Capacity Analysis on Distributed Antenna System with Imperfect CSI over Rayleigh Fading Channel

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Abstract: Considering that perfect channel state information (CSI) is hard to obtain in practice, the capacity of downlink distributed antennas system (DAS) with imperfect CSI is analyzed over Rayleigh fading channel. Based on the performance analysis, using the probability density function and numerical calculation, an accurate closed-form expression of ergodic capacity of downlink DAS under imperfect CSI is derived. It includes the one under perfect CSI as a special case. This theoretical expression can provide good performance evaluation for downlink DAS for both perfect and imperfect CSI due to its accuracy. Simulation results indicate that the theoretical analysis agrees well with the corresponding simulation, and the capacity can be increased effectively by decreasing the estimation error and /or path loss.

Key words: distributed antenna system; capacity analysis; imperfect CSI; downlink; path loss

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0 Introduction

Distributed antenna system (DAS), as a promising technique for next generation wireless mobile communications, has received significent attention thanks to its power efficiency and capacity improvement over traditional co-located antenna system (CAS)[1-2]. Different from conventional CAS, DAS consists of several widely spaced antennas, and each of them is called an antenna port (AP). Through coaxial cables or fiber optics, all the APs are connected to the main processing unit (MPU).

Ergodic capacity, as a measure of the system performance, plays an important role in communication systems. Based on different system models, the capacity of DAS has been extensively studied[3-7]. Ref. [3]analyzed the channel capacity of uplink, but neglected the large-scale fading for convenient analysis. The performance of DAS capacity over a composite fading channel was studied in Refs. [4—7]. Considering selective transmission and maximal ratio combining, using a log-normal distribution instead of the actual gamma-log-normal distribution, approximate expressions of the ergodic capacity were derived for downlink DAS[4-6], where Rayleigh fading channel [5-6] and Nakagami-*m* fading channel[4] were considered, respectively. However, the derived theoretical capacity formulae are not accurate to reflect the actual value because of the approximate substitution. For high signal-to-noise-ratio (SNR) analysis, Ref. [7] derived a simple ergodic capacity expression, which was close to the actual cell ergodic capacity at high SNR.

According to the analysis above, although the capacity of DAS has been well studied, the performance analyses were based on perfect channel state information (CSI). Whereas in practice, the perfect CSI is difficult to obtain due to channel estimation error. Therefore, we study DAS capacity with imperfect CSI over composite Ray-

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leigh fading channel, where both small-scale fading (Rayleigh fading) and large-scale fading (path loss) are considered. The channel model from imperfect estimation is firstly presented for DAS, and then the probability density function (PDF) and conditional PDF of output SNR are derived by means of Bayesian linear model. With these PDFs, using the numerical calculation, an accurate closed-form ergodic capacity expression of downlink DAS with imperfect CSI is derived. With this expression, the ergodic capacity in the presence of imperfect CSI can be effectively evaluated. Moreover, it includes the capacity expression under perfect CSI as a special case. Simulation results verify the effectiveness of our theoretical analysis.

1 System and Channel Models

We consider a distributed antenna system with multiple APs in a single-cell environment, and the APs are distributed in the cell with radius R and connected to the main processing unit via dedicated wireless (e. g. fiber option) for signal processing, where N_t APs are considered, and the ith AP is denoted as $\mathrm{AP_i}$. Considering the implementation of mobile terminal (MT), single receive antenna is available at the MT[5-6]. This is also due to the limitation of volume and size of the MT. The positions of the MT and the ith AP are denoted by the polar coordinates (ρ, ν) and (R_i, τ_i), $i=1,\cdots,N_t$, respectively, where ρ and ν are the distance and the angle of the MT to the cell center, respectively. R_i and τ_i are the distance and the angle of the ith AP to the cell center, respectively. To improve the performance, the antenna selection technology is employed for APs. If AP_i is selected to transmit signals, the received signals at MT can be expressed as

$$y_i=\sqrt{P_{\mathrm{t}}}h_i x+z \qquad i=1,\cdots,N_t \tag{1}$$

where y_i is the received signal at MT, P'_{t} the transmit signal power, h_i the composite channel fading coefficient between AP_i and MT, x the transmitted signal from AP_i with unity energy. z a complex Gaussian noise with zero mean and variance N_0. Thus, the average SNR $\bar{\gamma}=P_{\mathrm{t}}/N_0$.

Due to the structural features of DAS, h_i can be modeled as

$$h_i=k_i\sqrt{L_i} \tag{2}$$

where k_i represents the small-scale fast fading between AP_i and MT, L_i the path loss between AP_i and MT. The envelope of the fast fading is assumed to undergo a Rayleigh fading. The path loss term L_i can be modeled as

$$L_i=(d_0/d_i)^{\beta_i} \tag{3}$$

where β_i is the path loss exponent, d_0 the reference distance and d_i represents the distance from AP_i to MT. Based on this, the output SNR γ_i after maximal-ratio combining can be expressed as $\gamma_i=|h_i|^2\bar{\gamma}=g_i\bar{\gamma}'_i$, where $\bar{\gamma}'_i=\bar{\gamma}L_i$ and $g_i=|k_i|^2$.

In practice, the perfect CSI is hard to achieve due to the channel estimation error. Therefore, we investigate the effect of imperfect CSI on the system performance with estimation errors modeled as complex Gaussian random variables[8]. We assume that the channel is perfectly known at the receiver, but there is estimation error in the channel state information feedback from the receiver to the transmitter. For noisy channel estimation, the estimation of true channel k_i, $\hat{k}_i$, is related to k_i as[8-9]

$$\hat{k}_i=k_i+e_i \tag{4}$$

where e_i is the estimation error independent of k_i, and it brings about the imperfection of CSI. k_i and e_i are assumed to be independent and identically distributed (i. i. d.) complex Gaussian random variables with zero mean and variances given by 1 and σ_e^2, respectively. The larger the variance σ_e^2 is, the worse the estimation quality will be. When $\sigma_e^2=0$, the channel is perfectly known.

According to the analysis above, the estimated SNR $\hat{\gamma}_i$ between AP_i and MT can be expressed as

$$\hat{\gamma}_i=|\hat{h}_i|^2\bar{\gamma}=\hat{g}_i\bar{\gamma}'_i \tag{5}$$

where $\hat{g}_i=|\hat{k}_i|^2$. Based on the Bayesian linear model and Theorem 10. 3[10], given $\hat{k}_i$, k_i is a complex Gaussian variable, and its mean and covariance are given by

$$E[k_i\mid\hat{k}_i]=(1+\sigma_e^2)^{-1}\hat{k}_i$$
$$C[k_i\mid\hat{k}_i]=\sigma_e^2(1+\sigma_e^2)^{-1} \tag{6}$$

Thus, given $\hat{g}_i$, g_i is noncentral chi-square distributed, and corresponding conditional PDF is expressed as

$$f_{g_i|\hat{g}_i}(g \mid \hat{g}) = \frac{1+\sigma_e^2}{\sigma_e^2}\exp\left(-\frac{\hat{g}+(1+\sigma_e^2)^2 g}{\sigma_e^2(1+\sigma_e^2)}\right) I_0\left(\frac{2\sqrt{g\hat{g}}}{\sigma_e^2}\right) \quad (7)$$

where $I_v(x)$ is the modified Bessel function. Using Eqs. (5), (7) as well as the transformation of variables, the conditional PDF of γ given $\hat{\gamma}$ is obtained as

$$f_{\gamma_i|\hat{\gamma}_i}(\gamma \mid \hat{\gamma}) = \frac{1+\sigma_e^2}{\bar{\gamma}'\sigma_e^2}\exp\left(-\frac{\hat{\gamma}+(1+\sigma_e^2)^2\gamma}{\bar{\gamma}'_i\sigma_e^2(1+\sigma_e^2)}\right) I_0\left[\frac{2\sqrt{\gamma\hat{\gamma}}}{\bar{\gamma}'_i\sigma_e^2}\right] \quad (8)$$

With Eq. (5), $\hat{g}_i$ is chi-square distributed with 2 degrees of freedom, and its PDF can be written as

$$f_{\hat{g}_i}(\hat{g}) = \frac{1}{1+\sigma_e^2}\exp\left(-\frac{\hat{g}}{1+\sigma_e^2}\right) \quad (9)$$

Thus, through the variable transformation, the PDF of $\hat{\gamma}_i$ is

$$f_{\hat{\gamma}_i}(\hat{\gamma}) = A_i\exp(-\hat{\gamma}A_i) \quad (10)$$

where $A_i = 1/\bar{\gamma}'_i(1+\sigma_e^2)$.

In this paper, the antenna selection scheme is applied to the transmitter to improve the performance. Namely, based on the estimation information at the transmitter, one "best" AP is selected for transmission to maximize the estimated SNR. Accordingly, the estimated SNR $\hat{\gamma}$ can be expressed as

$$\hat{\gamma} = \max\{\hat{\gamma}_1, \cdots, \hat{\gamma}_{Nt}\} \quad (11)$$

$\hat{\gamma}_i$ is independent of each other due to the features of DAS , and then the cumulative distribution function (CDF) of $\hat{\gamma}$ can be obtained as

$$F_{\hat{\gamma}}(\hat{\gamma}) = \prod_{i=1}^{N_t}\left(\int_0^{\hat{\gamma}} f_{\hat{\gamma}_i}(\hat{\gamma})\mathrm{d}\hat{\gamma}\right) = \prod_{i=1}^{N_t}(1-\exp(-\hat{\gamma}A_i)) = \sum_{i=0}^{N_t}(-1)^i\sum_{\tau(i,N_t)}\exp\left(-\hat{\gamma}\cdot\sum_{k=1}^{N_t}\iota_k A_k\right) \quad (12)$$

where $\tau(i,N_t)$ is the set of N-tuples such that $\tau(i,N_t) = \{(t_1,\cdots,t_{N_t}):\iota_k \in \{0,1\}, \sum_{k=0}^{N_t}\iota_k = i\}$[11-12]. With the above CDF, the PDF of $\hat{\gamma}$ can be given by

$$f_{\hat{\gamma}}(\hat{\gamma}) = \sum_{i=1}^{N_t} f_{\hat{\gamma}_i}(\hat{\gamma})\prod_{p=1,p\neq i}^{N_t}F_{\hat{\gamma}_p}(\hat{\gamma}) = \sum_{i=1}^{N_t}\sum_{p=0}^{N_t-1}\sum_{\tilde{\tau}(p,N_t-1)}(-1)^p A_i\exp\left(-\hat{\gamma}\left(A_i+\sum_{k=1,k\neq i}^{N_t}\iota_k A_k\right)\right) \quad (13)$$

where $\tilde{\tau}(i,N_t-1)$ is the set of (N_t-1)-tuples such that $\tilde{\tau}(i,N_t-1) = \{(\iota_1,\cdots,\iota_{k-1},\iota_{k+1},\cdots,\iota_{N_t}): \iota_k \in \{0,1\}, \sum_{k=1,\neq n}^{N_t}\iota_k = i\}$.

2 Ergodic Capacity Analysis

In this section, we will give the capacity analysis of the DAS with imperfect CSI. The ergodic capacity of the mobile terminal at a given location can be expressed as

$$C = E_\gamma\{\log_2(1+\gamma)\} = \int_0^\infty \log_2(1+\gamma)f_\gamma(\gamma)\mathrm{d}\gamma = \int_0^\infty\int_0^\infty\sum_{i=1}^{N_t}\log_2(1+\gamma)f_{\gamma_i|\hat{\gamma}_i}(\gamma \mid \hat{\gamma}_i=\hat{\gamma}, i=u)\times f(i=u \mid \hat{\gamma}_i=\hat{\gamma})P_{\mathrm{rob}}(\hat{\gamma}_i=\hat{\gamma})\,\mathrm{d}\gamma\mathrm{d}\hat{\gamma} = \int_0^\infty\int_0^\infty\sum_{i=1}^{N_t}\log_2(1+\gamma)f_{\gamma_i|\hat{\gamma}_i}(\gamma \mid \hat{\gamma})f_{\hat{\gamma}_i}(\hat{\gamma})\cdot\prod_{p=1,p\neq i}^{N_t}F_{\hat{\gamma}_p}(\hat{\gamma})\mathrm{d}\hat{\gamma}\mathrm{d}\gamma \quad (14)$$

where $f(i=u \mid \hat{\gamma}_i=\hat{\gamma})P_{\mathrm{rob}}(\hat{\gamma}_i=\hat{\gamma}) = f_{\hat{\gamma}_i}(\hat{\gamma})\prod_{p=1,p\neq i}^{N_t}F_{\hat{\gamma}_p}(\hat{\gamma})$ [12], $f_{\gamma_i|\hat{\gamma}_i}(\gamma \mid \hat{\gamma}_i=\hat{\gamma}, i=u) = f_{\gamma_i|\hat{\gamma}_i}(\gamma \mid \hat{\gamma})$ and $u = \arg\max_{i\in \mathbf{N}_t}\{\gamma_i\}$. The inner integration in Eq. (14) can be given by

$$\sum_{i=1}^{N_t}\int_0^\infty f_{\gamma_i|\hat{\gamma}_i}(\gamma \mid \hat{\gamma})f_{\hat{\gamma}_i}(\hat{\gamma})\prod_{p=1,p\neq i}^{N_t}F_{\hat{\gamma}_p}(\hat{\gamma})\mathrm{d}\hat{\gamma} = \sum_{i=1}^{N_t}\sum_{p=0}^{N_t-1}\sum_{\tilde{\tau}(p,N_t-1)}\frac{(-1)^p A_i(1+\sigma_e^2)}{\bar{\gamma}'_i\sigma_e^2}\exp\left(-\frac{(1+\sigma_e^2)\gamma}{\bar{\gamma}'_i\sigma_e^2}\right)\times \int_0^\infty\exp\left(-\hat{\gamma}\left(\frac{1}{\bar{\gamma}'_i\sigma_e^2(1+\sigma_e^2)}+A_i+\sum_{k=1,k\neq i}^{N_t}\iota_k A_k\right)\right)\cdot I_0\left(\frac{2\sqrt{\gamma\hat{\gamma}}}{\bar{\gamma}'_i\sigma_e^2}\right)\mathrm{d}\hat{\gamma} \quad (15)$$

Using $\int_0^\infty x^{u-0.5}\mathrm{e}^{-ax}I_{2v}(2\beta\sqrt{x})\mathrm{d}x = \frac{\Gamma(u+v+0.5)}{\Gamma(2v+1)}\beta^{2v}a^{-u-v-1/2}\times\exp\left(\frac{\beta^2}{a}\right)$ and Eqs. (6.643.2), (9.220.2) in Ref. [13], Eq. (15) can be further simplified as

$$\sum_{i=1}^{N_t}\int_0^\infty f_{\gamma_i|\gamma_i}(\gamma \mid \gamma)f_{\gamma_i}(\gamma)\prod_{p=1,p\neq i}^{N_t}F_{\gamma_p}(\gamma)\mathrm{d}\gamma = \sum_{i=1}^{N_t}\sum_{p=0}^{N_t-1}\sum_{\tilde{\tau}(p,N_t-1)}\frac{(-1)^p}{\bar{\gamma}'_i\left(1+\bar{\gamma}'_i\sigma_e^2\sum_{k=1,k\neq i}^{N_t}\iota_k A_k\right)}\times$$

$$\exp\left[-\left(\frac{1}{\bar{\gamma}'_i}+\frac{\sum_{k=1,k\neq i}^{N_t}\iota_k A_k}{1+\bar{\gamma}'_i\sigma_e^2\sum_{k=1,k\neq i}^{N_t}\iota_k A_k}\right)\gamma\right] \quad (16)$$

Substituting Eq. (16) into Eq. (14) yields

$$C=\sum_{i=1}^{N_t}\sum_{p=0}^{N_t-1}\sum_{\bar{\tau}(p,N_t-1)}\frac{(-1)^p}{\ln 2\left[1+(1+\sigma_e^2)\bar{\gamma}'_i\sum_{k=1,k\neq i}^{N_t}\iota_k A_k\right]}\times$$

$$E_1\left[\frac{1}{\bar{\gamma}'_i}+\frac{\sum_{k=1,k\neq i}^{N_t}\iota_k A_k}{1+\bar{\gamma}'_i\sigma_e^2\sum_{k=1,k\neq i}^{N_t}\iota_k A_k}\right]\exp\left[\frac{1}{\bar{\gamma}'_i}+\frac{\sum_{k=1,k\neq i}^{N_t}\iota_k A_k}{1+\bar{\gamma}'_i\sigma_e^2\sum_{k=1,k\neq i}^{N_t}\iota_k A_k}\right] \quad (17)$$

where $E_1(x)$ is the exponential integral function[13]. Eq. (17) is an accurate closed-form expression of ergodic capacity of DAS under imperfect CSI, and will provide good agreement with simulation result. For perfect CSI, $\sigma_e^2=0$, and Eq. (17) is reduced to

$$C=\sum_{i=1}^{N_t}\sum_{p=0}^{N_t-1}\sum_{\bar{\tau}(p,N_t-1)}\frac{(-1)^p}{\ln 2\left[1+\bar{\gamma}'_i\sum_{k=1,k\neq i}^{N_t}\iota_k\bar{\gamma}'^{-1}_k\right]}\times$$

$$E_1\left(\frac{1}{\bar{\gamma}'_i}+\sum_{k=1,k\neq i}^{N_t}\frac{\iota_k}{\bar{\gamma}'_k}\right)\exp\left(\frac{1}{\bar{\gamma}'_i}+\sum_{k=1,k\neq i}^{N_t}\frac{\iota_k}{\bar{\gamma}'_k}\right) \quad (18)$$

Eq. (18) is an accurate closed-form expression of ergodic capacity of DAS with perfect CSI, and can match the simulation well. According to this, the derived Eq. (17) includes the ergodic capacity under perfect CSI as a special case.

3 Simulation Results

In this section, we use the derived theoretical formula and simulation results to evaluate the ergodic capacity of DAS with antenna selection under imperfect CSI. In the simulation, N_t APs are evenly and symmetrically placed in the cell, that is, the distances between each AP and the MPU are the same, and the angles between every two neighboring APs are also the same[5-6]. The Monte-Carlo method is employed for simulation and single receive antenna is considered. The simulation results are illustrated in Figs. 1—3. The main simulation parameters are listed in Table 1.

Table 1 Simulation parameters of DAS

Parameter	Value
R/m	1 000
N_t	5,9
β	2,4
(ρ,ν)	$(400,\pi/4)$
(R_1,τ_1)	(0,0)
(R_i,τ_i), $i=2,\cdots,N_t$	$(2R/3, 2\pi(i-1)/(N_t-1))$
d_0/m	80

In Figs. 1—2, we plot the theoretical capacity and corresponding simulation of DAS with perfect CSI ($\sigma_e^2=0$) and imperfect CSI ($\sigma_e^2=0.3$), where the path loss exponent $\beta=2,4$. The number of APs, $N_t=5$ and 9 are considered in Fig. 1 and Fig. 2, respectively. The theoretical capacities are calculated by Eqs. (18) and (17) for perfect and imperfect CSI, respectively. From these two figures, it is observed that the theoretical capacity agrees well with the simulation result. The capacity can be effectively improved with the decrease of path loss exponent. This is because the corresponding path loss becomes smaller. Besides, the capacity under imperfect CSI is lower than that under perfect CSI due to the estimation error. By comparing Fig. 1 and Fig. 2, it is found that the capacity of DAS with $N_t=9$ is larger than that with $N_t=5$ since the former has higher diversity gain. The results show that the derived theoretical formula is valid.

In Fig. 3, we evaluate the impact of the estimation error on the ergodic capacity, and plot the

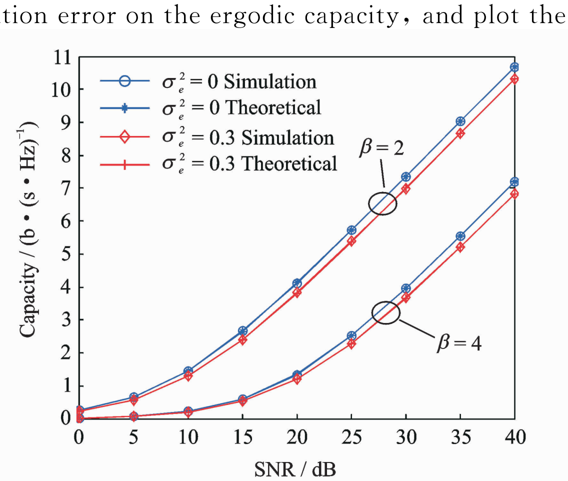

Fig. 1 Capacity of DAS with different path loss exponents and estimation errors ($N_t=5$)

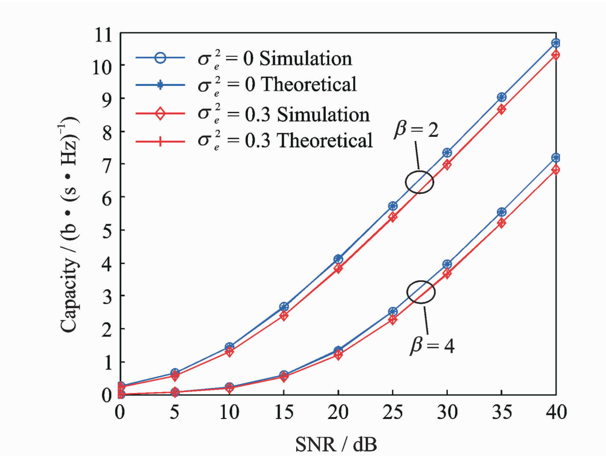

Fig. 2 Capacity of DAS with different path loss exponents and estimation errors ($N_t=9$)

DAS capacity versus channel estimation error variance, where the average SNR is set as 20 dB, path loss exponent $\beta=4$. As shown in Fig. 3, the theoretical formula is consistent with simulation result due to its accuracy. The capacity of DAS with $N_t=9$ is higher than that with $N_t=5$ since more APs are employed. As the estimation error increases, the system capacity will decrease because the reliable CSI becomes less, which accords with the existing knowledge. Besides, we observe that the system can tolerate the estimation error variance up to about 0.01 with a slight degradation in the capacity. But when σ_e^2 increases beyond 0.01, the capacity will decrease gradually. The above results further indicate that our theoretical analysis is effective.

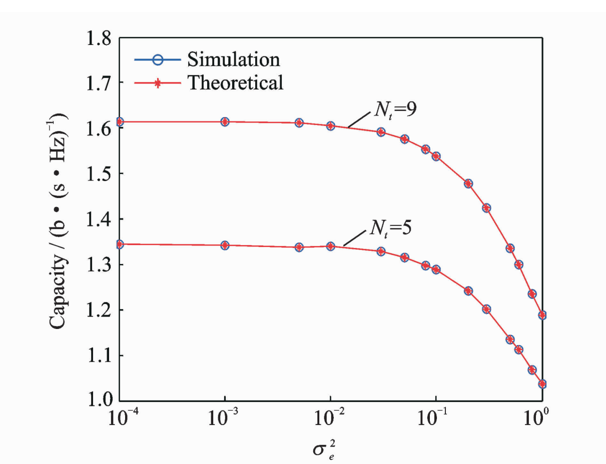

Fig. 3 Capacity of DAS with different estimnaton errors and APs

4 Conclusions

We have studied the performance of downlink DAS capacity with imperfect CSI caused by estimation error in composite Rayleigh fading channel. Based on the performance analysis and established channel model, the closed-form PDF and CDF of the estimated SNR are derived, respectively. Using these functions and numerical calculation, an accurate closed-form capacity expression of DAS with single receive antenna under imperfect CSI is obtained. When channel estimation has no error, this expression is reduced to the one under perfect CSI. Using this expression, the capacity of downlink DAS in the presence of perfect and imperfect CSI can be effectively evaluated. The analysis indicates that DAS capacity is insensitive to the estimation error variance smaller than 0.01. Simulation results show that the derived capacity expression can match the corresponding simulation well, and the capacity may be improved by decreasing the estimation error and/or path loss exponent, and /or increasing the number of APs.

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