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Transmission strategies and resource allocation for fading broadcast relay channels

Arif Onder Isikman*, Melda Yuksel

TOBB ETU, Turkey

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ABSTRACT

In this paper the broadcast relay channel, where the source communicates with multiple destinations with the help of a single relay is studied. Five different transmission protocols, direct transmission, multihop (MH), multihop with link combination (MHLC), path selection (PS) and path selection with link combination (PSLC) are investigated. In MH and MHLC, the relay decodes the source message and assists both destinations. In PS and PSLC, the relay can perform partial decoding and has the option to help only one of the destinations. Under long-term power constraint, power allocation for delay-limited transmission is performed to minimize common outage probability and individual outage probability region. For comparison, lower bounds on both common and individual outage probabilities are found. Numerical results suggest that path selection significantly lowers outage probabilities, while enforcing the relay to help both destinations simultaneously is limiting the system performance.

1. Introduction

The four-terminal broadcast relay channel (BRC), which is especially important for hierarchical downlink communications, is first studied in [1]. In the four-terminal BRC model, there are two destinations, which communicate with the source with the help of a single dedicated relay. Various achievability schemes are proposed for the BRC in [1–8]. The BRC can be especially important for next-generation wireless standards such as 3GPP Long Term Evolution Advanced standard (LTE-A) [9,10], which proposes using relays for enhanced data rates.

When channel state information is available at the transmitter, substantial gains can be achieved if transmission rate and power are adapted according to the channel conditions. Under long-term power constraint over multiple fading blocks, there are several adaptation techniques in the literature depending on the application:

- If an application is delay tolerant, waterfilling is the best strategy, which adjusts both power and rate over all fading blocks to maximize the ergodic rate [11].
- If an application is delay-limited, rate adaptation is not an option. Instead there is a fixed target transmission rate for each transmission block, and only power is adjusted. If the target rate is high, an outage is inevitable for some transmission blocks. For such an application the optimal power allocation scheme that minimizes outage probability is of threshold-type [12]. To maintain a fixed rate over time, channel inversion is performed. However, it is best to cease transmission if too much power is required to invert the channel.

In this paper, we are interested in delay-limited applications. Under long-term power constraint, optimal power allocation protocols for minimum outage probability for fading broadcast channels and relay channels are studied in [13–16]. In [16], opportunistic protocols, in which the relay is not utilized if cooperation consumes more power with respect to direct transmission are proposed and proved to perform close to the cut-set bound.

In this paper we investigate relaying strategies and related power allocation methods that minimize outage probability for the BRC with N destinations under long-term power constraint for delay-limited applications. Note that, the four-terminal BRC is different from the two-receiver relay-broadcast channel [17,18]. In the latter, the source communicates with two destinations one of which acts as a relay for the other. The relaying receiver conveys messages to a single node only and does not encounter the problem of assisting two different receivers simultaneously.

In the single-antenna BRC under study, the source uses superposition coding at fixed target rates to reach all destinations reliably. We first study the common outage probability for all of the

* Corresponding author. Tel.: +90 5389440004.
E-mail address: aisikman@etu.edu.tr (A.O. Isikman).

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destinations. In a broadcast channel, there is common outage, whenever any of the destinations is in outage [13]. Such an operation mode is necessary if coordination among receivers is to be established and transmission to all of the destinations has to take place at the same time. On the other hand, if coordination is not required, destinations can declare outage independently. As a result, for fixed rates, each destination can have a different outage probability, defining a region.

In the BRC setting, in addition to direct transmission (DT), we investigate four different protocols: multihop (MH), multihop with link combination (MHLC), path selection (PS) and path selection with link combination (PSLC). We also upper bound the achievable rates at the destinations and find a lower bound on common and individual outage probabilities and an upper bound on ϵ-outage rate regions. In MH, MHLC, PS, and PSLC the source uses superposition coding for the N independent messages it has for each of the N destinations and opportunistically resorts to DT, whenever it consumes less power than using the relay. In MH, the relay has to decode all N messages to help all destinations. We assume the destinations only listen to the relay as this is a practical assumption that enables simple receivers. In PS; we exploit superposition of messages, and allow the relay to assist a subset of destinations, where the other destinations directly listen to the source. Similar to MH, in this case, the destinations that listen to the relay do not listen to the source. Complementing MH and PS, in MHLC and PSLC, we study the effect of link combination and explore the gains introduced when the destinations can combine signals both from the source and the relay. Although, MHLC and PSLC are sure to perform better than MH and PS, respectively, they require complex receivers and their use is limited.

In our previous work [19], we only studied common outage probability for the four-terminal BRC for DT, MH, PS and PSLC. In this paper, we include MHLC and investigate individual outage probabilities. Moreover, in this work, the opportunistic behavior of the source and the relay are determined optimally, whereas in [19], the relay was utilized according to suboptimal rules. The contributions of this work are listed as follows:

- Under long-term power constraint and delay-limited transmission the minimum outage probability problem is posed for the 2-user BRC. Common and individual outage probability cases are solved separately.
- In addition to DT, four different opportunistic relaying strategies, MH, MHLC, PS and PSLC are proposed and achievable rate regions are given for the 2-user BRC. An upper bound on achievable rates is also found. For these achievable schemes and the upper bound, for fixed target rates, optimal power allocation policies are determined that minimize the common outage probability and the individual outage probability regions. The results are complemented with ϵ-outage rate regions, for a fixed common outage probability value and for a fixed individual outage probability vector.
- The broadcast relay channel under study is not necessarily degraded [2]. For some channel conditions it is better if both destinations decode both messages, and for some other channel conditions, less power is consumed if both destinations decode their own messages only.
- Computer simulations are performed for $N=2$ and $N=3$ to reveal the effects of partial decoding at the relay for increasing number of users. Our results indicate that PS is very close to optimal. We also observe that partial decoding has significant gains in the BRC setting.

The organization of the rest of the paper is as follows. In Section 2, system model and optimal power allocation principles under common and individual outage constraints are introduced. In Section 3, transmission protocols are described in detail. In Section 4, numerical results are presented. Finally in Section 5, the paper is concluded.

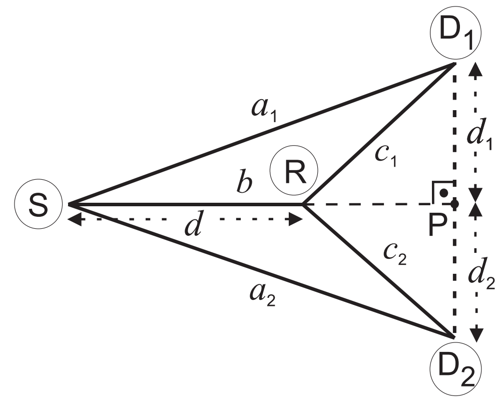

Fig. 1. The broadcast relay channel (BRC), with one source (S), one relay (R), and two destinations (D_1, D_2). For the numerical simulations in Section 4, all four nodes are located on a plane with S–R, D_1-point P and D_2-point P distances are respectively equal to d, d_1 and d_2.

2. System model

The BRC consists of one source (S), one relay (R), and N destinations ($D_1, D_2, \ldots, D_N$). The model is illustrated for $N=2$ in Fig. 1. The instantaneous amplitude squares of complex channel gains among S–D_j, S–R, and R–D_j are respectively denoted by a_j, b, and c_j, $j=1, 2, \ldots, N$. It is assumed that the channel gain amplitudes are known globally at all nodes, whereas channel gain phases are known only at corresponding receivers. The channel coefficients have quasi-static fading [12] and are independent from one block to the other. Complex Gaussian noise at the receivers are independent, and have zero mean and unit variance.

We assume that the relay is half-duplex and there is time division among the source and the relay. The source transmits for t fraction of the block, $0<t\leq 1$, and the relay transmits in the rest $1-t$.

The system is *delay-limited*. Communication lasts for B blocks, where B approaches infinity. Over each communication block, the source transmits N independent messages $W_1, \ldots W_N$ at *fixed* target rates $R_1, \ldots, R_N$ respectively to each destination. The source node encodes $W_1, \ldots, W_N$ into $X_1, \ldots, X_N$ using superposition coding [20]. It allocates power $P_{Sj}^{(i)}(s,t)$ to send X_j, $j=1, \ldots, N$, and transmits $X=X_1+X_2+\cdots+X_N$ to reach all destinations simultaneously. Here $s=(a_1, \ldots, a_N, b, c_1, \ldots, c_N)$ is the channel state vector and i, $i=$DT, MH, MHLC, PS, PSLC, denotes the transmission protocol that will be defined in the next subsection. Upon receiving the source signal X, the relay decodes W_j for all $j\in\mathcal{E}(s)$, where $\mathcal{E}(s)\subseteq\{1,2,\ldots,N\}$. Note that the subset $\mathcal{E}(s)$ depends on the channel state s, and on the transmission protocol. The relay then reencodes W_j, $\forall j\in\mathcal{E}(s)$ into $\tilde{X}_j$ using an independent codebook at power $P_{Rj}^{(i)}(s,t)$ and transmits the sum $\sum_{j\in\mathcal{E}(s)}\tilde{X}_j$.

Before explaining power and outage constraints, we next outline the transmission protocols, DT, MH, MHLC, PS and PSLC. Calculation of the instantaneous achievable rates at the destinations and the required power levels will be presented in Section 3.

2.1. Overview of transmission protocols

In DT, the relay is not utilized and the system is equivalent to a broadcast channel. The source node transmits all the time, $t=1$. Note that, DT will be a part of all other opportunistic protocols