Green Cooperative Communication Using Threshold-Based Relay Selection Protocols

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***Abstract*—This paper proposes new approach to relay selection using a threshold-based transmission protocol for a system with multiple *amplify-and-forward* relays and users. The novelty of this protocol includes (1) economical feedback that reduces signal processing complexity, as well as (2) adaptively interrupted transmission that can save significant RF power when the selection requirement is not met. Applied to the downlink, this protocol uses a threshold on the first-hop (base-station-to-relay) SNR for relay selection. One-bit feedback is sent from each relay to the base station, reporting the comparison result between the base station-relay link SNR and threshold. Transmission takes place for a relay satisfying the selection condition of having its received SNR greater than a threshold or is otherwise switched off. Numerical results show that for low average SNR scenarios (where relaying is required), the selection threshold can be appropriately chosen relative to the number of relays to dramatically reduce transmit power without sacrificing outage performance.**

I. Introduction

Cooperative communication has attracted considerable interest, since increasing both data rate and coverage at low cost is a central issue in next-generation multimedia communication systems. Relays are power-efficient network components that can replace power-hungry base stations while enabling denser networks. In particular, relay transmission helps combat heavy path loss and enables cooperative diversity without requiring multiple antennas at the receivers and transmitters [1].

Relaying protocols can be generally classified as non-regenerative or regenerative depending on the level of signal processing performed at the relay. A regenerative or *decode-and-forward* (DF) protocol decodes and then retransmits the re-encoded signal, whereas a non-regenerative or *amplify-and-forward* (AF) simply amplifies the signal before retransmitting. This work considers a multiuser and multirelay system deploying the low-complexity AF relays.

In multiuser and multirelay settings, relay selection has been shown to be an effective method to achieve full diversity. In [2] and [3], relay and user selection (or scheduling) schemes based on complete channel state information and perfect feedback have been proposed for multiuser and multirelay cellular networks. In both works, one relay and one user are selected for transmission based on maximum SNR scheduling. In [2], the authors consider a cellular network with a fixed infrastructure AF relays. In this kind of setup, a static AWGN channel can be used for modelling the links between the relays and the BS because both link ends are fixed nodes. The selection scheme is based on perfect knowledge of the end-to-end equivalent SNR of all the dual-hop links assumed to be available at the base station (BS). Based on this information, the BS schedules the two-hop link that has the maximum equivalent end-to-end SNR value.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada Discovery Grant 41731.

In [3], the authors present the downlink performance of a *distributed scheduling* (DS) scheme and a *centralized scheduling* (CS) scheme for multiuser and multirelay systems. The scheduling policies are based on a partitioned system model similar to that introduced in [4] and the considered channel model is Rayleigh fading for both BS-to-relay and relay-to-user links. The CS scheme is similar to the selection scheme in [2]. The DS scheme, however, differs by its decentralized selection : every transmitter performs scheduling in its own partition based on its own SNR measurements. More specifically, the BS selects the relay with the highest BS-to-relay SNR, while the selected relay simultaneously selects the user with the highest relay-to-user SNR in its partition. Thus, the DS scheme is strictly capacity-suboptimal compared to the CS scheme but reduces the amount of required feedback. Both the DS and CS schemes presented in [3] involve the benchmark unlimited gain (UG) relaying protocol which cannot be practically realized and therefore the derived performance results are only an upper bound of the performance of the practical variable gain (VG) protocol [5].

In [6], the problem of power allocation has been considered for multiple relay systems. The power allocation schemes in [6] divide the transmit power among the source and the relay(s) to maximize the channel capacity or the instantaneous SNR and thus minimizing the system outage probability. Those schemes have high computation and feedback requirements and cannot be applied for cellular system.

In this paper, we are concerned with outage probability, energy savings, and low feedback requirements. To the best of our knowledge, the existing literature on relay and user selection and scheduling for multiuser and multirelay systems requires perfect channel state information (CSI) knowledge and feedback. This paper proposes new relay selection protocols using a threshold-based transmission and one-bit feedback. The novelty of this work includes economical feedback that traverses only one hop from the relays to the BS, as well as adaptively interrupted transmission that can save significant RF power. This protocol might be seen as a power control scheme in which the relay transmit power is assigned either the value P or zero. The approach is novel in that we do not try to maximize the end-to-end equivalent SNR (or the channel capacity) but rather to save power whenever the SNR value is considered insufficient.

Applied to the downlink of a multirelay and multiuser system deploying AF relays, the proposed protocol uses a threshold on the first-hop (base-station-to-relay) SNR for relay selection. The threshold allows selecting a relay that guarantes a minimum first-hop SNR and thus a satisfactory end-to-end equivalent SNR. Substantial power saving can be obtained as the transmission is switched off whenever the SNR-greater-than-threshold selection condition is not met. The proposed selection protocols are also practical as the worst-case SNR values are discarded thus preventing relay gain saturation [5]. Numerical results show that the threshold can be chosen, depending on the number of relays, to reduce the transmit power while maintaining diversity order and good outage performance.

II. System and Channel model

A. Multiuser and Multirelay System model

We consider downlink communication of a wireless dual-hop system with multiple users and relays over flat Rayleigh fading channels.

The multiuser and multirelay system comprises N users and M AF relays divided into $M+1$ partitions as illustrated in Figure 1: one BS partition and M relay partitions. A similar system model has been introduced in [4]. The BS partition includes the BS and the M relays. The relay partition consists of one relay and all users that communicate through that relay.

In our system model, we only consider users far from the BS or in a deep fade. Thus, communication is always established through the dual-hop link and the direct link is omitted. Note that the users close enough to the BS would communicate through single-hop communication. Half-duplex transmission is employed so that the relays receive and transmit in two different time slots.

B. Dual-hop Channel model

Downlink transmission from the BS to a user through one selected relay forms the well-known dual-hop transmission model (Figure 2).

Assuming that the average source transmit power is normalized to unity and given a general AF relay gain β, the equivalent end-to-end SNR of the dual-hop path can be written as:

$$\gamma_{eq} = \frac{E_1 E_2 \mid h_1 \beta h_2 \mid^2}{E_2 \mid \beta h_2 \mid^2 \sigma_1^2 + \sigma_2^2} \tag{1}$$

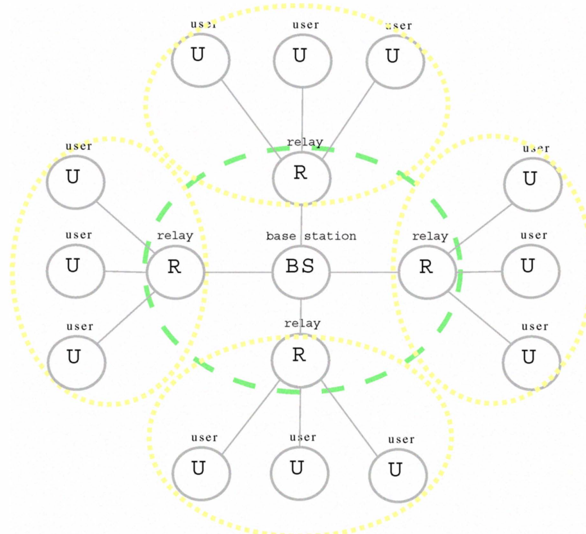


Fig. 1. Multiuser and multirelay system model

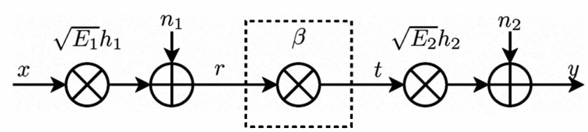


Fig. 2. Dual-hop communication system model

where for $i \in \{1,2\}$, i denotes the first or second hop of the dual-hop channel, E_i is the constant average channel energy factor, h_i is a complex Gaussian random variable that models the effect of flat fading, and σ_i is the variance of the additive Gaussian noise at the receivers. Note that E_i describes the effect of path loss and shadowing and its assumed constant value in our model results from the assumption of perfect long-term average power control.

C. Amplify-and-forward relaying protocol

An AF relay simply amplifies its received signal by a factor β before forwarding the signal to the destination. In this section, we define the existing AF protocols according to their amplification factors.

1) Variable Gain (VG) protocol: is a practical relaying protocol that equalizes the fluctuations of the first-hop channel based on the knowledge of the instantaneous fading amplitude. By limiting the transmit power at the relay to unity, the VG protocol is [1], [7]:

$$\beta_{VG} = \frac{1}{\sqrt{E_1 \mid h_1 \mid^2 + \sigma_1^2}}. \tag{2}$$

2) Unlimited Gain (UG) protocol: is a benchmark protocol able to invert the channel regardless of its magnitude:

$$\beta_{UG} = \frac{1}{\sqrt{E_1 \mid h_1 \mid^2}}. \tag{3}$$

Indeed, (2) is a tight upper bound of (3) in which the additive noise power at the relay has been neglected. As a result, if the fading coefficient drops to close-to-zero values as encountered under Rayleigh fading conditions, a resulting unlimited relay transmit power is making UG protocol impractical. However, as argued in [5], [7], its performance may serve as benchmark for practical protocols.

In [8], a practical alternative to implement the UG protocol is proposed. The Clipped Gain (CG) in [8] amplifies similarly to UG but clips the transmit power beyond a threshold and thus maintains a finite amplification gain.

3) Fixed Gain protocol: uses the first-hop average channel energy instead of the fading amplitude. By limiting the average transmit power at the relay to unity, the FG protocol is [7]:

$$\beta_{FG} = \frac{1}{\sqrt{E_1 + \sigma_1^2}}. \tag{4}$$

The threshold-based relay selection protocols introduced in this paper are applied to a system employing the above AF relaying protocols. We remark that as the transmission is stopped in poor SNR conditions, the amplifying gain remains finite even for the UG relaying protocol.

In our performance studies, the outage performance of the threshold-based relay selection scheme has been derived for Unlimited Gain relaying protocol.

III. Performance measure: Outage probability

The outage probability is defined as the probability that the SNR falls below the outage threshold γ_{th} [9], namely:

$$P_{out} = \int_0^{\gamma_{th}} p_\gamma(\gamma)\mathrm{d}\gamma. \tag{5}$$

Outage threshold γ_{th} is predetermined and may depend on the type of modulation employed and the application supported. When the equivalent end-to-end SNR of the system is above γ_{th}, the quality of service is considered to be satisfactory.

IV. Relay selection schemes

A. SNR-based threshold

For a dual-hop communication channel with a general AF relay gain β, if the first-hop SNR falls below the outage threshold, γ_{th}, the system is in outage regardless of the relay-destination SNR [10, Lemma 1]. Using this result, we introduce relay selection protocols that employ a transmission threshold, τ, proportional to γ_{th}:

$$\tau = d \cdot \gamma_{th}. \tag{6}$$

Clearly we have:

$$\begin{cases} \tau < \gamma_{th} & \text{for } d < 1 \\ \tau = \gamma_{th} & \text{for } d = 1 \\ \tau > \gamma_{th} & \text{for } d > 1 \end{cases}. \tag{7}$$

The chosen relay is selected among only the relays that satisfy the criterion of having the first hop SNR above threshold τ. From [10, Lemma 1], one can notice that a selection threshold smaller than the outage threshold ($d < 1$) cannot remove all the cases where the first hop SNR value leads to an outage event since $d = 1$ results in an end-to-end SNR smaller than γ_{th} for a dual-hop channel model [10, Lemma 1, proof]. Thus, $d = 1$ is the lowest efficient threshold for relay selection.

In the following, we assess the cases where d is greater or equal to 1 and study the significance of relay selection by also considering the cases where d is smaller than 1. Note that the case where $d = 0$ corresponds to a random selection of a relay.

B. Threshold-based relay selection (TRS) protocols

The selection principle is to choose a dual-hop transmission with first hop SNR above the selection threshold, τ (6).

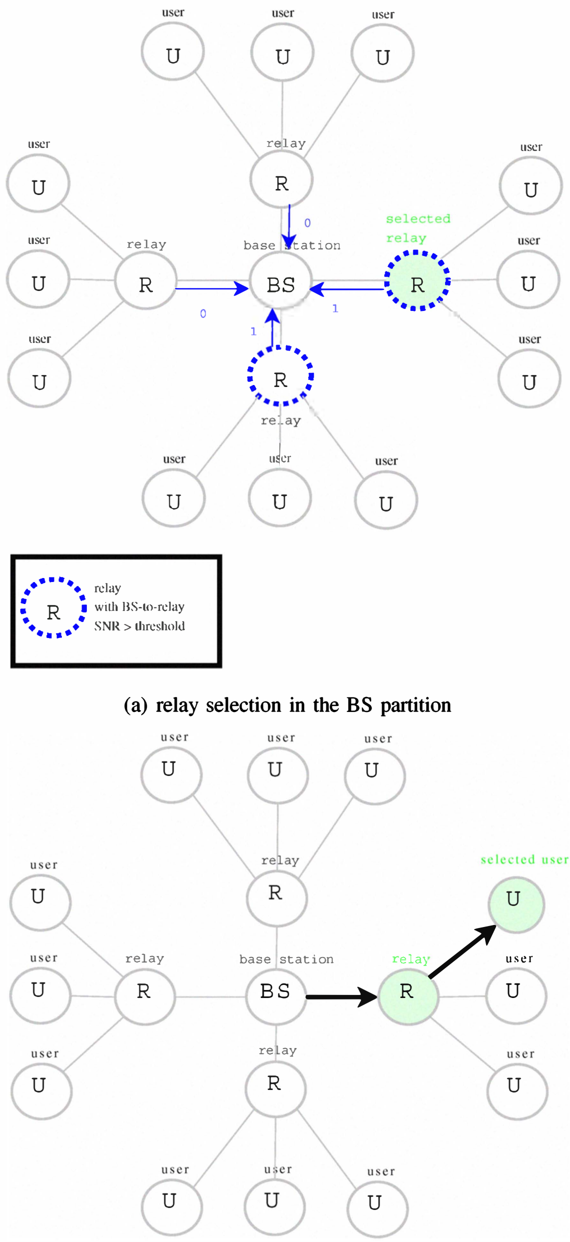
To perform selection, information about the BS-to-relay (or first hop) SNR is needed at the scheduler. Unlike the previously proposed scheduling schemes in [2], [3], exact SNR measurements are not required at the BS. Rather, the only information needed at the scheduler is whether the first hop SNR is above or below the selection threshold. This information can be obtained through one bit feedback from each relay as follows: The SNRs of the first hop links are computed and subsequently compared to the selection threshold at every relay based on a pilot signal sent by the BS. Then, one-bit feedback is sent from each relay to the BS indicating whether the BS-to-relay SNR is above the selection thresholdor not. Note that the feedback for TRS protocols uses one bit and traverses only one hop as opposed to existing selection schemes thus reducing the delay and probability of error.

The feedback bits at the BS allow to separate the relays into two pools: 1) relays that have BS-to-relay SNR above τ and 2) other relays that do not meet this requirement. The BS selects one relay from pool 1 randomly when this pool is not empty, and the selected relay simultaneously selects one user within its partition. Transmission takes place for the selected dual-hop link (see Figure 3).

In the case where the pool 1 is empty, no relay is selected and transmission is stopped for that time slot. Obviously, from the result in Section IV-A, TRS allows power savings and does not impair the outage performance when $d \leq 1$. For TRS with $d > 1$, additional transmit power can be saved at the cost of a poorer outage performance. In particular, the outage performance for TRS with $d > 1$ might be worse than that of TRS with $d \leq 1$ at low SNR, as there is a lower probability to find a dual-hop that satifies the selection criterion for lower average SNR values.

C. Relay selection without power-saving transmission

In this section, a relay selection scheme without power saving, threshold-based relay selection with continuous transmission (TRS-CT), is described. This scheme also uses binary feedback from each relay acknowledging the comparison result between the first hop SNR and the selection threshold to separate the relays into the 2 pools as above. Similarly, when the pool 1 is not empty, the BS selects one relay from that pool randomly, and the selected relay simultaneously selects one user. Transmission takes place for the selected dual-hop link with the selected relay and user. For the TRS-CT however, when the pool 1 is empty, the BS selects onerelay from pool 2 randomly. As before, the selected relay selects a user within



(a) relay selection in the BS partition

(b) user selection in the selected relay partition

Fig. 3. Threshold-based relay selection (TRS). The relay on the right is selected in the time slot shown.

its partition and transmission takes place for the selected dual-hop. In contrast to the TRS scheme, the transmission is not stopped even in the case where there is no relay satisfying the selection criterion.

From the discussion in Section IV-A, one can conclude that TRS-CT yields no outage performance improvement compare to TRS scheme for $d \leq 1$. For $d > 1$, TRS-CT should have better outage performance than that of TRS at low SNR region. However, the numerical results in the following section show that the improvement is small while requiring extra transmit power to maintain a non-interrupted transmission.

V. Performance analysis and discussion

A. *Performance analysis*

We have derived closed-form expressions of TRS outage probability for $d \leq 1$ in [11]. For $d > 1$, an upper bound and a lower bound to the outage probability of TRS and TRS-CT have been derived. The expressions corresponding to the cases where TRS protocols are applied to a network with an infinite number of relays ($M = \infty$) are also provided in [11]. $M = \infty$ corresponds to the ideal situation that there will always be at least one relay available for selection and thus $M = \infty$ outage probability expressions are the lower bound on the TRS outage probability for a finite number of relays, M.

The closed-form expressions are verified by Monte Carlo simulations in [11]. We do not provide the outage probability expressions in this paper due to space limitations.

In the following, the closed-form expressions mentioned above are used to plot the comparisons.

B. *Numerical results and discussion*

Figures 4, 5, and 6 compare the performance of the TRS protocols for different choices of d in terms of outage probability and power saving percentage (probability of stopping the transmission when the transmit condition is not met). The curves are obtained by numerically computing the closed-form equation mentioned above. The outage probability curves for TRS protocols with $d > 1$ represent the outage probability upper bound; outage performance might be slightly better in practice. Without loss of generality, the average SNR of the second hop is taken to be $\overline{\gamma}_2 = 5 \cdot \overline{\gamma}_1$ and the number of relays, M, takes on the following values: 50, 20, and 5. The value of the parameter d is taken to be 0.5, 1, 2, and 5.

The performance of the TRS-CT protocol is also displayed for comparison. Since the TRS-CT protocol does not save transmit power, it does not appear on the power saving subplots. Moreover, we have only plotted the outage performance of TRS-CT protocol for $d > 1$, i.e. $d = 2$ and $d = 5$ here, as its outage performance is the same than that of TRS protocols for $d \leq 1$.

TRS protocols with $d < 1$ corresponds to the case where τ is insufficiently high for relay selection (see Section IV-A). $d = 0$ correspond to the cases where a relay is selected randomly among all the M relays. Numerical results show that for $d = 0.5$, the diversity order is degraded compare to the cases where $d \geq 1$.

As shown, the number of relays, M, has a high impact on the performance of the TRS protocols. One can notice that TRS protocols with $d > 1$ are outperformed by TRS protocols with $d \leq 1$ in low SNR regions as expected. Indeed, even though TRS protocols with $d > 1$ outperforms TRS protocols with $d \leq 1$ for $M = \infty$, for a realistic number of relay M, there is a lower probability to find a relay for transmission in low SNR regions when $d > 1$ than when $d \leq 1$ which explains the results. Figure 6 also shows that for small numbers of relays, M, in the network, the TRS or TRS-CT protocols with $d > 1$ are always outperformed by TRS protocols with

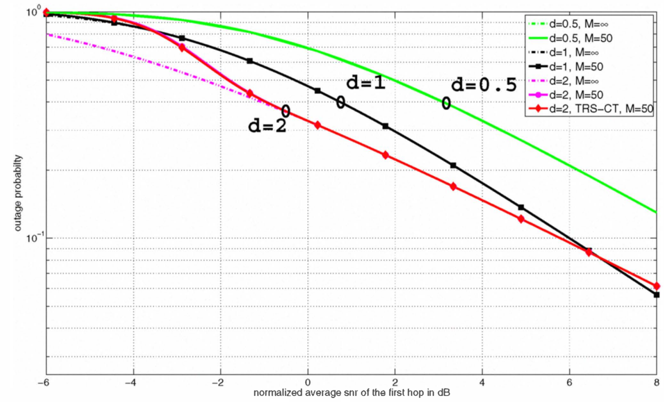
$d = 1$ for any SNR value. Thus, for small M, $d = 1$ should be preferred.

For medium-to-high number of relays, M, in the network, depending on the average SNR of the first hop, the parameter d should be appropriately chosen to save power without impairing the outage performance. Figures 4 and 5 show that for medium-to-high M, d should be set to 1 for small average SNR as the TRS protocols with $d = 1$ outperform both TRS protocols with $d = 2$ and with $d = 5$. However, for small to mid-range average SNR, the value of d could be chosen to be > 1 to save additional transmit power. In Figures 4 and 5, one observes that for small average SNR, ranging from approximately -3.5 to 1.6 dB in the case of $M = 50$ and from -2 to 3.5 dB in the case of $M = 20$, d set to 2 gives a better outage performance and extra power saving, up to 60% for $M = 50$ and up to 40% for $M = 20$, compared to TRS with $d = 1$. Similarly, for small to mid-range SNR, ranging approximately from 1.6 dB and above in the case of $M = 50$ and from 3.5 dB and above in the case of $M = 20$, the value of d can be increased to 5 for additional power saving.

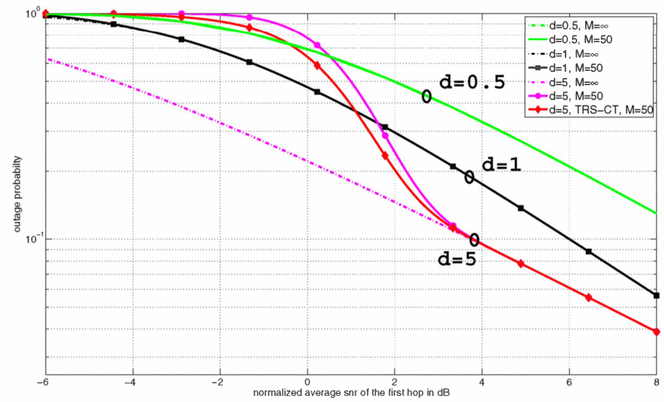
Note that the TRS-CT protocols perform only slightly better than the TRS protocols in general. Therefore whenever TRS with $d > 1$ is outperformed by TRS with $d \leq 1$, TRS-CT protocols, with similar outage behaviour, are also outperformed by the TRS protocols with $d \leq 1$. Given that the TRS-CT protocols do not allow any power saving, the TRS protocols have the clear advantage.

VI. Conclusion

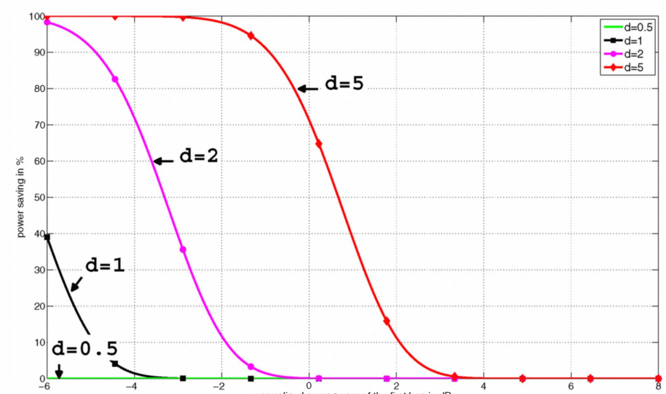
In this paper, new threshold-based relay selection protocols for multirelay and multiuser systems are presented. The proposed protocols use a selection threshold on the first-hop SNR and one-bit feedback. It is shown that transmit power can be dramatically reduced by appropriately choosing the selection threshold for a given number of relays and SNR range. Comparison to the threshold-based relay selection which does not switch off the transmissions are performed. Numerical results show that for medium-to-high numbers of relays, the outage performance of the TRS protocol is close to that of TRS-CT even in the case where the selection threshold is greater than the outage threshold. More significantly, for low to mid-range average SNR scenarios, where relaying is critical, the TRS selection threshold can be appropriately chosen to dramatically reduce transmit power without sacrificing outage performance.



(a) Outage performance of TRS compared to TRS-CT $d = 2$



(b) Outage performance of TRS compared to TRS-CT $d = 5$



(c) Power saving

Fig. 4. Performance comparison for the case of $M = 50$ relays

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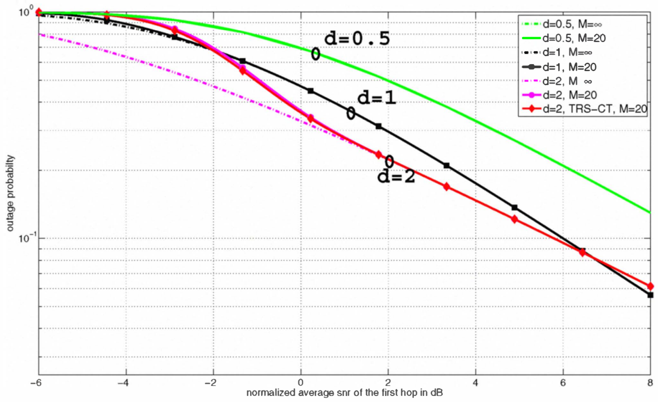
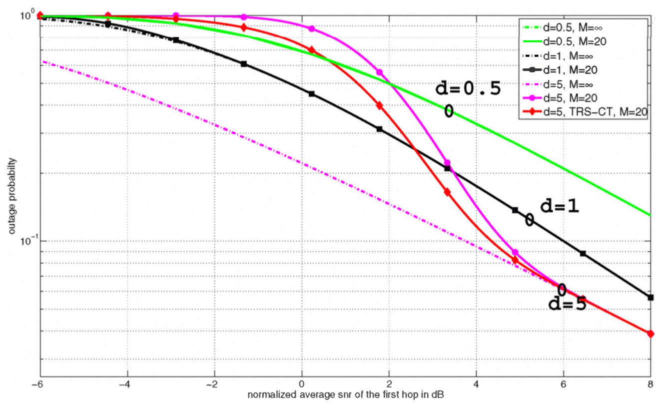
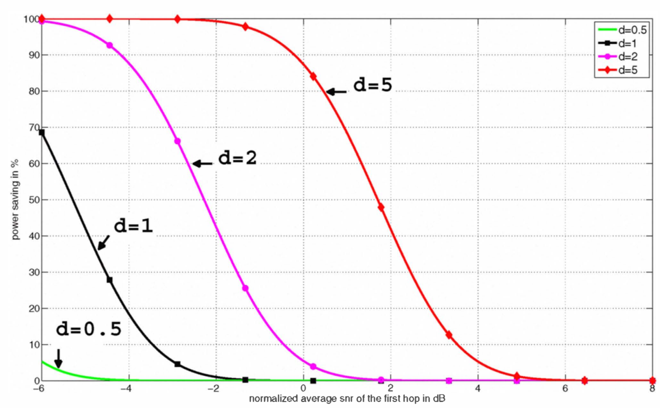


(a) Outage performance of TRS compared to TRS-CT $d = 2$

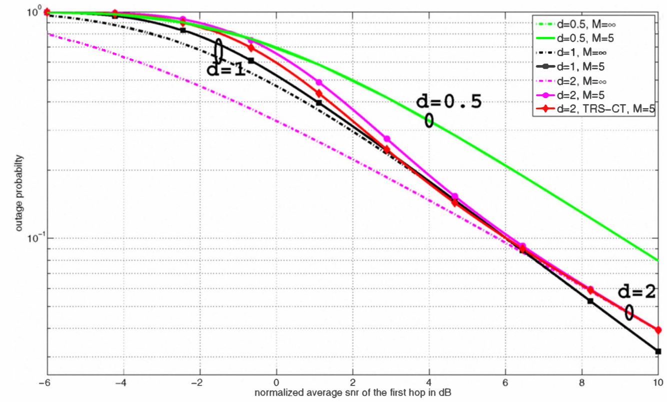


(b) Outage performance of TRS compared to TRS-CT $d = 5$

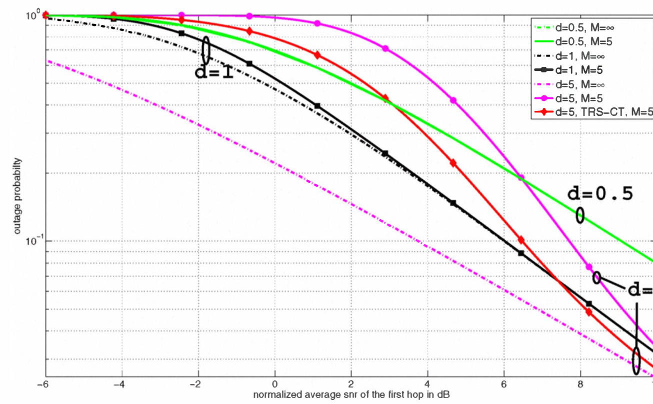


(c) Power saving

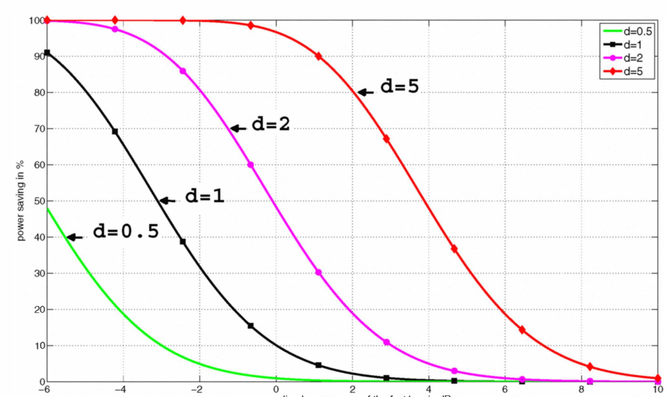
Fig. 5. Performance comparison for the case of $M = 20$ relays



(a) Outage performance of TRS compared to TRS-CT $d = 2$



(b) Outage performance of TRS compared to TRS-CT $d = 5$



(c) Power saving

Fig. 6. Performance comparison for the case of $M = 5$ relays

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