A Highly Efficient Protocol for Rateless Coding Aided Cooperative Cellular Networks

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***Abstract*—Cooperative relaying has been proposed as a promising technology to provide reliable high data rate services for future wireless networks. The work presented here focuses on a novel efficient three time-slot approach using rateless codes, *opportunistic fountain* (OF), for cellular networks with fixed relays. This scheme enjoys benefits from both *relay selection* and *inter-relay cooperation*, offering improved performance. As an extension, the *dynamic opportunistic fountain* (DOF) scheme is developed, in which the time slots are allowed to last for a duration that depends on the instantaneous channel realization. Solving for the outage-optimal relay selection and time-slot allocation is formulated as a *mixed integer programming* (MIP) problem. In comparison to the conventional counterpart, it is observed that the DOF offers significant performance gains, and the benefits are confirmed by extensive simulations.**

I. Introduction and Related Work

As a promising technology to provide reliable high data rate services in dynamic environments, cooperative relaying, currently under standardization by the IEEE 802.16j task group, offers enhancements to the ability of combating fading induced by multipath propagation [1], [2].

In this scenario, various kinds of cooperative protocol have been developed, especially the decode-and-forward (DF) strategy, which provides the possibility to vary the communication rate and prevent error propagation [3]. Most of the early work on the DF is based on repetition coding at the relay. Laneman proposes distributed space-time coding (DST) schemes [4]. Bletsas *et al*. develops the opportunistic relaying (OR) scheme by cooperating only with the best relay [5]. Then, it is argued that the cooperative protocol can benefit from rateless codes (see [6]–[10] and references therein), which provide incremental redundancy instead of repetition coding, adapt data rate to the channel realization and coordinate the various transmissions with only acknowledgments [11]. In [12], the distributed space-time rateless coding (DSTR) scheme is proposed under the assumption of synchronization among distributed transmitters. Asynchronous transmission protocol (ATP) is presented in [13] with multiple subchannels used up for the transmission of one source codeword.

In this paper, we are interested in exploring how to provide more efficient solutions for cooperative cellular networks. We present a novel three time-slot approach using rateless codes, *opportunistic fountain* (OF), which has two major advantages. First, at each time slot only the best element is permitted to transmit using rateless codes, while the power is shared by various transmitters in space-time coding and ATP schemes. Second, the second time slot creates the possibility for cooperation between the fixed relays, which offers improved performance. Thus, this scheme can be expected to enjoy benefits from both *relay selection* and *inter-relay cooperation*, which are not considered in the previous work. Furthermore, we present the *dynamic opportunistic fountain* (DOF) scheme as an extension under the assumptions that the mobile station (MS) has the full CSI about the cooperative network and the extra signaling traffic for feedback is permitted. This scheme manifests the dynamic nature in the fact we allow the time slots to last for a duration depending on the instantaneous channel realization. Solving for the outage-optimal relay selection and time-slot allocation is formulated as a *mixed integer programming* (MIP) problem. As the simulation results indicate, this protocol offers significant performance gains over the conventional counterpart.

The rest of the paper is organized as follows. In Sec. II, we introduce the system model and the assumptions underlying our analysis. Section III illustrates the opportunistic fountain protocol and the outage performance analysis and describes its extension, DOF scheme and the related optimization problem. Sec. IV presents numerical results to show the advantage of the new schemes, followed by the conclusions in Sec. V.

II. System Model

We consider a relay-assisted cellular network as shown in Fig. 1, which is used to model the cooperative relaying mode of a 802.16j MMR network [2]. In each cell, a base station (S) is located at the center, and multiple fixed relay stations (RS) are located around the BS. In downlink transmission, one mobile station (D) wants to receive an information codeword with bandwidth normalized transmission rate H_t, given in bps/Hz, directly from the BS (Direct Transmission, DT) or through the DF cooperative schemes, in which the adjacent two relays r_1 and r_2 try to help.[1] Only TDD transmission protocols are taken into account in the sequel due to the half-duplex constraint of the practical hardware, i.e., transmitting and receiving at the same time are precluded.

[1]For the scenario of multiple mobile stations, the central resource allocation unit at the BS will consider subchannel allocation according to the system resource and the rate requirements of MSs [14]. Without loss of generality, we focus on the one MS scenario in the sequel.

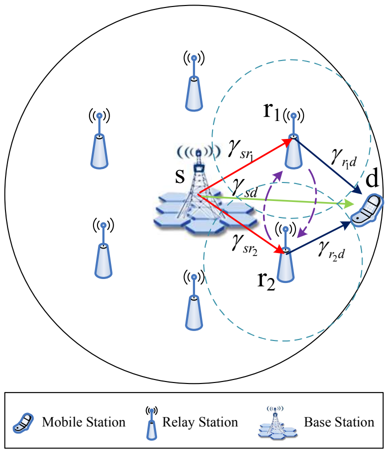

Fig. 1. The system model of downlink cooperative network

We model the propagation channel between the nodes as quasi-static flat-fading channel, which is applicable for scenarios of narrow-band transmissions in low-mobility environment [13]. The channel gains, which are constant during the transmission of one block, are assumed independent and exponentially distributed corresponding to Rayleigh fading of their amplitudes. Let

$$f_{\gamma_{mn}}(\gamma) = \frac{1}{\sigma_{mn}^2} \exp\left[-\frac{\gamma}{\sigma_{mn}^2}\right], mn \in \{sd, sr_i, r_i d, r_i r_j\} \tag{1}$$

be the probability density function (pdf) for the links S-D, S-RS, RS-D and RS-RS, where $\gamma > 0$ and σ_{mn}^2 denotes the mean channel gain from node m to node n. In addition, we assume that the network has an average transmission power constraint P, and the noise power is N_0.

For a given realization of the channel, the optimal power allocation across the time slots depends on CSI knowledge about the whole network at the BS. In this work, we do not assume the global CSI at the transmitter, so a reasonable strategy is to allocate equal power P over each of the time slots. Thus, an average transmit power constraint translates into a total power constraint of P at each time slot.

The following assumptions are made:

- Rateless codes can closely approach the channel capacity under Gaussian input distribution without CSI at the transmitter. Unlike fixed-rate codes, in which the transmission rate is a constant, rateless codes realize a rate depending on what channel realization is experienced and are close to the capacity even without CSI and channel statistics at the transmitter. The performance of rateless codes over fading channel has been demonstrated in [11].
- The encoded symbols generated by different transmitters are independent, i.e., there are no repetitions of symbols on the network. This could be realized by re-encoding the message with a different random generator seed [13].

We expect that some effective method of relay selection is utilized, e.g., a simple but intelligent technique so-called *distributed timers*, based on the instantaneous channel realization, can be found in [5]. Exactly how this selection is achieved and how the effects of different selection methods are on performance are beyond the scope of this paper.

III. Opportunistic Fountain Scheme

In this section, we describe the proposed *opportunistic fountain* scheme in detail and analyze the performance by outage probability. Then we present an extension of this scheme, *dynamic opportunistic fountain*.

A. The proposed protocol

In our proposed scheme, all the power available is poured on the best one in the transmitter candidate set (TCS), in which each element decodes the message and is ready for cooperation, at each time slot, i.e., only the best element is permitted to transmit. Moreover, the transmission codeword can also be heard and used by relay stations that are still receiving efficiently with the help of rateless codes. Thus, the proposed method creates the possibility for cooperation between the relays. As a result, they can decode the information faster, enlarging the TCS, in which the transmitter is selected.

The protocol is described as the following steps and illustrated through an example in Fig. 2.

- The BS starts to transmit information to the RSs and MS using rateless codes for the first time slot.
- The two RSs constantly receive information from the transmitter and try to decode the message.
- The best transmitter for the next transmission is selected at the end of each time slot from the TCS, comprised of the BS and the relays decoded the message (a possible solution for relay selection can be found in [5]). Then it switches from the reception mode to the transmission mode and transmits information utilizing rateless codes with a different seed from the previous ones.
- The destination continues to receive until sufficient information is accumulated to decode the message or the maximum time limit is reached.

B. Outage performance analysis

In this part, we primarily focus on the non-ergodic or time-constrained scenarios and characterize the performance in terms of outage events $I < H_t$ and associated outage probabilities $\Pr[I < H_t]$, which measure reliability of the transmission protocols to fading. The channel model is parameterized by the SNR random variables $\rho \cdot \gamma$, where $\rho = P/N_0$ is the common SNR without fading.

As discussed above, in *opportunistic fountain* the codewords are transmitted over three successive time slots. In every time slot, the node selected from the TCS transmits using rateless codes. According to the protocol, each RS has three possible events for the latter two time slots based on whether it successfully decodes the message, i.e., whether it can be one of the elements in the TCS (The various events for each station is shown in Table I, where $\surd$ and $\times$ represent the corresponding station is inside and outside the TCS, respectively.) Therefore,

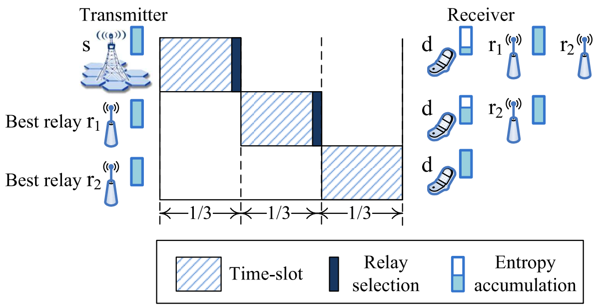

Fig. 2. Illustration of the proposed cooperative scheme through an example. The dark shaded band indicates when relay selection occurs, and the light shaded band corresponds to the amount of entropy accumulated at each node (the nodes with sufficient entropy will be as an element of the TCS). (a) The BS transmits the symbols encoded by rateless codes for the first time slot. If the RS r_1 accumulates sufficient entropy, it will be one of the elements in the TCS. At the end of the first time slot, the best transmitter r_1 for destination is selected from the TCS. (b) The selected relay forwards the re-encoded symbols for the second time slot, which are heard and used by the other RS that is still receiving. (c) The best transmitter, r_2, is selected among the enlarged TCS at the third time slot. (d) The destination decodes the message based on the received symbols across the three time slot.

the sample space of the states of RSs consists of the following nine cases:

$$\mathcal{K} = \{A_1B_1, A_1B_2, \cdots, A_3B_3\}$$

where A_iB_j is said to occur if event A_i appears on the RS r_1 and event B_j appears on the RS r_2. Consequently, the outage probability is given by

$$P_{out}^{\text{(OF)}} = \sum_{A_iB_j \in \mathcal{K}} P_{out}^{\text{(OF)}}|_{A_iB_j} \cdot \Pr[A_iB_j] \tag{2}$$

which is due to the total probability theorem over disjoint sets A_iB_j that partition the space. With no loss in generality, we take the probability of the case A_1B_3 and the corresponding conditional outage probability as an example. The expression of the other cases can be formulated in the same way.

In the case of A_1B_3, the RS r_1 decodes the message after the first time slot, while the RS r_2 fails to be an element of the TCS for the entire transmission time slot. From the proposed protocol, the best transmitter is selected from the TCS at the end of each time slot based on the instantaneous channel realization.

$$\begin{aligned}\Pr[A_1B_3] = \Pr[A_1B_3|\gamma_{sd} > \gamma_{r_1d}]\Pr[\gamma_{sd} > \gamma_{r_1d}] \\ + \Pr[A_1B_3|\gamma_{sd} < \gamma_{r_1d}]\Pr[\gamma_{sd} < \gamma_{r_1d}]\end{aligned} \tag{3}$$

where the first term, standing for the probability of the case A_1B_3 while BS is selected at the second time slot, is

Table I

TCS ELEMENTS FOR VARIOUS EVENTS. $\surd$ AND $\times$ REPRESENT THE CORRESPONDING STATION IS INSIDE AND OUTSIDE THE TCS, RESPECTIVELY.

Station	Time slot I	Time slot II	Time slot III
BS	$\surd$	$\surd$	$\surd$
Event A_1 for RS r_1	$\times$	$\surd$	$\surd$
Event A_2 for RS r_1	$\times$	$\times$	$\surd$
Event A_3 for RS r_1	$\times$	$\times$	$\times$
Event B_1 for RS r_2	$\times$	$\surd$	$\surd$
Event B_2 for RS r_2	$\times$	$\times$	$\surd$
Event B_3 for RS r_2	$\times$	$\times$	$\times$

$$\begin{aligned}&\Pr[A_1B_3|\gamma_{sd} > \gamma_{r_1d}] \\ &= \Pr\left[\frac{1}{3}I_{sr_1} > H_t, \frac{2}{3}I_{sr_2} < H_t\right] \\ &= \exp\left(\frac{1-2^{3H_t}}{\rho\sigma_{sr_1}^2}\right)\left[1-\exp\left(\frac{1-2^{\frac{3}{2}H_t}}{\rho\sigma_{sr_2}^2}\right)\right]\end{aligned} \tag{4}$$

The third term in (3) means the probability of the case A_1B_3 when RS r_1 is selected for transmission. It is given by

$$\begin{aligned}&\Pr[A_1B_3|\gamma_{sd} < \gamma_{r_1d}] \\ &= \Pr\left[\frac{1}{3}I_{sr_1} > H_t, \frac{1}{3}I_{sr_2} + \frac{1}{3}I_{r_1r_2} < H_t\right] \\ &= e^{\frac{1-2^{3H_t}}{\rho\sigma_{sr_1}^2}}\left[1 - e^{-\frac{g(\rho)}{\sigma_{sr_2}^2}} - \frac{1}{\sigma_{sr_2}^2}\int_0^{g(\rho)} \exp[f(\rho)]\, d\gamma_{sr_2}\right]\end{aligned} \tag{5}$$

where

$$g(\rho) = \frac{2^{\frac{3}{2}H_t} - 1}{\rho}$$

$$f(\rho) = -\frac{\gamma_{sr_2}}{\sigma_{sr_2}^2} + \frac{1}{\rho\sigma_{r_1r_2}^2} - \frac{2^{3H_t}}{\rho\sigma_{r_1r_2}^2(1+\rho\gamma_{sr_2})}$$

In addition, the probability $\Pr[\gamma_{sd} > \gamma_{r_1d}]$ in (3) is

$$\begin{aligned}\Pr[\gamma_{sd} > \gamma_{r_1d}] &= \int_0^{\infty}\int_0^{\gamma_{sd}} \frac{\exp\left[-\frac{\gamma_{sd}}{\sigma_{sd}^2} - \frac{\gamma_{r_1d}}{\sigma_{r_1d}^2}\right]}{\sigma_{sd}^2\sigma_{r_1d}^2} d\gamma_{r_1d}d\gamma_{sd} \\ &= \frac{\sigma_{sd}^2}{\sigma_{sd}^2 + \sigma_{r_1d}^2}\end{aligned} \tag{6}$$

where $\exp\left(-\frac{\gamma_{sd}}{\sigma_{sd}^2} - \frac{\gamma_{r_1d}}{\sigma_{r_1d}^2}\right)/\sigma_{sd}^2\sigma_{r_1d}^2$ is the joint distribution of γ_{sd} and γ_{r_1d}.

Combining (4), (5) and (6) to (3), the probability of event A_1B_3 can be expressed. Moreover, the corresponding conditional outage probability in (2) is derived as follows:

$$P_{out}^{\text{(OF)}}|_{A_1B_3} = \Pr\left[\frac{1}{3}I_{sd} + \frac{2}{3}I_{max}^{\text{(OF)}} < H_t\right] \tag{7}$$

where $I_{max}^{(\mathrm{OF})} = \max\left(I_{sd}, I_{r_1d}\right)$. According to the relationship of the two channels, (7) is expressed as

$$P_{out}^{(\mathrm{OF})}|_{A_1B_3} = \Pr\left[I_{sd} < H_t\right]\Pr\left[\gamma_{sd} > \gamma_{r_1d}|_{A_1B_3}\right] + \Pr\left[\frac{1}{3}I_{sd} + \frac{2}{3}I_{r_1d} < H_t\right]\Pr\left[\gamma_{sd} < \gamma_{r_1d}|_{A_1B_3}\right] \quad (8)$$

where every term can be derived as similar way as in (3), and we shall omit the details in this paper.

C. Extension of OF: dynamic opportunistic fountain (DOF)

The benefits of OF come from the facts that transmitter is selected effectively for every time slot among the TCS and the unconscious help between relays. However, this protocol, in which the length of every time slot is fixed to one third, can be improved to the DOF, if we assume the MS has the full CSI about the cooperative network and the extra signaling traffic for feedback is permitted. DOF, motivated by [15], manifests the dynamic nature of the protocol in the fact that we allow the time slots to last for a duration, t_i, being the result of the optimization problem stated next to improve the performance of outage probability, $\Pr[I_{DOF} < H_t]$, where I_{DOF} is the overall mutual information achieved through the three time slots. Without loss of generality the nodes are labeled according to their decoding order: $0, 1, 2$, i.e., the BS and the node with the better S-R channel is labeled as 0 and 1, respectively, while the other relay is labeled as 2.

We now state the objective function of the time-slot allocation problem as a linear function of the duration t_i. Our objective is to maximize

$$\sum_{i=0}^{2} I_{i,d} \cdot t_i \quad (9)$$

subject to: (a) the sum time constraint $\sum_{i=0}^{2} t_i = 1$, (b) the constraint on the nodes being an element of the TCS, (c) the constraint on the nodes being the transmitter, (d) the constraint on the time-slot duration. Then we will state the constraints (b)-(d) in turn.

First, consider the constraint on the nodes being an element of the TCS. Define K_j to be the binary variables with $K_j = 1$ indicating that the relay j is an element of the TCS and $K_j = 0$ otherwise. Thus, the constraint is

$$\sum_{i=0}^{j} I_{i,j} \cdot t_i \geq H_t K_j, \ \text{for}\, j \in \{1, 2\} \quad (10)$$

where the relay 1 receives information only from the BS, and the relay 2 receives from the BS and relay 1.

Second, we express the constraint on the nodes being the transmitter as

$$D_j \leq K_j, \ \text{for}\, j \in \{1, 2\} \quad (11)$$

where the binary variable D_j indicates whether the relay j is a transmitter. Note that if the relay j is not an element in TCS, $K_j = 0$, it will fail to be considered as a transmitter, i.e., $D_j = 0$; if the relay j decodes the message, $K_j = 1$, it will be considered to be a transmitter candidate, i.e., $D_j = 0$ or 1.

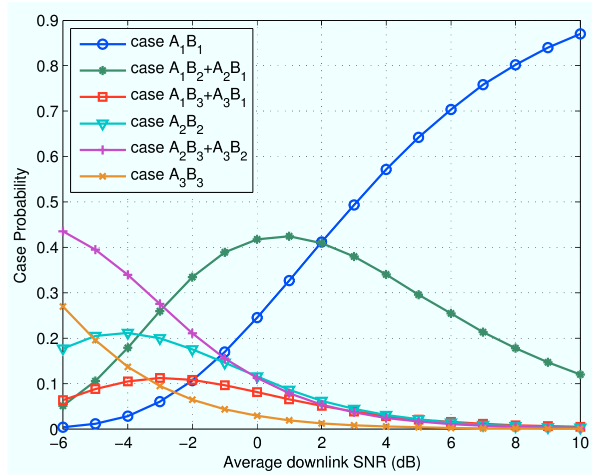

Fig. 3. The probability of various cases in Table I. $H_t = 1$ bps/Hz and $\Gamma_{r_1r_2} = \Gamma$.

Finally, we limit the allocations of the time-slot duration,

$$t_j \leq D_j, \ \text{for}\, j \in \{1, 2\} \quad (12)$$

where $0 \leq t_i \leq 1$, $i \in \{0, 1, 2\}$.

A couple of aspects of this optimization model are valuable to note. First, this mixed integer programming can be solved effectively by the *branch-and-bound enumeration*, even for a large sized problem. Second, this work can be generalized to the case when L relay stations try to help. To limit the complexity introduced, the constraint on the maximum hop number l can be given $\sum_{j=1}^{L} D_j \leq l$. Third, the algorithm is executed at the MS that can assess full knowledge of the cooperative network. After the computing, a feedback control channel is used to transmit the result of relay selection and time-slot duration, which is sent only once for the slow fading channel. Thus the DOF scheme can benefit from relay selection, inter-relay cooperation and time-slot allocation.

IV. Numerical Results

This section presents some analytical and empirical results to evaluate the performance of the proposed schemes. We consider the average channel SNR from node m to n as:

$$\Gamma_{mn} = \rho\sigma_{mn}^2, mn \in \{sd, sr_i, r_id, r_ir_j\} \quad (13)$$

where ρ is the transmit SNR and σ_{mn}^2 denotes the mean channel gain. For ease of exposition, we set $\Gamma_{sr_1} = \Gamma_{sr_2} = \Gamma_{r_1d} = \Gamma_{r_2d} = \Gamma$ for all cases (obviously true when the BS, the two RSs and the MS are located in the four corners of a diamond and the distance-dependent path loss model is used to compute the mean of the channel gains), which are better than the mean downlink channel, e.g., $\Gamma = \Gamma_{sd} + 10$ dB.

The first set of plots (Fig. 3-5) focus on the low-rate regime. Specifically, we consider as an example rate $H_t = 1$ bps/Hz. In Fig. 3, the probability of various cases listed in Table I is

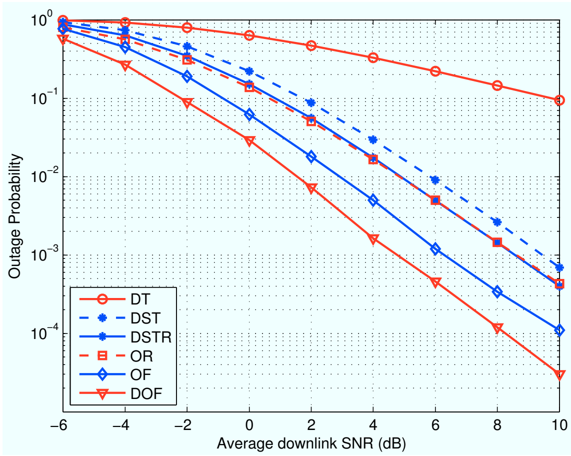

Fig. 4. Outage probability of various schemes versus average downlink SNR for rate $H_t = 1$ bps/Hz and $\Gamma_{r_1 r_2} = \Gamma$.

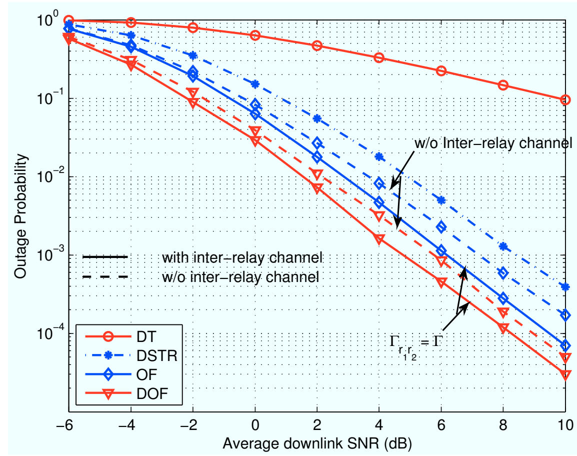

Fig. 5. Outage probability versus average downlink SNR for rate $H_t = 1$ bps/Hz. Various sets of curves correspond to the mean SNR of the inter-relay channel equal to S-RS channel, i.e., $\Gamma_{r_1 r_2} = \Gamma$ and equal to $-\infty$ dB, i.e., inter-relay channel is cut off, respectively.

plotted against the average downlink SNR Γ_{sd}. We combine the cases of identical probability for simplicity. The probability of $A_1 B_1$ (Table I) increases with the average downlink SNR, while the probability of $A_1 B_2$ or $A_2 B_1$ initially increases, but declines after a certain SNR, for the probability of failing to decode the message after the first time slot decreases with an increase in SNR after a specific value. Moreover, the probability of other cases drops drastically as can be seen in Fig. 3.

Fig. 4 shows the outage probability of various schemes as a function of the average downlink SNR Γ_{sd}. All the DF cooperative strategies are superior to direct transmission (DT). Both the distributed space-time rateless coding (DSTR) [12] and opportunistic relaying (OR) [5] provide almost the same performance, which can be explained that the benefit of relay selection of the OR is balanced by rateless codes used in DSTR. However, our proposed scheme OF, enjoying both benefits, outperforms them with a gain of about 2 dB at an outage probability of 10^{-2}, which is even greater than the gain between distributed space-time repetition coding (DST, [4]) and DSTR. As expected, DOF performs best with respect to other collaborative DF schemes since it can adapt its time-slot length to the instantaneous channel realization.

Fig. 5 shows the interesting points about the effect of the inter-relay channel quality. First, OF can generally maintain an advantage over DSTR even if the inter-relay channel is cut off. Second, DOF provides significant gains, manifesting the dynamic nature of the protocol and representing a low bound on the outage probability of OF.

Fig. 6 compares outage probability versus transmission rate under certain average downlink SNR for various schemes. All of the cooperative schemes provide significant improvement in the low-rate regime; however, in the high-rate regime the rateless coded based schemes (DSTR, OF and DOF), manifesting the efficiency, provide better performance to non-cooperative transmission. Clearly, our proposed schemes exhibit comparable performance to others.

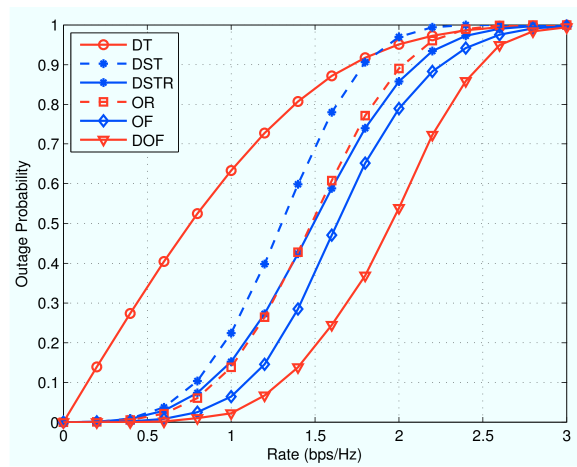

Fig. 6. Outage probability versus rate for the average downlink SNR 0 dB and $\Gamma_{r_1 r_2} = \Gamma$.

V. Summary and Conclusion

We have proposed a new three time-slot cooperative transmission protocol, *opportunistic fountain*, for half-duplex relaying, based on rateless codes. Our method has two major advantages, which distinguish it from other schemes. First, at each time slot only the best element is permitted to transmit using rateless codes, while the power is shared by various transmitters in space-time coding and ATP schemes. Second, the second time slot of our scheme creates the possibility for cooperation between the fixed relays. Therefore, the solution presented in this paper, combining relay selection with inter-relay cooperation, is much more efficient than the traditional cooperative protocols, and the benefits are confirmed by extensive simulations.

If the receiver has the full knowledge of the cooperative network and the extra signaling traffic is permitted, we propose the *dynamic opportunistic fountain* (DOF) scheme, in which the time slots are allowed to last for a duration that depends on the instantaneous channel realization. Solving for the outage-optimal relay selection and time-slot allocation can be formulated as a *mixed integer programming* (MIP) problem. In comparison to the conventional counterpart, it is observed that the DOF offers significant performance gains. The promising results obtained here represent a useful direction for continued research.

It is worthwhile to discuss whether three time slots are strictly necessary for this study. For the OF scheme, approximate performance can be achieved through two time-slot relay selection scheme using rateless codes, if the inter-relay channel is totally cut off. However, if the inter-relay channel is not too bad, at the second time slot the transmitter provides information to the MS as well as the RS that still receives. Thus, the second time slot shows the possibility of enlarging the TCS and altering the transmitter to a better one for the third time slot. Theoretically, the time slot can be split into more parts, but it is non-practical to account for the complexity introduced. For the DOF scheme, a constraint on the maximum time-slot number can be considered in the optimization problem to limit the complexity introduced.

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