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Performance analysis of ad-hoc routing in heterogeneous clustered multi-hop wireless networks

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ABSTRACT

This paper analyzes the performance of clustered decode-and-forward multi-hop relaying (CDFMR) wireless Rayleigh fading networks, and sheds light on their design principles for energy and spectral efficiency. The focus is on a general performance analysis (over all SNR range) of heterogeneous wireless networks with possibly different numbers of relays in clusters of various separations. For clustered multi-hop relaying systems, hop-by-hop routing is known as an efficient decentralized routing algorithm which selects the best relay node in each hop using local channel state information. In this article, we combine hop-by-hop routing and cooperative diversity in CDFMR systems, and we derive (i) a closed-form expression for the probability distribution of the end-to-end SNR at the destination node; (ii) the system symbol error rate (SER) performance for a wide class of modulation schemes; and (iii) exact analytical expressions for the system ergodic capacity, the outage probability and the achievable probability of the SNR (power) gain. We also provide simple analytical asymptotic expressions for SER and the outage probability in high SNR regime. Numerical results are provided to validate the correctness of the presented analyses.

1. Introduction

Wireless networks with multi-hop transmission capability facilitate forwarding packets from one node to other nodes in the network that may not be within direct wireless transmission range of each other. Recently, different aspects of multi-hop wireless networks, including both mobile ad hoc networks (MANETs) and hybrid cellular networks, are explored from signal processing, networking and information theory perspectives and prototypes have been developed (see, e.g., [1–3] and the references therein). Among three main relaying schemes, i.e., decode-and-forward (DF), compress-and-forward, and amplify-and-forward (AF), the DF protocol has the benefit of avoiding noise propagation, and therefore it provides a better link reliability. In addition, when the cooperative relay in each hop of the multi-hop transmission system is selected among several adjacent relays, in a so-called relay cluster, better transmission reliability may be provided by achieving diversity gain through the cooperation among cluster nodes. In this scheme, each relay node participates in an ad hoc routing protocol that allows to discover the best multi-hop path through the network towards the destination node. In practice, the networks are heterogeneous in the sense that they are composed of multiple clusters with possibly different distances and numbers of relays. This paper analyzes the performance of heterogeneous clustered decode-and-forward multi-hop relaying (CDFMR) wireless networks and aims to quantify how design parameters affect the network energy and spectrum efficiencies.

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1.1. Previous works

There have been significant efforts on the study of cooperative systems, e.g., [4–7], and more also on combining routing and cooperative diversity in multi-hop fading wireless networks [8–11]. In [12,13], for dual-hop cooperative systems, composed of one source–destination pair and a number of relays, the problem of finding the transmission path that achieves full diversity and the associated performance analysis are studied under AF and DF relaying protocols. Relay protocol design for IEEE 802.16 relay networks is considered in [14,15]. Deplying relays in cellular network is considered in [16,17] for satisfying users increased bit rate requirements while still retaining the benefits of a cellular structure. Addressing the same problem in general multi-hop networks with more than two hops is of great interest and is studied in, e.g., [18–21]. The main idea is to group the relay nodes in each hop into clusters and develop multi-hop transmission protocols based on data communication between adjacent cluster heads. In [20,21], optimal cooperator selection policies for arbitrary topologies are investigated, however, closed-form performance evaluation expressions are missing due to the huge complexity associated with the network setup. To tackle this problem, one must simplify the network setup to keep the analysis tractable and obtain the desired closed-form results. Following this approach, several routing strategies and their asymptotic outage probability performance in high SNR regime are investigated for CDFMR systems in [18]. As shown in [18], in a DF multi-hop network with L cooperating relays per hop, the maximum diversity order is L regardless of the number of hops. This is where the optimal routing strategy is defined as the one which identifies the path with the minimum end-to-end outage probability among all possible paths. In fact, the resulting routing protocol aims at finding the path with the greatest minimum SNR among hops, while relying on the knowledge of the channel state information (CSI) of all links. In [22], it is shown that arbitrary relay selection in the first $N-1$ clusters of an N cluster CDFMR system, and relay selection based on channel quality in the final cluster could achieve the same diversity gain as the optimal routing algorithm. Although, this leads to much lower power gain, but it only relies on the CSI of the last hop. A decentralized and more efficient routing strategy is also reported in which the relay selection is performed in a per-hop manner using only the CSI of relay links in the associated cluster. As verified in [18], when the number of hops in the network is small, this routing provides an outage performance very close to that of the optimal routing strategy, making it an attractive protocol with low algorithmic complexity and overhead.

The problem of maximizing the achievable rates by selecting a relaying subset and the allocation of transmission time in DF multi-relay systems is investigated in [23]. In [24], efficient routing algorithms for linear multi-hop networks are presented, which minimize the end-to-end system outage probability when equal-power or optimal-power allocation at the physical layer is employed. The performance analysis for an interference-aware opportunistic relay selection protocol in a multi-hop line network is considered in [25]. As relay assisted transmission has shown its merits for data transfer purposes, most recent wireless standards already provision for multi-hop relay networking [26–28]. It is expected that multi-hop networks also play key roles in next generation wireless systems for example in backhauling wireless mesh networks.

1.2. Outline of contributions and structure of the article

Here we consider a heterogeneous clustered decode-and-forward multi-hop relaying wireless network in which the relay cluster in each hop is predefined with its nodes, and the routing path is identified based on the hop-by-hop relay selection. We present exact performance analysis for packet transmission over this network. The proposed analysis quantifies the performance in terms of the outage probability, the ergodic capacity and symbol error rate (SER) over all range of the channel conditions. We combine hop-by-hop routing and cooperative diversity in CDFMR systems, with the consideration of a more realistic system and channel model. In particular, in the considered system model the number of relays in each cluster in addition to the distance between the relay clusters may be different, making the model more general compared to the prior art. Considering this general CDFMR network model, the main contributions of the current article are as follows:

1. We derive a closed-form expression for the probability distribution function (PDF) of the end-to-end SNR at the destination node.
2. Using the PDF in item 1, we derive exact analytical expressions for the system outage probability, the ergodic capacity, and the achievable probability of the SNR gain. Furthermore, we analyze the system symbol error rate performance for a wide class of modulation schemes. The first two metrics quantify how efficiently the spectrum is utilized and the last two are indicators of energy efficiency of the multi-hop network.
3. We also investigate the asymptotic behavior of the outage performance and SER in high SNR regime. In this line, we present simple analytical asymptotic expressions for SER and the outage probability.

Moreover, numerical results are provided to validate the correctness of the proposed analytical performance assessments.

The rest of this paper is organized as follows. In the next section, the system model is introduced. The exact performance of routing over CDFMR network in terms of outage, SER, rate, and probability of SNR gains is presented in Section 3. In Section 4, the asymptotic performance analyses are presented. Section 5 is devoted to numerical results and discussions. The concluding remarks are given in Section 6.

2. System model

Here we consider a multi-hop setting in which the relay cluster of each hop is predefined with its nodes. The routing path is known a priory, in terms of which clusters are used for relaying, and is found dynamically, in terms of