Energy Efficiency of Cooperative Beamforming in Wireless Ad-Hoc Networks

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***Abstract*—Energy efficiency is a critical issue in wireless communication networks since most of the communication devices have limited energy capacity. Various strategies for maximizing energy efficiency have been proposed. In this paper, we analyze the energy efficiency of cooperative beamforming where the source and relay nodes construct a virtual Multiple-Input Single-Output (MISO) beamforming system. In the analysis, we consider all the energy consumption overheads incurred in forming a virtual MISO system. We show that cooperative beamforming achieves not only a higher energy efficiency, but also better spectral efficiency for large transmission distances.**

I. Introduction

Wireless communications technology is developing rapidly especially with the migration to 4G systems. The large amount of data processing required for these systems results in significant increases in energy consumption; battery technology, however, has not kept up with this energy demand. Since mobile terminals are mainly powered by battery, it is critical to optimize the energy efficiency to prolong the operational life of mobile devices. Recently, much attention has been given to developing energy-efficient techniques.

Various communication resource allocation strategies have been developed with the goal of maximizing energy efficiency. In [1]-[3], energy-efficient adaptive modulation is investigated in which higher level modulation is adopted for short distances, where circuit power is more dominant than transmission power. The energy efficiency of centralized and distributed Multiple-Input Multiple-Output (MIMO) systems has been studied in [4], and, in [5], the extra training overhead required for MIMO is considered. In [6], a best-select cooperative relaying scheme based on a RTS-CTS MAC layer mechanism and power allocation is described. An energy-efficient clustered wireless sensor network with space-time coding is proposed in [7]. In [8], it is shown that mode switching between MIMO and Single-Input Multiple-Output (SIMO) improves energy efficiency in an uplink cellular network. The energy efficiency in a downlink cellular network with random opportunistic beamforming is studied in [9]; it is shown that activating a single antenna at the base station is optimal in terms of energy efficiency. In [10], energy-efficient cooperative beamforming (CBF) with simple relay selection is described; however, circuit power is not taken into account.

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In this paper, we consider the energy overhead in a CBF system with distributed relay nodes, and analyze the energy efficiency assuming constant circuit power. The rest of the paper is organized as follows. In Section II, we describe the energy consumption models used. In Section III, we present the energy efficiency of a CBF system, and of direct communication in Section IV. In Section V, the optimal constellation size for CBF and direct communication is considered. Finally, simulation results are presented in Section VI, and conclusions are given in Section VII.

II. System and Energy Consumption Model

In Fig. 1, we show a CBF scheme in which M relays form a virtual MISO beamforming system. We assume the M relays are uniformly distributed around the source within a radius R. In this case, the distance from the source to the relay, d, is a random variable, with probability density function, $f(d) = 2d/R^2$, $0 < d \leq R$ [7]. Denote $h_i \sim CN(0, \sigma_{h_i}^2)$ as the complex Gaussian channel from the source to relay i, and $g_i \sim CN(0, \sigma_{g_i}^2)$ as the channel from relay i to the destination. Let $g_0 \sim CN(0, \sigma_g^2)$ be the channel coefficient from the source to the destination. We assume that the channel variance incorporates the distance-based path-loss component, where the path loss, in dB, is

$$PL(d) = PL_F(d_0) + 10\beta\log_{10}\left(\frac{d}{d_0}\right) \tag{1}$$

where

$$PL_F(d_0) = -10\log_{10}\left(\frac{\lambda}{4\pi d_0}\right)^2 \tag{2}$$

and where λ is the wavelength, d_0 is the reference distance, and β is the path-loss exponent. In order to construct a virtual MISO beam to relay the source information to the destination, additional transmission phases are required to accomplish the following tasks: (1) channel estimation, (2) channel information sharing, (3) source information sharing, and (4) cooperative beamforming. In the next section, we consider the energy consumption for each phase.

A. Channel Estimation Phase

In this phase, the destination transmits training symbols, and each of M relays estimates the corresponding channel coefficient, g_i. Here, we assume TDD is used; thus, the

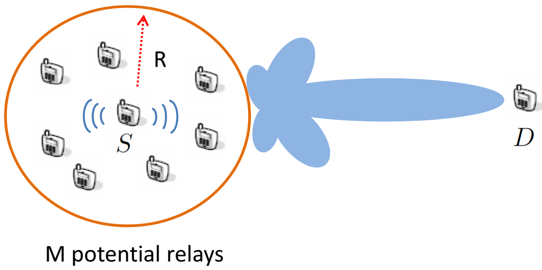

Fig. 1. Beamforming with M potential cooperating nodes

forward and reverse channels are assumed to be the same. The transmit power for training, P_{TR}, is chosen such that the SNR of the worst link between the destination and the relays is γ_{TR}. Including the circuit power consumption from the destination and M relays estimating the channel, the corresponding energy consumption is

$$E_{TR} = (P_{TR}/\rho + (1+M)P_C)\, N_{TR}T_S \tag{3}$$

where ρ is the amplifier efficiency, P_C is the circuit power (assumed to be the same at the transmitter and the receiver), N_{TR} is the number of training symbols, and $T_S \approx \frac{1}{B}$ is the symbol duration where B is the transmission bandwidth.

B. Channel Information Sharing Phase

The estimated channel coefficients are shared with each relay to find the beamforming weights. During this phase, the source node estimates the channel gain from the source to each relay by overhearing the transmission of each relay. Thus, M transmission times are required, and, for each transmission, $(1+M)P_C$ is consumed. Then, the energy consumption in this phase is

$$E_{CS} = M\,(P_{CS}/\rho + (1+M)P_C)\,\frac{b_Q}{b_{CS}}T_S \tag{4}$$

where P_{CS} is the transmit power in this phase, and is chosen such that the outage at the maximum possible distance (2R, diameter of the relay set) satisfies the target outage threshold. b_{CS} is the number of bits/symbol for sharing, and b_Q is the number of quantized bits for the estimated channel gain.

C. Source Information Sharing Phase

We assume the source node has an L-bit packet to send. In this phase, the L bits are shared with the M relay nodes. The energy consumption to share L bits is then

$$E_{SR} = (P_{SR}/\rho + (1+M)P_C)\,T_{SR} \tag{5}$$

where $T_{SR} = \frac{L}{b_{SR}B}$ is the required transmission time to share L bits and b_{SR} is the number of bits/symbol for transmission. We consider an adaptive transmission where the transmit power is adapted over the fading channel. Then, the instantaneous required transmit power is

$$P_{SR} = \frac{\gamma_{th}(b_{SR})P_N}{H_{min}} \tag{6}$$

where $P_N = N_0B$ is the noise power, with N_0 the noise power spectral density. $H_{min} = \min_{i=1\cdots M}[|h_1|^2 \cdots |h_M|^2]$ is the minimum channel gain among all source-to-relay links. For the analysis, we assume that the relays are located at the same average distance, $\bar{d} = E[d]$, and the correspoding variance is σ_h^2. Then, from the order statistics of independent exponential random variables, we can easily obtain that H_{min} is also exponentially distributed, but with mean $\sigma_{sr}^2 = \sigma_h^2/M$. $\gamma_{th}(b_{SR})$ is the SNR required to achieve the target M-QAM bit error probability, p_{th}, and is given by

$$\gamma_{th}(b_{SR}) = -\frac{1}{c_2}\left(2^{b_{SR}}-1\right)\ln\left(\frac{p_{th}}{c_1}\right) \tag{7}$$

which is obtained by inverting the approximation [11]

$$p_{th}(b) = c_1\exp\left(-\frac{c_2\gamma}{2^b-1}\right) \tag{8}$$

where $c_1 = 0.2$, $c_2 = 1.5$, and γ is the received SNR.

D. Cooperative Beamforming Phase

M relays create a virtual beam to the destination. Since each source and relay has all the channel gains, $|g_i|^2$, each node can find its own beamforming weight (for node i, $w_i = \frac{g_i}{||\mathbf{g}||}$, $\mathbf{g} = [g_1, \cdots, g_M]^T$). Then, the energy consumption is

$$E_{CB} = (P_{CB}/\rho + (1+M)P_C)\,T_{CB} \tag{9}$$

where P_{CB} is the instantaneous required transmit power, $P_{CB} = \frac{\gamma_{th}(b_{CB})P_N}{||\mathbf{g}||^2}$, $T_{CB} = \frac{L}{b_{CB}B}$ is the total transmission time to send L bits, and b_{CB} is the number of bits/symbol for CBF.

E. Energy Overhead in CBF

The energy overhead for CBF is

$$\begin{aligned} E_{OV} &= E_{TR}(\text{training}) + E_{CS}(\text{channel information sharing}) \\ &\quad + E_{SR}(\text{source information sharing}) \end{aligned} \tag{10}$$

Combining all of the overheads, we get

$$\begin{aligned} E_{OV} &= \frac{1}{\rho}\left(P_{TR}N_{TR} + MP_{CS}\frac{b_Q}{b_{CS}}\right)T_S + \frac{1}{\rho}P_{SR}T_{SR} \\ &\quad + P_C\left((1+M)N_{TR} + M(1+M)\frac{b_Q}{b_{CS}}\right)T_S \\ &\quad + (1+M)P_CT_{SR} \end{aligned} \tag{11}$$

We obtain the equivalent power overhead by dividing E_{OV} in (11) by the total transmission time, T_{CB}, giving

$$\begin{aligned} P_{OV} &= \frac{b_{CB}}{L\rho}\left(P_{TR}N_{TR} + MP_{CS}\frac{b_Q}{b_{CS}}\right) + \frac{P_{SR}b_{CB}}{\rho b_{SR}} \\ &\quad + \frac{b_{CB}}{L}P_C\left((1+M)N_{TR} + M(1+M)\frac{b_Q}{b_{CS}}\right) \\ &\quad + (1+M)P_C\frac{b_{CB}}{b_{SR}} \end{aligned} \tag{12}$$

For a slow fading channel, the coherence time, T_C can be large compared to T_S; thus, we assume the total number of bits in a packet, L, is very large. In this case, the overhead mainly comes from the source information sharing phase, giving

$$P_{OV} \approx (P_{SR}/\rho + (1+M)P_C)\frac{b_{CB}}{b_{SR}} \tag{13}$$

III. Energy Efficiency of CBF

In this section, we evaluate the energy efficiency of CBF in the presence of a constraint on the maximum transmit power, P_{max}. Since the source and relays have all of the channel information, each can decide whether to transmit or not based on the constraint. If, for a given channel gain, the required power is greater than P_{max}, then an outage is declared, and transmission will be suspended. We define the efficiency in bits/Joule as

$$\begin{aligned} EE_{CT} &= \frac{Lp_{on}}{(P_{CB}/\rho + (1+M)P_C)\,T_{CB} + E_{OV}} \\ &= \frac{(b_{CB}B)p_{on}}{P_{CB}/\rho + (1+M)P_C + P_{OV}} \end{aligned} \tag{14}$$

where p_{on} is the probability that an outage does not occur during either the source information sharing phase or the CBF phase. Then, for large L, we approximate P_{OV} as in (13) and

$$EE_{CT} \approx \frac{(b_{CB}B)p_{on}}{\frac{1}{\rho}(P_{CB} + P_{SR}\frac{b_{CB}}{b_{SR}}) + (1+\frac{b_{CB}}{b_{SR}})(1+M)P_C} \tag{15}$$

Since P_{CB} and P_{SR} are adapted over the fading, we can use the average power, giving

$$EE_{CT} \approx \frac{(b_{CB}B)p_{on}}{\frac{1}{\rho}(\bar{P}_{CB} + \bar{P}_{SR}\frac{b_{CB}}{b_{SR}}) + (1+\frac{b_{CB}}{b_{SR}})(1+M)P_C} \tag{16}$$

where $\bar{P}_{CB} \triangleq E[P_{CB}|P_{CB} \leq P_{max}]$ and $\bar{P}_{SR} \triangleq E[P_{SR}|P_{SR} \leq P_{max}]$.

A. Average Power for CBF

Let $X = ||\mathbf{g}||^2$ which has a Gamma distribution with M degrees of freedom. Then, for $M \geq 2$, the average power with the power constraint is

$$\begin{aligned} \bar{P}_{CB} &= P_{CB}^{req} E\left[1/X | X \geq \frac{P_{CB}^{req}}{P_{max}}\right] \\ &= \frac{P_{CB}^{req}}{(M-1)\sigma_g^2}\left[\frac{\sum_{i=0}^{M-2}\frac{\eta_{cb}^i}{i!}}{\sum_{i=0}^{M-1}\frac{\eta_{cb}^i}{i!}}\right] \end{aligned} \tag{17}$$

where $\eta_{cb} = \frac{\gamma_{th}(b_{CB})P_N}{P_{max}\sigma_g^2} = \frac{P_{CB}^{req}}{P_{CB}^{rec}}$. P_{CB}^{req} is the required received power to meet the target SNR, $\gamma_{th}(b_{CB})$, and P_{CB}^{rec} is the average received power when the maximum power is used. For large transmission distances, we assume that $\sigma_{g_i}^2 \approx \sigma_g^2$, for $\forall i$. Thus, $1/\eta_{cb}$ can be thought of as the system power margin. We can also show that $\frac{P_{CB}^{req}}{(M-1)\sigma_g^2}$ is equivalent to $E[P_{CB}]$, the average transmit power without a power constraint. Then, by denoting the term in brackets in (17) as $f(M, \eta_{cb})$, we have

$$\bar{P}_{CB} = E[P_{CB}]f(M, \eta_{cb}) \tag{18}$$

In (18), the second term comes from the power constraint. It can be seen that $f(\cdot)$ converges to 1 as the power margin becomes large, and becomes smaller as the margin reduces. This is because, for a large margin, the outage will be small, in which case the adaptive CBF system almost always transmits. Thus, $\bar{P}_{CB} = E[P_{CB}]$. Conversely, as the margin decreases, the adaptive CBF system only transmits when the channel gain is above the threshold which leads to $\bar{P}_{CB} \leq E[P_{CB}]$. However, even if the margin is not enough to make the outage very small, we can increase the margin by having more relays, increasing the diversity order.

B. Average Power for Source Infomation Sharing

Let $Y = H_{min}$. Then, the average power for source information sharing is

$$\begin{aligned} \bar{P}_{SR} &= P_{SR}^{req} E\left[1/Y | Y \geq \frac{P_{SR}^{req}}{P_{max}}\right] \\ &= -\frac{P_{SR}^{req}}{\sigma_{sr}^2}\frac{E_i(-\eta_{sr})}{e^{-\eta_{sr}}} \end{aligned} \tag{19}$$

where $\eta_{sr} = \frac{\gamma_{th}(b_{SR})P_N}{P_{max}\sigma_{sr}^2} = \frac{P_{SR}^{req}}{P_{SR}^{rec}}$. P_{SR}^{req} is the required received power to meet the target SNR and P_{SR}^{rec} is the average received power. $E_i(\cdot)$ is the exponential integral function.

C. Probability of Transmission, p_{on}

The outage during the source information sharing phase is given by

$$\begin{aligned} p_{out}^{SR} &= \Pr\left(\frac{P_{max}}{P_N}H_{min} < \gamma_{th}(b_{SR})\right) \\ &= 1 - e^{-\eta_{sr}} \end{aligned} \tag{20}$$

Since $||\mathbf{g}||^2$ has a Gamma distribution with M degrees of freedom, the outage during the CBF phase is

$$p_{out}^{CB} = 1 - e^{-\eta_{cb}}\sum_{i=0}^{M-1}\frac{\eta_{cb}^i}{i!} \tag{21}$$

Then, the probability of transmission, p_{on}, is $(1 - p_{out}^{SR})(1 - p_{out}^{CB})$.

IV. Energy Efficiency of Direct Communication

In this section, we derive the energy efficiency of two different direct communication systems: non-adaptive and adaptive. For non-adaptive direct communication, the source node always transmits at the maximum allowed transmit power, P_{max}. In the adaptive system, the power is adjusted so that the bit error probability meets the target, p_{th}.

A. Non-Adaptive Direct Communication

The energy efficiency for the non-adaptive case is

$$\begin{aligned} EE_{nonadp} &= \frac{Lp_{sd}}{(P_{max}/\rho + 2P_C)\,T_{SD}} \\ &= \frac{(b_{SD}B)p_{sd}}{P_{max}/\rho + 2P_C} \end{aligned} \tag{22}$$

where b_{SD} is the bits/symbol for the direct link, $p_{sd} = 1 - p_{out}^{SD}$, and $T_{SD} = \frac{L}{b_{SD}B}$. For direct communication, we can easily find the outage probability, p_{out}^{SD}, as

$$\begin{aligned} p_{out}^{SD} &= \Pr\left(\frac{P_{max}}{P_N}|g_0|^2 < \gamma_{th}(b_{SD})\right) \\ &= 1 - e^{-\eta_{sd}} \end{aligned} \tag{23}$$

where $\eta_{sd} = \frac{\gamma_{th}(b_{SD})P_N}{P_{max}\sigma_g^2} = \frac{P_{SD}^{req}}{P_{SD}^{rec}}$. P_{SD}^{req} is the required received power to meet $\gamma_{th}(b_{SD})$ and P_{SD}^{rec} is the average received SNR.

B. Energy Efficiency of Adaptive Direct Communication

For large L, the energy overhead from training becomes negligible. Thus, the efficiency of adaptive direct communication is

$$\begin{aligned} EE_{adp} &= \frac{(b_{SD}B)p_{sd}}{\bar{P}_{SD}/\rho + 2P_C + \frac{E_{TR}b_{SD}B}{L}} \\ &\approx \frac{(b_{SD}B)p_{sd}}{\bar{P}_{SD}/\rho + 2P_C} \end{aligned} \tag{24}$$

As in Section III-B, we obtain $\bar{P}_{SD}$, as

$$\begin{aligned} \bar{P}_{SD} &= E[P_{SD}|P_{SD} \le P_{max}] \\ &= -\frac{P_{SD}^{req}}{\sigma_g^2}\frac{E_i(-\eta_{sd})}{e^{-\eta_{sd}}} \end{aligned} \tag{25}$$

where $P_{SD}(b_{SD}) = \frac{P_{SD}^{req}}{|g_0|^2}$.

V. Optimal Constellation Size

Previously, we only considered a fixed constellation size for transmission. However, we can improve the efficiency by deriving an optimal size. Here, we consider the optimal constellation size for CBF and direct communication with a maximum power constraint. First, the optimal size for CBF can be obtained by solving

$$(b_{SR}^*, b_{CB}^*) = \max_{b_{CB}, b_{SR}} EE_{CT}(b_{CB}, b_{SR}) \tag{26}$$

In (26), the maximum power constraint has been absorbed into the objective function. Since it is difficult to find a closed-form solution for this problem, we find the optimal solution by numerical search over b_{CB} and b_{SR}. Similarly, we choose the optimal constellation size for adaptive direct communication by maximizing

$$b_{SD}^* = \max_{b_{SD}} EE_{adp} \tag{27}$$

A numerical search is also used in this case.

VI. Results

In the simulations, we assume M relay nodes are uniformly distributed around the source node. The system parameters are listed in Table I unless otherwise stated. In Fig. 2, we present simulation and theoretical results for the energy efficiency (EE) of CBF and direct communication with 4-QAM. We observe that direct communication with power adaptation provides a higher EE for short distances. This is due to the fact that, in this case, the circuit power is more dominant than the transmission power. Thus, the energy overhead from increased circuit power by adding more relays outweighs the savings from CBF. However, as the transmission distance becomes larger, the circuit power becomes relatively smaller than the transmission power. Thus, CBF schemes with more relays perform better due to the beamforming gain that reduces the required transmit power. We see this behavior in Fig. 2.

TABLE I
System Parameters

Radius of relay set, R	10 m
Reference distance, d_0	1 m
Bandwidth, B	10 MHz
Amplifier efficiency, ρ	38 %
Path-loss exponent, β	3.0
Maximum power constraint, P_{max}	100 mW
Noise power spectral density, N_0	-174 dBm/Hz
Circuit power, P_C	100 mW
Target bit error probability, p_{th}	10^{-4}
Carrier frequency, f_c	2.5 GHz

In the simulations, we have assumed that the number of available transmission times, N_T, is limited by the coherence time, T_C, and is given as $N_T = \lfloor \frac{T_C}{T_S} \rfloor$. Thus, the total number of bits in a packet for direct communication can be represented as $L_D = N_T b_{SD}$, and the corresponding spectral efficiency (SE) is calculated as $\frac{L_D}{BT_{SD}}p_{sd}$. For the CBF system, the effective number of available transmission times is $N_{CT} = N_T - N_{OV}$ where N_{OV} represents the total number of transmission overhead symbols in the training and channel gain sharing phases. Using the fact that the total number of bits in a packet for the CBF system, L_{CT}, is the same for the source information sharing and CBF phases, $L_{CT} = \left\lfloor \frac{b_{CB}}{b_{CB}+b_{SR}} \right\rfloor N_{CT} b_{SR} = \left\lfloor \frac{b_{SR}}{b_{CB}+b_{SR}} \right\rfloor N_{CT} b_{CB}$. Thus, the SE can be calculated as $\frac{L_{CT}}{BT_{CT}}p_{on}$. The total transmission time to send L_{CT} bits is the sum of the transmission times during the source information sharing and CBF phases which is given by $T_{CT} = T_{SR} + T_{CB}$. In Fig. 3, the SE of CBF and direct communication is presented for 4-QAM. We notice that the SE of CBF is less than 2 for short distances due to the overhead. As the distance increases, the outage for direct communication increases faster than for CBF. Thus, the SE of direct communication is decreasing more rapidly.

In Figs. 4 and 5, we present the EE and SE for CBF and direct communication using the optimal constellation size, with $P_{max} = 40$ dBm. From the figures, we notice that the EE of CBF and direct communication is optimized by adopting higher order modulations at short distances, and the optimal size reduces as the distance increases. This is because, with increased distance, the outage increases, which worsens the EE. Thus, it is necessary to reduce the modulation size. We also observe that the EE for direct communication is now worse than CBF even using the optimal constellation size. This is due to the fact that, with increased P_{max}, direct communication has improved outage performance, but it also increases the required transmit power due to the increased chance of transmiting over worse channel condtions.

VII. Conclusion

In this paper, we presented an analysis of the energy efficiency of adaptive cooperative beamforming where the transmit power is adapted over the fading with a maximum power constraint. In the analysis, we considered the energy overhead incurred in forming cooperative beamforming, assuming a constant level of circuit power consumption. We showed that,

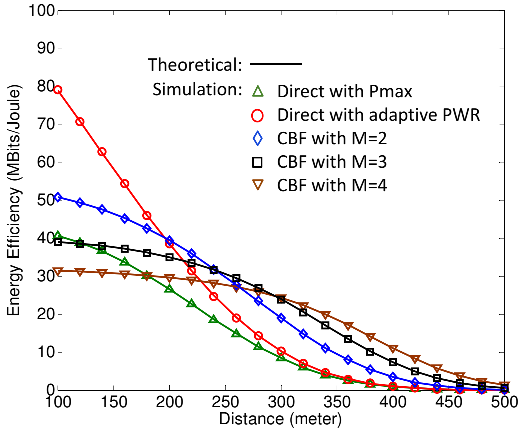

Fig. 2. Energy efficiency of CBF and direct communication with 4-QAM. With increasing distance, CBF outperforms direct communication since the transmission power becomes dominant compared to the circuit power.

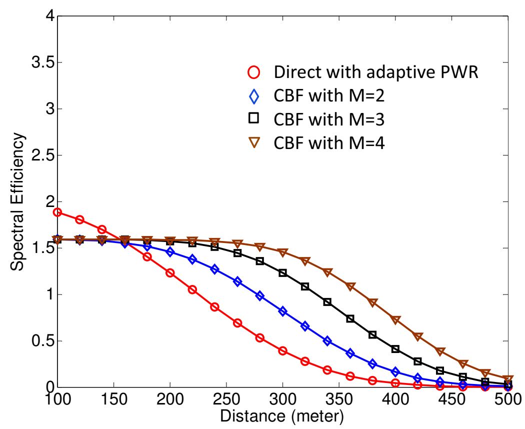

Fig. 3. Spectral efficiency of CBF and direct communication with 4-QAM. The spectral efficiency of direct communication decreases more rapidly than that for CBF because it has less diversity gain.

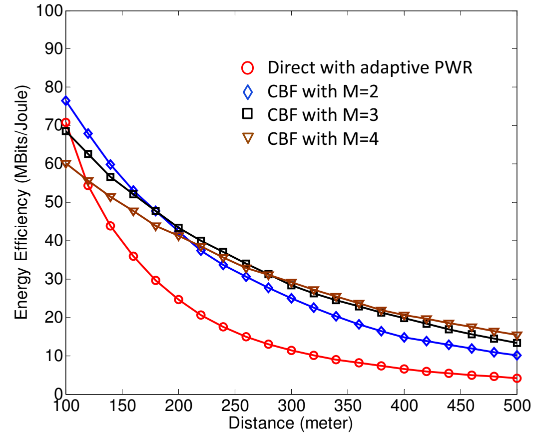

Fig. 4. Energy efficiency of CBF and direct communication with optimal constellation size and P_{max}=40 dBm. Using the optimal constellation size, CBF outperforms direct communication even at short distances.

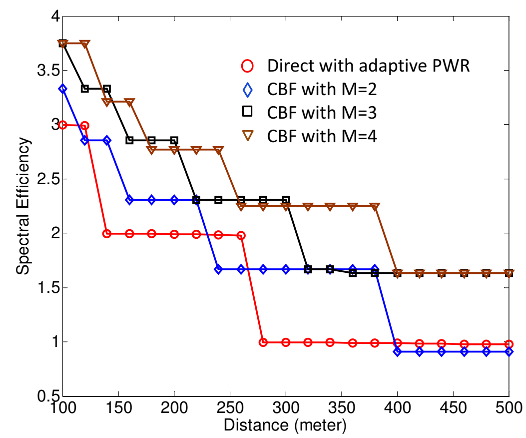

Fig. 5. Spectral efficiency of CBF and direct communication with optimal constellation size and P_{max}=40 dBm. CBF systems achieve higher spectral efficiency due to the beamforming gain.

even with an extra energy overhead, the cooperative beamforming system can provide both higher energy efficiency and spectral efficiency, using either fixed or adaptive modulation, compared to a system using direct communication. We also investigated the effect of a maximum power constraint on the energy efficiency, and cooperative beamforming, in this case, also achieved a higher energy efficiency.

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