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***Abstract*—In this paper, we develop a queueing analysis for opportunistic decode-and-forward (DF) relay networks. It is assumed that the networks undergo Nakagami-m fading and that the external arrival process follows a Poisson distribution. By selecting the best relay according to the opportunistic relaying scheme, the source first transmits its signal to the best relay which then attempts to decode the reception and forwards the output to the destination. It is assumed that each relay operates in full-duplex mode, i.e., it can receive and transmit signals simultaneously. The communication process throughout the network can be modeled as a queueing network which is structured from sub-systems of M/G/1 and G/G/1 queueing stations. We invoke the approximate analysis, so-called method of decomposition, to analyze the performance behavior of the considered relay network. The whole queueing network is broken into separate queues which are then investigated individually. Based on this approach, the end-to-end packet transmission time and throughput of the considered relay network are quantified in comparison with the networks with partial relay selection (PRS).**

***Keywords*—Opportunistic relaying, decode-and-forward, queueing networks, Nakagami-m fading, delay, throughput.**

I. Introduction

Over the past couple of decades, cooperative communications have been advanced remarkably and have been widely applied to contemporary mobile wireless infrastructures. Accompanying with this development, multimedia applications in wireless networks have emerged as a major trend. However, challenges arising from providing multimedia services may originate from severe fading of wireless channels which reduce the transmission rate and increase the end-to-end delay. In fact, there exists a number of studies quantifying these quality-of-service (QoS) parameters. In [1], statistical distributions of the queue length and delay of a multi-rate wireless relay network under scheduling and automatic repeat request (ARQ)-based error control are derived by modeling the network as a queue with vacation. In addition, a unified tandem queue framework with both exact and approximation decomposition approaches for multi-rate transmission in the physical layer and ARQ in the link layer of a multi-hop wireless network were presented in [2]. Accordingly, end-to-end loss rate, and delay distribution are obtained which are used to address the problem of QoS routing. In [3], behavior of the relay node in a wireless relay network at packet level is analyzed by modeling the network as an M/G/1 queue. In particular, average packet transmission delay is examined and a new relay selection scheme based on joint consideration of the channel and queueing conditions is proposed. In [4], Pappas et al. analyzed the impact of the relaying node on the throughput per user and aggregate throughput of a group of users in a multiple user relay network at packet level. Also, arrival and service rates, stability conditions, and average length of the queue of the relay are examined. In [5], an analysis of queueing performance of multiuser relay networks with ARQ-based error control has been developed. Therein, the considered relay networks are modeled as a probabilistic tandem of two finite queues of which the end-to-end packet loss rate, throughput, and delay are evaluated. Recently, system performance in terms of throughput and end-to-end delay of a cooperative relay network with rateless codes and buffered relays over Rayleigh fading has been investigated in [6]. Therein, the impact of the fading channels is taken in account, but this study has adopted the assumption that only the behavior of the queues at the relays is considered.

In this paper, we therefore present a queueing analysis for decode-and-forward (DF) relay networks with opportunistic relaying (OR) scheme over Nakagami-m fading wherein the effect of the queues at both the source and relays is examined. Assume that the external arrival process at the source follows a Poisson distribution. Then, the communications over the network can be modeled as a queueing network consisting of M/G/1 and G/G/1 queues. The method of decomposition is employed to analyze the system performance. To be specific, the end-to-end packet transmission time from the source to the destination and the fraction of arriving packets at the source is successfully received at the destination, called throughput of the considered relay network, are evaluated. Numerical results are provided which show that the OR scheme outperforms the partial relay selection (PRS) scheme in terms of both end-to-end delay and throughput.

II. System Model

The dual-hop relay network under consideration comprises one source S, K relays named as $\mathrm{R}_1, \ldots, \mathrm{R}_K$, and one destination D as depicted in Fig. 1 (a) and the corresponding queueing network is described in Fig. 1 (b). All involved communication channels are modeled as independent Nakagami-m fading and stay constant over the duration of one packet transmission and change independently for every packet transmission time interval. For analysis tractability, it is assumed that $\mathrm{R}_1, \ldots, \mathrm{R}_K$

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are placed at locations such that all the channels of each relaying hop are identically distributed. The coherence time of the fading channels are assumed to be equal to the time of each packet transmission. The exponent path-loss attenuation model is adopted to quantify the decay of the channel mean powers relative to the distance of the communication channel. Also, all the relays are presumed to operate in DF and full-duplex mode. Orthogonal channels are allocated to different terminals and do not interfere with each other. Packet arrivals at source S are assumed to follow a Poisson process with mean arrival rate λ [packets/s]. Since most commercial equipments are now equipped with the very large buffers, we can assume that all the nodes have infinite queueing length.

Source S communicates with destination D through one of the K relays, say R_i, $i \in \{1, \ldots, K\}$, which may be selected upon a specific scheme. The two relay selection policies include the PRS and OR schemes wherein relay R_i can be selected as, respectively,

$$i = \underset{k\in\{1,\ldots,K\}}{\arg\max} \{|h_{1k}|^2\} \quad (1)$$

$$i = \underset{k\in\{1,\ldots,K\}}{\arg\max} \{\min\{|h_{1k}|^2, |h_{2k}|^2\}\} \quad (2)$$

where h_{1k} and h_{2k} are the channel coefficients of the links $\mathrm{S} \to \mathrm{R}_k$ and $\mathrm{R}_k \to \mathrm{D}$, respectively. The average transmission rates of the channel from source S to relay R_i and of the channel from relay R_i to destination D are denoted as μ_1 and μ_2, respectively.

In this paper, we consider relay networks with OR scheme. Communications among terminals is described in the sequel. Source S first transmits its signal s with power P_1 to relay R_i which is selected according to the OR scheme. The received signal at R_i can be expressed as

$$y_i = h_{1i}s + n_i \quad (3)$$

where h_{1i} is the channel coefficient of the link $\mathrm{S} \to \mathrm{R}_i$ with fading severity parameter m_{1i} and channel mean power Ω_{1i}, and n_i is additive white Gaussian noise (AWGN) at R_i with zero mean and variance N_0. Relay R_i then attempts to decode the received signal to recover the original symbol and continues to forward it to destination D with transmit power P_2 provided successful decoding. The received signal at D is given by

$$y = h_{2i}\hat{s} + n \quad (4)$$

where h_{2i} is the channel coefficient of the link $\mathrm{R}_i \to \mathrm{D}$ with fading severity parameter m_{2i} and channel mean power Ω_{2i}, $\hat{s}$ is the decoded symbol of the transmit symbol s, and n is AWGN at D with zero mean and variance N_0. Recalling that fading channels among each relaying hop are identical distribution such that $m_{jk} = m_j$ and $\Omega_{jk} = \Omega_j$ for $k \in \{1, \ldots, K\}$ and $j \in \{1, 2\}$. According to the Shannon capacity theorem, transmission time of each packet consisting of L bits over the channel $\mathrm{S} \to \mathrm{R}_i$ and $\mathrm{R}_i \to \mathrm{D}$ can be identified as

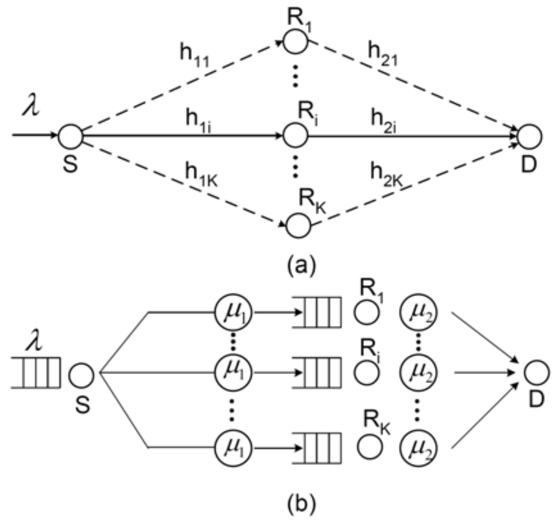

Fig. 1. System models: (a) Opportunistic relay network, (b) Queueing network model of opportunistic relay networks.

$$T_{ji} = \frac{B}{\log_2(1 + \gamma_{ji})} \quad (5)$$

where $j \in \{1, 2\}$, $B = \frac{L}{W}$, W is the channel bandwidth, and γ_{1i} and γ_{2i} are the SNRs of the links $\mathrm{S} \to \mathrm{R}_i$ and $\mathrm{R}_i \to \mathrm{D}$, respectively. If packet transmission time exceeds a predefined time-out value, called t_o, the packet can be treated as dropped. Otherwise, packet transmission is considered to be not dropped if the packet transmission time is less than t_o. Thereby, the transmission time over each relaying hop for each successfully received packet can be defined as $T_{ji}^{ud} = [T_{ji}|T_{ji} < t_o]$, $j \in \{1, 2\}$, [6].

III. Queueing Performance Analysis

In this section, we analyze packet transmission time as well as throughput of the considered relay network over Nakagami-m fading. To be specific, analytical expressions for packet transmission time as well as its higher moments for each relaying hop are established. These outcomes are further utilized to quantify the mentioned queueing performance measures.

A. Moments of Packet Transmission Time

Considering both the channel state information (CSI) of the source-relay and relay-to-destination hops, the best relay R_i is selected according to the criteria given by (2). Accordingly, the SNR for $\mathrm{S} \to \mathrm{R}_i$ and $\mathrm{R}_i \to \mathrm{S}$ channel can be quantified as

$$\gamma_{ji} = P_j|h_{ji}|^2, \ j = 1, 2 \quad (6)$$

Taking dropped packets under consideration, we have transmission time of an un-dropped packet as $T_{ji}^{ud} = [T_{ji}|T_{ji} < t_o]$.

From the property of conditional probability, basically, we get

$$f_{T_{ji}^{ud}}(x) = \begin{cases} \frac{f_{T_{ji}}(x)}{1-P_{outj}}, \ 0 < x \le t_o \\ 0, \ j \in \{1,2\}, \ t_o < x \end{cases} \quad (7)$$

where $f_X(\cdot)$ is the probability density function (PDF) of random variable X. Here, P_{out1} and P_{out2} are, respectively, the probabilities that packet transmission over the source-relay hop and relay-destination hop can be treated as dropped, i.e., $P_{outj} = 1 - F_{T_{ji}}(t_o)$ where $F_X(\cdot)$ is the cumulative distribution function (CDF) of random variable X. As a result, we have [6]

$$\mathbb{E}[(T_{ji})^m] = (1-P_{outj})\mathbb{E}[(T_{ji}^{ud})^m] + P_{outj}t_o^m \quad (8)$$

By definition, $\mathbb{E}[(T_{ji}^{ud})^m]$ can be expressed by the respective PDF as $\mathbb{E}[(T_{ji}^{ud})^m] = \frac{1}{1-P_{outj}}\int_0^{t_o} x^m f_{T_{ji}}(x)dx$. Employing the method of integration by parts, we get

$$\mathbb{E}[(T_{ji}^{ud})^m] = t_o^m - \frac{m}{1-P_{outj}}\int_0^{t_o} x^m F_{T_{ji}}(x)dx \quad (9)$$

To calculate $F_{T_{ji}}(x)$, we invoke the analysis approach provided in [7, eq. (6)], i.e., the CDF of γ_{ji} can be given by

$$F_{\gamma_{ji}}(x) \approx F_\gamma(x)\left[1-\beta_j+\beta_j(F_{\gamma_{jk}}(x))^K\right] \quad (10)$$

where $\beta_j = \Omega_j/(\Omega_1+\Omega_2)$, and

$$F_{\gamma_{jk}}(x) = 1 - \frac{\Gamma(m_j,\alpha_j x)}{\Gamma(m_j)} \quad (11)$$

$$F_\gamma(x) = \left[1 - \frac{\Gamma(m_1,\alpha_1 x)\Gamma(m_2,\alpha_2 x)}{\Gamma(m_1)\Gamma(m_2)}\right]^K \quad (12)$$

$$\gamma = \max_{k\in\{1,\dots,K\}}\{\min\{P_1|h_{1k}|^2, P_2|h_{2k}|^2\}\} \quad (13)$$

Here, $\alpha_j = m_j/\Omega_j$, $j \in \{1,2\}$, $\Gamma(\cdot)$ is the gamma function [8, eq. (8.310.1)], and $\Gamma(\cdot,\cdot)$ is the incomplete gamma function defined as [8, eq. (8.350.2)]. Applying the series expansion [8, eq. (8.352.2)] and the binomial theorem as well as the identity product, after some manipulations, we have

$$\begin{aligned} F_{\gamma_{ji}}(x) &= 1 + \sum_{u=1}^{K} C_u^K(-1)^u \sum_{i_1=0}^{m_1-1}\sum_{j_1=0}^{m_2-1}\cdots\sum_{i_u=0}^{m_1-1}\sum_{j_u=0}^{m_2-1} \\ &\frac{\alpha_1^{i_1+\ldots+i_u}\alpha_2^{j_1+\ldots+j_u}}{i_1!\ldots i_u! j_1!\ldots j_u!} x^{i_1+\ldots+i_u+j_1+\ldots+j_u} e^{-(\alpha_1+\alpha_2)ux} \\ &+ \beta_j \sum_{v=1}^{K} C_v^K(-1)^v \sum_{r_1=0}^{m_j-1}\cdots\sum_{r_v=0}^{m_j-1}\frac{\alpha_j^{r_1+\ldots+r_v}}{r_1!\ldots r_v!}x^{r_1+\ldots+r_v} \\ &\times e^{-\alpha_j v x} + \sum_{u=1}^{K} C_u^K(-1)^u \sum_{i_1=0}^{m_1-1}\sum_{j_1=0}^{m_2-1}\cdots\sum_{i_u=0}^{m_1-1}\sum_{j_u=0}^{m_2-1} \\ &\frac{\alpha_1^{i_1+\ldots+i_u}\alpha_2^{j_1+\ldots+j_u}}{i_1!\ldots i_u! j_1!\ldots j_u!}\beta_j\sum_{v=1}^{K} C_v^K(-1)^v \sum_{r_1=0}^{m_j-1}\cdots\sum_{r_v=0}^{m_j-1} \\ &\frac{\alpha_j^{r_1+\ldots+r_v}}{r_1!\ldots r_v!}x^{i_1+j_1+\ldots+i_u+j_u+r_1+\ldots+r_v}e^{-((\alpha_1+\alpha_2)u+\alpha_j v)x} \end{aligned} \quad (14)$$

where C_k^n stands for the binomial coefficient $\binom{n}{k}$. Using the fact that $T_{ji} = \frac{B}{\log_2(1+\gamma_{ji})}$ and (14), we can easily arrive at a closed-form expression for $F_{T_{ji}}(x)$. This outcome is then substituted into (9) to obtain the m-th moment of packet transmission time over the source-relay and relay-destination hops as

$$\begin{aligned} \mathbb{E}[(T_{ji})^m] &= t_o^m - m\sum_{u=1}^{K} C_u^K(-1)^{u+1}\sum_{i_1=0}^{m_1-1}\sum_{j_1=0}^{m_2-1}\cdots\sum_{i_u=0}^{m_1-1} \\ &\times \sum_{j_u=0}^{m_2-1}\frac{\alpha_1^{i_1+\ldots+i_u}\alpha_2^{j_1+\ldots+j_u}}{i_1!\ldots i_u! j_1!\ldots j_u!}\xi(u) + m\beta_j\sum_{v=1}^{K} C_v^K(-1)^{v+1} \\ &\times \sum_{r_1=0}^{m_j-1}\cdots\sum_{r_v=0}^{m_j-1}\frac{\alpha_j^{r_1+\ldots+r_v}}{r_1!\ldots r_v!}\psi_j(v) + m\sum_{u=1}^{K} C_u^K(-1)^{u+1} \\ &\times \sum_{i_1=0}^{m_1-1}\sum_{j_1=0}^{m_2-1}\cdots\sum_{i_u=0}^{m_1-1}\sum_{j_u=0}^{m_2-1}\frac{\alpha_1^{i_1+\ldots+i_u}\alpha_2^{j_1+\ldots+j_u}}{i_1!\ldots i_u! j_1!\ldots j_u!} \\ &\times \beta_j\sum_{v=1}^{K} C_v^K(-1)^v\sum_{r_1=0}^{m_j-1}\cdots\sum_{r_v=0}^{m_j-1}\frac{\alpha_j^{r_1+\ldots+r_v}}{r_1!\ldots r_v!}\varphi_j(u,v) \end{aligned} \quad (15)$$

where $\mathbb{E}\{\cdot\}$ denotes the expectation operator, and

$$\xi(u) = \int_0^{t_o} x^{m-1}\left(2^{\frac{B}{x}}-1\right)^{\sum_{q=1}^{u}(i_q+j_q)} \times e^{-(\alpha_1+\alpha_2)u(2^{B/x}-1)}dx \quad (16)$$

$$\psi_j(v) = \int_0^{t_o} x^{m-1}\left(2^{\frac{B}{x}}-1\right)^{\sum_{q=1}^{v} r_q} e^{-\alpha_j v(2^{B/x}-1)}dx \quad (17)$$

$$\varphi_j(u,v) = \int_0^{t_o} x^{m-1}\left(2^{\frac{B}{x}}-1\right)^{\sum_{q=1}^{u}(i_q+j_q)+\sum_{q=1}^{v} r_q} \times e^{-((\alpha_1+\alpha_2)u+\alpha_j v)(2^{B/x}-1)}dx \quad (18)$$

B. Delay and Throughput Performance

In our system, the network is modeled as a queueing network including M/G/1 queueing systems which present the transmission from S $\rightarrow$ R$_i$, $i \in (1,\ldots,K)$ and G/G/1 queueing systems which model the transmission from R$_i$ $\rightarrow$ D. Assume that packets to be transmitted arrive at S according to a Poisson process with mean arrival rate λ. These packets are transmitted to the selected relay wherein the packet transmission time is modeled as a general distributed process. At the decomposition point of S, the arrival rate λ is equally routed towards each relay with identical probability since identically distributed fading channels of the source-relay hop are assumed. Due to the Markovian property associated with the external arrival process, the arrival process at the channel S $\rightarrow$ R$_i$ is also a Markovian process with mean arrival rate $\lambda_{1i} = \frac{\lambda}{K}$ and the squared coefficient of variance of interarrival times $C_{A_{1i}}^2 = 1$ [9]. Therefore, each transmission channel S $\rightarrow$ R$_i$ can be modeled as an M/G/1 system with mean service time $\mathbb{E}[T_{1i}]$. As a result, the mean waiting time of a packet transmitted from S to R$_i$ through this M/G/1 system can be computed as [9]

$$\mathbb{E}[W_{1i}] = \frac{\rho_{1i}\mathbb{E}[T_{1i}](C_{1i}^2+1)}{2(1-\rho_{1i})} \tag{19}$$

where ρ_{1i} is the utilization of the M/G/1 system defined as $\rho_{1i} = \lambda/(\mathbb{E}[T_{1i}]K)$ and C_{1i}^2 is the squared coefficient of variance of packet transmission time $C_{1i}^2 = (\mathbb{E}[T_{1i}^2] - \mathbb{E}[T_{1i}]^2)/\mathbb{E}[T_{1i}]^2$. To keep the queueing system stable, it is required that $\rho_{1i} < 1$, or $\mathbb{E}[T_{1i}] < \lambda/K$.

In our queueing network, the output process of this M/G/1 system can be treated as the arrival process of the transmission from R$_i$ to D which now can be modeled as a G/G/1 system with mean service rate $1/\mathbb{E}[T_{2i}]$. When considering about dropped packets, mean arrival rate of this G/G/1 queueing sytem can be determined as $\lambda_{2i} = \frac{\lambda(1-P_{out1})}{K}$. Furthermore, applying [10, eq. (10.10)], the squared coefficient of variance of inter-arrival time of transmission channel R$_i \to$ D can be approximated as $C_{A_{2i}}^2 = 1+(C_{1i}^2-1)(1-P_{out1})$. As a result, mean waiting time of a packet transmitted through channel R$_i \to$ D can be approximated as [10, eq. (6.91)]

$$\mathbb{E}[W_{2i}] = \frac{\rho_{2i}g_{2i}\mathbb{E}[T_{2i}](C_{2i}^2+C_{A_{2i}}^2)}{2(1-\rho_{2i})} \tag{20}$$

where $\rho_{2i} = \lambda(1-P_{out1})\mathbb{E}[T_{2i}]/K < 1$ for the stability condition, and

$$g_{2i} = e^{-2(1-\rho_{2i})(1-C_{A_{2i}}^2)^2/(3\rho_{2i}(C_{2i}^2+C_{A_{2i}}^2))}, \text{ if } C_{A_{2i}}^2 < 1 \tag{21}$$

$$g_{2i} = e^{-(1-\rho_{2i})(C_{A_{2i}}^2-1)/(4C_{2i}^2+C_{A_{2i}}^2)}, \text{ if } C_{A_{2i}}^2 \geq 1 \tag{22}$$

Then, the end-to-end packet transmission time can be approximated as

$$T = \mathbb{E}[W_{1i}] + \mathbb{E}[T_{1i}^{ud}] + \mathbb{E}[W_{2i}] + \mathbb{E}[T_{2i}^{ud}] \tag{23}$$

Eventually, the approximated throughput of the considered relay network is quantified as

$$TP = \frac{K(1-P_{out2})}{\max\{\mathbb{E}[T_{2i}], \mathbb{E}[A_{2i}]\}} \tag{24}$$

where the mean inter-arrival time of the channel R$_i \to$ D is defined as $\mathbb{E}[A_{2i}] = 1/\lambda_{2i}$.

IV. Numerical Results

In this section, numerical results are provided showing the performance in terms of end-to-end packet transmission time and throughput of OR in comparison to PRS. For all cases, fading severity parameters of all the channels are set as $m = 2$, the normalized distances of the links S $\to$ R$_i$ and R$_i \to$ D are selected as $d_1 = d_2 = 0.6$, and the path-loss exponent is $\delta = 4$, representing suburban areas. In addition, packet length and bandwidth are chosen as 4096 bits and 1 MHz, respectively. The arrival rate is $\lambda = 100$ packets/s. Throughout the paper, we define average SNR as P_1/N_0 provided that the transmit powers at the source and the relay are identical, i.e., $P_1 = P_2$.

Fig. 2 shows end-to-end packet transmission time of the OR

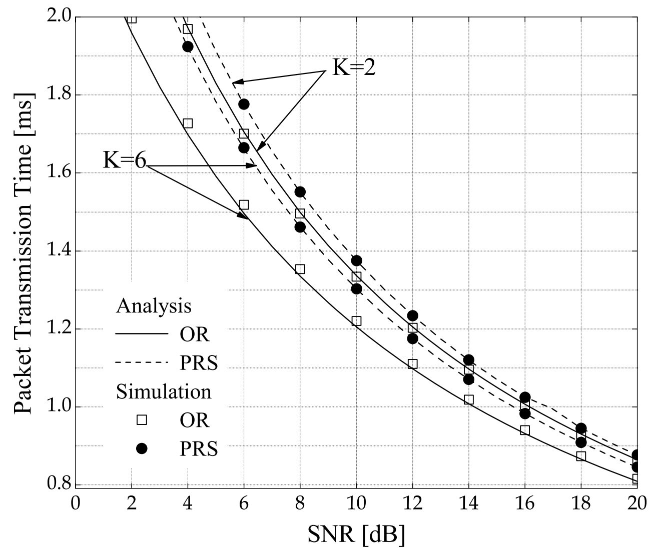

Fig. 2. End-to-end packet transmission time for different number of relays.

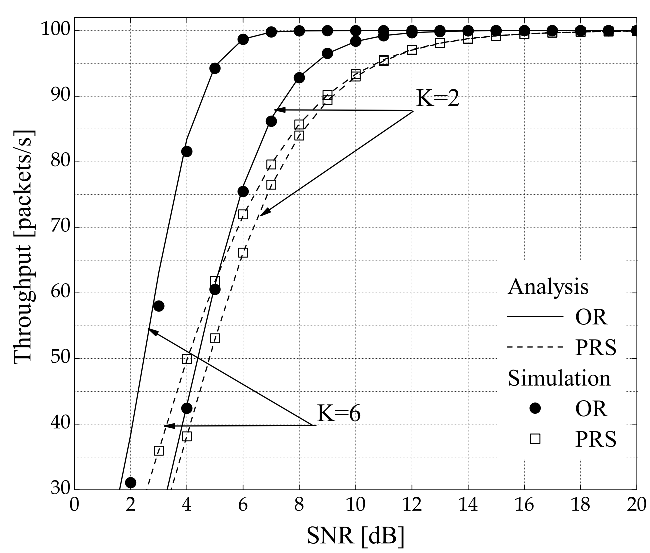

Fig. 3. Throughput of the relay networks with OR scheme for different number of relays.

in comparison to the PRS versus average SNR. As can be seen from the figure, the end-to-end packet transmission time of the OR network is smaller than that of the PRS network. This delay performance improvement of the OR network over the PRS network can be understood from the fact that the overall fading conditions of OR networks will be more favorable than those of PRS networks. The reason for this is that OR networks take the fading conditions of the two relaying hops into account when selecting the best relay to forward the signal. On the contrary, for the PRS networks, only the channel conditions of the source-relay hop are utilized to select the best relay. Therefore, the channel condition from the best relay to the destination in the PRS networks can be severely faded which may reduce the performance. In addition, for each relay selection scheme, when the number of relays increases, the end-to-end packet transmission time decreases. This is due to the fact that when the number of relays increases, the fading quality of the relaying channel is in favorable conditions with higher probability, resulting in the reduction in packet transmission time.

Fig. 3 presents throughput of the OR and PRS systems versus average SNR. As observed from this figure, the OR scheme achieves improvement in throughput over the PRS scheme. For both these two schemes, as the number of relays increases the better performance in terms of throughput can be achieved.

V. Conclusions

In this paper, we have presented an analytical approach to investigate the end-to-end packet transmission time and throughput of multiple relay networks using the OR. The communication channels are modeled as Nakagami-m fading which captures a variety of fading channels as special cases. The corresponding performance in terms of end-to-end packet transmission time and throughput is investigated and compared to the PRS scheme. It has been shown that the OR scheme outperforms the PRS scheme in terms of both end-to-end packet transmission time and throughput.

References

[1] L. B. Le, E. Hossain, and A. S. Alfa, "Delay statistics and throughput performance for multi-rate wireless networks under multiuser diversity," *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, pp. 3234–3243, Nov. 2006.

[2] L. Le and E. Hossain, "Tandem queue models with applications to QoS routing in multihop wireless networks," *IEEE Trans. Mobile Comput.*, vol. 7, no. 8, pp. 1025–1040, Aug. 2008.

[3] J. Cai, A. Alfa, P. Ren, X. Shen, and J. Mark, "Packet level performance analysis in wireless user-relaying networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5336–5345, Dec. 2008.

[4] N. Pappas, A. Traganitis, and A. Ephremides, "Stability and performance issues of a relay assisted multiple access scheme," in *Proc. IEEE Global Telecommunications Conference*, Miami, Florida, USA, Dec. 2010, pp. 1–5.

[5] M. Moghaddari, Y. Farazmand, and E. Hossain, "End-to-end queueing performance evaluation for multiuser wireless relay networks," in *Proc. IEEE Global Telecommunications Conference*, Houston, Texas, USA, Dec. 2011, pp. 1–5.

[6] N. B. Mehta, V. Sharma, and G. Bansal, "Performance analysis of a cooperative system with rateless codes and buffered relays," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1069–1081, Apr. 2011.

[7] K.-S. Hwang, Y.-C. Ko, and M.-S. Alouini, "Outage probability of cooperative diversity systems with opportunistic relaying based on decode-and-forward," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5100–5107, Dec. 2008.

[8] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*, 6th ed. A. Jeffrey, Ed. Academic Press, 2000.

[9] P. Kuehn, "Approximate analysis of general queuing networks by decomposition," *IEEE Trans. Commun.*, vol. 27, no. 1, pp. 113–126, Jan. 1979.

[10] G. Bolch, S. Greiner, H. de Meer, and K. S. Trivedi, *Queueing networks and Markov chains*, 2nd ed. John Wiley & Sons, 2006.