

Energy Efficient Power Control for Distributed Transmitters with ZF-Based Multiuser MIMO Precoding

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Abstract—Distributed transmitter (D-TX) system with multiple distributed TXs is considered. To support multiple users, the D-TX system employs a zero-forcing based multiuser multiple-input multiple-output precoding. An energy efficiency (EE) maximization problem is formulated under constraints on per-user data rate and per-antenna *instantaneous* transmit power. The latter constraint is to avoid severe distortion of transmit signals at a power amplifier, i.e., the clipping effects. A low-complexity and performance-effective power control method is then proposed by solving the modification of the original, intractable optimization problem. Transmit antenna selection is elucidated with respect to the EE. Numerical results verify the efficacy of D-TX system employing the proposed EE-aware power control and antenna selection with respect to both system EE and outage performance, and also impart the importance of equal power output capability, i.e., equal maximum output power of the distributed TXs, for energy efficient D-TX systems.

Index Terms—Energy efficiency, power control, distributed transmitters, power output capability, multiuser MIMO.

I. INTRODUCTION

ENERGY efficiency (EE) has been studied widely for various wireless communication systems, recently [1]–[8]. On the other hand, to achieve high spectral efficiency (SE), a distributed antenna system (DAS) and a coordinated multipoint (CoMP) transmission technology, which can recover severe path loss and increase coverage, have been employed to multiuser multiple-input multiple-output (MU-MIMO) downlink communications [9], [10]. The SE-maximizing solution, however, does not necessarily achieve the maximum EE.

In this letter, we propose a *power control* method with transmitter (TX) antenna selection to enhance the EE for a distributed TX (D-TX) system. The D-TX system has N multiple *distributed* TXs, in which TX n has M_n distributed or co-located antennas as illustrated in Fig. 1, and supports a general configuration combining DAS and CoMP. To maximize EE, we compare all maximum achievable EEs obtained from all possible TX antenna sets. To obtain the maximum achievable EE for a given antenna set, D-TXs perform cooperative processing, that is a zero-forcing (ZF)-based MU-MIMO linear precoding. The transmit power of D-TX systems employing the cooperative MU-MIMO precoding should be carefully (i.e., jointly instead of individually) managed due to the following issues.

- D-TX system has either equal (i.e., $P_1 = \dots = P_N$) or unequal (i.e., there exists n and n' such that $P_n \neq P_{n'}$) power output capability (POC). The unequal POC means that D-TXs have dissimilar power amplifiers (PAs) with different clipping levels constraining the maximum

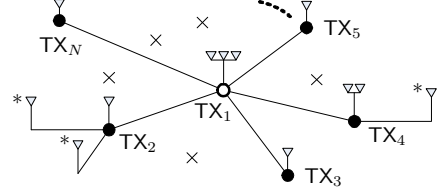


Fig. 1. D-TX system consisting of N transmitters: One central TX (\circ) TX_1 and $(N - 1)$ extended TXs (\bullet) TX_n , $n = 2, \dots, N$, connecting to TX_1 . Users and distributed antenna are illustrated by ‘ \times ’ and ‘*’, respectively.

output power P_n for TX n . The clipping effect increases spectral regrowth and inter-user interferences.

- Since the transmit power of each D-TX is coupled with one another through the cooperative processing and power allocation variables, EE deteriorates significantly if there are unintentionally high power allocation and consumption at an antenna port located very far from the receiver.

To resolve the issues, we propose an EE-aware power control and antenna selection method. The joint optimization of transmit power and active antenna set, however, is intractable due to the nonlinear, nonconvex objective function and the coupled, nonlinear power constraints. Thus, we consider a suboptimal decomposition approach with two subproblems: i) an EE-aware power allocation subproblem in Sections III and IV, and ii) an antenna selection subproblem in Section V. We first propose an EE-aware power control for a given antenna set which satisfies a *per-user data rate* constraint and a *per-antenna instantaneous transmit power* constraint. The instantaneous power constraint is a more stringent constraint than an *average* transmit power constraint (see e.g., [2] and [3]), and it makes the original optimization problem intractable. Thus, the modification of the power allocation subproblem is considered. If there is no feasible power control satisfying the constraints, an outage happens. Based on the achievable EE obtained from the EE-aware power control for a particular antenna set, we can readily select the EE-aware antenna set, which is an essential procedure to improve the network EE. Note that even zero-power transmission consumes overhead circuit power in practice; therefore, the power control does not capture antenna selection in an EE maximization problem. Numerical results verify the potential efficacy of the D-TX systems with the proposed EE-aware power control, and provide informative results regarding the ZF-based MU-MIMO D-TX systems: for example, i) EE-optimal number of active antennas increases as a target rate increases (see Fig. 2(a)); and ii) equal POC achieves higher EE than unequal POC (see Fig. 4).

II. SYSTEM MODEL

We consider N TXs, denoted by TX_n , where $n \in \mathcal{N} = \{1, \dots, N\}$. One central TX TX_1 performs centralized power control for itself and all $(N - 1)$ extended TXs, $\text{TX}_n, n = 2, \dots, N$. The extended TXs are connected to TX_1 through a noise-free wired backhaul (e.g., optical fiber) for coordinated MU-MIMO communications. Generally, any TX can be a central TX, and any type of network topology can be applied to the D-TX systems according to the network applications.

In the network, U user equipments (UEs), denoted by UE_u where $u \in \mathcal{U} = \{1, \dots, U\}$, are supported simultaneously by using the same frequency band through MU-MIMO techniques. We assume that all UEs have a single receive antenna¹ for simplicity and have the same priority and delay constraint with a proper admission control.

Let us define an antenna index set, \mathcal{M} , including $M \leq \sum_{n \in \mathcal{N}} M_n$ distributed or co-located antennas, whose corresponding channels between transmit and receive antennas are independent and identically distributed (i.i.d.). Hence, the channel matrix of the selected antennas from \mathcal{M} is full rank. Since at least rank U MIMO channel is required to support U UEs with a ZF-based² MU-MIMO, M should be greater than or equal to U to perfectly eliminate the interferences. If $M < U$, we have to schedule the UEs with orthogonal time and/or frequency resources. With enough number of TXs or TX antennas, we assume $M \geq U$ throughout the paper.

III. POWER ALLOCATION SUBPROBLEM FORMULATION

Denoting a received signal at UE_u by y_u , its vector form $\mathbf{y} = [y_1 \cdots y_U]^T$ is written for the fixed TX antenna set $\mathcal{I} \subseteq \mathcal{M}$ as

$$\mathbf{y} = \mathbf{H}\mathbf{W}\sqrt{\mathbf{p}} \circ \mathbf{x} + \mathbf{n}, \quad (1)$$

where \mathbf{H} is a U -by- $|\mathcal{I}|$ MU-MIMO channel matrix corresponding to the selected $|\mathcal{I}|$ antennas and the U UEs, and $|\mathcal{I}|$ is a cardinality of \mathcal{I} ; \mathbf{W} is a $|\mathcal{I}|$ -by- U MU-MIMO preprocessing matrix; $\mathbf{p} \triangleq [p_1 \cdots p_U]^T$ is a U -by-1 power allocation vector whose u th element p_u determines a power portion to UE_u ; \circ represents an entrywise product; $\mathbf{x} = [x_1 \cdots x_U]^T$ is a transmit signal vector where x_u is a transmit symbol to UE_u with Gaussian distribution and $\mathbb{E}|x_u|^2 = 1$; and $\mathbf{n} = [n_1 \cdots n_U]^T$ is an additive white Gaussian noise (AWGN) vector whose u th element n_u is an AWGN at UE_u with a zero mean and a σ^2 variance. The (u, i) th element of \mathbf{H} represents a channel gain $\sqrt{A_{u,i}}h_{u,i}$ consisting of the large-scale fading $\sqrt{A_{u,i}}$ (i.e., path loss) and the small-scale fading $h_{u,i}$ between TX antenna $i \in \mathcal{I}$ and UE_u . The i th TX antenna is located at $\text{TX}_{\pi(i)}$ where $\pi(i)$ is a mapping function from antenna index i to TX index $n \in \mathcal{N}$, i.e., $\pi(i) = n$. For the ZF-based MU-MIMO, \mathbf{W} is obtained from a pseudo-inverse matrix of \mathbf{H} as $\mathbf{W} = [\mathbf{w}_1 \cdots \mathbf{w}_{|\mathcal{I}|}]^T \triangleq \mathbf{H}^+$, where \mathbf{w}_i is a U -by-1 ZF weight vector for antenna i ; therefore, $\mathbf{H}\mathbf{W}$ becomes a U -dimensional identity matrix.

¹The results in this letter can be directly extended to the case of multiple receive antennas at UE, if we treat each UE antenna as a virtual user, or if each UE employs receive beamforming or combining.

²Since a ZF-based method can achieve near optimal SE in MU-MIMO systems if the signal-to-noise ratio (SNR) is high enough [11], [12], we employ it under the high SNR assumption. The assumption is relevant for the D-TX systems which can effectively reduce the path loss.

Using the ZF-based MU-MIMO preprocessing to (1), we derive the received SNR of stream u as $\text{SNR}_u = p_u\sigma^{-2}$. With high input backoff, we assume that a PA input signal is linearly amplified and the PA output signal has a Gaussian distribution [4], and we can further assume that UE_u can correctly decode $\log_2(1 + \text{SNR}_u)$ -bit information per unit frequency and time (bits/sec/Hz). In practice, however, the backoff is restricted for the efficient transmission; therefore, there is a clipping on the amplified signals, and Gaussian signaling assumption is invalid. Non-Gaussian signaling causes an SNR penalty and equivalently increase the noise variance from σ^2 to $\hat{\sigma}^2 = \sigma^2 + \Delta$. Accordingly, for any arbitrary signaling, we write the achievable throughput of UE_u over bandwidth Ω Hz as $\text{TP}(p_u) = \Omega \log_2(1 + p_u\hat{\sigma}^{-2})$, $\forall u \in \mathcal{U}$, and obtain the system throughput per unit time (bits/sec) as $\text{TP}(\mathbf{p}) = \sum_{u \in \mathcal{U}} \text{TP}(p_u)$.

MIMO system's power consumption (Watt) corresponding to \mathbf{p} and $|\mathcal{I}|$ is modeled as $\text{PC}(\mathbf{p}) = f(\mathbf{p}) + P_o$ (see [5], [13]), where the transmit power dependent and independent terms are defined as $f(\mathbf{p}) \triangleq \sum_{i \in \mathcal{I}} \frac{c}{\eta_i} P_i(\mathbf{p})$ and $P_o \triangleq |\mathcal{I}|P_{\text{cc}} + |\mathcal{I}|\Omega P_{\text{sp1}} + \Omega P_{\text{sp2}} + P_{\text{fix}}$, respectively. Here, c is a system dependent power loss coefficient which can be empirically measured and obtained, and $c > 1$; η_i is the efficiency of PA at $\text{TX}_{\pi(i)}$ and $0 < \eta_i \leq 1$; $P_i(\mathbf{p}) = |\mathbf{w}_i^T \sqrt{\mathbf{p}} \circ \mathbf{x}|^2$ is an instantaneous transmit power of the selected TX antenna i of $\text{TX}_{\pi(i)}$; P_{cc} is radio frequency (RF) circuit power consumption which is proportional to the number of RF chains, i.e., $|\mathcal{I}|$; P_{sp1} and P_{sp2} are signal processing related power consumption per unit frequency and P_{sp1} is proportional to $|\mathcal{I}|$; and P_{fix} is a fixed power consumption which is independent of $P_i(\mathbf{p})$ and Ω , for example, a part of power consumption at a power supply and a cooling system.

We now formulate a power allocation problem to maximize EE (bits/Joule) for given \mathcal{I} as follows:

$$\mathbf{p}^* = \arg \max_{\mathbf{p} \in \mathbb{R}^{U \times 1}} \text{EE}(\mathbf{p}) \quad (2a)$$

$$\text{s.t. } \Omega \log_2(1 + p_u\hat{\sigma}^{-2}) \geq R_u, \quad \forall u \in \mathcal{U} \quad (2b)$$

$$|\mathbf{w}_i^T \sqrt{\mathbf{p}} \circ \mathbf{x}|^2 \leq C_{\pi(i)}, \quad \forall i \in \mathcal{I}, \quad (2c)$$

where $\text{EE}(\mathbf{p}) = \text{TP}(\mathbf{p})/\text{PC}(\mathbf{p})$; the inequalities in (2b) follow the per-user rate constraints with a target rate R_u of UE_u ; and (2c) is a per-antenna instantaneous power constraint, which is induced by the distributed TXs with different POC of PAs, i.e., clipping level C_n . The transmit power of each antenna, i.e., the output power of each RF-chain, is limited by P_n/M_n to cover the case when all M_n antennas of TX_n are selected for the MU-MIMO and to fulfill the radio regulations. Thus, each PA is designed to satisfy that $C_n \leq P_n/M_n$. Directly solving (2) is formidable due to the nonlinear, non-convex objective function in (2a) and the coupled nonlinear³ constraints in (2c) over $\{p_u\}$. To obtain a tractable power control method, modification or relaxation of (2) is inevitable. In the letter, we decide to modify (2) to obtain a tractable, closed form expression of \mathbf{p} .

³Note that the left hand side of (2c) is *power of sum of $\sqrt{p_n}$* . On the other hand, an average transmit power constraint in [2] and [3] is a linear constraint, i.e., *sum of power of $\sqrt{p_n}$* , which makes the EE maximization problem be solvable, yet an instantaneous clipping effect at PA is not considered.

IV. MODIFIED PROBLEM AND ITS SOLUTION

We first consider maximizing the EE lower bound instead of the actual EE in (2). To this end, we define a common power scaling factor α and a relative power portion \bar{p}_u of UE_u , such that $p_u = \alpha \bar{p}_u$, $\forall u \in \mathcal{U}$ and $\sum_u \bar{p}_u = 1$. We then derive the EE lower bound and define it as a function of α and $\bar{\mathbf{p}} = [\bar{p}_1 \cdots \bar{p}_U]^T$ as follows:

$$EE(\mathbf{p}) \geq \frac{\Omega U \log_2 \left(1 + \alpha \min_u \{ \bar{p}_u \} \hat{\sigma}^{-2} \right)}{\alpha \sum_{i \in \mathcal{I}} \frac{c}{\eta_i} |\mathbf{w}_i \sqrt{\bar{\mathbf{p}}} \circ \mathbf{x}|^2 + P_o} \triangleq EE_L(\alpha, \bar{\mathbf{p}}). \quad (3)$$

Substituting the objective function in (2a) with the EE lower bound in (3), and using α and $\bar{\mathbf{p}}$ to (2b) and (2c), we modify the original optimization problem (2) as

$$\{\alpha, \bar{\mathbf{p}}\} = \arg \max_{\alpha, \bar{\mathbf{p}}, \sum_u \bar{p}_u = 1} EE_L(\alpha, \bar{\mathbf{p}}) \quad (4a)$$

$$\text{s.t. } \alpha \geq \max_{u \in \mathcal{U}} \{ \gamma_u \bar{p}_u^{-1} \} \triangleq \alpha_L(\bar{\mathbf{p}}) \quad (4b)$$

$$\alpha \leq \min_{i \in \mathcal{I}} \left\{ C_{\pi(i)} |\mathbf{w}_i^T \sqrt{\bar{\mathbf{p}}} \circ \mathbf{x}|^{-2} \right\} \triangleq \alpha_U(\bar{\mathbf{p}}), \quad (4c)$$

where $\gamma_u \triangleq \hat{\sigma}^2 (2^{R_u/\Omega} - 1)$ is *minimum-required power* for R_u , and (4b) and (4c) follow (2b) and (2c), respectively. The modified problem (4) enables us to design the energy efficient systems by simply optimizing α if the optimal power ratio vector $\bar{\mathbf{p}}$ is given. This is because the problem structure of (4) is now well-defined, namely the modified objective function (4a) is quasi-concave⁴ (unimodal) over α and the one-dimensional feasible set is bounded by $\alpha_L(\bar{\mathbf{p}})$ and $\alpha_U(\bar{\mathbf{p}})$. However, to optimally determine $\bar{\mathbf{p}}$ remains still unresolved. One method what we could directly consider to tackle this issue is an iterative approach, in which α and $\bar{\mathbf{p}}$ are updated alternately, yet convergence and complexity issues arise. In this letter, we determine \bar{p}_u to be proportional to the minimum-required power for R_u , i.e., γ_u , and denote it by \tilde{p}_u . After the normalization to satisfy $\sum_u \tilde{p}_u = 1$, we have

$$\tilde{p}_u = \gamma_u \left(\sum_{k \in \mathcal{U}} \gamma_k \right)^{-1}, \quad \forall u \in \mathcal{U}. \quad (5)$$

Though the strategy in (5) is heuristic, it is appropriate with respect to the fairness of power allocation to users who require different target rates.

For given $\bar{\mathbf{p}}$ by $\tilde{\mathbf{p}} = [\tilde{p}_1 \cdots \tilde{p}_U]^T$, problem (4) maximizing the EE lower bound is rewritten with respect to α as

$$\alpha^* = \arg \max_{\alpha} \frac{\Omega U \log_2 (1 + c_1 \alpha)}{c_2 \alpha + P_o} \quad (6a)$$

$$\text{s.t. } \alpha_L \leq \alpha \leq \alpha_U, \quad (6b)$$

where $c_1 \triangleq \min_u \{ \tilde{p}_u \} \hat{\sigma}^{-2}$; $c_2 \triangleq \sum_{i \in \mathcal{I}} \frac{c}{\eta_i} |\mathbf{w}_i \sqrt{\tilde{\mathbf{p}}} \circ \mathbf{x}|^2$; $\alpha_L = \hat{\sigma}^2 \sum_{k \in \mathcal{U}} \gamma_k$; and $\alpha_U = \min_{i \in \mathcal{I}} \{ C_{\pi(i)} |\mathbf{w}_i^T \sqrt{\tilde{\mathbf{p}}} \circ \mathbf{x}|^{-2} \}$. Note that all c_1 , c_2 , α_L , and α_U in (6) are constant values for given $\tilde{\mathbf{p}}$. Now, we can readily find the maximizer α_o which makes the first derivative of the objective function (6a) to zero as

$$\alpha_o = \frac{1}{c_1} \left(\exp \left(1 + W \left(-\frac{1}{\exp(1)} + \frac{c_1 P_o}{c_2 \exp(1)} \right) \right) - 1 \right),$$

⁴It can be readily proved by using the facts that a log function is concave and that the denominator of $EE_L(\alpha, \bar{\mathbf{p}})$ is a monotonically increasing function over α within a positive convex domain.

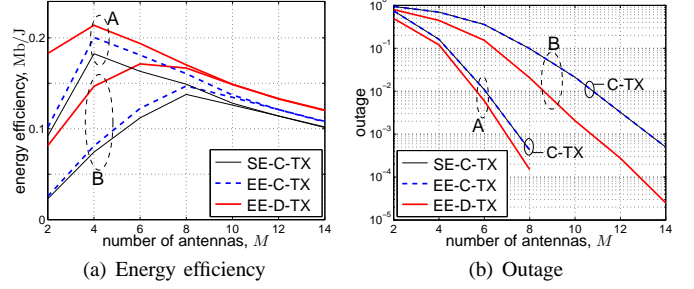


Fig. 2. Performance evaluation over the number of active antennas, M , when $\{R_1, R_2\} = \{40, 60\}$ Mbps (A) and $\{R_1, R_2\} = \{50, 70\}$ Mbps (B).

where $\exp(\cdot)$ is an exponential function and $W(\cdot)$ denotes the Lambert W function that satisfies $q = W(q)e^{W(q)}$. Considering feasible region (6b), we get the optimal feasible solution of (6) as

$$\alpha^* = [\alpha_o]_{\alpha_L}^{\alpha_U}, \quad (7)$$

where $[x]_a^b$ takes x if it is between a and b , and the closest boundary a or b otherwise. If the optimization set is infeasible, i.e., $\alpha_L > \alpha_U$, an outage happens and at least one UE cannot be supported. Remind that α_L follows the minimum-required power to support *all* users' target rates in (2b), while α_U is desired to fulfill *all* antennas' instantaneous transmit power limitation in (2c) and it is also restricted jointly over all selected antennas due to the ZF property as shown in (4c).

V. ANTENNA SELECTION SUBPROBLEM

Fig. 2 shows EE and outage performance over M when we activate all M antennas. Two users are supported by ZF-based MU-MIMO, and equal POC is considered, i.e., $P_n = 46$ dBm, $\forall n$ (refer to Section VI for other parameters). Two collocated-TX (C-TX) systems are compared. SE-C-TX selects the TX antennas to maximize SE and uses the maximum available transmit power, while EE-C-TX focuses on EE maximization like the proposed D-TX system, EE-D-TX. We observe that the EE highly depends on the number of active antennas, and that the EE-aware antenna set \mathcal{I}^* depends on the target rate. From the observation, it is clear that optimization of antenna set \mathcal{I} is a crucial procedure for EE enhancement. We recall the original problem formulated as

$$\{\mathcal{I}^*, \mathbf{p}^*\} = \arg \max_{\mathcal{I} \subseteq \mathcal{M}, \mathbf{p}} [EE(\mathbf{p}) | \mathcal{I}], \text{ s.t. (2b) and (2c)}. \quad (8)$$

For a given \mathcal{I} , we can readily perform a fair and EE-aware power control with $\tilde{\mathbf{p}}^* = [\tilde{p}_1^* \cdots \tilde{p}_U^*]^T$ where $\tilde{p}_u^* = \alpha^* \tilde{p}_u$ from (5) and (7). Note that EE becomes zero if there is no feasible $\tilde{\mathbf{p}}^*$ satisfying (2b) and (2c). Eventually, a remaining problem is to find \mathcal{I}^* , which is a combinatorial optimization problem to select \mathcal{I} with the cardinality $U \leq |\mathcal{I}| \leq M$.

Various suboptimal searching algorithms can be applied to solve the combinatorial problem of (8). We, however, defer devisal of searching algorithm to solve the combinatorial problem to future work, and at this moment, we emphasize that the combinatorial search becomes more tractable due to our closed-formed $\tilde{\mathbf{p}}^*$. No matter what type of searching algorithms we employ, we can combine $\tilde{\mathbf{p}}^*$ with the searching

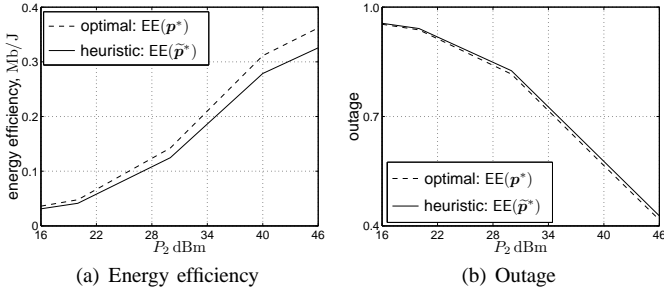


Fig. 3. Comparison between optimal and heuristic power control methods.

algorithm without any confliction. However, the optimality loss from \tilde{p}_u^* causes inevitable performance degradation. To quantify the performance degradation, EE and outage of D-TX system are evaluated with p^* and \tilde{p}^* for a small-scale network ($U = 2$, $N = 2$, $M_1 = 1$, $M_2 = 1$, and $P_1 = 46$ dBm). We find p^* for the small network via two-dimensional line search, exhaustively. Remind that it is formidable to solve (2) and find p^* in a general network setup. From Fig. 3, it is observed that EE (\tilde{p}^*) follows the same trend as EE (p^*). Furthermore, though there is nontrivial EE gap (no greater than 10%), the outage performance gap is negligible.

VI. PERFORMANCE EVALUATION AND DISCUSSION

In this section, we evaluate EE and outage performance with the proposed power control. Simulation parameters are summarized as follows. The path loss is modeled as $A_{u,i} = G - 128 + 10 \log_{10}(d_{u,i}^{-\nu})$ in dB scale, where G includes the transceiver feeder loss and antenna gains, $d_{u,i}^{-\nu}$ is the path loss for the distance $d_{u,i}$ between $\text{TX}_{\pi(i)}$ and UE_u , and ν is a path loss exponent. The small-scale fading is modeled as Rayleigh fading with a zero mean and a unit variance. In our simulation, we set $G = 5$ dB, $\nu = 3.76$, $\hat{\sigma}^2 = -174$ dBm/Hz, $C_n = P_n/M_n$, $\Omega = 5$ MHz, $R_1 = 40$ Mbps, and $R_2 = 60$ Mbps. Power related parameters are as follows [5], [13]: $c = 2.63$, $P_{cc} = 66.4$ W, $P_{\text{fix}} = 36.4$ W, $P_{\text{sp1}} = 1.82 \mu\text{W}/\text{Hz}$, and $P_{\text{sp2}} = 3.32 \mu\text{W}/\text{Hz}$. The efficiency of all PAs is assumed to be sustained by 30% through a PA selection [5], i.e., $\eta_i = 0.3, \forall i$. For D-TX network setup with two UEs and four TXs, we assume that i) all TXs have two co-located antennas, i.e., $M = 8$; ii) the extended TXs, TX_2 , TX_3 , and TX_4 , are located at 0.5 km from the central TX_1 and they are equidistant from one another; and iii) UEs are distributed uniformly within 0.8 km from TX_1 . Equal and unequal POCs are compared. For the unequal POC case, denoted by ‘u-POC,’ we fix P_1 by 46 dBm and vary $P_2 = P_3 = P_4$. For the equal POC case, denoted by ‘e-POC,’ the maximum output power of all TXs is the same as $\sum_{n=1}^4 P_n/M$.

Figs. 4(a) and (b) show EE and outage performance, respectively. From the numerical results, we verify three remarks: i) The proposed EE-aware power control and antenna selection methods improve EE. ii) D-TX system outperforms C-TX in terms of both EE and outage performance. iii) Equal POC outperforms unequal POC in terms of both EE and outage performance. From the remarks, we can surmise that the most promising system for both EE and outage is an EE-maximizing D-TX system with equal POC.

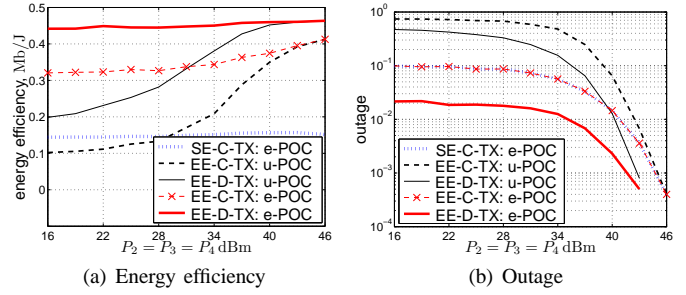


Fig. 4. Numerical results when $R_1 = 40$ Mbps and $R_2 = 60$ Mbps.

VII. CONCLUSION

In this letter, we have considered a D-TX system employing a ZF-based MU-MIMO linear precoding. A simple, heuristic power control method has been proposed to improve system EE under constraints on per-user target rate and on per-antenna instantaneous transmit power. Numerical results have highlighted the importance of antenna selection in terms of EE, and confirmed that the proposed multiuser power control with antenna selection improves both EE and outage performance.

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