Energy Efficient Comparison between Distributed MIMO and Co-located MIMO in the Uplink Cellular Systems

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***Abstract*—In this paper, we compare EE of the distributed MIMO (D-MIMO) and co-located MIMO (C-MIMO) in the uplink cellular systems since mobile stations are battery powered. The total energy consumption includes both the circuit energy consumption and the transmission energy. We get the closed-form expression for EE of D-MIMO and C-MIMO systems. What's more, an optimization algorithm is proposed to get the optimal EE values while satisfying given spectral efficiency (SE) requirement for both D-MIMO and C-MIMO systems. Simulation results show that the D-MIMO systems are more energy efficient than C-MIMO systems in composite fading channel, and the optimal EE value can be obtained by the proposed algorithm while satisfying given SE requirement.**

***Index Terms*—energy efficiency, distributed MIMO, co-located MIMO**

I. INTRODUCTION

Information and communication technology (ICT) is playing an increasingly important role in global greenhouse gas emissions since the amount of energy consumption for ICT increases dramatically with the exponential growth of service requirement [1]. Wireless communications, which is an important part of ICT, is responsible for energy saving. The mobile devices have limited battery resources. What's worse, the evolution of battery technology is much slower compared with the increase of energy consumption. Therefore, pursuing high energy efficiency (EE) is becoming more and more important in future wireless communications.

Various EE methods have been proposed for different layers of wireless communication networks. For network planning, it has been shown that reducing cell size can increase EE [2]. For physical layer, different transmission techniques such as orthogonal frequency division multiple access (OFDMA), multiple input multiple output (MIMO) techniques, and relay transmission have been reconsidered from the EE point of view instead of traditional spectral efficiency (SE). Energy efficient OFDM systems have been first addressed with consideration of circuit consumption in [3]. It has been demonstrated that there is at least a 20% reduction in energy consumption with performing EE optimization. In [4], cross-layer EE optimization in time, frequency, and spatial domains has been discussed in detail. It has been shown that using both power and modulation order adaptation, the EE-oriented design always consumes less energy than the traditional fixed power schemes. In [5]–[7], EE expressions have been derived considering the transmission associated electronic circuit energy consumption. In [5], it is shown that, by adapting modulation order to balance transmit power and circuit power consumption, MISO systems outperform single-input single-output (SISO) systems. A detailed circuit model has been discussed in [6]. However, to the best of the authors' knowledge, no closed-form expression for the EE of D-MIMO system has been proposed in the literatures.

In this paper, we consider both circuit and transmit power and derive an analytical EE expression. Energy efficient of D-MIMO and C-MIMO systems are compared in the uplink systems. What's more, we propose an optimization algorithm to get the sub-optimal EE for both D-MIMO and C-MIMO systems while satisfying given SE requirement.

The rest of this paper is organized as follows. The system model is presented in the second section. Section III introduces the average energy efficiency of D-MIMO and C-MIMO systems. An optimization algorithm is proposed in Section IV. In Section V, simulation results are described. Section VI concludes the paper.

Notation: In this paper, $(.)^T$, $(.)^H$ denote transpose and Hermitian transpose, respectively, I_k denotes identity matrix of size $k \times k$, det(A) denotes the determinant of A, $\otimes$ denotes the Kronecker product. The operator $E(.)$ denotes expectation.

II. SYSTEM MODEL

A. Distributed MIMO System and Channel Model

A D-MIMO system that employs N RAUs (Remote Access Unit), L antennas per RAU and M antennas the mobile terminal is referred to as (M, L, N) [8]. The D-MIMO system model is the same as [8]. We assume a single user scenario for simplicity of analysis. It is also assumed that the channel state information information (CSI) is unknown at the transmitter and perfectly known at the receiver, and a single cell is considered in the uplink systems. When $N = 1$, it becomes a C-MIMO system. The overall uplink received signal by the

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distance d is given by

$$Y = \mathbf{H}(d)X + z, \tag{1}$$

where Y and X are $NL \times 1$ received signal vector and $M \times 1$ transmitted signal vector, respectively. z is the complex additive white Gaussian noise vector with covariance matrix $E(zz^H) = \sigma_n^2 I_{NL}$. $d = [d_1, d_2, ..., d_N]^T$ is the distances from the N RAUs to the user. $\mathbf{H}(d) = [\mathbf{H}_1(d_1), \mathbf{H}_2(d_2), ..., \mathbf{H}_N(d_N)]^T$ is the channel matrix, where subchannel matrix $\mathbf{H}_n(d_n)$ in the composite fading channel is modeled as [9]

$$\mathbf{H}_n(d_n) = h_{sh,n}\mathbf{H}_{w,n}, \quad 1 \leq n \leq N, \tag{2}$$

where $\mathbf{H}_{w,n}$ is the small-scale fading channel, and the large scale fading can be expressed as [9]

$$h_{sh,n} = \sqrt{\frac{cs_n}{d_n^\alpha}}, \tag{3}$$

where α is the path loss exponent, c is the median of the mean path gain at a reference distance $d_n = 1km$, s_n is a log-normal shadow fading variable, $10 \lg s_n$ is a zero-mean Gaussian random variable with standard deviation σ_{sh}.

We assume that the cell shape is approximated by a circle of radius R and the mobiles are uniformly distributed in the cell. (D_n, θ_n) denotes the RAUs' polar coordinates, and (ρ, θ) denotes the mobile terminals polar coordinates, Then, the distance d_n from the n-th RAU to the mobile is calculated as [9]

$$d_n = \sqrt{\rho^2 + D_n^2 - 2\rho D_n \cos(\theta - \theta_n)}. \tag{4}$$

The probability density functions (PDF) of (ρ, θ) are given by

$$p(\rho) = \frac{2\rho}{R^2}, \quad 0 \leq \rho \leq R \tag{5}$$

$$p(\theta) = \frac{1}{2\pi}, \quad 0 \leq \theta \leq 2\pi. \tag{6}$$

B. Transceiver Circuit Power Models

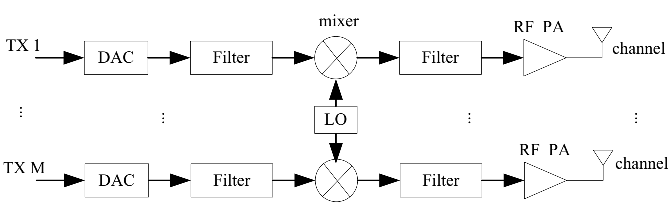

Fig. 1. M transmit antennas circuit blocks(analog)

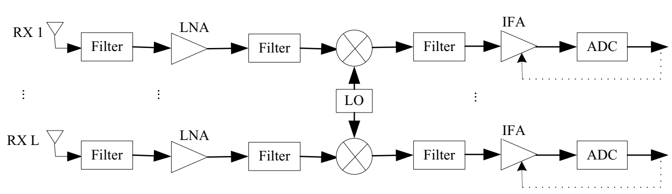

Fig. 2. L receive antennas circuit blocks(analog)

In order to maximize the EE, all signal processing blocks at the transmitter and the receiver should be included in the optimization model. We assume that the complicated signal processing techniques (e.g. digital modulation, multiuser detection iterative decoding) are not considered for simplicity of analysis. The resultant signal paths on the transmitter and receiver sides are shown in Fig. 1 and 2, respectively [5], where M and L are the numbers of transmitter and receiver antennas, respectively, and we also assume that the frequency synthesizer which is as a local oscillator (LO) is shared among all the antenna paths. The total average power consumption contains two main parts: the power consumption of all the power amplifiers and the power consumption of all the other circuit blocks.

The power consumption of the first part can be approximated as [5]

$$P_{PA} = (1 + \beta)P_t, \tag{7}$$

where P_t is the transmission power, $\beta = \frac{\xi}{\eta} - 1$ with η the drain efficiency of the RF power amplifier and ξ the peak-to-average ratio (PAR), which is dependent on the modulation scheme and the associated constellation size [5].

The circuit power consumption of C-MIMO can be written as [5]

$$\begin{aligned} P_{c\_CMIMO} =& M(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} \\ &+ NL(P_{LNA} + P_{mix} + P_{IFA} + P_{filr}) \\ &+ NLP_{ADC}, \end{aligned} \tag{8}$$

where P_{DAC}, P_{mix}, P_{filt}, P_{syn}, P_{LNA}, P_{IFA}, P_{filr} and P_{ADC} are the power consumption values for the DAC, the mixer, the active filters at the transmitter side, the frequency synthesizer, low noise amplifiers (LNA), the intermediate frequency amplifier (IFA), the active filters at the receiver side, and the ADC, respectively. To estimate the values of P_{DAC} and P_{ADC}, we use the model introduced in [6]. The related circuit parameters are defined in Table I, where the power consumption values of various circuit blocks have discussed in [6].

The RAUs are low complexity processing nodes and equipped only with up/down converters and LNA. So the circuit power consumption of D-MIMO can be written as

$$\begin{aligned} P_{c\_DMIMO} =& M(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} \\ &+ NP_{LNA} + NL(P_{LNA} + P_{mix} + P_{IFA}) \\ &+ NL(P_{filr} + P_{ADC}). \end{aligned} \tag{9}$$

III. The Energy Efficiency of D-MIMO and C-MIMO Systems

In this paper, we define EE as the ratio of SE over the total energy consumption (unit:bit/J/Hz):

$$\eta_{EE}(C) = \frac{C}{(1 + \beta)P_t(C) + P_c}, \tag{10}$$

where C is the SE, P_t is the transmit power. The uplink celluar system is optimized for the highest EE. Thus, the intended SE is

$$C^* = \arg\max_C \eta_{EE}(C)$$
$$= \arg\max_C \frac{C}{(1+\beta)P_t(C)+P_c}. \quad (11)$$

A. Lower Bound (LB) of Energy Efficiency in D-MIMO System with $M \le L$

In this paper, we assume that the number of mobile terminal antennas M is less than L. The mutual information (MI) of the corresponding D-MIMO channel can be expressed as [9]

$$I = \log_2 \det[I_{NL} + \frac{P_t}{M\sigma_n^2}\mathbf{H}(d)\mathbf{H}^H(d)]$$
$$= \log_2 \det[I_M + \frac{P_t}{M\sigma_n^2}\mathbf{H}^H(d)\mathbf{H}^H(d)]. \quad (12)$$

Substituting (2) and (3) into (12), we get

$$I = \log_2 \det[I_M + \frac{P_t}{M\sigma_n^2}\mathbf{H}_w^H(S\otimes I_L)\mathbf{H}_w], \quad (13)$$

where

$$\mathbf{H}_w = [\mathbf{H}_{w,1}, \mathbf{H}_{w,2}, ..., \mathbf{H}_{w,N}]^T, \quad (14)$$

$$S = \begin{bmatrix} cs_1/d_1^\alpha & & \\ & \ddots & \\ & & cs_N/d_N^\alpha \end{bmatrix}. \quad (15)$$

Theorem 1: For (M, L, N) D-MIMO system, suppose that $M \le L$ and the distances from the user to the RAUs are known. At high SNR, the upper bound transmission power of D-MIMO system can be written as (16), shown at the top of next page.

Proof: When $M \le L$ and SNR is large, using the Minkowski inequality [9], [10], we can get

$$C(\rho,\theta) \ge ME_{s,H}\{\log_2[1+\frac{cP_t}{M\sigma_n^2}\sum_{n=1}^{N}\frac{s_n}{d_n^\alpha}\times\det(\mathbf{H}_{w,n}^H\mathbf{H}_{w,n})^{\frac{1}{M}}]\}$$
$$\approx M\log_2\frac{cP_t}{M\sigma_n^2}$$
$$+ M\log_2\sum_{n=1}^{N}\frac{1}{d_n^\alpha}E_s(s_n)E_H[\det(\mathbf{H}_{w,n}^H\mathbf{H}_{w,n})^{\frac{1}{M}}]. \quad (17)$$

Applying theorem 2.11 in [9], [11], yields

$$E_H[\det(\mathbf{H}_{w,n}^H\mathbf{H}_{w,n})^{\frac{1}{M}}] = \frac{\prod_{i=0}^{M-1}\Gamma(L-i+\frac{1}{M})}{\prod_{i=0}^{M-1}\Gamma(L-i)}, \quad (18)$$

where $\Gamma(.)$ is the Gamma function. Then we can get

$$C(\rho,\theta) = M(\log_2\frac{cP_t}{M\sigma_n^2R^\alpha} + \frac{\lambda^2\sigma_{sh}^2}{2In2} - \sum_{i=0}^{M-1}\log_2\Gamma(L-i))$$
$$+ M(\sum_{i=0}^{M-1}\log_2\Gamma(L-i+\frac{1}{M}) + \log_2\sum_{n=1}^{N}\frac{1}{d_n^\alpha}). \quad (19)$$

where $\lambda = \frac{\ln 10}{10}$. The lower bound SE of D-MIMO channel can be written as [9]

$$\overline{C}_{D-MIMO,LB} = M(\sum_{i=0}^{M-1}\log_2\Gamma(L-i+\frac{1}{M}) + \frac{\alpha+\lambda^2\sigma_{sh}^2}{2\ln 2})$$
$$+ M(\log_2\sum_{n=1}^{N}\exp(-\frac{\alpha D_n^2}{2R^2}) + \log_2\frac{cP_t}{M\sigma_n^2R^\alpha})$$
$$- M(\sum_{i=0}^{M-1}\log_2\Gamma(L-i)). \quad (20)$$

Then the expression of the upper bound transmission power (16) can be obtained immediately. So, the lower bound EE of D-MIMO system can be written as

$$\eta_{DMIMO\_EE} = \frac{\overline{C}_{D-MIMO,LB}}{(1+\beta)P_{T\_DMIMO}+P_{c\_DMIMO}}. \quad (21)$$

B. Upper Bound (UB) of Energy Efficiency in D-MIMO System with $M \le L$

Theorem 2: For (M, L, N) D-MIMO system, suppose that $M \le L$ and the distances from the RAUs to user are known. At high SNR, the lower bound transmission power of D-MIMO system is given as (22), shown at the top of next page.

Proof: When $M \le L$, using the following inequality [10]

$$|\det(A+B)| \le [\det(I+AA^H)\det(I+BB^H)]^{\frac{1}{2}},$$

we can write (12) as

$$I \le \frac{1}{2}\log_2[\det(I_M+I_MI_M^H)\det(I_M+BB^H)]$$
$$= \frac{M}{2} + \frac{1}{2}\log_2[\det(I_M+BB^H)], \quad (23)$$

where

$$B = \frac{cP_t}{NL\sigma_n^2}\sum_{n=1}^{N}\frac{s_n}{d_n^\alpha}\mathbf{H}_{w,n}^H\mathbf{H}_{w,n}.$$

At high SNR, we can upper bound the MI in (23) as

$$C(\rho,\theta) = \frac{M}{2} + E_{s,H}\{\log_2\det(B)\}$$
$$= \frac{M}{2} + E_s\{M\log_2\frac{cP_t}{M\sigma_n^2}\sum_{n=1}^{N}\frac{s_n}{d_n^\alpha}\}$$
$$+ E_H\{\log_2[\det\mathbf{H}_{w,n}^H\mathbf{H}_{w,n}]\}$$
$$= M(\frac{1}{2} + \log_2\frac{cP_t}{M\sigma_n^2} + \frac{\lambda^2\sigma_{sh}^2}{2\ln 2} + \log_2\sum_{n=1}^{N}\frac{1}{d_n^\alpha})$$
$$+ \sum_{i=0}^{M-1}\log_2\Gamma(L-i+1) - \sum_{i=0}^{M-1}\log_2\Gamma(L-i). \quad (24)$$

$$P_{t\_DMIMO,UB} = \frac{MR^{\alpha}\sigma_n^2}{c} 2^{\frac{C_{D-MIMO}}{M} - \frac{\alpha+\lambda^2\sigma_{sh}^2}{2\ln 2} - \log_2 \sum_{n=1}^{N} \exp(-\frac{\alpha D_n^2}{2R^2}) - \sum_{i=0}^{M-1} \log_2 \Gamma(L-i+\frac{1}{M}) + \sum_{i=0}^{M-1} \log_2 \Gamma(L-i)}. \tag{16}$$

$$P_{t\_DMIMO,LB} = \frac{MR^{\alpha}\sigma_n^2}{c} 2^{(C_{D-MIMO} - \frac{M}{2} - M\frac{\alpha+\lambda^2\sigma_{sh}^2}{2\ln 2} - M\log_2 \sum_{n=1}^{N} \exp(-\frac{\alpha D_n^2}{2R^2}) - \sum_{i=0}^{M-1} \log_2 \Gamma(L-i+1) + \sum_{i=0}^{M-1} \log_2 \Gamma(L-i))/M} \tag{22}$$

Then we can get the upper bound SE

$$\begin{aligned} \overline{C}_{DIMO,UB} =& \frac{M}{2} + M\log_2 \frac{cP_t}{MR^{\alpha}\sigma_n^2} + M\frac{\alpha+\lambda^2\sigma_{sh}^2}{2\ln 2} \\ &+ \sum_{i=0}^{M-1} \log_2 \Gamma(L-i) - \sum_{i=0}^{M-1} \log_2 \Gamma(L-i) \\ &+ M\log_2 \sum_{n=1}^{N} \exp(-\frac{\alpha D_n}{2R^2}). \end{aligned} \tag{25}$$

Then the expression of the lower bound transmission power (22) can be obtained immediately. So, the upper bound EE of D-MIMO system can be written as

$$\eta_{DMIMO\_EE} = \frac{\overline{C}_{DIMO,UB}}{(1+\beta)P_{t\_DMIMO} + P_{c\_DMIMO}}. \tag{26}$$

C. The Energy Efficiency of C-MIMO System

We assume that all of the NL antennas are collocated at the center of a cell for the C-MIMO system. From (12), the MI of the C-MIMO system can be written as

$$I_{C-MIMO} = \log_2 \det[I_M + \frac{cP_t}{Md^{\alpha}} s\mathbf{H}_w^H \mathbf{H}_w]. \tag{27}$$

At high SNR, the approximated capacity is given by [9], [12]

$$\overline{C}_{CMIMO} = M_1 \log_2 \frac{cP_t}{MR^{\alpha}\sigma_n^2} + \frac{\alpha M_1}{2In2} + \frac{1}{\ln 2}\sum_{i=0}^{M_1-1} \psi(M_2-i), \tag{28}$$

where $M_1 = min(NL, M)$, $M_2 = max(NL, M)$. So we can get the transmit power as

$$P_t = \frac{MR^{\alpha}\sigma_n^2}{c} 2^{(\overline{C}_CMIMO - \frac{\alpha M_1}{2\ln 2} - \frac{1}{In2}\sum_{i=0}^{M_1-1}\psi(M_2-i))/M_1}. \tag{29}$$

And the EE of C-MIMO system can be written as

$$\eta_{CMIMO\_EE} = \frac{C_{C\_MIMO}}{(1+\beta)P_{t\_CMIMO} + P_{c\_CMIMO}}. \tag{30}$$

IV. OPTIMIZATION ALGORITHM

Given SE requirement, the optimal EE problem can be modeled as

$$\begin{aligned} \min \quad & f(C) = -\eta(C) \\ s.t. \quad & a_1 \le C \le b_1, \end{aligned}$$

where a_1 and b_1 are the minimum and maximum value of SE, respectively. It is seen that the task is to find the most efficient SE so that the EE is maximized. Based on the heuristics method [13], we propose an optimal algorithm to get the maximum EE. It can be expressed as follows:

- ***Step 1:*** Given initial SE interval $[a_1, b_1]$ and the final interval length L, let

  $$F_n \ge (b_1 - a_1)/L,$$

  Where F_n is Fibonacci Series. Then, find the simulation times n, set the identify constant $\delta > 0$ and calculate the test point λ_1 and μ_1

  $$\lambda_1 = a_1 + \frac{F_{n-2}}{F_n}(b_1 - a_1), \mu_1 = a_1 + \frac{F_{n-1}}{F_n}(b_1 - a_1).$$

  Then calculate $f(\lambda_1)$ and $f(\mu_1)$, let $k = 1$;
- ***Step 2:*** If $f(\lambda_1) > f(\mu_1)$, go to step 3. Otherwise, go to step 4;
- ***Step 3:*** Let $a_{k+1} = \lambda_k$, $b_{k+1} = b_k$, $\lambda_{k+1} = \mu_k$, calculate the test point μ_{k+1},

  $$\mu_{k+1} = a_{k+1} + \frac{F_{n-k-1}}{F_{n-k)}}(b_{k+1} - a_{k+1}).$$

  If $k = n-2$, go to step 6. Otherwise, calculate $f(\mu_{k+1})$, go to step 5;
- ***Step 4:*** Let $a_{k+1} = a_k$, $b_{k+1} = \mu_k$, $\mu_{k+1} = \lambda_k$, calculate the test point λ_{k+1},

  $$\lambda_{k+1} = a_{k+1} + \frac{F_{n-k-2}}{F_{n-k)}}(b_{k+1} - a_{k+1}).$$

  If $k = n-2$, go to step 6. Otherwise, calculate $f(\lambda_{k+1})$, go to step 5;
- ***Step 5:*** Let $k = k+1$, go to step 2;
- ***Step 6:*** Let $\lambda_n = \lambda_{n-1}$, $\mu_n = \lambda_{n-1} + \delta$, calculate $f(\lambda_n)$ and $f(\mu_n)$,
  If $f(\lambda_n) > f(\mu_n)$, let $a_n = \lambda_n, \quad b_n = b_{n-1}$.
  If $f(\lambda_n) \le \eta(\mu_n)$, let $a_n = \lambda_{n-1}, \quad b_n = \lambda_n$.
  Stop the algorithm.

We can get the most efficient transmission SE $C^* = (a_n + b_n)/2$ and corresponding optimal EE value, which can be expressed as $\eta_{opt} = \eta(C^*)$.

V. SIMULATION RESULTS

The simulation and circuit parameters are listed in Table I. (1,1,5) and (2,2,7) D-MIMO systems, and the corresponding

(1,5,1) and (2,14,1) C-MIMO systems are considered. For the cell with 7 RAUs, the polar coordinates of the RAUs are

$$(D_1,0),(D_2,2\pi/3),(D_3,2\pi/3),(D_4,5\pi),\\(D_5,4\pi/3),(D_6,5\pi/3),(D_7,2\pi),$$

where $D_1 = D_2 = D_3 = D_4 = D_5 = D_6 = D_7 = R/2$. For the cell with 5 RAUs, the polar coordinates of the RAUs are

$$(D_1,0),(D_2,0),(D_3,\pi/2),(D_4,\pi),(D_5,3\pi/2),$$

where $D_1 = D_2 = D_3 = D_4 = D_5 = R/2$.

TABLE I
CIRCUIT AND SYSTEM PARAMETERS

$\sigma_n^2 = -104dBm$	$R = 1Km$
$P_{mix} = 30.3mW$	$P_{syn} = 50.0mW$
$P_{filt} = P_{filr} = 2.5mW$	$P_{LNA} = 20mW$
$P_{IFA} = 3mW$	$\eta = 0.35$
$\alpha = 3.7$	$\sigma_{sh} = 8dB$

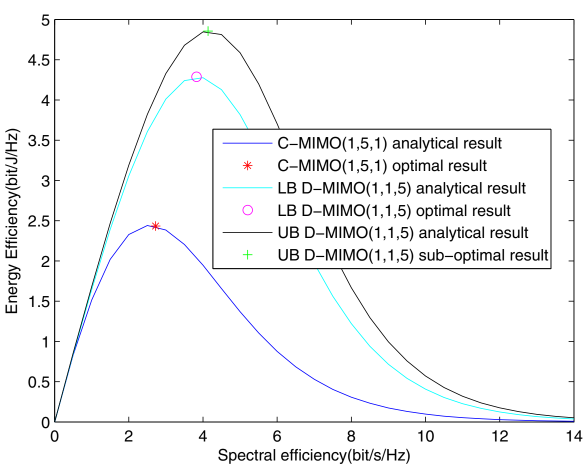

Fig. 3. Comparison of energy efficiency with $M \leq L$ $(M = 1)$

Fig.3-4 compare the EE of the D-MIMO and C-MIMO systems. When $M = 1$, in Fig.3, it is shown that the EE of (1,1,5) D-MIMO system is approximately 120%∼150% higher than the (1,5,1) C-MIMO system when SE is 4bit/s/Hz. When $M = 2$, in Fig.4, it is shown that the EE of (2,2,7) D-MIMO system is approximately 40%∼60% higher than the (2,14,1) C-MIMO system when SE is 9bit/s/Hz. From Fig.3-4, we can draw the conclusion that compared with C-MIMO systems, D-MIMO systems can significantly improve EE. The reason is that the average access distance between the RAU and user is decreased. So the transmit power is also decreased and the EE of D-MIMO systems is increased. We can also see that the optimal EE value can be obtained by the proposed algorithm when the SE range is from 1 to 10 bit/s/Hz.

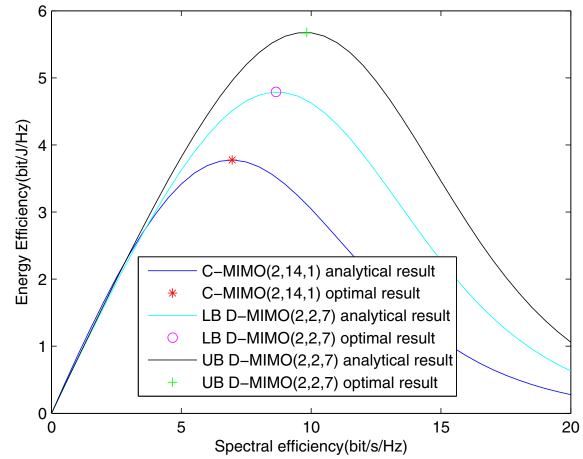

Fig. 4. Comparison of energy efficiency with $M \leq L$ $(M = 2)$

VI. CONCLUSION

In this paper, we compared EE of D-MIMO and C-MIMO in a composite Rayleigh-lognormal channel. Both circuit and transmit energy consumption are taken into account. Simulation results show that D-MIMO systems can significant improve EE when compared to CMIMO systems.

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