Cooperative Communications System With Spatially Random Relays

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Abstract—**Cooperative communications is a multiuser framework for wireless network environments. The collaboration among the users can exploit the inherent spatial diversity gains to thereby enhance the system performance significantly. Due to the mobility of users, especially in cellular systems, the exact locations of them are usually unknown *a priori* and hard/costly to discover. Therefore it is reasonable to model their locations as Bernoulli process. In this work, the uplink of a microcell in a decode-and-forward cooperative cellular system is investigated. The outage probability is derived based on a practical channel model including not only path loss but also shadowing and multipath fading effects. It is shown that considerable performance gains can be obtained.**

Index Terms—**Cooperative communications, Bernoulli process, path loss, shadowing, multipath fading**

I. INTRODUCTION

Wireless communications usually suffers from several significant impairments. Despite the additive noise, radio signals are generally affected by reflection, diffraction, and scattering mechanisms [1]. On the other hand, the broadcast nature of radio propagation offers opportunity to exploit the inherent spatial diversity gains and thereby to enhance the performance further. Cooperative communications is such a system, utilizing the unique feature of wireless communications, to provide higher quality of service and better communications experience via coordinations among participants [2], [3]. The benefits of cooperative communications have been justified by a large amount of work, e.g., [2]–[5].

In [2], [3], a simple CDMA system with decode-and-forward cooperative scheme is proposed, which can considerably increase the system's performance. In [4], Laneman *et al.* investigate several cooperation methods and show that the system's outage probability can be significantly decreased by exploiting the so-called cooperative diversity. Most of the literature, especially the work on three-node relay model, focuses on a fixed network topology. It means that the locations of users are exactly known. In practice, however, the users' locations may not be perfectly known due to limited localization accuracy and the mobility of users, especially in cellular systems. Therefore, the randomness of the users should be considered in system design. In [6], a distributed antenna system for the downlink of a cellular system is investigated. The antenna elements are assumed to be randomly distributed and the outage probability in several configurations

is analyzed. The links from the base station to the antenna elements are assumed to be fiber optics or line-of-sight RF. That is, the links are error-free, which simplifies the analysis.

In this paper, the uplink of a microcell in a cellular system, where a particular user would like to communicate with the base station through the assistances of other idle users, is considered. Due to the randomness of users, the locations of them are modeled as a Bernoulli process. Unlike the model in [6], no error-free links are assumed in our model, which is usually the case in cellular systems. In addition, to be practical, the channel in this paper considers not only path loss, but also shadowing and multipath fading. Based on the model, the effects of random locations of users on the system performance is analyzed and the outage probability is derived.

II. SYSTEM MODEL

A. System Description

In this paper, we consider the uplink of a microcell in a cellular system, shown in Fig. 1, where the base station is located at the center and denoted as "destination", and a particular user who has information to transmit is called "source". The cell size is R_S and the distance from the source to the destination is L. The idle users who may offer cooperations in the cell are represented by other points in the figure, and the total number of idle users is n. Due to the mobility of these idle users and possible environment restrictions, their exact locations are unknown to the particular user. Without loss of generality, we assume that there is no clear patterns or trends in the density of these users. Consequently, these location-unknown users can be modeled as a uniform point process [7], i.e., a special case of Bernoulli process.

Definition 1 (Bernoulli process [8]): A Bernoulli process on area A with parameters n and probability measure $P(\cdot)$ is a random finite set $\mathbf{\Psi} \subset A$ for which the totality of $\mathbf{\Psi}$ is n, and

$$\Pr(N(A_1) = n_1, N(A_2) = n_2, \ldots, N(A_k) = n_k)$$
$$= \frac{n!}{n_0! n_1! \cdots n_k!} P(A_0)^{n_0} P(A_1)^{n_1} \cdots P(A_k)^{n_k} \quad (1)$$

where $A_0, A_1, \ldots, A_k$ are arbitrary disjoint subsets of A with $\bigcup_{i=0}^{k} A_i = A$. $N(A_i)$ denotes the number of points of $\mathbf{\Psi}$ falling in A_i, and $\sum_{i=0}^{k} n_i = n$. When the n points are

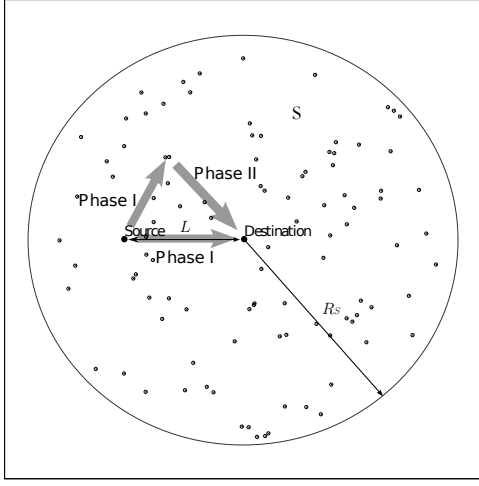Fig. 1. The uplink of a microcell in a cellular system.

uniformly distributed on A, the probability measure $P(\cdot)$ can be simplified as

$$P(A_i) = |A_i|/\pi R_S^2 \qquad (2)$$

where $|A_i|$ denotes the area of A_i.

In the uplink system the particular user (the source) intends to transmit information to the base station. In order to increase his/her communications quality, some kind of coordination among these idle users will be utilized and the whole session is divided into two phases: the broadcast phase and the cooperation phase. In the broadcast phase (phase I), the source broadcasts the desired information to the base station (the destination). The received signal at the destination is

$$d_1 = h_{sd}\sqrt{P_s}s + z_1, \qquad (3)$$

where h_{sd} is the channel response from the source to the destination, P_s is the power utilized by the source, s is the transmitted symbol with unit variance, and z_1 is the additive white Gaussian noise (AWGN) with power density N_0. The destination will save copies of the received signal and h_{sd} for later use.

The idle users will also obtain the signal. Similarly, the received signal at an arbitrary idle user is

$$d_{sr} = h_{sr}\sqrt{P_s}s + z_r, \qquad (4)$$

where h_{sr} is the channel response from the source to the user, and the AWGN z_r is also assumed to have power density N_0. This user may or may not successfully decode the desired symbol depending on whether his/her instantaneous signal-to-noise ratio (SNR) is greater than the threshold Θ which is a given system parameter. Here the instantaneous SNR γ_{sr} is defined as $|h_{sr}|^2 P_s/N_0$. If the user does successfully decode s, he/she will be selected as a relay user and will be involved in the second phase. For notational simplicity, we define a set $\mathbf{D}$ to represent all these relay users.

In phase II, these relay users from $\mathbf{D}$ decode and forward s to the base station in a cooperative way. The received signal

at the destination is

$$d_2 = \sum_{i \in \mathbf{D}} h_{rd,i} v_i \sqrt{P_r}s + z_2, \qquad (5)$$

where $h_{rd,i}$ is the channel response from ith relay user to the destination, v_i is the combination weight, and P_r is the power shared by all relay users. The symbol z_2 represents the AWGN with power density N_0. Let $P_{\text{tot}} = P_s + P_r$ be the total power utilized in these two phases. Maximum ratio transmission (MRT) is adopted to achieve the maximum SNR [9], and the weight v_i is thus designed as

$$v_i = \frac{h_{rd,i}^*}{\sqrt{\sum_k |h_{rd,k}|^2}}. \qquad (6)$$

The destination will then constructively combine d_1 and d_2 to get the desired information more reliably. Since these two signals are received at different phases, maximum ratio combining (MRC) can be used [10]. It follows that the combined received signal at the destination is

$$d = g_1 d_1 + g_2 d_2 \qquad (7)$$

where

$$\begin{cases} g_1 = \frac{h_{sd}^*\sqrt{P_s}}{\sqrt{|h_{sd}|^2 P_s + \sum |h_{rd,i}|^2 P_r}} \\ g_2 = \frac{\sqrt{\sum |h_{rd,i}|^2 P_r}}{\sqrt{|h_{sd}|^2 P_s + \sum |h_{rd,i}|^2 P_r}}. \end{cases} \qquad (8)$$

After combination, the final SNR γ_d at the destination is

$$\gamma_d = \gamma_{sd} + \sum_{i \in \mathbf{D}} \gamma_{rd,i} = \frac{P_s|h_{sd}|^2}{N_0} + \sum_{i=1}^{K} \frac{P_r|h_{rd,i}|^2}{N_0} \qquad (9)$$

where $K = |\mathbf{D}|$, γ_{sd} is the SNR at the destination contributed by the source in phase I, and $\gamma_{rd,i}$ is the SNR at the destination contributed by ith relay user in phase II.

B. Channel Model

To be practical, the channel model here includes both path loss, slow shadowing, and fast multipath fading effects. Path loss $\overline{PL}$ describes the attenuation of the RF signal and gives an area-mean of signal power, which is a decreasing function of distance r, i.e., $\overline{PL}(P_0, r) = P_0/N_0 r^{-\alpha}$ and α is the path loss exponent. Slow shadowing introduces additional fluctuation of signal strength around $\overline{PL}$, which is a local mean of signal power and is modeled as a log-normal RV ω. Given both path loss and shadowing, the instantaneous signal envelope also suffers fast multipath fading effect, which is modeled as Rayleigh fading here, corresponding to the combination of a large number of independent paths. Based on the channel model, at the end of phase I, the instantaneous SNR γ_{sr} at an arbitrary idle user, conditioned on the distance ρ from the source to this user, follows the composite exponential log-normal distribution [6], i.e.,

$$p_{\gamma_{sr}|\rho}(\gamma) = \int_0^\infty \frac{1}{\omega} \exp\left(-\frac{\gamma}{\omega}\right) \frac{\xi}{\sqrt{2\pi}\sigma\omega}$$
$$\exp\left(-\frac{(10\log_{10}\omega - 10\log_{10}\overline{PL}(P_s, \rho))^2}{2\sigma^2}\right) d\omega \qquad (10)$$

where $\xi = 10/\ln 10$, and σ is the standard deviation for the log-normal shadowing in dB and assumed to be constant. Given the distance l_i from the ith relay user to the destination, the instantaneous SNR $\gamma_{rd,i}$ has a similar conditional probability distribution

$$
\begin{aligned}
p_{\gamma_{rd,i}|l_i}(\gamma) = \int_0^\infty & \frac{1}{\omega} \exp\left(-\frac{\gamma}{\omega}\right) \frac{\xi}{\sqrt{2\pi}\sigma\omega} \\
& \exp\left(-\frac{(10\log_{10}\omega - 10\log_{10}\overline{\mathrm{PL}}(P_r, l_i))^2}{2\sigma^2}\right) d\omega
\end{aligned}
$$
(11)

The instantaneous SNR γ_{sd} obeys the following distribution

$$
\begin{aligned}
p_{\gamma_{sd}}(\gamma) = \int_0^\infty & \frac{1}{\omega} \exp\left(-\frac{\gamma}{\omega}\right) \frac{\xi}{\sqrt{2\pi}\sigma\omega} \\
& \exp\left(-\frac{(10\log_{10}\omega - 10\log_{10}\overline{\mathrm{PL}}(P_s, L))^2}{2\sigma^2}\right) d\omega.
\end{aligned}
$$
(12)

III. Outage Probability Analysis

In this section, we derive the outage probability of the system. The outage probability is defined as $P_{\mathrm{out}} = \Pr(\gamma_d < \Theta)$. According to (9), γ_d is a sum of γ_{sd} and $\gamma_{rd,i}$. Since the distribution of $\gamma_{rd,i}$ depends on the location of the ith relay, the statistical information of l_i, which is the distance from the ith relay to the destination, is needed for the outage probability analysis. It will be discussed first in the following.

A. Distribution of l_i

Since different idle user may have different instantaneous SNR depending on his/her location, the selection of relay users is location-dependent. Mathematically, the relay selection procedure is to mark the points of the uniform point process with two values 0 and 1, and the points marked with 1 represent selected relays. To derive the exact distribution of l_i, some facts about marked uniform point process need to be stated as follows.

Definition 2 (Location-dependent mark): For each point X of $\boldsymbol{\Psi}$, we associate a random variable m_X (the mark of X) taking values in some space M. If the distribution of m_X depends on X but not on the other points of $\boldsymbol{\Psi}$, and the m_X for different X are independent, the mark m_X is called location-dependent.

Given this definition, we can prove the following theorem for uniform Bernoulli process.

Theorem 1 (Marking theorem for uniform point process): Let $\boldsymbol{\Psi}$ be an n-point uniform point process on area A. With each point X of $\boldsymbol{\Psi}$, we associate a location-dependent mark m_X taking values in 0 or 1. The points with mark i ($i = 0$, 1) form a variable-size Bernoulli process with parameter K_i and probability measure $P_i(\cdot)$, for which

$$
\begin{aligned}
\Pr(K_i = k) = \binom{n}{k} & \Pr(m_X(x) = i)^k \\
& \cdot (1 - \Pr(m_X(x) = i))^{n-k}, \quad k = 0, 1, \ldots, n
\end{aligned}
$$
(13)

and

$$
P_i(A') = \frac{\int_{A'} \Pr(m_X(x) = i|x)\, dx}{\int_A \Pr(m_X(x) = i|x)\, dx}
$$
(14)

where A' is an arbitrary measurable sub-area in A.

Note that for notational simplicity we use x to represent the position of a point such that the 2-dimensional integration in terms of (ρ, θ) in polar coordinate system can be expressed by a normal integration in terms of x.
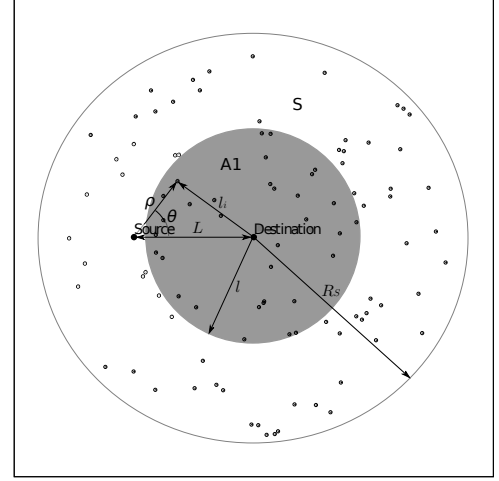

Fig. 2. A pictorial explanation of the distribution of the distance l_i.

In order to derive the distribution of l_i, a polar coordinate system with the pole being the source is setup, shown in Fig. 2. Then for an arbitrary idle user located at (ρ, θ) who is uniformly distributed in S, define a binary mark m_X satisfying $m_X = 1$ if $\gamma_{sr} > \Theta$ and $m_X = 0$ otherwise, i.e.,

$$
\Pr(m_X = 1|X) = \Pr(\gamma_{sr} > \Theta|\rho) = \int_\Theta^\infty p_{\gamma_{sr}|\rho}(\gamma)\, d\gamma, \quad (15)
$$

Then, applying Theorem 1, the probability that a point marked by 1 (relay user) is located in an area $A' \in S$ is

$$
\Pr(X \in A') = \frac{\iint_{A'} \rho \Pr(\gamma_{sr} > \Theta|\rho)\, d\rho d\theta}{\iint_S \rho \Pr(\gamma_{sr} > \Theta|\rho)\, d\rho d\theta}.
$$
(16)

Furthermore, the number of relay users $K = |\mathbf{D}|$ is a binomial RV following the distribution

$$
\begin{aligned}
\Pr(K = k) = \binom{n}{k} & \Pr(\gamma_{sr} > \Theta)^k (1 - \Pr(\gamma_{sr} > \Theta))^{n-k}, \\
& k = 0, 1, \ldots, n
\end{aligned}
$$
(17)

where

$$
\Pr(\gamma_{sr} > \Theta) = \frac{\int_0^{2\pi} \kappa\left(L\cos\theta + \sqrt{R_S^2 - L^2\sin^2\theta}\right) d\theta}{\pi R_S^2}
$$
(18)

and the auxiliary function $\kappa(\cdot)$ is defined as

$$
\kappa(y) = \int_0^y \rho \Pr(\gamma_{sr} > \Theta|\rho)\, d\rho = \int_0^y \rho \int_\Theta^\infty p_{\gamma_{sr}|\rho}(\gamma)\, d\gamma d\rho.
$$
(19)

Let l_i denote the distance from the ith relay user to the destination. For any $l \in [0, R_S]$, the probability that $l_i \leq l$ is equal to the probability that a relay user is located in the area A_1, i.e., $\Pr(X \in A_1)$, where A_1 is the circle area with radius l around the destination, as shown in Fig. 2. Consequently, through (10), (15), and (16), the cumulative distribution function (cdf) of l_i can be derived as

$$
P_{l_i}(l) = \begin{cases} \dfrac{2\int_0^{\theta_1} \kappa(L\cos\theta + \sqrt{l^2 - L^2\sin^2\theta})d\theta}{\int_0^{2\pi} \kappa(L\cos\theta + \sqrt{R_S^2 - L^2\sin^2\theta})d\theta} \\ \quad - \dfrac{2\int_0^{\theta_1} \kappa(L\cos\theta - \sqrt{l^2 - L^2\sin^2\theta})d\theta}{\int_0^{2\pi} \kappa(L\cos\theta + \sqrt{R_S^2 - L^2\sin^2\theta})d\theta} \\ \quad 0 \leq l < L \\ \dfrac{\int_0^{2\pi} \kappa(L\cos\theta + \sqrt{l^2 - L^2\sin^2\theta})d\theta}{\int_0^{2\pi} \kappa(L\cos\theta + \sqrt{R_S^2 - L^2\sin^2\theta})d\theta} \\ \quad L \leq l \leq R_S \end{cases} \tag{20}
$$

where

$$
\theta_1 = \arcsin(l/L). \tag{21}
$$

B. Outage Probability

According to (9), when $K = |\mathbf{D}| = 0$, i.e., no relay users are found after phase I, the destination gets only d_1 through the direct link from the source to the destination. In this case, the pdf of γ_d is simply given by (12) and can be approximated by the pdf of a single log-normal RV [11]

$$
p_{\gamma_d|K=0}(\gamma) = p_{\gamma_{sd}}(\gamma) \approx \frac{\xi}{\sqrt{2\pi}\sigma_s\gamma} \exp\left(-\frac{(10\log_{10}\gamma - \mu_s)^2}{2\sigma_s^2}\right), \tag{22}
$$

with

$$
\begin{cases} \mu_s = 10\log_{10}\frac{P_s}{N_0} - 10\alpha\log_{10}L - \xi\Upsilon, \\ \sigma_s^2 = \sigma^2 + \xi^2\frac{\pi^2}{6}. \end{cases} \tag{23}
$$

Υ is the Euler's constant [12].

When $K > 0$, i.e., at least one relay is found, with the distribution of l_i in (20), the pdf of $\gamma_{rd,i}$ is

$$
p_{\gamma_{rd,i}}(\gamma) = \int_0^{R_S} p_{\gamma_{rd,i}|l}(\gamma) \, dP_{l_i}(l) \tag{24}
$$

The complicated expressions of $p_{\gamma_{rd,i}|l}$ and P_{l_i} make it difficult to obtain analytical results, and motivate us to apply approximations. We propose to approximate $\gamma_{rd,i}$ as a single log-normal RV with pdf being

$$
p_{\gamma_{rd,i}}(\gamma) \approx \frac{\xi}{\sqrt{2\pi}\sigma_r\gamma} \exp\left(-\frac{(10\log_{10}\gamma - \mu_r)^2}{2\sigma_r^2}\right), \tag{25}
$$

with

$$
\begin{cases} \mu_r = 10\log_{10}\frac{P_r}{N_0} - 10\alpha\mathbb{E}[\log_{10}l] - \xi\Upsilon, \\ \sigma_r^2 = \sigma^2 + \xi^2\frac{\pi^2}{6} + 100\alpha^2\mathbb{D}[\log_{10}l]. \end{cases} \tag{26}
$$

Given system parameters, e.g., L, Θ etc, $\mathbb{E}[\log_{10}l]$ and $\mathbb{D}[\log_{10}l]$ are constant numbers that can be calculated numerically. The approximation is accurate which can be justified by plotting their cdf curves, i.e., the strategy used in [11].

Consequently, given $K > 0$, γ_d becomes a sum of log-normal RVs. The distribution of γ_d has no close-form expression, but can be fairly approximated by a single log-normal distribution with pdf being

$$
p_{\gamma_d|K}(\gamma) = \frac{\xi}{\sqrt{2\pi}\sigma_d(K)\gamma} \exp\left(-\frac{(10\log_{10}\gamma - \mu_d(K))^2}{2\sigma_d^2(K)}\right) \tag{27}
$$

There are several methods to calculate the parameters $\mu_d(K)$ and $\sigma_d(K)$ [13]–[16]. The approach given in [16] is adopted here since it has the best accuracy. The basic idea is to match the moment generating function (MGF) of γ_d with the MGF of the approximated single log-normal RV with parameters $\mu_d(K)$ and $\sigma_d(K)$, so that two independent equations can be setup as follows

$$
\widehat{\Psi}(t_i; \mu_d(K), \sigma_d(K)) = \widehat{\Psi}^K(t_i; \mu_r, \sigma_r) \cdot \widehat{\Psi}(t_i; \mu_s, \sigma_s), \quad i = 1, 2 \tag{28}
$$

where

$$
\widehat{\Psi}(t; \mu_x, \sigma_x) = \sum_{n=1}^N \frac{w_n}{\sqrt{\pi}}\left[-t\exp\left(\frac{\sqrt{2}\sigma_x a_n + \mu_x}{\xi}\right)\right] \tag{29}
$$

is the Gauss-Hermite representation of MGF of log-normal pdf [16]. The weights w_n and abscissas a_n are tabulated in [12], and $N = 16$ is used. The t_1 and t_2 are two arbitrarily selected different, real and positive values to make these two equations independent. The parameters $\mu_d(K)$ and $\sigma_d(K)$ can then be calculated by solving these equations.

Combining the cases of $K = 0$ and $K > 0$, the pdf of γ_d can be finally derived as

$$
\begin{aligned}
p_{\gamma_d}(\gamma) &= \sum_{k=1}^n p_{\gamma_d|K}(\gamma)\Pr(K=k) + p_{\gamma_{sd}}(\gamma)\Pr(K=0) \\
&= \sum_{k=1}^n \frac{\xi}{\sqrt{2\pi}\sigma_d(k)\gamma} \exp\left(-\frac{(10\log_{10}\gamma - \mu_d(k))^2}{2\sigma_d^2(k)}\right) \\
&\quad \cdot \binom{n}{k}\Pr(\gamma_{sr} > \Theta)^k(1 - \Pr(\gamma_{sr} > \Theta))^{n-k} \\
&\quad + \frac{\xi}{\sqrt{2\pi}\sigma_s\gamma} \exp\left(-\frac{(10\log_{10}\gamma - \mu_s)^2}{2\sigma_s}\right) \\
&\quad \cdot (1 - \Pr(\gamma_{sr} > \Theta))^n,
\end{aligned} \tag{30}
$$

where $\Pr(\gamma_{sr} > \Theta)$ is given by (18).

The outage probability is

$$
\begin{aligned}
P_{\text{out}} &= \int_0^\Theta p_{\gamma_d}(\gamma)\,d\gamma \\
&= \frac{1}{2} + \frac{1}{2}\sum_{k=1}^n \text{erf}\left(\frac{10\log_{10}\Theta - \mu_d(k)}{\sqrt{2}\sigma_d(k)}\right) \\
&\quad \cdot \binom{n}{k}\Pr(\gamma > \Theta)^k(1 - \Pr(\gamma > \Theta))^{n-k} \\
&\quad + \frac{1}{2}\text{erf}\left(\frac{10\log_{10}\Theta - \mu_s}{\sqrt{2}\sigma_s}\right) \\
&\quad \cdot (1 - \Pr(\gamma > \Theta))^n.
\end{aligned} \tag{31}
$$

IV. NUMERICAL AND SIMULATION RESULTS

In the following simulations, the total power P_{tot} is set to be 40dB, and R_S is selected so that the edge SNR is 0dB. The threshold Θ is 5dB. The power allocation factor β is defined as the ratio of P_s to P_{tot}. Notice that in order to calculate the parameters $\mu_d(K)$ and $\sigma_d(K)$, the Fenton-Wilkinson (F-W) method [13] is first used to generate rough estimation, which are then used as the initial values to solve the non-linear equations in (28). The path loss exponent α is 4, and standard deviation for the log-normal shadowing σ is 8dB.

Fig. 3 plots the outage probability of the system as the function of power allocation factor β with different number of users n. It can be seen that the simulation results and the analysis results are well matched. In addition, the optimal power allocation factor is between 0.6 to 0.8. Furthermore, when the power allocation factor is 1.0, the system becomes the conventional non-cooperative system. It shows that the outage probability increases significantly, which justifies the adoption of cooperation among mobile users in cellular systems.

Fig. 4 shows how the normalized distance L/R_S affects the system's performance in the terms of outage probability. Obviously, the system will have better performance as the user is getting closer to the destination.
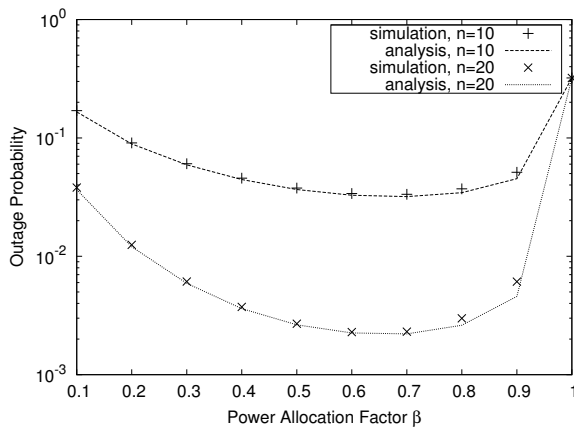

Fig. 3. Power allocation for different n. Θ is 5dB. L/R_S is 0.5. P_{tot} is 40dB.

V. CONCLUSION

The uplink of a microcell in a cellular system, containing a number of location-random users acting as relays, has been investigated. The outage probability has been derived and verified by the simulations. It has been shown that, with a decode-and-forward cooperative strategy, a particular user can obtain considerable performance gains and has better communications experience than conventional non-cooperative ways. Furthermore, the optimal power allocation scheme has been provided through numerical computations and verified by simulations.
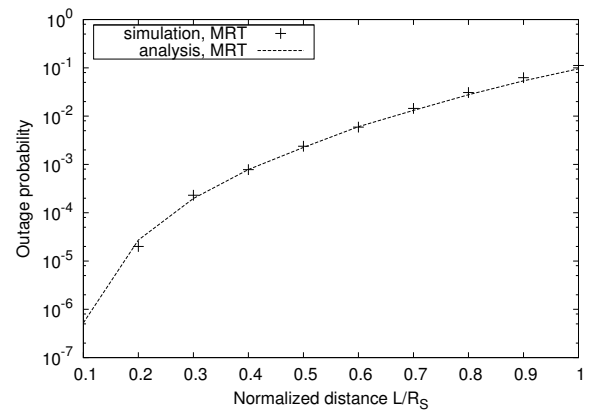
ACKNOWLEDGMENT

Fig. 4. Outage probability as a function of normalized distance L/R_S. P_{tot} is 40dB. Power allocation factor is 0.7. $n = 20$. Θ is 5dB.

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