The Ergodic and Outage Capacities of Distributed Antenna Systems in Generalized-K Fading Channels

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***Abstract*—Distributed antenna systems (DASs) are expected to play an important role in the delivery of high data rates in future cellular networks. In DASs, the multipath fading and shadowing effects have to be analyzed concurrently due to the geographical scattering of the distributed antenna ports. The Gamma-Gamma (generalized-K) probability density function (PDF) has been adopted recently to model composite fading in wireless channels. In this paper, the ergodic capacity and the information outage probability for DASs in generalized-K fading channels are considered. The analysis is based on the approximation of the PDF of the weighted sum of independent generalized-K random variables by another generalized-K PDF. The obtained results provide insights into the gains of DASs in generalized-K composite fading channels.**

***Index Terms*—Distributed antenna systems, composite fading, generalized-K model, multipath fading, shadowing, ergodic capacity, outage capacity, amount of fading, H-function distribution.**

I. Introduction

The increasing demand for higher data rates in future cellular systems has motivated looking for communication technologies that would support such demands. Distributed antenna systems (DASs), which have emerged first in indoor radio communications to improve the signal coverage, have been shown to offer capacity and coverage improvements as compared to conventional outdoor cellular architectures [1-5]. However, the design and analysis of different trans-receive schemes for such systems is dependent on the underlying channel statistical model. In DASs, the geographically distributed antenna ports (DAPs) experience different small-scale (multipath) and large-scale (shadow) fading statistics so that a composite fading model need to be used to analyze the performance of different diversity combining schemes. The lognormal-based composite fading models have been used in past literature to analyze the performance of DASs [3-5]; however, the analytical difficulties associated with lognormal-based models have hampered the derivation of a closed-form expression for the instantaneous power distribution and consequently the different related performance measures. In [3-5], the analysis of both ergodic capacity and outage capacity is based mainly on numerical methods due to the use of the lognormal-based model. On the other hand, the generalized-K (Gamma-Gamma) model, where the shadowing is modeled by a Gamma distribution instead of the lognormal one, has recently received attention as an alternative model [6-10]. In this paper, the ergodic capacity and information outage probability of DASs over generalized-K fading channels are investigated for both the single-cell and multi-cell environments where the weighted sum of independent generalized-K random variables (RVs) is approximated by another generalized-K RV using the moment matching method to compute these performance metrics. The obtained results provide approximate analytical expressions that quantify the expected gains due to reduced access distance, less severe multipath fading, and macrodiversity in DASs as compared to collocated antenna systems (CASs).

II. The DAS Model

The DAS model considered here is based on the integration of an arrangement of N DAPs in each cell where these DAPs are connected to the base station (BS) via dedicated wired medium such as fiber-optic links. Each DAP is assumed to perform only up and down radio frequency conversion and to have an individual (per-port) power constraint. Both the direct link transmission/reception mode (between the user terminal and the BS) and the cooperative transmission/reception mode through the DAPs are possible depending on a certain criterion such as the path loss (distance) and/or the instantaneous signal-to-noise ratio (SNR) between the user terminal (UT) and the BS and/or the neighboring DAPs. However, in this paper, cell-edge UTs are considered.

III. Performance of Single-cell DAS

A. The Signal and Channel Model

The received signal at the BS, through the set of the cooperating (participating) DAPs, can be expressed as

$$\mathbf{y} = \begin{pmatrix} \sqrt{\frac{w_1}{r_1}} h_1 \\ \vdots \\ \sqrt{\frac{w_{N_{cp}}}{r_{N_{cp}}}} h_{N_{cp}} \end{pmatrix} x + \mathbf{n}, \tag{1}$$

where h_i denotes the small-scale (multipath) channel coefficient from the UT to the ith DAP, w_i is the shadowing component, x is the transmitted signal and $\mathbf{n}$ is the $N_{cp} \times 1$ zero-mean complex additive white Gaussian noise vector distributed

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as $Gaus\left(0, \sigma_n^2 I_{N_{cp}}\right)$. The number of cooperating DAPs is $N_{cp} \subseteq N$.

The normalized distance r can be expressed as

$$r_i = \left(\frac{d_{BS}}{d_1}\right)^{\beta} \left(\frac{d_1}{d_i}\right)^{\beta},\ i = 1, \ldots, N_{cp}, \quad (2)$$

where d_i denotes distance between the UT and the ith DAP with a minimum of d_1 and d_{BS} denotes the distance between the UT and the BS which is included to reveal the gain of reducing the access distance when the UT is far away from the BS but near one or more of the DAPs. For analytical tractability, the path loss, β, (typically ranging from 2 to 4) is assumed to be the same for all cooperating antennas. Such an assumption is reasonable since the cooperating DAPs are expected to lie in the same environment (typical urban, suburban, etc.). The ratios $\left(\frac{d_{BS}}{d_1}\right)^{\beta}$ and $\left(\frac{d_1}{d_i}\right)^{\beta}$ will be used in the selection criterion of the cooperating DAPs as described later.

The envelope of the fading signal, $|h|$, is modeled by the versatile Nakagami distribution due to its applicability in different propagation scenarios where the fading statistics between the UT and nearby DAPs are expected to follow a Nakagami distribution rather than the Rayleigh one due to the higher probability of having a line-of-sight component or strong specular components. So,

$$p_{|h|}(x) = \frac{2 m_m^{m_m} x^{2m_m - 1}}{\Gamma(m_m)\Omega^{m_m}} \exp\left(-\frac{m_m x^2}{\Omega^2}\right), \quad (3)$$

where $\Gamma(\cdot)$ is the Gamma function, m_m is the Nakagami multipath fading parameter and $\Omega = E(|h|^2)$. The shadowing component, w, is modeled by the Gamma distribution as proposed [7] as alternative to the less tractable lognormal model[1]

$$p_w(x) = \frac{(\frac{m_s}{\Omega_0})^{m_s}}{\Gamma(m_s)} x^{m_s - 1} \exp(-\frac{m_s x}{\Omega_0})\ , x \geq 0, m_s > 0, \quad (4)$$

where m_s is the shadowing parameter and Ω_0 is the mean of the mean local power. The parameters m_m and m_s quantify the severity of multipath fading and shadowing in the sense that small values of m_m and m_s indicate severe multipath fading and shadowing conditions, and vice versa.

B. The Capacity of a Single-user DAS over Independent Generalized-K Channels

For the single-user with a single-antenna and single-antenna DAPs, the equivalent model of the uplink channel is a distributed single-input multiple-output (D-SIMO) channel whose ergodic capacity, assuming an ergodic channel and a long coding period, can be expressed as

$$C_{erg} = E\left[\log_2\left(1 + \mathsf{SNR}\left(\frac{d_{BS}}{d_1}\right)^{\beta} \sum_{i=1}^{N_{cp}} \left(\frac{d_1}{d_i}\right)^{\beta} z_i w_i\right)\right], \quad (5)$$

[1]In [7, 9], using the moment matching method between the Gamma probability density function (PDF) in (4) and the lognormal PDF, it was shown that $m_s = \frac{1}{e^{(\sigma_s/8.686)^2} - 1}$ where σ_s denotes the standard deviation in the lognormal shadowing model.

where $z_i = |h_i|^2$ for $i = 1, \ldots, N_{cp}$, and SNR is the input signal-to-noise ratio P/σ^2. On the other hand, if coding is only over a small number of the coherence periods, then one needs to resort to the notion of the probability of outage for a target rate R which can be expressed as

$$P_{out}(R) = P\left(\log_2\left[1 + \mathsf{SNR}\left(\frac{d_{BS}}{d_1}\right)^{\beta} \sum_{i=1}^{N_{cp}} \left(\frac{d_1}{d_i}\right)^{\beta} z_i w_i\right] \leq R\right). \quad (6)$$

Clearly, both performance measures are dependent on the distribution of the following

$$\zeta = \sum_{i=1}^{N_{cp}} \left(\frac{d_1}{d_i}\right)^{\beta} z_i w_i. \quad (7)$$

Now it is well-known that z will follow a Gamma distribution as

$$p_z(x) = \frac{(\frac{m_m}{\Omega})^{m_m}}{\Gamma(m_m)} x^{m_m - 1} \exp(-\frac{m_m x}{\Omega})\ , x \geq 0, m_m \geq 0.5. \quad (8)$$

Moreover, the RV $\gamma = zw$, i.e., the instantaneous power of the composite fading channel, follows a generalized-K distribution as [6, 8]

$$p_\gamma(x) = \frac{2(b/2)^{m_m + m_s}}{\Gamma(m_m)\Gamma(m_s)} x^{(m_m + m_s)/2 - 1} K_{m_s - m_m}(b\sqrt{x}), \quad (9)$$

where $K_{m_s - m_m}(\cdot)$ is the modified Bessel function of the second kind and order $m_s - m_m$, $b = 2\sqrt{\frac{m_m m_s}{\Omega_0}}$. Hence, the expression in (7) is a weighted sum of generalized-K RVs and its distribution is sought.

C. The Approximate Distribution of the Weighted Sum of Independent Generalized-K RVs

In general, the weighted sum of independent generalized-K RVs can be expressed as

$$\zeta_1 = c_1 z_1 w_1 + c_2 z_2 w_2 + ... + c_N z_N w_N, \quad (10)$$

where the $c_i s$ are assumed to be deterministic and are ordered in a descending order such that $c_1 \geq c_2 \geq \ldots \geq c_N > 0$. In the DAS set-up considered here, this is in accordance with the fact that we may set $\left(\frac{d_1}{d_1}\right)^{\beta} = 1 \geq \left(\frac{d_1}{d_2}\right)^{\beta} \geq \left(\frac{d_1}{d_N}\right)^{\beta}$.

The derivation of the exact distribution of ζ_1 has shown to be quite involved even for the sum of equally-weighted independent and identically distributed (i.i.d.) generalized-K RVs with integer m_m and m_s [11-12]. This has motivated looking for an approximate distribution; in [13], it was shown that the distribution of the sum of independent generalized-K RVs can be closely approximated by another generalized-K distribution whose parameters can be obtained through the tractable moment matching method. This approach is extended here to the weighted sum of independent generalized-K RVs.

The amount of fading (AF) of ζ_1, for the i.i.d. case, can be expressed as

$$\mathsf{AF}_{\zeta_1,i.i.d.} = \frac{\sum_{j=1}^{N} c_j^2}{\left(\sum_{j=1}^{N} c_j\right)^2} \mathsf{AF}_0, \tag{11}$$

where AF_0 denotes the AF of each of the individual summands that is given as $\mathsf{AF}_0 = \frac{1}{m_m} + \frac{1}{m_s} + \frac{1}{m_m m_s}$. Equating the AF in (11) to the AF of the approximating generalized-K RV, ζ, will result in the following parameters of the approximating distribution

$$m_{m,\zeta} = \frac{\left((1+a) + \sqrt{(1+a)^2 + \frac{4}{\tilde{c} m_m m_s} k_1 a}\ \right)}{2(1 + a + \frac{1}{m_s})} \tilde{c} m_m, \tag{12a}$$

$$m_{s,\zeta} = \frac{m_{m,\zeta}}{a}, \tag{12b}$$

$$\Omega_{0,\zeta} = \sum_{j=1}^{N} c_j \Omega_{0,j}\ , \tag{12c}$$

where $k_1 = (m_m + m_s + 1)$, $a = \frac{m_m}{m_s}$, and $\tilde{c} = \frac{\left(\sum_{j=1}^{N} c_j\right)^2}{\sum_{j=1}^{N} c_j^2}$.

The parameter $\tilde{c}$ is always greater than unity since the sum of squares of positive numbers is less than or equal to the square of the sum and is maximum when the weights are equal. So, the parameters of the approximating generalized-K PDF decrease as the disparity between the weights increases; however, the expressions in (12a) and (12b) tend to underestimates values of $m_{m,\zeta}$ that of the best-fitting generalized-K PDF in the lower tail region as the values of m_m and m_s decrease and/or the disparity between the weights increases. For these cases, the introduced approximation represents a lower bound and the approximation accuracy can be enhanced by an adjustment parameter ϵ (i.e., $\tilde{m}_{m,\zeta} = m_{m,\zeta} + \epsilon_m$ and $\tilde{m}_{s,\zeta} = m_{s,\zeta} + \epsilon_s$) that can be determined numerically. Nevertheless, for the DASs set-up considered, since the participating (cooperating) set of DAPs contains only the ones having relatively strong weights (small access distances), then the approximation accuracy, without adjustment, will be sufficient to accurately approximate the cumulative distribution function (CDF) of the weighted sum of N_{cp} generalized-K RVs.

Now, we may set the criterion for cooperation so that (i) the ratio $\left(\frac{d_{BS}}{d_1}\right)^\beta >> 1$ (i.e., near cell-edge users) and (ii) only DAPs having $\left(\frac{d_1}{d_i}\right)^\beta \geq 0.5$ participate in the transmission/reception. The CDF plots are shown in Figs. 1 and 2 for $m_m = m_s = 2$ and $m_m = m_s = 4$ (such values of m_m and m_s are expected since the fading severity gets less for reduced access distances). The plots demonstrate that the approximation accuracy improves as the values of m_m and m_s increase. To express the ergodic capacity over generalized-K channels, we may first express the generalized-K PDF, being the PDF of the product of two Gamma RVs, as a special case of the H-function distribution family

$$p_\gamma(y) = \frac{m_{m,\zeta} m_{s,\zeta}}{\Gamma(m_{m,\zeta})\Gamma(m_{s,\zeta})\Omega_{0,\zeta}} H_{0,2}^{2,0}\left[\left(\frac{m_{m,\zeta} m_{s,\zeta}}{\Omega_{0,\zeta}}\right) y \middle| (m_{m,\zeta} - 1, 1), (m_{s,\zeta} - 1, 1)\right], \tag{13}$$

where $H_{p,q}^{m,n}[z]$ is the (Fox) H-function as defined in [14]. Reducing the expression in (13) to the corresponding Meijer's function and using the fact that $\ln(1+x) = G_{0,2}^{2,0}\left[x\middle|_{1,0}^{1,1}\right]$, then, using [15, eqn. 7.811.1], we may express the ergodic capacity as

$$C_{erg} = \frac{1}{\Gamma(m_{m,\zeta})\Gamma(m_{s,\zeta})} G_{2,4}^{4,1}\left[\frac{m_{m,\zeta} m_{s,\zeta}}{\Omega_{0,\zeta}\mathsf{SNR}_e}\middle|_{0,0,m_{m,\zeta},m_{s,\zeta}}^{0,1}\right], \tag{14}$$

where $G_{p,q}^{m,n}$ denotes the Meijer's function [15, eqn. 9.310] and $\mathsf{SNR}_e = \frac{P}{\sigma^2}\left(\frac{d_{BS}}{d_1}\right)^\beta$. The information outage probability can be expressed as

$$P_{out}(R) = \frac{G_{1,3}^{2,1}\left[\frac{m_{m,\zeta} m_{s,\zeta}}{\Omega_{0,\zeta}} \frac{2^R - 1}{\mathsf{SNR}_e}\middle|_{m_{m,\zeta},m_{s,\zeta},0}^{1}\right]}{\Gamma(m_{m,\zeta})\Gamma(m_{s,\zeta})}. \tag{15}$$

To quantify the performance gains as compared to CASs (i.e., conventional cellular systems), we may consider, for a CAS, a BS being equipped with four collocated antennas and a DAS with a varying number of cooperating DAPs. The path loss exponent is set as $\beta = 3$ and the UT is assumed to be far from the BS so that $d_{BS}/d_1 = 3$. The values of the weights $c_i' s$ are dependent on the geometrical layout of the deployed DAPs; however, in here we assume that the UT, for different UT locations and DAPs' configurations, can be cooperating with one, two or four DAPs with the following weights $c_1 = 1 = c_2 = 1$ and $c_1 = 1 = c_2 = 1$, $c_3 = c_4 = \left(\frac{1}{1.25}\right)^3 \approx 0.5$ for $N_{cp} = 2$ and $N_{cp} = 4$, respectively.

In Figs. 3 and 4, the plots of the information outage probability versus the target rate and the ergodic capacity of the DAS system, as compared to the CAS (where, in general, N_{BS} antennas are collocated at the BS), demonstrate the attained gains due to reduced access distance and macrodiversity; and that most of this gain is attained through two to three cooperating DAPs only. For both plots, we set $m_m = 2$ for the DAS and $m_m = 1$ for the CAS (as explained in Section III.A) and $m_s = 2$ ($\sigma_s = 5.5$ dB) for both systems. Note that for the collocated case, it can be shown that the sum, at the BS, has a generalized-K PDF with $m_{m,sum} = N_{BS} m_m$ (assuming that the multipath components are independent), $m_{s,sum} = m_s$ (since fully correlated shadowing is experienced), and $\Omega_{0,sum} = N_{BS}\Omega_0$. The previous results can be extended to the case where each of the distributed ports has multiple antennas (L of them); in that case, the output, after maximal ratio combining, can be expressed as

$$\gamma_t = \sum_{i=1}^{N_{cp}} \sum_{l=1}^{L} \gamma_{l,i}. \tag{16}$$

However, since the signals received at all ports experience the same shadowing statistics, the expression in (16) reduces to

$$\gamma_t = \sum_{i=1}^{N_{cp}} \gamma_{p,i}, \tag{17}$$

where each $\gamma_{p,i}$ has a generalized-K PDF with $m_{m,p} = Lm_m$, $m_{s,p} = m_s$, and $\Omega_{0,p} = L\Omega_0$. Similar analysis applies for the distributed multiple-input single-output (D-MISO) downlink channel.

IV. Performance of Multi-cell DAS

In a multi-cell DAS consisting of B_b BSs with N DAPs per cell. The signal-to-interference ratio (SIR) for the single user at the 0th cell can be expressed (through generalizing the expression in [5, eqn. 4]) as

$$\gamma_{mc} = \frac{\left(\frac{d_{BS}}{d_1}\right)^{\beta} \sum_{i=1}^{N_{co}} \left(\frac{d_1}{d_i}\right)^{\beta} \gamma_i}{\sum_{j=1}^{B_I} \left(\frac{d_{BS,j}}{d_{1,j}}\right)^{\beta_j} \sum_{i=1}^{N_{co}} \left(\frac{d_{1,j}}{d_{i,j}}\right)^{\beta_j} \gamma_{i,j}}, \tag{18}$$

where $B_I < B_b$ denotes the cardinality of the subset of interfering BSs, $d_{1,j}$ denotes the minimum distance from the ith interfering DAP in the jth interfering cell to the desired user, $d_{BS,j}$ is the distance from the desired user to the BS of the jth interfering cell. In (18), it is assumed that the interfering signals from the jth cell experience the same path loss exponent β. The expression in (18) indicates that while the integration of DAPs tends to enhance the desired signal, it also enhances the inter-cell interference, by the factor $\left(\frac{d_{BS,j}}{d_{1,j}}\right)^{\beta_j}$, where the nearest interfering DAP, from the jth cell, is almost always nearer to the desired user than the BS in that interfering cell.

Since each of the instantaneous powers of both the desired user and the interferer's, in (18), has a generalized-K PDF, then the PDF of γ_{mc} can be obtained by approximating both the PDFs of the numerator and the denominator by generalized-K PDFs (using a two-step approximation for the denominator). To express the distribution of the quotient of two generalized-K RVs, we use again the expression of the generalized-K PDF as a special case of the H-function distribution family as in (13). Hence, if we denote the quotient of two independent generalized-K RVs, X_1 and X_2, whose parameters are $m_{m,1}$, $m_{s,1}$, and $m_{m,2}$, $m_{s,2}$, respectively, as $\chi = \frac{X_1}{X_2}$, then, using [14, theorem 6.4.3], the PDF of χ can be expressed as

$$p(\chi) = d_1 G_{2,2}^{2,2}\left[\left(\frac{m_{m,1}m_{s,1}\Omega_{0,2}}{m_{m,2}m_{s,2}\Omega_{0,1}}\right)\chi\Big|_{m_{m,1}-1,m_{s,1}-1}^{-m_{m,2},-m_{s,2}}\right], \tag{19}$$

where $d_1 = \frac{m_{m,1}m_{s,1}\Omega_{0,2}}{\Gamma(m_{m,1})\Gamma(m_{s,1})\Gamma(m_{m,2})\Gamma(m_{s,2})\Omega_{0,1}}$. The expression in (19) is more compact than the expression obtained, using tedious algebraic manipulations, in [9, eqn. 15] and [16, eqn. 17]. The corresponding ergodic capacity can be expressed as

$$C_{erg} = E\left[\log_2\left(1 + \gamma_{mc}\right)\right], \tag{20}$$

and can be derived using [15, eqn. 7.811.1].

V. Conclusion

The integration of DASs in current and future cellular systems necessitates the devise of the appropriate analytical tools to study the performance of such systems. In this paper, a closed-form approximation for the PDF of the weighted sum of independent generalized-K RVs is introduced. Then, this approximation is utilized to compute both the ergodic capacity and the outage probability of DASs over generalized-K composite fading channels. Furthermore, the introduced approximation is used to approximate the PDF of the SIR for DASs in multi-cell environments. Extensions of this work may include the instantaneous SNR in the cooperation selection criterion which will require the ordered statistics for the weighted sum of generalized-K RVs.

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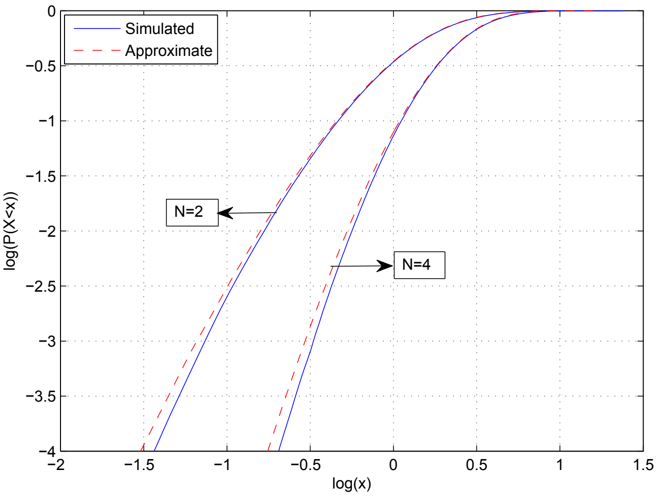

Fig. 1. The log-log (to base 10) CDF plots for the weighted sum of generalized-K RVs and the approximating generalized-K RV for different values of N with $m_m = m_s = 2$ and $c_1 = 1, c_2 = 0.75, c_3 = 0.5$, and $c_4 = 0.5$.

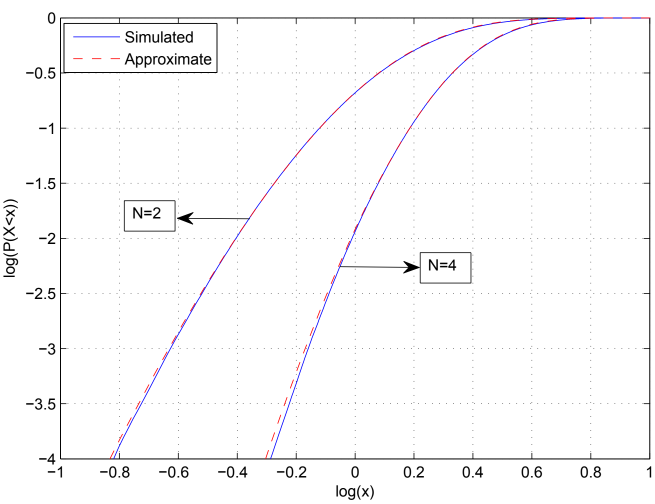

Fig. 2. The log-log (to base 10) CDF plots for the weighted sum of generalized-K RVs and the approximating generalized-K RV for different values of N with $m_m = m_s = 4$, and $c_1 = 1, c_2 = 0.75, c_3 = 0.5$, and $c_4 = 0.5$.

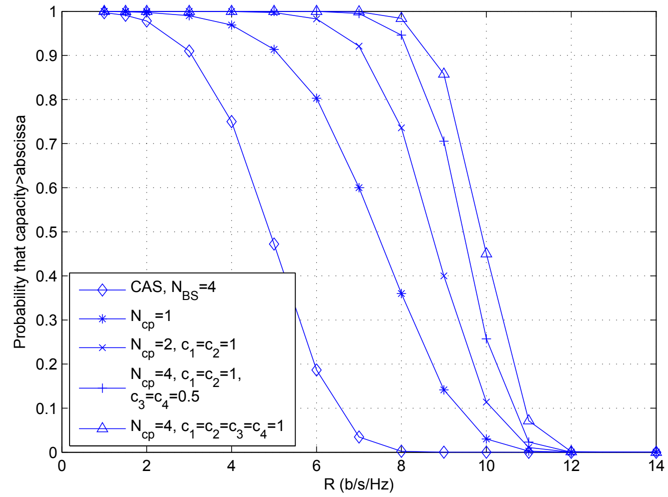

Fig. 3. The plot of the outage probability versus the target rate for different number of cooperating DAPs at $P/\sigma^2 = 10$ dB.

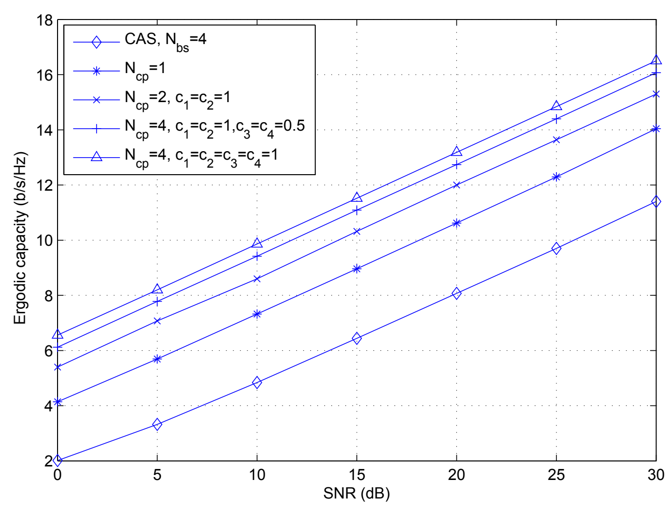

Fig. 4. The plot of the ergodic capacity for different number of cooperating DAPs.