The Gateway Channel: Outage Analysis

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***Abstract*— We consider a relay that simultaneously assists multiple source-destination pairs that do not have a direct link, the so-called gateway channel, and explore the sum capacity of this network in the presence of quasi-static fading. In the absence of transmitter-side channel state information (CSI), we study superpostion as well as orthogonal channel access. In the presence of transmitter CSI, we consider opportunistic channel access with full CSI, as well as limited CSI via a 1-bit feedback (per user). In each case, the outage capacity and the diversity-multiplexing tradeoff are calculated. It is observed that orthogonal channel access is almost as good as superposition coding, and that opportunistic access provides signficiant gains. It is shown that a 1-bit feedback per user captures most of the gains available in opportunistic communication.**

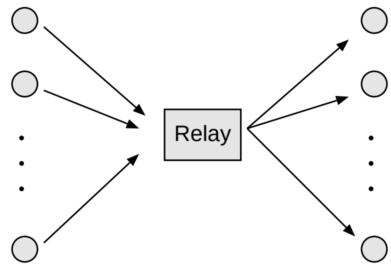

Fig. 1. The gateway channel

I. Introduction

This work considers a network where many source-destination pairs communicate through one relay (Figure 1). We call this geometry the *gateway channel*. We note that the dual of this network geometry, where one source communicates with one destination through multiple relays (Figure 2), has been widely studied in the past. The geometry studied in this paper is motivated by the usage of relays for coverage extension in ad-hoc and cellular networks, where a number of dedicated relay stations may be added to a network to assist in the communication of other nodes. To minimize cost, it is natural that any operator would wish to minimize the number of deployed relays, thus the sharing of a relay among several node pairs has a strong practical motivation. We investigate the problem in the presence of varying amounts of channel state information (CSI), unveiling interesting results especially in the case of opportunistic communication with both perfect channel-state feedback as well as limited feedback.

A brief history of related past work is as follows. Tajer and Nosratinia [1] considered a broadcasting relay that assists two source-destination pairs under orthogonal channels. There are several works [2], [3] that consider multiple source-destination pairs along with multiple relays, but they require that the number of relays meets or exceeds the number of source-destination pairs. In [2], A network of M single-antenna source-destination pairs communicate concurrently through a set of K single-antenna relays using two hop relaying is considered. They found that in the large limit of M, provided that K grows fast enough as a function of M, the links converge to non-fading links. In [3], a relaying strategy using MIMO fixed relay with linear processing to support multiple user transmission is proposed.

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We consider a superposition channel access scheme, where all the sources access the channel simultaneously. We also consider an opportunistic channel access scheme, where at each point in time only one source-destination pair is allowed to use the relay. We calculate the outage probability and the diversity multiplexing trade-off (DMT) in both channel access schemes. We develop an opportunistic schemes for selecting the best source-destination pair with full channel state information (CSI) at the relay and with only a limited-feedback (one-bit) CSI.

The remainder of the paper is organized as follows: in Section II we describe the system model. In Section III we calculate the outage probability when all the sources access the channel at the same time, superposition access. We also calculate the outage probability with opportunistic channel access. We introduce a new 1-bit feedback opportunistic scheme. The diversity multiplexing trade-off analysis of the problem is introduced in Section IV. In Section V a numerical results are introduced to compare between the different communication schemes. We conclude our work at Section VI.

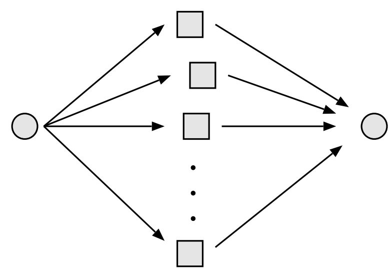

Fig. 2. Cooperative relaying

II. System Model

We consider a multi-node network with M source-destination pairs that communicate with the help of a relay. Each source wishes to communicate with its corresponding destination. A two-hop communication scheme is used, where at the first hop the sources send to the relay and at the second hop the relay sends to the destinations. All the nodes in the network are single antenna and half duplex.

In this work, we do not assume data buffering at the relay. If we had assumed an infinite buffer at the relay, it would be possible to decompose the network into a multiple-access part and a broadcast part. But it would also increase the overall latency as well as the hardware complexity for the relay. We consider the more interesting case where there is no long-term buffer at the relay. The relay must decode and directly retransmit the data of each user, and cannot keep it for future transmission intervals.

The channel between any two nodes is modeled by flat Rayleigh fading. A block fading model is used, where The length of the fading states (coherence length) is such that two transmissions (source-relay and relay-destination) can be made within one coherence interval, and furthermore, each of these transmissions can support a codeword of sufficient length so that standard coding arguments may be used. We assume that successive fading states of the channel are independent of each other.

We consider an average source power constraint P_i and an average relay power constraint P_r. The source-relay channel gain coefficients h_i and the relay-destination channel gain coefficients g_j are identically distributed circularly symmetric complex Gaussian random variables. The noise at the relay is distributed additive white Gaussian noise (AWGN) $\mathcal{CN}(0, N)$ and the AWGN noises at destinations are $z_j \sim \mathcal{CN}(0, N_j)$. The relay and destinations have recieve-side CSI. The relay uses a decode-and-forward (DF) protocol, where the received messages from the sources are decoded and forwarded to the destinations. Without loss of generality, in the following we assume all noises have unit variance, i.e., $N = N_j = 1 \;\; \forall j$.

III. Outage calculation

A. No Transmit CSI

We first consider the case where all nodes have receive-side CSI, but the nodes, and in particular the relay, do not have transmit-side CSI. Under these conditions, we cannot choose source-destination pairs according to their SNR. Then the choice of transmission strategies on the MAC and broadcast side of the network are as follows.

On the broadcast side, the channel gains are random, but the relay does not know the channel gains, therefore, in light of symmetric rate requirements, the strategy must be symmetric with respect to the destinations. Under this symmetry, the best achievable rate is according to orthogonal transmission [4] and superposition coding will give results that are no better.

For the multiple-access side, under symmetric rate requirement for all users, both orthogonal and superposition channel access are viable. It has been shown that superposition access gives slightly better performance at medium SNR, while at high and low SNR the two methods have asymptotically the same capacity under symmetric rates [4, pp. 243-245].

In the absence of transmit-side CSI, and with symmetric rate requirements, the network does indeed decompose into a cascade of a multiple-access and broadcast subnetworks, and the overall outage probability is given by:

$$\begin{aligned} P_{out} =& 1-(1-P_{MAC})(1-P_{BC}) \\ =& P_{MAC}+P_{BC}-P_{MAC}P_{BC}. \end{aligned} \tag{1}$$

Where P_{MAC} (respectively P_{BC}) denotes the outage of the MAC (respectively broadcast channel), defined as the probability that one or more of the users in the MAC (respectively broadcast channel) cannot support rate R. In a slowly fading environment, for a power allocation vector $P_s = (P_1, \dots, P_M)$ and a fading state $H = (h_1, \dots, h_M)$, the following rates are achievable for the MAC under superposition coding

$$\mathcal{C}_{MAC}(H,P) = \left\{ \bar{R} : \sum_{i\in S} R_i \le \frac{1}{2}\log\left(1+\frac{1}{N}\sum_{i\in S}|h_i|^2 P_i\right)\right\}, \tag{2}$$

where $\bar{R}$ is the rate vector and $S \subseteq \{1, \dots, M\}$. The outage is:

$$\begin{aligned} P_{MAC} =& Pr\{\bar{R} \notin \mathcal{C}_{MAC}\} \\ =& Pr\left\{|S|R > \frac{1}{2}\log\left(1+P\sum_{i\in S}|h_i|^2\right)\right\} \\ =& Pr\left\{\sum_{i\in S}|h_i|^2 < \frac{2^{2|S|R}-1}{P}\right\}, \end{aligned} \tag{3}$$

where $|S|$ denotes the cardinality of the set S, and P denotes the transmit power per user. From Equation (3), with the assumption of identically independent Rayleigh fading coefficients, the outage probability in the MAC can be shown to be

$$\begin{aligned} P_{MAC} =& 1-\left(Pr\left\{|h|^2 \ge \frac{2^{2R}-1}{P}\right\}\right)^M \\ &\times \prod_{i=2}^{M}\left(\frac{Pr\left\{\sum_{j=1}^{i}|h_j|^2 \ge \frac{2^{2iR}-1}{P}\right\}}{Pr\left\{\sum_{j=1}^{i}|h_j|^2 \ge \left(\frac{2^{2(i-1)R}-1}{P}\right)\frac{i}{i-1}\right\}}\right)^{\binom{M}{i}} \\ =& 1-\left(e^{\left(-\lambda\frac{2^{2R}-1}{P}\right)}\right)^M \\ &\times \prod_{i=2}^{M}\left(\frac{1-\gamma\left(i,\lambda\frac{2^{2iR}-1}{P}\right)}{1-\gamma\left(i,\lambda\left(\frac{2^{2(i-1)R}-1}{P}\right)\frac{i}{i-1}\right)}\right)^{\binom{M}{i}}, \end{aligned} \tag{4}$$

where $\gamma(i,x) = \frac{\int_0^x t^{i-1}e^{-t}dt}{y}\Gamma(i)$ is the incomplete gamma function, and $\Gamma(\cdot)$ is the regular Gamma function.

The above outage was using superposition coding. With a time-sharing MAC, the outage probability is:

$$P_{MAC} = Pr\left\{R_i > \frac{1}{2M}\log\left(1+P|h_i|^2\right), \;\; \forall i \in \{1, \dots, M\}\right\}$$

$$= 1 - \exp\left(- M\lambda \frac{2^{2MR} - 1}{P} \right) \tag{5}$$

On the broadcast side, the following rates are achievable in the fading state $G = (g_1, \ldots, g_M)$ with total power P_r at the relay node

$$\mathcal{C}_{BC}(G, P_r) = \left\{ \bar{R} : \sum_{i=1}^{M} R_i \leq \frac{1}{2} \log\left(1 + P_r |g|^2\right) \right\}. \tag{6}$$

which can be achieved, as mentioned earlier, by time sharing. Thus the outage is

$$\begin{aligned} P_{BC} =& Pr\{\bar{R} \notin \mathcal{C}_{BC}\} \\ =& Pr\{R_i > \frac{1}{2M} \log\left(1 + P_r |g_i|^2\right), \ \ \forall i \in \{1, \ldots, M\}\} \\ =& Pr\{|g_i|^2 \leq \frac{2^{2MR} - 1}{P_r}, \ \ \forall i \in \{1, \ldots, M\}\} \\ =& 1 - \left(e^{\left(-\lambda \frac{2^{2MR}-1}{P_r}\right)} \right)^M. \end{aligned} \tag{7}$$

B. Opportunistic Channel Access

In this scenario, the relay is assumed to have channel state information (either perfect or incomplete) about its incoming and outgoing links. Using this information, during each transmission interval the relay selects the best overall source-destination pair, and gives it access to the channel. We start by assuming perfect CSI at the relay.

1) Full channel state information at relay: In the decode-and-forward protocol, end-to-end data transmission is feasible if and only if both source-relay and relay-destination links can support the desired rate. Thus, the effective end to end instantaneous signal to noise ratio (SNR) of any of the source-destination pairs is considered to be the minimum of the source-relay SNR and the relay-destination SNR. The pair with maximum end to end instantaneous SNR γ_{i^*} is allowed to access the channel, where i^* is the index of the pair with maximum end to end SNR, i.e.,

$$i^* = \arg\max_i \{\min\{\gamma_{s_i,r}, \gamma_{r,d_i}\}\}, \tag{8}$$

where $\gamma_{s_i,r} = MP|h_i|^2$ and $\gamma_{r,d_i} = P_r|g_i|^2$ are the SNR of the source-relay and relay-destination channels, respectively.

The network is in outage when none of the source-destination pairs can support the desired transmission rate R. The outage probability of the system is

$$\begin{aligned} P_{out} =& Pr\left\{ R > \frac{1}{2} \log\left(1 + \gamma_{i^*}\right) \right\} \\ =& Pr\left\{ \gamma_{i^*} < 2^{2R} - 1 \right\}. \end{aligned} \tag{9}$$

Since the channel fading coefficients g_i and h_i are complex Gaussian random variables, the channel gain coefficients $|g_i|^2$ and $|h_i|^2$ obey exponential distributions. it is known that the minimum of M exponential random variables with parameters λ_i is an exponential random variable with parameter $\sum_{i=1}^{M} \lambda_i$. The pdf of the SNR of the relay-destination link $\gamma_i = \min\{MP|h_i|^2, P_r|g_i|^2\}$ is an exponential distribution with parameter $\lambda_t = \frac{\lambda_h}{MP} + \frac{\lambda_g}{P_r}$.

The cdf of the maximum SNR for all the source-relay-destinations links γ_{i^*} is

$$F_{\gamma_{i^*}}(x) = \left(1 - e^{-\lambda_t x}\right)^M, \tag{10}$$

where $\lambda_t = \frac{\lambda_h}{MP} + \frac{\lambda_g}{P_r}$ is the exponential parameter of the source relay destination pdf. Hence, the outage probability of the system is

$$P_{out} = \left(1 - e^{-\lambda_t\left(2^{2R}-1\right)}\right)^M. \tag{11}$$

2) Limited Feedback: In this part, we assume the relay no longer has perfect CSI, but has access to one bit of information per node from each destination, and is further able to send one bit of information per node to each of the sources. We wish to explore the outage capacity of this network using a one-bit feedback strategy.

Each destination node knows its incoming channel gain via the usual channel estimation techniques. Each destination compares its incoming channel gain to a threshold α, reporting the result via the one-bit feedback to the relay. The k destination nodes that report "1"(and their respective channels) are characterized as eligible for data transmission in that interval. From among these k eligible destinations, the relay chooses the one whose corresponding source-relay channel is the best.

In this paper, the sources transmit with fixed rate R which is given by (proof omitted)

$$\begin{aligned} R =& E\left[\frac{1}{2} \log\left(1 + \max_i \min\left\{MP|h_i|^2, P_r|g_i|^2\right\}\right) \right] \\ =& \frac{1}{2} M \sum_{k=1}^{M} \binom{M-1}{k-1} (-1)^{k-1} \frac{e^{\lambda_t k}}{k} \ Ei\left(-\lambda_t k\right). \end{aligned} \tag{12}$$

The network is considered in outage If there is no source-relay-destination link that can support that rate. We design the threshold of the second hop of the network such that each destination reports "1" if the corresponding relay-destination link can support this rate R, i.e., $\alpha = \frac{2^{2R}-1}{\rho}$. The outage event will happen if no destination reports positively, or if some destinations are eligible, but none of the corresponding source-relay links can support the rate R. If there is more than one source-destination link that can support the rate R, the relay choose one pair randomly.

We define A_i as the event of i destinations reporting "1", and $P(e|A_i)$ as the probability of error given that i destinations report "1", which equals to the probability of none of i eligible channels to have source-relay link supports the rate R. The probability of outage in this case is

$$P_{out} = P(A_0) + \sum_{i=1}^{M} P(A_i) P(e|A_i). \tag{13}$$

The probability of i destinations reporting "1" and $M - i$ destinations reporting "0" is

$$P(A_i) = \binom{M}{i} F_g(\alpha)^i \left(1 - F_g(\alpha)\right)^{M-i}$$

$$=\binom{M}{i}\left(e^{-\lambda_g \alpha}\right)^i\left(1-e^{-\lambda_g \alpha}\right)^{M-i}. \quad (14)$$

where $F_g(x)$ is the cdf of the relay-destination channel gain. The probability of error given that i destinations report "1" is

$$P(e|A_i) = P\left(\max_{j\in S}\left\{|h_j|^2\right\} \le \alpha\right) = \left(1-F_h(\alpha)\right)^i = \left(1-e^{-\lambda_h \alpha}\right)^i. \quad (15)$$

where $S \subset \{1,\dots,M\}$, $|S| = i$ and $F_h(x)$ is the cdf of the source-relay channel gain. Substituting (14), (15) in (13), the outage probability becomes

$$P_{out} = \left(1-e^{-\lambda_g \alpha}\right)^M + \sum_{i=1}^{M}\binom{M}{i}\left(e^{-\lambda_g \alpha}\right)^i\left(1-e^{-\lambda_g \alpha}\right)^{M-i}\left(1-e^{-\lambda_h \alpha}\right)^i = \sum_{i=0}^{M}\binom{M}{i}\left(e^{-\lambda_g \alpha}\right)^i\left(1-e^{-\lambda_g \alpha}\right)^{M-i}\left(1-e^{-\lambda_h \alpha}\right)^i. \quad (16)$$

IV. Diversity Multiplexing Trade-off

In the high SNR regime, it has been shown [5] that there exists a trade off between the spatial multiplexing gain r where $R = r\log\rho$ and the diversity gain d, as follows

$$d(r) = -\lim_{\rho\to\infty}\frac{\log P_{out}}{\log\rho}, \quad (17)$$

where ρ is the system signal-to-noise ratio.

A. No Transmit CSI

Without transmit CSI, as shown earlier the analysis can be decomposed into MAC and broadcast components. In this case, the DMT is the minimum of the DMT of the MAC and the broadcast channel. For the MAC channel, it has been shown [6] that for multiplexing gains $r \le \frac{M}{M+1}$, the diversity $d = 1 - r/M$ is achievable, while for higher rates $\frac{M}{M+1} < r \le 1$, the diversity of $d = M(1-r)$ is obtained.

For the broadcast channel, since time sharing achieves the maximum sum-rate bound, the broadcast DMT is similar to the single-user DMT. The DMT of the network is bounded by the DMT of the broadcast part of the network. Thus, including the half-duplex consideration, the best achievable DMT is

$$d(r) = (1-2r)^+. \quad (18)$$

The same DMT can be obtained with orthogonal channel access; superposition coding has no effect on the DMT.

B. Opportunistic Channel Access

For the opportunistic channel access with full CSI at the relay, the cdf of $\gamma_{i^*_{SRD}}$ as shown in Equation (10) is

$$F_{\gamma_{i^*_{SRD}}}(x) = \left(1-e^{-\lambda_t x}\right)^M = \left(\sum_{i=1}^{\infty}\frac{(-\lambda_t x)^i}{i!}\right)^M = (-\lambda_t x)^M\left(\sum_{i=0}^{\infty}\frac{(-\lambda_t x)^i}{i!}\right)^M. \quad (19)$$

The probability of outage is given by

$$P_{out} = Pr\left(\frac{1}{2}\log\left(1+\rho\max_i\min\left(|h_i|^2,|g_i|^2\right)\right) \le r\log\rho\right)$$
$$\doteq \min\left\{\text{sgn}(r), Pr\left(\max_i\min\left(|h_i|^2,|g_i|^2\right) \le \rho^{2r-1}\right)\right\}$$
$$\doteq \min\left\{\text{sgn}(r), (-2\lambda_t\rho^{2r-1})^M\sum_{i=0}^{\infty}\left(\frac{(-2\lambda_t\rho^{2r-1})^i}{i!}\right)^M\right\}$$
$$\doteq \min\left\{\text{sgn}(r), \rho^{M(2r-1)}\right\}, \quad (20)$$

where $\text{sgn}(r) = \max(r,0)$ is the sign function.

Hence, the proposed opportunistic communication scheme achieves the diversity gain

$$d(r) = M(1-2r)^+. \quad (21)$$

It is interesting to note that if the system were to have an infinite buffer, the DMT would not improve. With an infinite buffer, the opportunistic MAC and opportunistic broadcast operations could be performed independently, each giving rise to a diversity $d = M(1-2r)^+$, thus the overall diversity would also be $d = M(1-2r)^+$.

It is also noteworthy that in the absence of a buffer, local opportunistic choices on one side of the network would indeed result in a loss of diversity. For example, if we consider maximizing on the MAC side of the network. The SNR of the selected source destination link is $\gamma_i = \min(|h_{i^*}|^2, |g_i|^2)$ where $i^* = \arg\max|h_i|^2$. Since the network channels are i.i.d, the selection of the relay-destination link is considered random and this dominates the diversity order.

To summarize, a buffer would not improve the DMT, however, it would allow us to achieve the optimal DMT via local decision making (using MAC information on the MAC side, and broadcast channel information on the broadcast side). Without buffering the relay must make decisions jointly in order to achieve optimal DMT.

With 1-bit feedback, from (13), the outage probability is

$$P_{out} = Pr\left(\frac{1}{2}\log\left(1+\max_i\left\{|g_i|^2\right\}\rho\right) \le r\log\rho\right)$$
$$+\sum_{i=1}^{M}\binom{M}{i}Pr\left(\frac{1}{2}\log\left(1+|g|^2\right) \le r\log\rho\right)^{M-i}$$
$$\times Pr\left(\frac{1}{2}\log\left(1+|g|^2\right) \le r\log\rho\right)^i$$
$$\times Pr\left(\frac{1}{2}\log\left(1+\max_{j\in S,|S|=i}\left\{|h_j|^2\right\}\right) \le r\log\rho\right)$$
$$\doteq \min\left\{\text{sgn}(r), Pr\left(\max_i\left\{|g_i|^2\right\} \le \rho^{2r-1}\right)\right.$$
$$+\sum_{i=1}^{M}Pr\left(|g|^2 \le \rho^{2r-1}\right)^{M-i}Pr\left(|g|^2 \ge \rho^{2r-1}\right)^i$$
$$\left.\times Pr\left(\max_{j\in S,|S|=i}\left\{|h_j|^2\right\} \le \rho^{2r-1}\right)\right\}$$

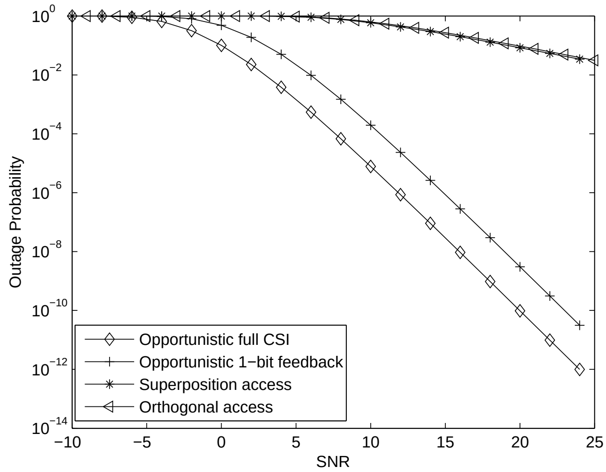

Fig. 3. Outage probability for M=5, R=0.1 bits/sec/Hz per user

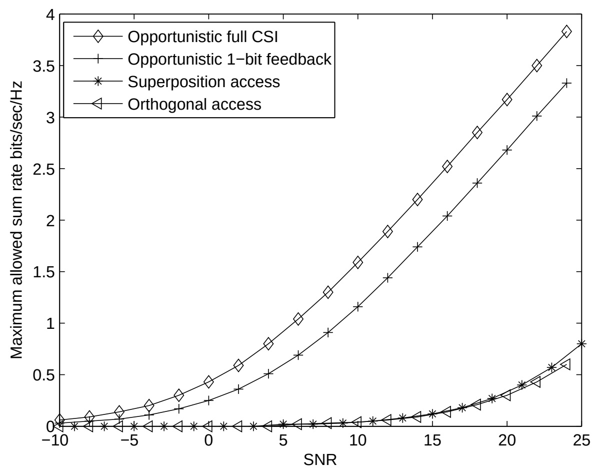

Fig. 4. Maximum transmission sum-rate for M=5, outage probability=0.05

$$\doteq \min\Big\{\mathrm{sgn}(r), \sum_{i=1}^{M} \big(e^{-\lambda_g \rho^{2r-1}}\big)^i \big(1-e^{-\lambda_g \rho^{2r-1}}\big)^{M-i} \big(1-e^{-\lambda_h \rho^{2r-1}}\big)^i\Big\}$$
$$\doteq \min\Big\{\mathrm{sgn}(r), \rho^{M(2r-1)}\Big\}. \quad (22)$$

Hence, it follows

$$d(r) = M(1-2r)^+. \quad (23)$$

Thus we show that even 1-bit feedback is enough to achieve optimal DMT.

V. Numerical results

Figures 3 shows the outage probability of the network under various channel access schemes and CSI. We assume a rate of 0.1 bits/sec/Hz per user, five source-destination pairs and i.i.d. link gains. The schemes without CSI suffer from higher outage probability, due to the fact that all links must be in operation in each fading interval. As explained earlier (also in [4]) in the absence of CSI the superposition scheme provides only a small advantage over orthogonal access.

Opportunistic schemes, on the other hand, choose only one of the link pairs at each point in time, and are considered to be in outage only if no link can be found to support the desired rate. Experiments show that the existence of CSI (opportunistic scheme) is vastly helpful, but more interestingly, that even one bit of CSI per user can give signficant benefits over no CSI.

The gap between the 1-bit and full-CSI opportunistic schemes decreases with higher number of users. It is worth remembering that the improved outage performace of the opportunistic schemes have been achieved at the cost of increased delay. In this context, one may also wish to perform analysis on various fairness criteria, which is unfortunately is not permitted by the size of this paper.

Figures 4 shows the maximum allowed transmission rate to achieve a fixed outage probability of 0.05. Again, the orthogonal access without CSI achieves the worst rates. The superposition access achieves barely better results. The opportunistic schemes achieve higher rates than the non opportunistic schemes. The 1-bit feedback opportunistic results are very close to the full CSI opportunistic results.

VI. Conclusion

In this paper, we investigate the gateway network under quasi-static fading conditions. We calculate the outage probability under various CSI conditions. A 1-bit feedback opportunistic scheme is proposed. The numerical results show that the performance of the opportunistic channel access with 1-bit feedback is close to the opportunistic channel access with full CSI. It is shown that even one bit of feedback per user significantly improves the performance of the system. We analyze the system under the high-SNR regime and calculate the diversity-multiplexing tradeoff. Opportunistic channel access with 1-bit feedback and the opportunistic channel access with full CSI both acheive a maximum diversity gain of M.

References

[1] A. Tajer and A. Nosratinia, "A broadcasting relay for orthogonal multiuser channels," in *IEEE Globecom*, San Francisco, CA, Nov. 2006.

[2] V. Morgenshtern and H. Bölcskei, "Crystallization in large wireless networks," *IEEE Trans. Inform. Theory*, vol. 53, no. 10, pp. 3319–3349, Oct 2007.

[3] C. B. Chae, C. T. Tang, R. W. Heath, and S. Cho, "MIMO relaying with linear processing for multiuser transmission in fi xed relay networks," *IEEE Trans. Signal Processing*, vol. 56, no. 2, pp. 727–738, Feb 2008.

[4] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.

[5] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inform. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[6] D. N. C. Tse, P. Viswanath, and L. Zheng, "Diversity-multiplexing tradeoff in multiple-access channels," *IEEE Trans. Inform. Theory*, vol. 50, no. 9, pp. 1859–1874, Sep. 2004.