Energy-Efficient Power Allocation Scheme Based on Discrete-Rate Adaptive Modulation in Distributed Antenna System

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Abstract. In this paper, the energy efficiency (EE) for a distributed antenna system (DAS) with discrete-rate adaptive modulation (AM) is investigated, and an optimal adaptive power allocation (PA) scheme for maximizing EE is developed. First of all, the system model of DAS based on discrete-rate AM is presented. Then, subject to transmit power per antenna and target bit error rate (BER), a constrained optimized problem is formulated to maximize EE of DAS. By solving KKT conditions, we derive the optimal solution as a closed form. The obtained closed-form expression is applicable to DAS with an arbitrary number of distributed antennas (DA) ports and general per-DA port power and target BER constraints. To illustrate the validity of the developed scheme, the exhaustive search method is used in the simulation to compare with the developed scheme. As a result, the proposed power allocation method produces the EE and spectrum efficiency (SE) identical to the exhaustive search method with remarkably reduced computational complexity. Moreover, the EE and SE of the DAS with AM increase as the target BER increases.

Keywords: Energy efficiency · Optimal power allocation
Discrete-rate adaptive modulation · Distributed antenna system
Spectrum efficiency

1 Introduction

Green communication, which pursues lower energy consumption and higher energy efficiency in wireless communication systems, has drawn increasing attention nowadays. In order to provide massive connections from various terminals, including not only smartphones but also machine-type communication devices with diverse quality of service (QoS) requirements, the 5G mobile network is required to have tremendous EE improvement. Energy efficiency (EE) is

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defined as the ratio of the sum-rate to the total power consumption measured in bit/Hz/Joule. Various energy efficient methods have been proposed to improve the EE [1–4].

A key technology for green communication is a distributed antenna system (DAS). Compared with a conventional antenna system (CAS), which has centralized antennas at the central location, higher energy efficiency can be obtained in DAS. The reason why the distributed antenna system can achieve higher energy efficiency is that its structure makes the user closer to the antenna. Actually, the distributed antenna (DA) ports in DAS are distributed in different locations of the cell. As the locations of DA are different, the distances between the users and antennas are different, which brings different pass losses. In DAS, the large scale fading like pass loss needs to be taken into account. Consequently, compared with the CAS, where the average access distance between the user and antennas is longer, the transmit power and co-channel interference can be substantially reduced in DAS due to smaller access distance.

Adaptive modulation can select the most appropriate modulation, based on the current channel state information (CSI) [5]. It was shown that adaptive modulation can effectively improve the capacity, spectral efficiency (SE) and bit error rate (BER) performance of the system. Reference [6] demonstrated that adaptive modulation can improve the transmission rate and energy efficiency in fading channels. In [7], the performance of adaptive modulation was systematically observed in MIMO systems. The closed-form expressions of average SE and BER are given, respectively. Considering the incomplete CSI, [8] investigated the performance of adaptive modulation in a DAS, and the closed-form of the SE and average BER were presented.

However, the works above basically address the SE and BER study of DAS with AM, and the EE performance is studied less. Moreover, the superiority of power allocation (PA) is not considered, and the resultant system performance is limited. For this, we give the energy-efficient power allocation scheme with adaptive modulation in [9], but the modulation mode is based on continuous rate, that is, the modulation method continuously changes. Whereas in practice, the modulation mode need to work in discrete rate.

Motivated by the reason above, in this paper, we will study the power allocation of DAS with AM for obtaining more practical application and superior EE performance, where discrete-rate adaptive modulation and power allocation are both considered. We firstly present the system model of DAS with discrete-rate modulation. In constraint of the maximum transmit power and target BER, a constrained optimized problem is then formulated to maximize the EE of DAS. By using the KKT conditions, a general expression of optimal PA is derived. With this result, the optimal solution having closed form is further derived, and an effective algorithm is presented to achieve the optimal power allocation.

2 System model

We consider a downlink single cell DAS with N DA ports, denoted as $DA_i, i = 1, 2, \ldots N$, and all DA ports are connected to central processing unit (CPU) via dedicated channels, such as optical fibers. Considering the implementation of mobile station (MS) as well as its limitation of volume and size, only single receive antenna is available at the MS. The location of the mobile station (MS) is random. The adaptive modulation and transmit power adjustment are performed by the CPU based on the channel information feedback. When the CSI changes, the current modulation mode and transmit power will be changed accordingly (Fig. 1).

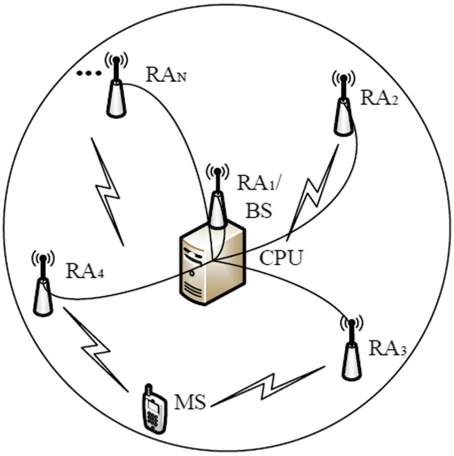

Fig. 1. Structure of DAS.

Assuming that both the transceiver and the receiver know the channel state information, the effective signal-to-noise ratio (SNR) at the MS can be expressed as

$$\rho = \sum_{i=1}^{N} \gamma_i P_i \tag{1}$$

where P_i is the transmit power of the i-th DA port DA_i, γ_i denotes the ratio of power gain to noise power between the i-th DA and MS. We take path loss, shadow fading and Rayleigh fading into account.

$$\gamma_i = \frac{d_i^{-\alpha_i} S_i |h_i|^2}{\sigma_z^2} \tag{2}$$

where d_i denotes the distance between the i-th DA and MS, α_i is the path loss exponent, shadowing fading S_i is a log-normal shadow fading variable with the standard deviation σ_i, h_i indicates the independent and identically distributed circularly symmetric complex Gaussian channel coefficient between the i-th distributed antenna and MS with zero mean and unit variance, σ_z^2 represents the noise power.

Considering high efficiency, MQAM is used for the AM scheme. For the two-dimensional Gray coded MQAM modulation, the instantaneous bit error rate of the n-th modulation scheme under additive white Gaussian noise (AWGN) channel can be tightly approximated as [10].

$$BER_n(\rho) \simeq a_n \, erfc(\sqrt{b_n \rho}) \tag{3}$$

where a_n and b_n are parameters of the n-th MQAM modulation,$n = 1, 2, \ldots, M$, $erfc(\cdot)$ is a complementary error function. By setting the instantaneous bit error rate of the system equal to the target BER(BER_0), the switching threshold of the n-th modulation can be given by

$$\phi_n = [erfc^{-1}(BER_0/a_n)]^2/b_n \tag{4}$$

where $erfc^{-1}(\cdot)$ denotes the inverse complementary error function. When the effective SNR falls into the n-th region, i.e., $\phi_n \leq \sum_{i=1}^{N} \gamma_i P_i \leq \phi_{n+1}$, the n-th MQAM modulation is employed for the current modulation mode.

3 Optimal Power Allocation Scheme

In this section, we will develop an optimal power allocation scheme for DAS with discrete-rate adaptive modulation by maximizing the EE, and the corresponding algorithm for calculating the PA is also presented.

The EE for DAS is defined as

$$\eta_{EE} = \frac{R}{\sum_{i=1}^{N} P_i + P_c} \tag{5}$$

where P_c denotes the circuit power, which is a constant value, R represents the transmission rate. Considering the discrete-rate adaptive modulation, the EE under different SNR conditions can be given by

$$\eta_{EE} = \begin{cases} 0 & \sum_{n=1}^{N} \gamma_i P_i < \phi_1 \\ \dfrac{R_1}{\sum_{i=1}^{N} P_i + P_c} & \phi_1 \leq \sum_{i=1}^{N} \gamma_i P_i < \phi_2 \\ \vdots & \vdots \\ \dfrac{R_M}{\sum_{i=1}^{N} P_n + P_c} & \sum_{i=1}^{N} \gamma_i P_i \geq \phi_M \end{cases} \tag{6}$$

where $R_n = log_2 Q_n (n = 1, 2, \ldots M)$ denotes the transmission rate of the n-th MQAM with size Q_n, and it is constant.

By maximizing the (6) subject to maximum power constraint, we can get the optimal power allocation scheme. However, we find that it is difficult to optimize the piecewise function (6) directly. For this, we firstly optimize each segment of (6) separately, and the respective results are then compared to obtain an optimal solution which corresponding to the maximum EE.

According to (6), and considering maximum power constraint, the energy efficiency optimization problem for the n-th modulation can be written as

$$\begin{aligned} \max_{\boldsymbol{P}(n)} \eta_{EE,n} &= \frac{R_n}{\sum_{i=1}^{N} P_i + P_c} \\ s.t.\ \phi_n &\le \sum_{i=1}^{N} \gamma_i P_i < \phi_{n+1} \\ 0 &\le P_i \le P_{max,i} \end{aligned} \tag{7}$$

where $P_{max,i}$ indicates the maximum power of the i-th RA. Without loss of generality, we assume that all γ_i are different due to the structure of DAS, and they are sorted in descending order as

$$\gamma_1 > \gamma_2 > \cdots > \gamma_N \tag{8}$$

By means of the KKT conditions, we can analytically solve the optimization problem of the DAS with general per DA port power constraint. According to the KKT conditions, the optimal values ρ_i^*, κ, λ, μ_i, v_i should satisfy the following equations:

$$-\frac{R_n}{(\sum_{i=1}^{N} P_i^* + P_c)^2} - \kappa\gamma_i + \lambda\gamma_i + \mu_i - v_i = 0 \tag{9}$$

$$\kappa(\phi_{n+1} - \sum_{i=1}^{N} \gamma_i P_i^*) = \lambda(\sum_{i=1}^{N} \gamma_i P_i^* - \phi_n) = \mu_i P_i^* = v_i(P_{max,i} - P_i^*) = 0 \tag{10}$$

$$\kappa, \lambda, \mu_i, v_i \ge 0 \tag{11}$$

where κ, λ, μ_i, v_i are the Lagrangian multipliers.

According to (9–11), by means of mathematical derivation, we can obtain $\sum_{i=1}^{N} \gamma_i P_i^* = \phi_n$, and the corresponding general expression of the optimal power allocation for the n-th modulation, i.e., it is expressed as

$$\boldsymbol{P}^*(n) = [P_{max,1}, \ldots, P_{max,N_0-1}, P_{N_0}^*, 0, \ldots, 0]^T \tag{12}$$

and

$$\begin{aligned} N_0 &= \max_{1 \le k \le N} \{j : \sum_{i=1}^{j-1} \gamma_i P_{max,i} < \xi\} \\ P_i^* &= P_{max,i}, 1 \le i \le N_0 \\ P_{N_0}^* &= (\rho - \sum_{i=1}^{N_0-1} \gamma_i P_{max,i})/N_0 \end{aligned} \tag{13}$$

The detailed derivation on Eqs. (12) and (13) is not provided because of the paper length limitation. With (12) and (13), we can calculate the EE of the system with n-th modulation, i.e., $\eta_{EE,n}$, $n = 1, 2, \ldots, M$. By comparing the obtained $\{\eta_{EE,n}\}$, the optimal PA and modulation mode can be attained, which corresponds to maximum $\eta_{EE,n}$. In other words, if $n^* = arg\max_{n=1,2,\ldots M}\{\eta_{EE,n}\}$, then the n^*-th modulation mode is selected for data transmission, and the corresponding PA is the optimal one.

Besides, considering that $\sum_{i=1}^{N}\gamma_i P_{max,i}$ is the achievable maximum SNR of the system under current channel conditions, we can determine which modulation mode can be used in the current channel by comparing this maximum SNR and the switching threshold. Namely, When $\phi_n \le \sum_{i=1}^{N}\gamma_i P_{max,i} \le \phi_{n+1}$, the n-th method of modulation will be used, and when $\phi_n > \sum_{i=1}^{N}\gamma_i P_{max,i}$, the n-th method of modulation will not be employed. Furthermore, when $\sum_{i=1}^{N}\gamma_i P_{max,i} < \phi_1$, even the lowest modulation will not be used, and thus the communication will be interrupted.

According to the analysis above, the algorithm of optimal power allocation for EE maximization with adaptive modulation in DAS can be summarized in Table 1.

Table 1. Power allocation method.

Algorithm 1

1. Sort all the $\{\gamma_i, i = 1, , N\}$ in descending order;
2. Calculate the switching thresholds $\{\phi_n\}, n = 1, 2, ..., M$, of all the modulations according to (4);
3. Calculate $\sum_{i=1}^{N}\gamma_i P_{max,i}$;
4. Initialize $n = 1, \boldsymbol{P}_{opt} = 0, \eta_{opt} = 0$;
5. If $\phi_n \le \sum_{i=1}^{N}\gamma_i P_{max,i}$
    continue 6;
   Else
    go to 11;
   End
6. Calculate the optimal PA for n-th modulation method $\boldsymbol{P}^*(n)$ according to (12) and (13);
7. Calculate the EE of the n-th modulation method $\eta_{EE,n}$ based on $\boldsymbol{P}^*(n)$ using (7);
8. If $\eta_n > \eta_{opt}$
    continue 9
   Else step to 10;
   End
9. $\boldsymbol{P}_{opt} = \boldsymbol{P}_n$, $\eta_{opt} = \eta_n$;
10. $n = n + 1$, step to 5;
11. If $n = 1$
    return "communication outage";
   Else continue 12;
   End
12. Return the optimal power allocation $\boldsymbol{P}_{opt}$, and maximum EE η_{opt} .

Moreover, it is worth mentioning that not only our proposed optimal scheme is applicable to MQAM, but also can be applied to MPSK. And what varies is only the instantaneous BER and further the switching thresholds need to be recalculated.

4 Simulation Results and Analysis

In this section, we evaluate the performance of the proposed scheme through computer simulations. To illustrate the validity of the scheme, an exhaustive search method, which examines all possible power allocation combinations with a resolution 0.01 in the range of 0 to $P_{max,i}$, is used to compare with the algorithm presented in Sect. 3. We choose six modulation modes for adaptive modulation in simulations, i.e., BPSK, 4QAM, 8QAM, 16QAM, 32QAM and 64QAM. For simplicity, we assume that $P_{max,i} = P_{max}, \alpha_i = \alpha = 3$, and $\sigma_i = \sigma = 8dB$ for $\forall i$ throughout the simulations. For DAS with N DA ports, one DA port is set in the center of the cell located at (0,0), and the others are located at $(\sqrt{3/7}R, 2\pi i/(N-1)), i = 1, 2, \ldots, N-1$. The radius of the cell $R = 1000$ m. We set $P_{max} = 1W$ and the circuit power $P_c = 5W$ in simulation. The computer we used for simulation is an AMD 2.2-GHz dual core with 3.25 GB of RAM, and the simulation software is MATLAB 2012b.

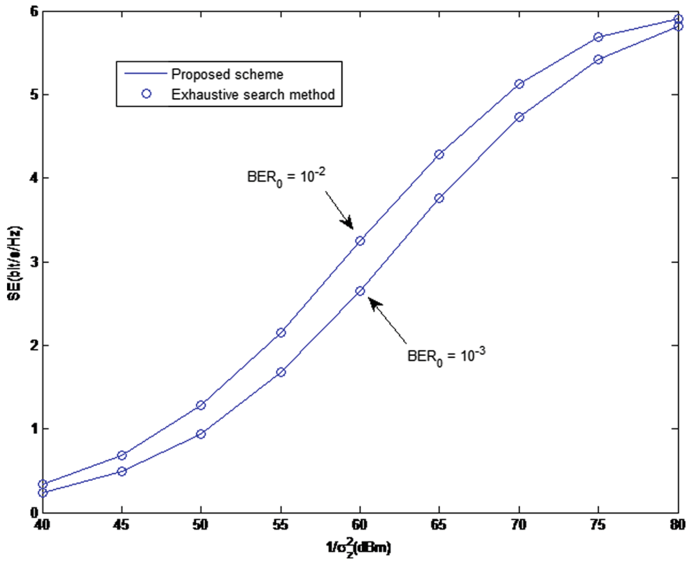

Fig. 2. SE of DAS with AM for different BER_0.

In Fig. 2, we plot the system SE as a function of the reciprocal of the maximal transmit power $1/\sigma_z^2$ for different BER_0 and three DA ports, where $BER_0 = 10^{-2}, 10^{-3}$. As shown in Fig. 2, the performance of the proposed scheme is identical to that of exhaustive search method, but our scheme has lower complexity than the latter. Explicitly, the running time of the proposed scheme is 0.21 s only, while the exhaustive search method needs 326 s. Hence, our scheme obviously reduces the complexity and has much less running time. Moreover, with the increase of the target BER, the SE also increases. This is due to the fact that the larger the BER_0 is, the lower is the BER performance requirement of the system. Thus higher order modulation mode will be selected and the resultant SE increases as well.

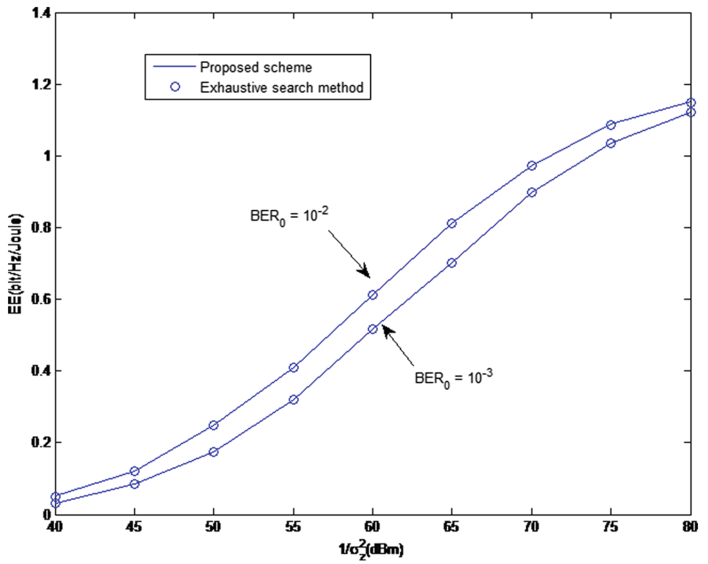

Fig. 3. EE of DAS with AM for different BER_0.

Figure 3 illustrates the EE of the DAS with AM and three DA ports for different tar-get BER, where $BER_0 = 10^{-2}, 10^{-3}$. From Fig. 3, it is found that the EE performance of the proposed scheme is same as that of exhaustive search method with substantially reduced complexity. Specifically, the running time of the proposed scheme is 0.136 s only, but the exhaustive search method needs the time of 173 s. Thus, our scheme need less time. Moreover, the system with $BER_0 = 10^{-3}$ has lower EE than that with $BER_0 = 10^{-2}$. This is because for stricter BER requirement, the lower order modulation will be adopted, which will decrease the SE and corresponding EE. Besides, the EEs of the system using the proposed scheme and the exhaustive search method both gradually improve as $1/\sigma_z^2$ increases, as expected. The reason for this result is that as $1/\sigma_z^2$ increases, the noise power decreases, the corresponding SNR increases. As a result, the system can choose a better power allocation and higher modulation scheme, which brings about larger energy efficiency.

5 Conclusions

In this paper, we formulated the system model of DAS based on discrete-rate adaptive modulation. We have studied the EE performance of DAS with discrete-rate AM over composite fading channels including path loss, shad-owing and Rayleigh fading. The optimal power allocation is derived by maximizing the EE in constraint of transmit power antenna and target BER of the system. By using the KKT conditions and mathematical derivation, the constrained optimized problem is solved well, and the closedform solution of PA is attained. With these results, the optimal PA can be obtained by comparing the EEs of the system with all possible modulation modes, and it corresponds to the largest EE. Based on this, a computationally efficient algorithm is presented to calculate the PA. Simulation results show that the proposed scheme produces the optimal EE performance with remarkably reduced complexity compared to the exhaustive search method. Also, the EE and SE of the DAS with AM increase as the target BER increases.

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