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Performance of Cooperative Multi-hop Multiuser Relaying Networks

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Abstract: This paper presents both capacity and error performances of cooperative multi-hop multiuser relay system. All multi-hop cooperative relays in the system apply maximal-ratio combining (MRC) scheme, while signal transmission to end users is carried out using opportunistic scheduling algorithm. Numerical results for spectral efficiency and average symbol error probability (ASEP) for considered system are presented and discussed.

Keywords: Amplify-and-forward relay, Average symbol error probability, Multi-hop, Multiuser, Rayleigh fading, System capacity.

1 Introduction

Relaying is a promising technique that can improve a quality of wireless communications. Its advantages relative to traditional direct transmission include: easy implementation and good scalability, increased coverage area, robustness to changeable channel conditions and reduced required operating power. Originally, cooperative communication refers to scenario where relay nodes assist in transmission of information from source to destination. However, in modern wireless communications, the cooperation does not assume only information transmission which is known as a cooperative diversity. Namely, nodes can collaborate in exchanging information regarding the networks and channel status, in assessing the common wireless medium, in employing new technologies in favor of coordinated communications [1]. Performance improvements in dual-hop and multi-hop relay systems realized via diversity gain are presented in [2 – 4]. In respect of priority given to multi-hop relay system with diversity [4], in [5] multi-hop cooperative diversity system with maximum-ratio combining (MRC) is reduced to dual-hop relay systems in order to get a tractable expression for the probability density function (PDF) of end-to-end signal-to-noise ratio (SNR).

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In a direct wireless link, a fading is treated as a source of unreliability and therefore it has to be mitigated. In multiuser system, it is viewed as a source of randomization that should be exploited [6]. This means that a proper user scheduling algorithm plays a crucial role in realization of multiuser diversity. An opportunistic scheduling algorithm can increase the system capacity by exploiting the independent varying channel of users and schedule users with the best channel conditions [7, 8]. To realize a reliable communication of high data rates, combining relaying with multiuser is a promising approach. Moreover, in that way communication between the base station and the destination close to cell boundary is enabled. Analysis of multiuser diversity in cooperative relay system is processed in many papers. For example, in [9] and [10], authors analyze the symbol error probability (SEP) of cooperative relay system with multiuser in which relays use amplified-and-forward (AF) and decode-and-forward (DF) protocols, respectively. The closed-form expressions for two very important performance metrics, i.e. SEP and outage probability (OP), for dual-hop cooperative relay system with multiuser diversity are derived in [11]. Capacity analysis for such system is done in [12], while capacity of cooperative multi-relay multiuser system with relay and user selection processes based on outdated SNR is analyzed in [13]. Outage performance of multiuser relay system with one AF relay is studied in [14]. Multi-hop relay system in which last relay transfers the information to user selected by opportunistic user scheduling algorithm is investigated in [15]. Namely, OP expression for the considered system over Rayleigh fading channels is derived. Presented results represent boundary outage performance. Using that expression for OP, PDF of instantaneous end-to-end SNR is derived in [16]. Based on it, in this paper, we analyze spectral efficiency and error performance of the cooperative multi-hop multiuser relay system.

2 System Model

A proposed system consists of a source S (R_0) which sends information to mobile users D_k ($k=\overline{1,K}$) via AF relays R_i ($i=\overline{1,L}$). The last relay, R_L, plays the role of fusion center which collects information from source and relays and transfers it to selected mobile users (Fig. 1). Non-line-of-sight environment is explored, so amplitude and phase of channel gains are Rayleigh distributed and uniformly distributed over [0, 2π), respectively. For the Rayleigh fading channel exposed to the influence of a zero mean complex additive white Gaussian noise (AWGN), the instantaneous SNR of link between nodes i and j, denoted as $\gamma_{i,j}$, is modeled as

$$p_{\gamma_{i,j}}(\gamma)=\frac{1}{\bar{\gamma}_{i,j}}\exp\left(-\frac{\gamma}{\bar{\gamma}_{i,j}}\right), \tag{1}$$

with $\overline{\gamma}_{i,j} = \mathrm{E}[\gamma_{i,j}] = \mathrm{E}\left[\left|h_{i,j}\right|^2\right] E_{si} / \sigma^2$, where E_{si} is the average symbol energy of the i-th transmission node and σ^2 is the noise variance. Channel gain from the i-th transmission node to the j-th receiving node is denoted as $h_{i,j}$. Index i = 0 is reserved for the source.

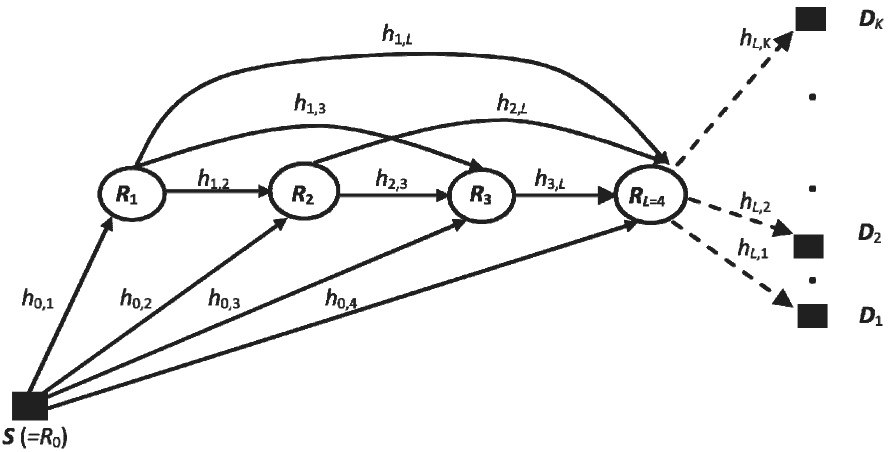

Fig. 1 – *Multi-hop multiuser relay network* (L = 4).

The strategy which should ensure interference free transmission supposes that time resource, T, is divided into L+1 time slots, $\Delta t = T/(L+1)$, and source and all relays transmit signals over appropriate time slot associated to them. Namely, in the first time slot, known as 0-th time slot, source broadcasts signal to all relays. During the next L-1 steps, in the k-th time slot the k-th relay receives the signal from the source and the previous k-1 relays and combines them using MRC technique. Then, that relay amplify and forward signal to the rest of relays. In the last time slot, the last relay combines all previously received signals and sends information to selected user. Following the described process, SNR at the first relay and j-th relay can be expressed as [17, Eq. (7)]

$$A_1 = \gamma_{0,1}, \tag{2}$$

and

$$A_j = \gamma_{0,j} + \sum_{m=1}^{j-1} \frac{A_m \gamma_{m,j}}{A_m + \gamma_{m,j} + 1}, \quad j = \overline{2, L}, \tag{3}$$

respectively. In order to develop a tractable framework for performance analysis of cooperative multi-hop relay system, transformation multi-hop relay into dual-hop relay systems is presented in detail in [5] (Fig. 2).

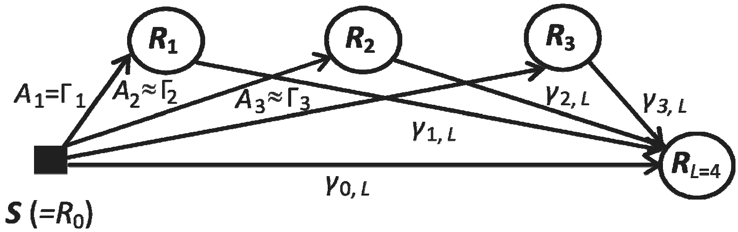

Fig. 2 – *Illustration of multi-hop relay system approximation with dual-hop relay systems* ($L = 4$).

Namely, A_j is bounded by $A_j < \Gamma_j = \gamma_{0,j} + \sum_{m=1}^{j-1} \min\left\{\Gamma_m, \gamma_{m,j}\right\}$, where $A_1 = \Gamma_1 = \gamma_{0,1}$. Now, the resulting SNR at the last relay can be expressed as

$$\gamma_L \approx \gamma_{0,L} + \sum_{j=1}^{L-1} \frac{\Gamma_j \gamma_{j,L}}{\Gamma_j + \gamma_{j,L}}, \tag{4}$$

which PDF is derived in [5, Eq. (11)] as

$$p_{\gamma_L}(\gamma) = \sum_{r=1}^{L} \sum_{p=1}^{N_r} \frac{\pi'_{r,p}}{\overline{\Gamma}'_{r,p}} \exp\left(-\frac{\gamma}{\overline{\Gamma}'_{r,p}}\right), \tag{5}$$

where

$$N_r\Big|_{r=1}^{L-1} = r,\ N_L = 1,\ \overline{\Gamma}'_{L,1} = \overline{\Gamma}'_{0,0} = \overline{\gamma}_{0,L},\ \frac{1}{\overline{\Gamma}'_{r,p}} = \frac{1}{\overline{\Gamma}_{r,p}} + \frac{1}{\overline{\gamma}_{r,L}},$$
$$\overline{\Gamma}_{r,r} = \overline{\gamma}_{0,r},\ \frac{1}{\overline{\Gamma}_{r,p}}\Bigg|_{p=1}^{r-1} = \frac{1}{\overline{\Gamma}_{r-1,p}} + \frac{1}{\overline{\gamma}_{r-1,p}}, \tag{6}$$

and

$$\pi'_{L,1} = \pi'_{0,0} = \prod_{r=1}^{L-1}\left[\sum_{p=1}^{r} \pi_{r,p} \frac{\overline{\gamma}_{0,L}}{\overline{\gamma}_{0,L} - \overline{\Gamma}'_{r,p}}\right],$$
$$\pi'_{l,q}\Big|_{l=1}^{L-1} = \pi_{l,q} \frac{\overline{\Gamma}'_{l,q}}{\overline{\Gamma}'_{l,q} - \overline{\gamma}_{0,L}} \prod_{r=1, r\neq l}^{L-1}\left[\sum_{p=1}^{r} \pi_{r,p} \frac{\overline{\Gamma}'_{l,p}}{\overline{\Gamma}'_{l,p} - \overline{\Gamma}'_{r,p}}\right], \tag{7}$$
$$\pi_{r,p}\Big|_{p=1}^{r-1} = \pi_{r-1,p} \frac{\overline{\Gamma}'_{r,p}}{\overline{\Gamma}'_{r,p} - \overline{\Gamma}_{r,r}},\ \pi_{1,p} = 1,\ \pi_{r,r} = \sum_{p=1}^{r-1} \pi_{r-1,p} \frac{\overline{\Gamma}_{r,r}}{\overline{\Gamma}_{r,r} - \overline{\Gamma}_{r,p}}.$$

The last relay transmits signal to the destination with the best channel condition, i.e. the destination that ensures the most advantageous system performance based on opportunistic scheduling. As it is presented in Fig. 1, K

users are linked to the last relay. Opportunistic multiuser scheduling algorithm provides information to the user with the best channel, i.e. user with the highest instantaneous SNR out of K, $\gamma_m = \max_{1\le k\le K} \gamma_{L,k}$. We assume that all average SNRs of link between the last relay and destinations are equal $\overline{\gamma}_{L,1} = \overline{\gamma}_{L,2} = ... = \overline{\gamma}_{L,K} = \overline{\gamma}_m$. Therefore, the equivalent instantaneous end-to-end SNR is

$$\gamma_{eq} = \frac{\gamma_L \gamma_m}{\gamma_L + \gamma_m}, \tag{8}$$

which cumulative distribution function (CDF) is derived in [15, Eqs. (10) and (12)] as

$$F_{\gamma_{eq}}(\gamma) = I_1 + I_2,$$

$$I_1 = \sum_{r=1}^{L}\sum_{p=1}^{N_r} \pi'_{r,p}\left(1 - \exp\left(-\frac{\gamma}{\overline{\Gamma}'_{r,p}}\right)\right), \tag{9}$$

$$I_2 = \sum_{r=1}^{L}\sum_{p=1}^{N_r}\sum_{k=1}^{K}\binom{K}{k}\sqrt{\frac{k\gamma^2}{\overline{\Gamma}'_{r,p}\overline{\gamma}_m}}\,2\pi'_{r,p}(-1)^k \mathrm{e}^{-\left(\frac{k}{\overline{\gamma}_m}+\frac{1}{\overline{\Gamma}'_{r,p}}\right)\gamma}\,\mathrm{K}_1\left(2\sqrt{\frac{k\gamma^2}{\overline{\gamma}_m\overline{\Gamma}'_{r,p}}}\right) + \sum_{r=1}^{L}\sum_{p=1}^{N_r}\pi'_{r,p}\,\mathrm{e}^{-\frac{\gamma}{\overline{\Gamma}'_{r,p}}},$$

where $\mathrm{K}_n(\cdot)$ is the modified Bessel function of the second kind and n-th order [18, Eqs. (8.407)]. Its PDF function is obtained in [16, Eq. (8)] as

$$\begin{aligned} p_{\gamma_{eq}}(\gamma) &= \sum_{r=1}^{L}\sum_{p=1}^{N_r}\sum_{k=1}^{K}\alpha_{k,r,p}e^{-\beta_{k,r,p}\gamma} \\ &\times\left[\mathrm{K}_1(\delta_{k,r,p}\gamma)(1-\beta_{k,r,p}\gamma) - 0.5\left(\mathrm{K}_0(\delta_{k,r,p}\gamma) + \mathrm{K}_2(\delta_{k,r,p}\gamma)\right)\delta_{k,r,p}\gamma\right], \end{aligned} \tag{10}$$

with parameters $\alpha_{k,r,p}$, $\beta_{k,r,p}$ and $\delta_{k,r,p}$ defined as

$$\alpha_{k,r,p} = (-1)^k\binom{K}{k}\delta_{k,r,p}\pi'_{r,p},\quad \beta_{k,r,p} = \frac{k}{\overline{\gamma}_m} + \frac{1}{\overline{\Gamma}'_{r,p}},\quad \delta_{k,r,p} = 2\sqrt{\frac{k}{\overline{\gamma}_m\overline{\Gamma}'_{r,p}}}. \tag{11}$$

3 System Performance

In this section, we present performance study for the considered cooperative multi-hop multiuser relay system. Namely, average system capacity and average SEP (ASEP) are analyzed.

3.1 System capacity

The average system capacity is defined as the sum of the average link capacity delivered to each user on average, i.e. [6, Eq. (19)]

$$\overline{C}=\sum_{k=1}^{K}\overline{C}_k p_k\ , \tag{12}$$

where p_k is the average probability of user k receiving service. To maintain the fairness, all p_k are equal to be $1/K$, so system capacity can be written as

$$\overline{C}=\overline{C}_k=\overline{C}_{\gamma_{eq}}=\frac{BW}{L+1}\int_{0}^{+\infty}\log_2\left(1+\gamma\right)p_{\gamma_{eq}}\left(\gamma\right)d\gamma, \tag{13}$$

where BW is bandwidth and factor $1/(L+1)$ accounts for the use of $L+1$ time slots for relaying. The integral in (13) can not be derived in closed-form, so for its evaluation some math tools, such as Matlab, Mathematica, etc. can be used.

For numerical evaluation in this paper, it is assumed that $E_{si}\big|_{i=1}^{L}=E_{s0}\big/\left(L-1\right)$ and that relays are uniformly distributed between the source and the destination, so the channel gain between i-th and j-th relays is

$$\mathrm{E}\left[\left|h_{i,j}\right|^2\right]=\mathrm{E}\left[\left|h_{0,L}\right|^2\right]\Big/\left(\frac{j-i}{L}\right)^{\mu}\ , \tag{14}$$

where μ represents path loss-factor corresponding to the outdoor hotzone model [5]. The average SNR of link between the source and the last relay is defined as

$$\overline{\gamma}_{0,L}=\mathrm{E}\left[\left|h_{0,L}\right|^2\right]E_{s0}\Big/\sigma^2 . \tag{15}$$

Numerical results for the normalized average system capacity are shown in Figs. 3 and 4.

The impact of both the number of hops and the strength of source-last relay link on spectral efficiency is depicted in Fig. 3. Note that spectral efficiency increases with increase of direct link power. In addition, it is evident from presented results that cooperative diversity reduces realized system throughput and it is in accordance with previously published results [12]. Namely, cooperative diversity enables the system to be more reliable, i.e. reduces severity of destructive fading, but in the same time do not allow constructive fading peaks important for higher throughput. Therefore, the trade off between reliability and spectral efficiency has to be done from number of relays point of view.

In order to observe the influence of user number on system capacity, we plot curves for spectral efficiency versus number of users in Fig. 4. Presented results point out the positive influence of multiuser diversity on the system capacity, i.e. higher number of users guarantees higher spectral efficiency. The capacity gain achieved by using multiuser diversity has the largest value for small number of users in the system. The further increase in number of users leads to higher capacity, but realized growth in capacity gain is less.

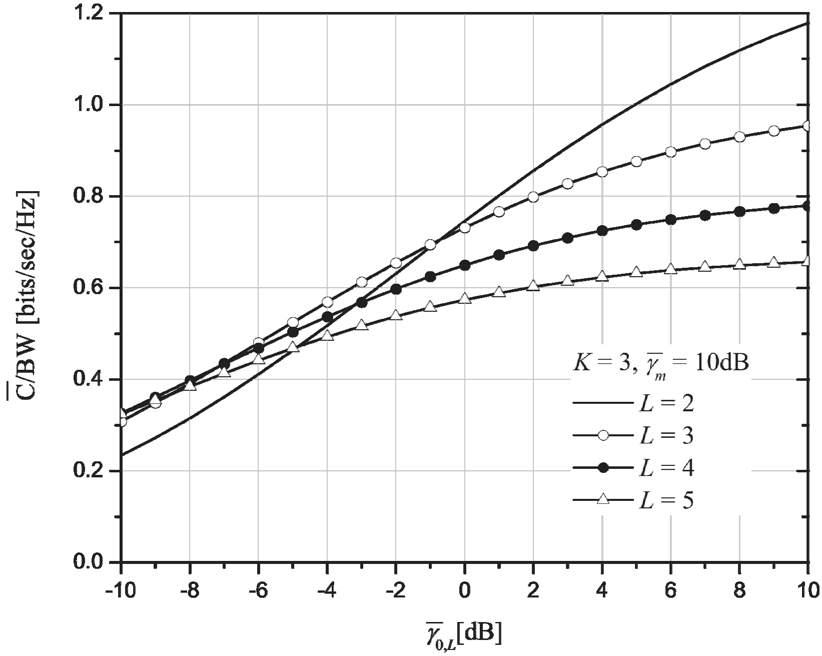

Fig. 3 – *Normalized average system capacity versus average SNR of link between source and last relay.*

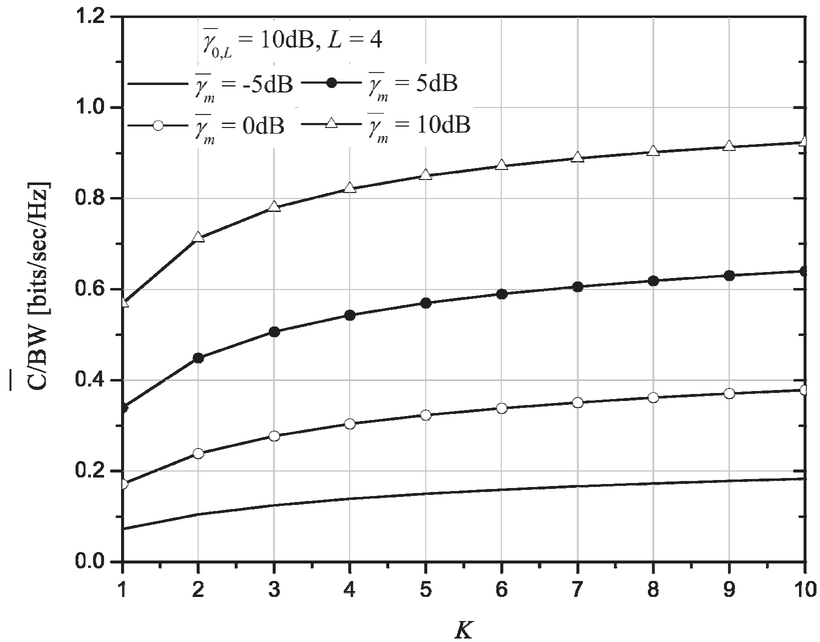

Fig. 4 – *Normalized average system capacity versus number of users.*

3.2 Average SEP

Uniform expression for conditional SEP at certain SNR (which is sufficiently accurate for high SNR values) depending on an applied modulation scheme can be found in [19, Table I]. The ASEP can be evaluated averaging the conditional SEP, $P_{se}(\gamma)$, over the PDF of γ_{eq}, i.e.

$$\overline{P}_{se} = \int_0^{+\infty} P_{se}(\gamma)\, p_{\gamma_{eq}}(\gamma)\,\mathrm{d}\gamma. \tag{16}$$

For non-coherent modulation schemes, such as differential binary phase shift keying (DBPSK) and M-ary noncoherent frequency shift keying (M-NFSK), for which $P_{se}(\gamma)$ is in the form of exponential function, i.e. $P_{se}(\gamma) = A\exp(B\gamma)$, after substituting (10) in (16), the definite integral can be solved in the closed-form as

$$\begin{aligned}\overline{P}_{se} = \sum_{r=1}^{L}\sum_{p=1}^{N_r}\sum_{k=1}^{K} A\alpha_{k,r,p}\Bigg[&\frac{1}{2\left(B+\beta_{k,r,p}\right)}\mathrm{H}_{1,2}^{2,1}\left(\frac{\delta_{k,r,p}^2}{4\left(B+\beta_{k,r,p}\right)^2}\middle|\begin{matrix} -,\ (0,2),\ -,\ - \\ \left(\frac{1}{2},1\right),\left(-\frac{1}{2},1\right),\ -,\ -,\ - \end{matrix}\right) \\ &- \frac{\beta_{k,r,p}}{2\left(B+\beta_{k,r,p}\right)^2}\mathrm{H}_{1,2}^{2,1}\left(\frac{\delta_{k,r,p}^2}{4\left(B+\beta_{k,r,p}\right)^2}\middle|\begin{matrix} -,\ (-1,2),\ -,\ - \\ \left(\frac{1}{2},1\right),\left(-\frac{1}{2},1\right),\ -,\ -,\ - \end{matrix}\right) \\ &- \frac{\delta_{k,r,p}}{4\left(B+\beta_{k,r,p}\right)^2}\mathrm{H}_{1,2}^{2,1}\left(\frac{\delta_{k,r,p}^2}{4\left(B+\beta_{k,r,p}\right)^2}\middle|\begin{matrix} -,\ (-1,2),\ -,\ - \\ (0,1),(0,1),\ -,\ -,\ - \end{matrix}\right) \\ &- \frac{\delta_{k,r,p}}{4\left(B+\beta_{k,r,p}\right)^2}\mathrm{H}_{1,2}^{2,1}\left(\frac{\delta_{k,r,p}^2}{4\left(B+\beta_{k,r,p}\right)^2}\middle|\begin{matrix} -,\ (-1,2),\ -,\ - \\ (1,1),(-1,1),\ -,\ -,\ - \end{matrix}\right)\Bigg],\end{aligned} \tag{17}$$

using

$$\exp(-x) = G_{0,1}^{1,0}\left(x\middle|\begin{matrix} - \\ 0 \end{matrix}\right),\ \mathrm{K}_n(x) = \frac{1}{2}G_{0,2}^{2,0}\left(\frac{x^2}{4}\middle|\begin{matrix} - \\ n/2, -n/2 \end{matrix}\right)$$

and [20], where $G_{p,q}^{m,n}\left(x\middle|\begin{matrix} a_1\cdots a_n, a_{n+1}\cdots a_p \\ b_1\cdots b_m, b_{m+1}\cdots b_q \end{matrix}\right)$ is Meijer-G function and

$$\mathrm{H}_{p,q}^{m,n}\left(x\middle|\begin{matrix} (a_1, A_1)\cdots(a_n, A_n),(a_{n+1}, A_{n+1})\cdots(a_p, A_p) \\ (b_1, B_1)\cdots(b_m, B_m),(b_{m+1}, B_{m+1})\cdots(b_q, B_q) \end{matrix}\right)$$

is Fox-H function.

Modulation schemes for which $P_{se}(\gamma_t)$ is in the form of complementary error function, $P_{se}(\gamma) = A\,erfc\sqrt{B\gamma}$, are *M*-ary phase shift keying (M-PSK), *M*-ary quadrature amplitude modulation (M-QAM), *M*-ary frequency shift keying (M-FSK), Gaussian minimum shift keying (GMSK), etc. Unfortunately, in that case, the appearing integral for ASEP can not be solved in the closed-form, so it has to be calculated using numerical integration.

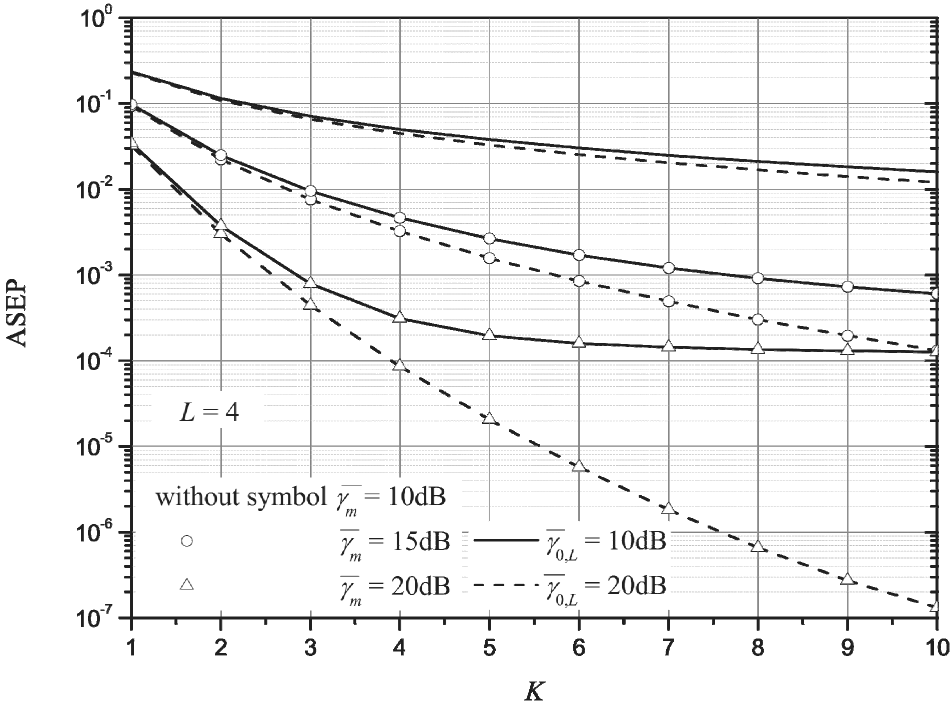

Fig. 5 – *Average symbol error probability of 8-PSK versus number of users.*

The error performance of the considered system is pointed out in the last two figures. Actually, Fig. 5 presents ASEP versus number of users existing in the system. Depicted curves are evaluated for different average power values of both source-last relay link and last relay-selected user link. Results from that figure show that influence of number of users on the error system performance is more significant in the case when selected user is closer placed to the last relay, i.e. when its average power is higher and when direct link is stronger. It is also clear that relation between number of users and growth of multiuser diversity gain is not linear. Fig. 6 shows the impact of number of relays on the error performance. Opposite to the results for spectral efficiency, increase of number of relays in the system improves its error performance, since higher order of cooperative diversity provides more reliable transmission. It is interesting, that there is no need to increase number of relays uncontrollably in order to improve the error system performance and it is in accordance with tradeoff about we have already written when we have commented results for the spectral efficiency.

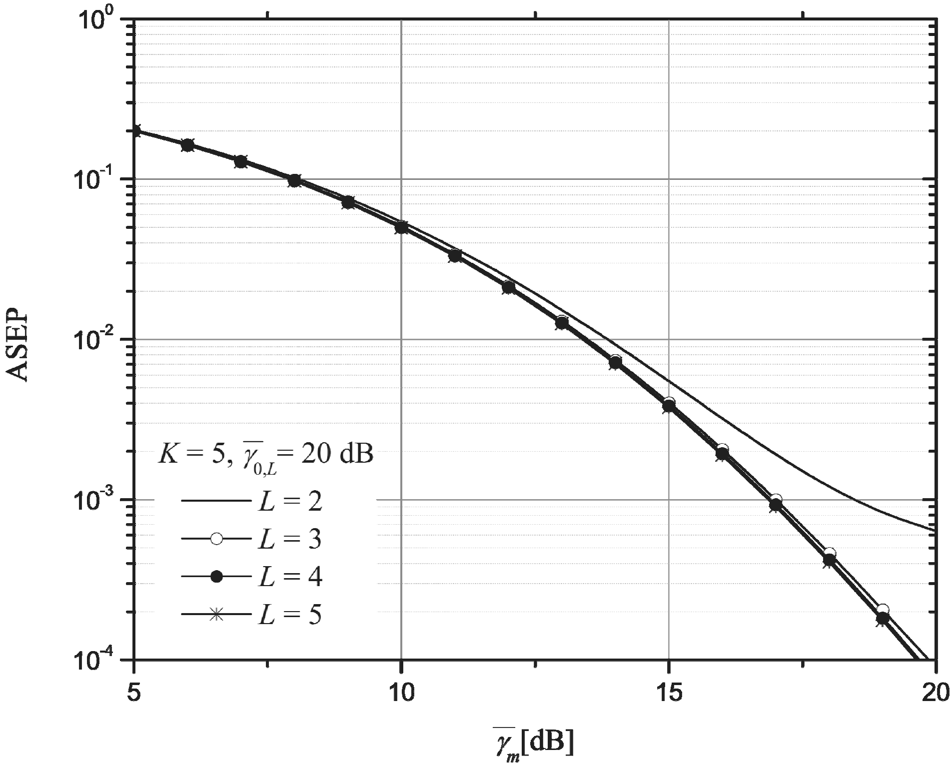

Fig. 6 – *Average symbol error probability of 16-QAM versus average power of selected user.*

4 Conclusion

This paper has analyzed the cooperative multi-hop multiuser relay system in which all cooperative relays have used MRC scheme, while the opportunistic scheme for signal transmission to end users has been applied. Namely, we have analyzed the capacity and the error performance of system in function of average SNR of links and number of users and relays. The general conclusion is that the number of relays in the system should not be huge, but great enough to satisfy quality of service in terms of realized capacity and reliable transmission. In addition, it is not necessary to serve huge number of users in order to achieve high multiuser diversity gain.

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