar. 2004, pp. 1–5.
[2] H. Dai, "Distributed versus co-located MIMO systems with correlated fading and shadowing," in *Proc. IEEE ICASSP*, May 2006, vol. 4, pp. 1–4.
[3] H. Dai, H. Zhang, and Q. Zhou, "Some analysis in distributed MIMO systems," *J. Commun.*, vol. 2, no. 3, pp. 43–50, May 2007.
[4] H. Hu, Y. Zhang, and J. Luo, *Distributed Antenna Systems: Open Architecture for Future Wireless Communications*. Boca Raton, FL, USA: CRC Press, 2007.
[5] D. Castanheira and A. Gamiero, "Distributed antenna system capacity scaling," *IEEE Wireless Commun.*, vol. 17, no. 3, pp. 68–75, Jun. 2010.
[6] H. Zhu, "Performance comparison between distributed antenna and microcellular systems," *IEEE J. Select. Areas Commun.*, vol. 29, no. 6, pp. 1151–1163, Jun. 2011.
[7] J. Zhang, C.-K. Wen, S. Jin, X. Q. Gao, and K.-K. Wong, "On capacity of large-scale MIMO multiple access channels with distributed sets of correlated antennas," *IEEE J. Select. Areas Commun.*, vol. 31, no. 2, pp. 133–148, Feb. 2013.
[8] A. Tolli, M. Codreanu, and M. Juntti, "Cooperative MIMO-OFDM cellular system with soft handover between distributed base station antennas," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1428–1440, Apr. 2008.
[9] H.-F. Chong, M. Motani, and F. Nan, "Transmitter optimization for distributed Gaussian MIMO channels," in *Proc. IEEE ITA Workshop*, 2010, pp. 1–6.
[10] R. Zhang, "Cooperative multi-cell block diagonalization with per-base-station power constraints," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1435–1445, Dec. 2010.
[11] B. O. Lee, O.-S. Shin, and K. B. Lee, "Distributed MIMO precoding strategies in a multicell environment," *IEEE Commun. Lett.*, vol. 15, no. 9, pp. 938–940, Sep. 2011.
[12] J. Zhang, X. Yuan, and L. Ping, "Hermitian precoding for distributed MIMO systems with individual channel state information," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 241–250, Feb. 2013.
[13] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.
[14] J. Hoydis, S. Ten Brink, and M. Debbah, "Massive MIMO: How many antennas do we need?" in *Proc. IEEE 49th Annu. Allerton*, 2011, pp. 545–550.
[15] Y. Jing and B. Hassibi, "Distributed space-time coding in wireless relay networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 12, pp. 3524–3536, Dec. 2006.
[16] S. Yiu, R. Schober, and L. Lampe, "Distributed space-time block coding," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1195–1206, Jul. 2006.
[17] M. Matthaiou, C. Zhong, M. R. McKay, and T. Ratnarajah, "Sum rate analysis of ZF receivers in distributed MIMO systems," *IEEE J. Select. Areas Commun.*, vol. 31, no. 2, pp. 180–191, Feb. 2013.
[18] M. Chiani, M. Z. Win, and A. Zanella, "On the capacity of spatially correlated MIMO Rayleigh-fading channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2363–2371, Oct. 2003.
[19] R. J. Muirhead, *Aspects of Multivariate Statistical Theory*. NewYork, NY, USA: Wiley, 1982.
[20] Y. Ding, T. N. Davidson, Z.-Q. Luo, and K. M. Wong, "Minimum BER block precoders for zero-forcing equalization," *IEEE Trans. Signal Process.*, vol. 51, no. 9, pp. 2410–2423, Sep. 2003.