Optimal Energy-Efficient Power Allocation Scheme with Low Complexity for Distributed Antenna System

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Abstract. *In this paper, by maximizing the energy efficiency (EE), an optimal power allocation scheme is developed for downlink distributed antenna system (DAS). Different from conventional optimal power allocation schemes that need iterative calculation, the developed scheme can provide closed-form power allocation and no iteration is required. Based on the definition of EE, the optimized objective function is firstly formulated, and then a computationally efficient algorithm is proposed to obtain the optimal number of active remote antennas and the corresponding power allocation. Using the optimal number, the multidimensional solution for the optimized function is transformed into searching one-dimensional solution. As a result, closed-form expression of power allocation coefficients is attained. Numerical results verify the effectiveness of the proposed scheme. The scheme can obtain the same EE as the conventional optimal scheme but with lower complexity, and it has more accuracy than the existing low-complexity scheme.*

Keywords

Energy efficiency, distributed antenna system, power allocation, low complexity, Rayleigh channel

1. Introduction

Recently, green communication, where energy efficiency (EE) is pursued [1–3], has received much attention, since energy demand and prices increase dramatically. As an important technology for green communication, distributed antenna system (DAS) can expand cell coverage and improve the EE [4–6]. For this reason, different energy-efficient power allocation (PA) schemes have been developed for DAS [7–11]. In [7], using iterative search and numerical calculation, an approximate PA scheme is proposed for generalized DAS. An adaptive PA scheme for achieving maximum EE while satisfying spectral efficiency requirement in multiuser DAS is developed in [8]. In [9], by maximizing the upper bound of average EE, a suboptimal energy-efficient PA scheme is presented for DAS over composite fading channel. An optimal PA algorithm to maximize EE is proposed in [10], where the optimization problem is solved by using the Karush-Kuhn-Tucker (KKT) conditions and Lambert function. Considering that the above schemes need iterations, a low-complexity PA scheme aiming at maximizing EE is presented in [11], but there exist some errors in the theoretical derivations on PA. Hence, the accuracy of the optimal PA cannot be guaranteed. Besides, the above schemes basically consider single receive antenna for analysis convenience, and thus the corresponding EE performance will be limited.

Motivated by the reasons above, we propose a low-complexity energy-efficient power allocation scheme for DAS in composite Rayleigh channel, where path-loss, shadowing, fading, and multiple receive antennas are all considered. Also we present a new computationally efficient algorithm to achieve the optimal number of active remote antennas and the corresponding closed-form power allocation coefficients. It is shown that the proposed power allocation scheme and algorithm are both valid, the power allocation scheme can obtain the same energy efficiency as the conventional optimal one [10], and the algorithm has more accuracy than the existing low-complexity algorithm [11]. Furthermore, no iteration is required.

The rest of this paper is organized as follows. Section 2 introduces the system model. In Section 3, a low-complexity power allocation scheme is developed, and the comparison between different PA schemes is presented. Simulation results are provided in Sec. 4, and Section 5 concludes the paper.

The notations throughout this paper are as follows. Bold lower case letters denote column vectors. The superscript $(\cdot)^{\mathrm{T}}$ denotes transposition, $E\{\cdot\}$ denotes statistical expectation, $W(\cdot)$ denotes Lambert W function.

2. System Model

We consider a downlink DAS with N_{t} remote antennas (RAs) and multiple receive antennas operating in a single cell environment as illustrated in Fig. 1, where N_t RAs are distributed in the cell, the i-th RA is denoted as RA_i, and Base Station (BS) is referred as RA_1. All RAs are linked to the central processing unit via dedicated wired connection. The mobile station (MS) is equipped with N_t antennas, and the received signal at MS from RA_i is given by

$$\mathbf{y}_i = \sqrt{P_i}\left[h_i^1, \cdots, h_i^{N_r}\right]^{\mathrm{T}} x_i + \mathbf{z} \tag{1}$$

where P_i, $i = 1,..., N_t$, is the transmit power consumed by the RA_i, x_i stands for the transmitted symbol from RA_i with unit energy, $\mathbf{z}$ is the complex Gaussian noise vector with zero mean and variance σ_n^2, and $h_i^j = g_i^j \Omega_i$, $j = 1,..., N_r$, is the composite channel fading coefficient between RA_i and the j-th antenna of MS, where g_i^j denotes the small-scale Rayleigh fading between RA_i and the j-th receive antenna, $\Omega_i = (S_i d_i^{-\alpha_i})^{½}$ denotes the large-scale fading between RA_i and the MS, where α_i is the path loss exponent, d_i is the distance from RA_i to the MS, and S_i denotes the shadowing effect.

In general, EE is defined as the ratio of data transmission rate to the total consumed power. Based on this, the EE of DAS can be written as

$$\eta_{\mathrm{EE}} = \frac{\log_2\left(1 + \sum_{i=1}^{N_t} \gamma_i P_i\right)}{\sum_{i=1}^{N_t} P_i + P_c} \tag{2}$$

where $\gamma_i = \sum_{j=1}^{N_r} |g_i^j|^2 \Omega_i^2 / \sigma_n^2$ is defined as the channel to noise ratio (CNR) after maximal ratio combining at the receiver. Per RA power constraint is $0 \le P_i \le P_{\max, i}$, where $P_{\max, i}$ is the maximum transmit power available at RA_i. P_c denotes the circuit power and is a constant.

3. Low-complexity Power Allocation Scheme

In this section, we will develop an optimal power allocation scheme with low complexity, and present a computationally efficient algorithm to obtain the optimal number of active remote antennas and the corresponding PA coefficients.

Subject to the power constraint, we firstly formulate the objective function of the optimal PA as

$$\begin{aligned} \max_{\mathbf{P}} \quad & \eta_{\mathrm{EE}} = \frac{\log_2(1 + \sum_{i=1}^{N_t} \gamma_i P_i)}{\sum_{i=1}^{N_t} P_i + P_c} \\ \text{subject to} \quad & 0 \le P_i \le P_{\max,i}, \forall i \in \{1, ..., N_t\} \end{aligned} \tag{3}$$

where $\mathbf{P} = [P_1, \ldots, P_{N_t}]^{\mathrm{T}}$. Without loss of generality, we assume that $\gamma_1 > \gamma_2 > \ldots > \gamma_{N_t}$. It has been proved in [10] that the optimal PA solution will have the following general form:

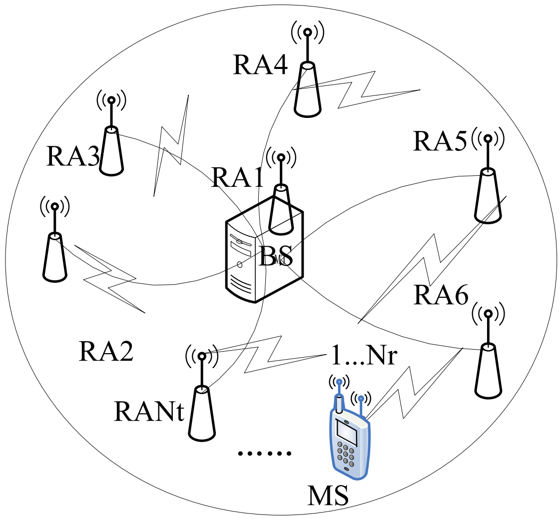

Fig. 1. A circle-cell DAS structure.

$$\mathbf{P}^* = [P_{\max,1}, ..., P_{\max,N_0-1}, P_{N_0}^*, \underbrace{0, ..., 0}_{N_t - N_0}]^{\mathrm{T}}. \tag{4}$$

According to this, the optimization of PA in (3) will become to search the optimal number of active RAs (i.e., N_0) and the corresponding PA. The optimized problem in (3) can be converted into finding the optimal solution of the following segmented function:

$$\psi(k, \mathbf{P}_k) = V_k(P_k), \quad k = 1, \ldots, N_t \tag{5}$$

where $\mathbf{P}_k = [P_{\max,1}, \ldots, P_{\max,k-1}, P_{\max,k}, 0, \ldots, 0]^{\mathrm{T}}$ and $V_k(P_k)$ is shown as

$$V_k(P_k) = \frac{\log_2(1 + \sum_{i=1}^{k-1} \gamma_i P_{\max,i} + \gamma_k P_k)}{\sum_{i=1}^{k-1} P_{\max,i} + P_k + P_c}. \tag{6}$$

Obviously, (5) is a continuous function. Taking the derivative of $V_k(P_k)$ with respect to P_k yields

$$V_k'(P_k) = \frac{\gamma_k \Phi_k - (1 + \Psi_k)\ln(1 + \Psi_k)}{(1 + \Psi_k)\Phi_k^2 \ln 2} = \frac{A_k(P_k)}{B_k(P_k)} \tag{7}$$

where $\Phi_k = \sum_{i=1}^{k-1} P_{\max,i} + P_k + P_c$, $\Psi_k = \sum_{i=1}^{k-1} \gamma_i P_{\max,i} + \gamma_k P_k$. Since $B_k(P_k)$ is positive, the sign of $V'_k(P_k)$ is determined by $A_k(P_k)$ only.

Taking the derivative of $A_k(P_k)$ with respect to P_k gives

$$A_k'(P_k) = -\gamma_k \ln\left(1 + \sum_{i=1}^{k-1} \gamma_i P_{\max,i} + \gamma_k P_k\right) < 0. \tag{8}$$

It means that $A_k(P_k)$ is decreasing in any segment. With (7), we have:

$$A_k(P_{\max,k}) = \gamma_k\left(\sum_{i=1}^{k} P_{\max,i} + P_c\right) - \left(1 + \sum_{i=1}^{k} \gamma_i P_{\max,i}\right)\ln\left(1 + \sum_{i=1}^{k} \gamma_i P_{\max,i}\right), \tag{9}$$

$$A_{k+1}(0)=\gamma_{k+1}\left(\sum_{i=1}^{k}P_{\max,i}+P_{\mathrm{c}}\right)-\left(1+\sum_{i=1}^{k}\gamma_i P_{\max,i}\right)\ln\left(1+\sum_{i=1}^{k}\gamma_i P_{\max,i}\right). \quad (10)$$

Because $\gamma_k > \gamma_{k+1}$, $A_k(P_{\max,k}) > A_{k+1}(0)$. Based on this, considering that $A_k(P_k)$ is decreasing function in a segment, the $A_k(P_k)$ in different segments has the following relation:

$$\forall P_k, P_{k+1}, A_k(P_k) > A_{k+1}(P_{k+1}). \quad (11)$$

It means that $A_k(P_k)$ is always greater than $A_{k+1}(P_{k+1})$. According to the analysis above, the optimal PA, $P_{N_0}^*$ will be achieved. Specifically:

If $A_{N_0}(P_{\max,N_0})>0$ and $A_{N_0+1}(0)<0$ hold, then we have $V'_{N_0}(P_{\max,N_0})>0$ and $V'_{N_0+1}(0)<0$. From (11), it is easily found that $V_{N_0+1}(P_{N_0+1})$ is decreasing function for $0<P_{N_0+1}<P_{\max,N_0+1}$, and $V_{N_0}(P_{N_0})$ is increasing function for $0<P_{N_0}<P_{\max,N_0}$. Moreover, (5) is a continuous function. Hence, $P_{N_0}^*$ in (4) equals $P_{\max,N_0}$ under this case.

If $\exists 0<P_{N_0}^*<P_{\max,N_0}$, $A_{N_0}(P_{N_0}^*)=0$, then with (11), for $k<N_0, A_k(P_k)>A_{N_0}(P_{N_0}^*)=0$, so $V'_k(P_k)>0$ for $k<N_0$. Similarly, $V'_k(P_k)<0$ for $k>N_0$. According to (8), and considering $V'_{N_0}(P_{N_0}^*)=A_{N_0}(P_{N_0}^*)=0$, we have: $V'_{N_0}(P_{N_0})>0$ for $0\le P_{N_0}<P_{N_0}^*$, and $V'_{N_0}(P_{N_0})<0$ for $P_{N_0}^*<P_{N_0}<P_{\max,N_0}$. Hence $A_{N_0}(P_{N_0})=0$ has sole solution, i.e., $P_{N_0}^*$.

From (7), $A_{N_0}(P_{N_0})$ can be written as

$$\begin{aligned}A_{N_0}(P_{N_0}) &= \gamma_{N_0}\Big(\sum_{i=1}^{N_0-1}P_{\max,i}+P_{N_0}+P_{\mathrm{c}}\Big)- \\ &\Big(1+\sum_{i=1}^{N_0-1}\gamma_i P_{\max,i}+\gamma_{N_0}P_{N_0}\Big)\ln\Big(1+\sum_{i=1}^{N_0-1}\gamma_i P_{\max,i}+\gamma_{N_0}P_{N_0}\Big).\end{aligned} \quad (12)$$

Let $\phi_1=\gamma_{N_0}(\sum_{i=1}^{N_0-1}P_{\max,i}+P_c)$, $\phi_2=1+\sum_{i=1}^{N_0-1}\gamma_{N_0}P_{\max,i}$, then (12) is changed to

$$A_{N_0}(P_{N_0})=\phi_1+\gamma_{N_0}P_{N_0}-(\phi_2+\gamma_{N_0}P_{N_0})\ln(\phi_2+\gamma_{N_0}P_{N_0}). \quad (13)$$

Equating $A_{N_0}(P_{N_0})$ to zero gives

$$\phi_1-\phi_2=(\phi_2+\gamma_{N_0}P_{N_0})[\ln(\phi_2+\gamma_{N_0}P_{N_0})-1]. \quad (14)$$

With (14), we have:

$$\frac{\phi_1-\phi_2}{\mathrm{e}}=\frac{\phi_2+\gamma_{N_0}P_{N_0}}{\mathrm{e}}\ln\Big(\frac{\phi_2+\gamma_{N_0}P_{N_0}}{\mathrm{e}}\Big). \quad (15)$$

Using (15) and the Lambert function [12], we can obtain the solution of P_{N_0}, i.e., $P_{N_0}^*$, as follows:

$$P_{N_0}^*=\frac{1}{\gamma_{N_0}}\left\{\exp\left[W\left(\frac{\phi_1-\phi_2}{e}\right)+1\right]-\phi_2\right\} \quad (16)$$

where $W(\cdot)$ denotes the Lambert function. Equation (16) provides a closed-form expression of $P_{N_0}^*$ in (4). Based on the analysis above, a low-complexity optimal PA algorithm is proposed, and correspondingly, the algorithm procedure is summarized as follows:

Algorithm 1 Efficient PA calculation method

1: Sort the γ_i with descending order.

2: Calculating the $V_k(0)$, for $k = 1,\dots, N_t$, and finding K that makes $V_K(0)$ be the largest among $\{V_k(0)\}$.

3: If $V'_K(0) > 0$ & $V'_{K-1}(P_{\max,K-1}) > 0$, then

Return $N_0 = K$, go to 4.

Else

If $V'_K(0) < 0$ & $V'_{K-1}(P_{\max,K-1}) < 0$ then

Return $N_0 = K - 1$, go to 4.

Else

Return $N_0=K-1, P_{N_0}=P_{\max,N_0}$, go to 5.

End

End

4: Using (16) to obtain the $P_{N_0}^*$

5: Return $\mathbf{P}^*$ in (4), end the algorithm.

Using the above algorithm, the optimal number of active RAs is determined correctly, and the multi-dimensional root finding for the optimized objective function becomes one-dimensional root finding. As a result, closed-form power allocation is computed and no iteration is required. For this algorithm, the number of Lambert W function is calculated by one or zero. Note that in [11], a low-complexity PA scheme is also proposed for maximizing the energy efficiency in DAS, but the scheme cannot always guarantee the optimal values since there are errors in [11, (9)] and [11, (11)], i.e., the derived derivative $V'_k(P_k)$ and optimal PA $P_{N_0}^*$ are not accurate so that the obtained power value may exceed the given maximum transmit power. For example, using the CNRs as $\{\gamma_i\}_{i=1,\dots,7}=$ {6.3608e+05, 4.8028e+05, 1.6016e+05, 1.3177e+05, 6.6877e+04, 6.4877e+03, 1.2921e+03}, we plot the corresponding numerical results of the energy efficiency in Fig. 2.

As shown in Fig. 2, the proposed scheme can be in good agreement with the conventional optimal scheme [10], but the existing low-complexity scheme [11] has obvious difference because the derived (9) and (11) in [11] have errors, which result in inaccurate power allocation.

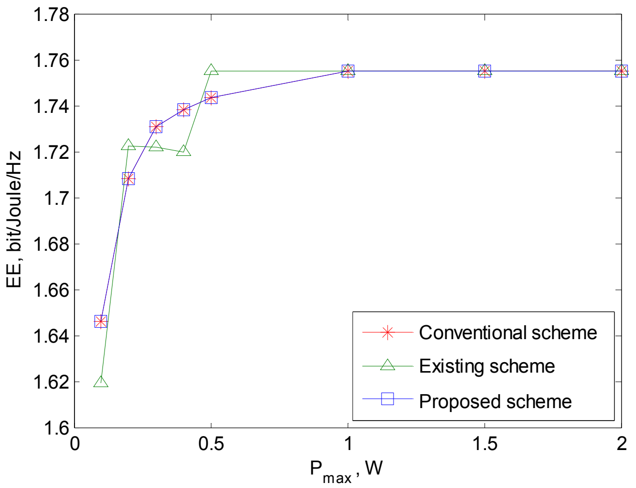

Fig. 2. EE comparison of DAS with different PA schemes.

	Proposed scheme	Scheme [11]	Scheme [10]
Lambert W function calculations	0 or 1	1	N_t
N_0	accurate	inaccurate	-
$P^*_{N_0}$	accurate	inaccurate	accurate

Tab. 1. Comparison of different schemes.

Taking the example of Fig. 2, let $P_{\max,i} = P_{\max} = 0.5$, then $V'_2(0) = -0.1460 < 0$, so $N_0 = 1$ according to the algorithm in [11] (this algorithm is based on the [(9),11]), but in fact, $V'_2(0) = 0.0417 > 0$, and correspondingly, $N_0 = 2$ according to our algorithm. Besides, using [(11), 11], $p^*_{N_0} = \frac{1}{\gamma_{N_0}}\left[\exp\left\{W\left(\frac{\phi_1-\phi_2}{e}\right)+1\right\}-\left(\sum_{i=1}^{N_0-1}P_{\max,i}+P_c\right)\right] = 0.8219 > 0.5$, i.e., $p^*_{N_0} > P_{\max}$, but according to our algorithm, $p^*_{N_0} = \frac{1}{\gamma_{N_0}}\left[\exp\left\{W\left(\frac{\phi_1-\phi_2}{e}\right)+1\right\}-\left(1+\sum_{i=1}^{N_0-1}\gamma_i P_{\max,i}\right)\right] = 0.1650 < 0.5$, where $\varphi_1 = \gamma_{N_0}(\sum_{i=1}^{N_0-1}P_{\max,i}+P_c)$ and $\varphi_2 = 1+\sum_{i=1}^{N_0-1}\gamma_i P_{\max,i}$. Obviously, the result from [(11), 11] is larger than $P_{\max,N_0}$, whereas our result can satisfy the maximum power constraint.

The above results indicate that the proposed scheme is valid. Besides, the complexity analysis measured by the number of Lambert function calculation and comparison among three schemes are listed in Tab. 1. From Tab. 1, it is shown that the proposed scheme has lower calculation complexity than the other two and is more accurate than the existing scheme [11].

4. Simulation Results

In this section, we will assess the validity of the proposed scheme via computer simulation. In simulation, it is assumed that $P_{\max,i} = P_{\max}$ $(i = 0, \ldots, N_t)$ for analysis convenience. The BS (RA_1) is in the center of the cell and the RAs are evenly and symmetrically placed in the cell. The main parameters used in simulations are listed in Tab. 2. The simulation results are shown in Fig. 3 and Fig. 4.

Parameters	value
Number of remote antennas N_t	7
Path loss exponent α_i	3, 3.5, 4
Shadow fading standard deviation σ_i	8 dB
Noise power N_0	–104 dBm
Circuit power P_c	10 W
Cell radius D	1000 m
MS distribution	Uniform
(D_1, τ_1)	(0,0)
(D_i, τ_i), $i = 2, \ldots, N_t$	$(\sqrt{\frac{3}{7}}D, \frac{2\pi(i-1)}{N_t-1})$
Number of receive antennas N_r	1, 2, 3

Tab. 2. Simulation parameters.

Figure 3 illustrates the EE performance of DAS with different receive antennas. Considering that the optimal scheme in [10] is based on single receive antenna, we extend the scheme in [10] to multiple receive antennas case after some modifications. From Fig. 3, it is observed that the EE of the proposed scheme is the same as that of the conventional optimal scheme [10]. Moreover, the EE increases with the growth of the number of receive antennas. Namely, the EE of DAS with three receive antennas ($N_r = 3$) is higher than that with two receive antennas ($N_r = 2$) because of more spatial diversity gain, and due to the same reason, the EE of DAS with two receive antennas ($N_r = 2$) is higher than that with single receive antenna ($N_r = 1$). The results above indicate that the developed scheme is effective and reasonable, and the application of multiple receive antennas does improve the EE performance effectively.

In Fig. 4 we plot the EE performance of DAS with different path loss exponents, where two receive antennas are considered. It is found that the EE of the proposed scheme is still consistent with that of conventional optimal

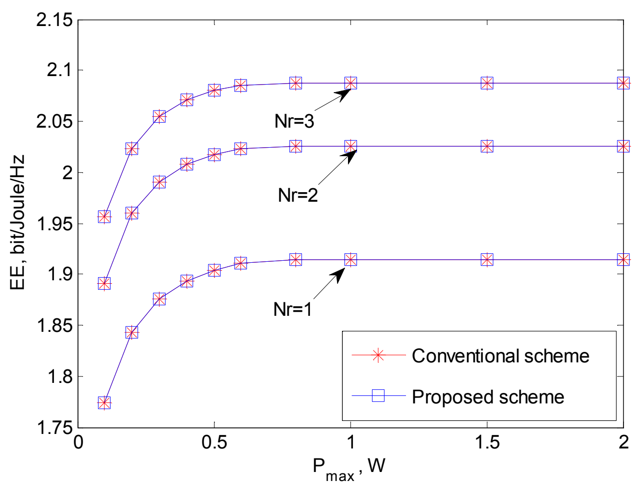

Fig. 3. EE of DAS with different receive antennas.

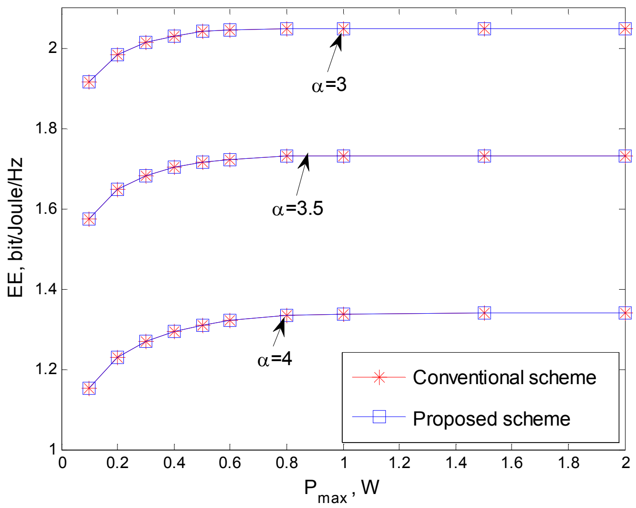

Fig. 4. EE of DAS with different path loss exponents.

scheme [10]. Besides, the EE decreases with the growth of the path loss exponent α as expected. Namely, the EE of DAS with $\alpha = 4$ is lower than that with $\alpha = 3.5$, and the EE of DAS with $\alpha = 3.5$ is lower than that with $\alpha = 3$. This is because the system with higher path loss exponent will experience greater path loss, which leads to a decline in EE performance.

5. Conclusions

We have developed an optimal energy-efficient power allocation scheme for DAS using multiple receive antennas in composite Rayleigh fading channel, and proposed a computationally efficient algorithm to obtain the optimal number of active RAs. Based on this, optimal power allocation is derived, and the corresponding closed-form expression is attained. The results indicate that our scheme has lower complexity than the existing schemes. Moreover, it can obtain the same EE performance as the existing optimal scheme, and provide the optimal active antenna number and power allocation accurately.

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