



Investigating cost-effective relay selection in multi-hop cooperative networks

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Abstract

The multi-hop cross-layer cooperative relaying system is essential for reliable wireless transmission over long distances. Relaying technology enhances performance and expands coverage areas through cooperative diversity. In this system, each node receives a signal from previous nodes and forwards it to the next, maintaining diversity gain without requiring more antennas at any node. Relay networks have garnered significant interest for their use in deploying limited-size, power-constrained nodes in severely fading environments. In these networks, signals are processed by amplify-and-forward (AF) or decode-and-forward (DF) operations before being relayed. This study focuses on a cooperative single-input single-output (SISO) cross-layer AF multi-hop relaying network, proposing a novel and efficient approach to route selection. The proposed low-cost, near-optimal routing and power allocation strategies significantly improve system performance while reducing computational complexity. Theoretical and simulated results demonstrate the superiority of the proposed methods over traditional schemes, offering notable enhancements in bit error rate (BER) and outage probability.

Keywords: Amplify-and-forward (AF), Selection relaying, Cooperative system, Multi-hop transmission, Rayleigh

Introduction

Reliable wireless transmission over long distances is a cornerstone of modern communication systems, and the multi-hop cross-layer cooperative relaying system plays a pivotal role in achieving this reliability. By leveraging relaying technology, these systems enhance performance and extend coverage areas through cooperative diversity. Unlike traditional systems that require multiple antennas at each node, cooperative relaying enables each node to receive signals from preceding nodes and forward them to subsequent ones. This approach not only maintains diversity gain but also addresses the limitations of size and power constraints inherent in wireless nodes operating in severely fading environments.

The interest in relay networks has surged due to their effectiveness in deploying compact, power-efficient nodes capable of functioning in challenging conditions. Within these networks, signals are typically processed using amplify-and-forward (AF) or decode-and-forward (DF) operations before being relayed to the next node. This study zeroes in on a cooperative single-input single-output (SISO) cross-layer AF multi-hop relaying network. The primary focus is on developing an innovative and efficient approach to route selection and power allocation.

Traditional routing and power allocation methods often entail significant computational complexity and may not be suitable for large-scale networks. To address these challenges, this study proposes a low-cost, near-optimal strategy that significantly improves system performance. Theoretical analysis and simulation results confirm that the proposed methods outperform existing schemes, delivering notable enhancements in key performance metrics such as bit error rate (BER) and outage probability. This research not only contributes to the advancement of cooperative relaying systems but also paves the way for more efficient and reliable wireless communication networks. The multi-hop cross-layer cooperative relaying system is very useful for reliable wireless transmission over long distances. Relaying technology in the wireless network is a reliable and efficient way to improve performance with more coverage areas through cooperative diversity. In cooperative communication, each node receives signal from previous nodes and forwards it to the next node. This structure retains the diversity gain without employing more antennas in any node, and this is because the sender can transmit its signal to the destination via multiple intermediate relay nodes. In recent years, relay networks have drawn a lot of interest for their use in deploying limited-size, power-constrained nodes in severely fading environments. In multi-hop relay networks, the source signal is transmitted through a series or parallel/cross-layer of cascade intermediate nodes. A signal to a relay node is often processed by amplify-and-forward (AF) or decode-and-forward (DF) operation before being forwarded to the following node. Authors in El-Zahr and Abou-Rjeily (2022) derived a closed-form analytical expression for any number of DF relays, and improves on the existing schemes. The error correction coding of DF makes the analysis very complex, while AF relaying is considered to be simpler to implement. In this work, a cooperative single-input single-output (SISO) cross-layer AF multi-hop relaying network will be taken into consideration. In comparison to prior works, the proposed work provides a unique and innovative approach to route selection in a multi-hop relay network. The low-cost near-optimal routing and power allocation strategies presented in this work can significantly improve system performance while reducing the computational complexity of the network.

Per hop relay scheduling for data transmission has been selected in Kandelusy and Kirsch (2020) based on the local CSI to maximize signal-to-noise ratio (SNR) through the best path known as selection relaying. The best path only counts the source-relay-destination path having the highest SNR or lowest error signals. Authors in Li et al. (2023) used multiple relaying for Internet-of-Thing (IoT) devices, where a source is communicating with a destination via multiple relays. Usually, two types of relaying are used, reactive relaying and proactive relaying for finding the best relay in a SISO scheme. Reactive relaying involves sending the source signal to every relay, and only the best relay will then convey the decoding signal to the target location. When relaying is proactive, only the best relay is used to transfer data to the destination, leaving the others inert. The optimal relay selection using the best relay provides better system performance and is shown in Hashemi et al., 2020, Tseng et al., 2022. Deng et al. (2022) presented a low-complexity multi-hop task relaying for maximizing overall throughput for both spot communication and computing through task routing.

Literature review

A very good example of Max–min relay for a multi-hop cross layer SISO DF relay has been proposed in Gui et al. (2009) using the minimum outage probability path. In Mondelli et al.

(2014), authors proposed optimal path selection for multi-hop DF relaying using exhaustive search to minimize system bit error rate (BER). By establishing an exact formulation of the average BER, Deng et al. (2022) created a max–min best route selection in a multi-hop cooperative system. Hasna and Alouini Hasna and Alouini (2003) researched the best path outage probability in multi-hop cooperative systems. Ding et al. (2010) considered AF and DF relay selection for dual-hop communication based on the highest end-to-end SNR. In Zhao et al. (2006), authors proposed a dual-hop relaying selection by minimizing symbol error rate (SER). Consequently, the dual-hop selection requires the exact CSI of all possible links. However, large amount of computations and memory requirements, as well as transmission of exact CSI of all links to the central controller through the fading channel make its implementation impractical for medium to large scale networks You et al. (2016). A dynamic programming path selection has been carried out in Wang et al. (2013) for cross-layer multi-hop AF relay networks. We note that dynamic programming in cross-layer multi-hop relaying necessitates connectivity between all hops; thus, its computational cost grows linearly with the number of hops Dayarathna et al. (2022). The drawback of the above routing protocols in cross-layer design is the requirement of high computational complexity and large storage. To our knowledge, no previous study has attempted to tackle the low-cost optimum relay selection problem for cross-layer (or parallel layer) multi-hop relaying in order to reduce BER and outage probability using a single algorithm.

Power is a critical resource for relaying information on several hops, and optimal uses of this resource are essential to prolong the system lifetime. Water-filling-based power allocation has been proposed in Khoshnevisan and Laneman (2012) to maximize the ergodic capacity in the Rayleigh fading channel. Power allocation of a 2-hop parallel AF SISO relay network with partial CSI was studied in Zafar et al. (2012) to minimize network power consumption with keeping SNR above a certain threshold. An energy-efficient multi-hop routing algorithm for Wireless Sensor Networks (WSN) has been proposed in work Hasna and Alouini (2004). The algorithm selects the best path for data transmission using the Taylor C-SSA algorithm. Optimum power allocation for non-regenerative systems has been proposed to enhance system performances Vinitha et al. (2022). An iterative optimal power allocation was given in Farhadi and Beaulieu (2009) under both short-term (ST) and long-term (LT) power limits, for maximizing the instantaneous SNR. Power allocation is directly related to the channel conditions, and is the one the design challenges Naeem et al. (2017). However, node cooperation increases the system performance through the power allocation Del Coso et al. (2007).

Contributions and organization

The primary goal of this research is its focus on relay selection in multi-hop cross-layer relay networks for reducing both BER and system outage probability. The route selection using exhaustive search Gui et al. (2009) is extensively used in literature that requires perfect channel knowledge of all possible links which is very difficult to obtain for medium or/and large scale complex networks. Dynamic programming usually breaks the global best path problem into a series of local sub-optimal solutions Wang et al., 2013, Dayarathna et al., 2022. Each sub-optimal problem is then solved separately, and it requires high computation for the large-scale network. Alternatively, we proposed a low-cost near-optimal path selection in this work. Theoretical and simulated studies demonstrate that our proposed path selection strategy beats previous work in terms of BER and outage probability.

Moreover, we obtain a low-cost power allocation that gives better performance than equal power allocation (EPA) and ST power allocation (STPA). We have two power allocations, namely, recursive power allocation (RPA) with total power constraint and RPA with individual and total power constraint, and is the another contribution of this paper. We first find the optimal path according to our proposed routing, then in the second step, we employ our proposed power allocation for enhanced system performance. Our suggested power allocation surpasses the power allocation cited in Farhadi and Beaulieu (2009) in terms of BER and outage probability, according to analytical and experimental data. The proposed work presents a new route selection algorithm for a cooperative wireless multi-hop cross-layer relay network with perfect channel state information. This work is distinct from prior works in the following ways as follows:

Multi-hop Parallel SISO Relay Network Simplification: The proposed work converts a multi-hop parallel SISO relay network into an equivalent series multi-hop network by identifying the optimum route that provides the highest end-to-end SNR. The unique method of simplification can make the network less complicated.

Low-cost near-optimal routing strategy:

The proposed work presents a low-cost near-optimal routing strategy to provide close to optimal performance with much less complexity compared to traditional routing. This is a significant improvement over traditional routing schemes, which are often computationally complex and impractical for large-scale networks.

Low-cost Power Allocation Scheme:

In addition to the routing strategy, the proposed work also presents a low-cost power allocation scheme to further improve system performance over traditional power allocation found in the literature. This approach can also reduce the complexity of the network.

Excellent Performance Improvement:

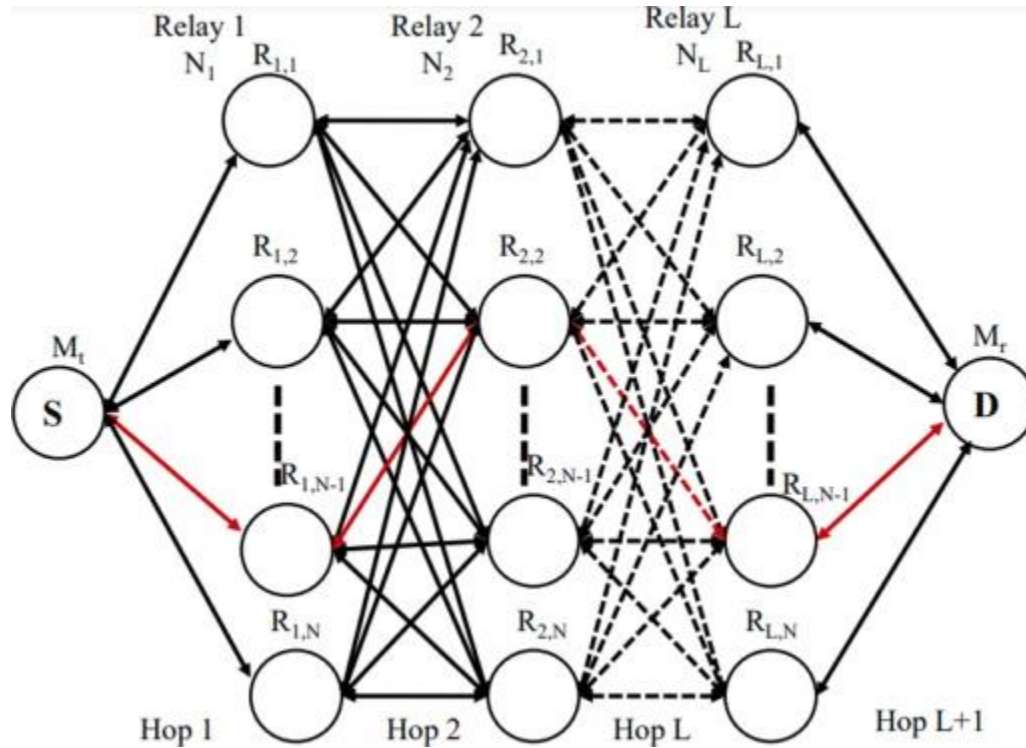
In comparison to conventional relaying and power allocation algorithms, computer simulations demonstrate that the suggested approaches offer excellent performance improvements in terms of bit error rate (BER) and outage probability.

The rest of the article is divided into the following sections. The system and channel models under examination are presented. Additionally, the same Section has defined the multi-hop relaying optimization issue. We propose a near-optimal routing strategy by derivation of closed-form BER and outage probability expressions. The optimal routing strategy is able to minimize the BER as well as system outage. Sets up the two iterative power allocation solutions under total power constraint. The efficiency of the proposed power allocation techniques is compared with techniques in the literature respecting system BER and outage probability. Numerical results are presented in to compare these strategies. Finally, Section 6 summarizes the paper.

Signal analysis and problem formulation

We start with considering a L hop N cross-layers SISO networks as shown and there is no immediate path from the sender to the receiver due to the large distances between them. Cross-layer multi-hop relay involves intermediate relays placed between the source and destination for

forwarding data. In this relaying, information metrics from the physical layer can be used to make routing decisions at the network layer based on the dynamic network behaviors. We refer to this model as the idealized linear network model, similar to Wang et al. (2013, Figure1), Gui et al. (2009).



Best path selection

In this section, we will develop an algorithm to find the best path corresponding to the optimal set of channels depending on the highest SNR at the destination which gives the minimum error objective function.

Experimental results and analysis

Experimental setup

Let us consider at least 107 channel excitations in the simulation to evaluate the proposed algorithm in this paper. The distance between the source and the destination is 30 m with each node power set at 3 W. The value of path loss exponent for any link is taken to be between 1.5 to 1.8. All complex channel components are created from $CN(0,1)$ distributions. Each channel is modeled as quasi-static which implies that during transmitting a message channel excitation remains unchanged in any hop. We compare BER and outage performances of the above system with equal power allocation for ad hoc relaying, S-AF relaying, the proposed near-optimal relaying, and optimal relaying.

Comparison to prior works

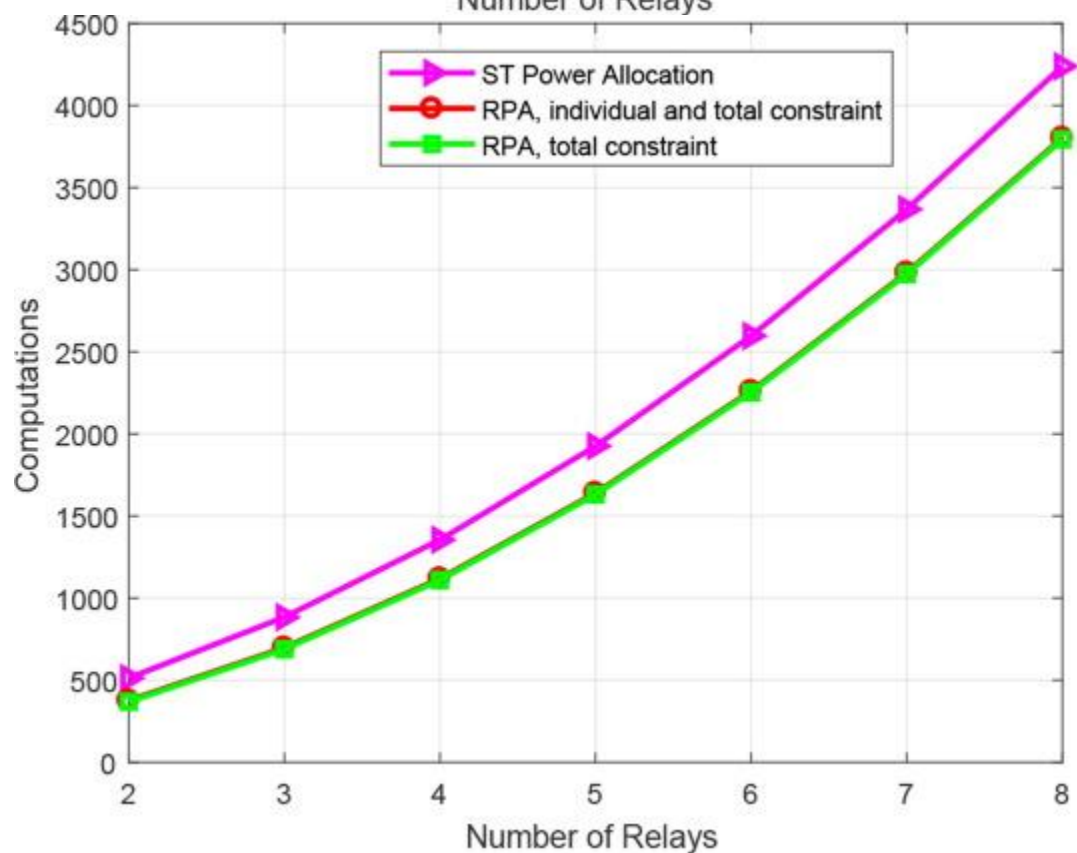
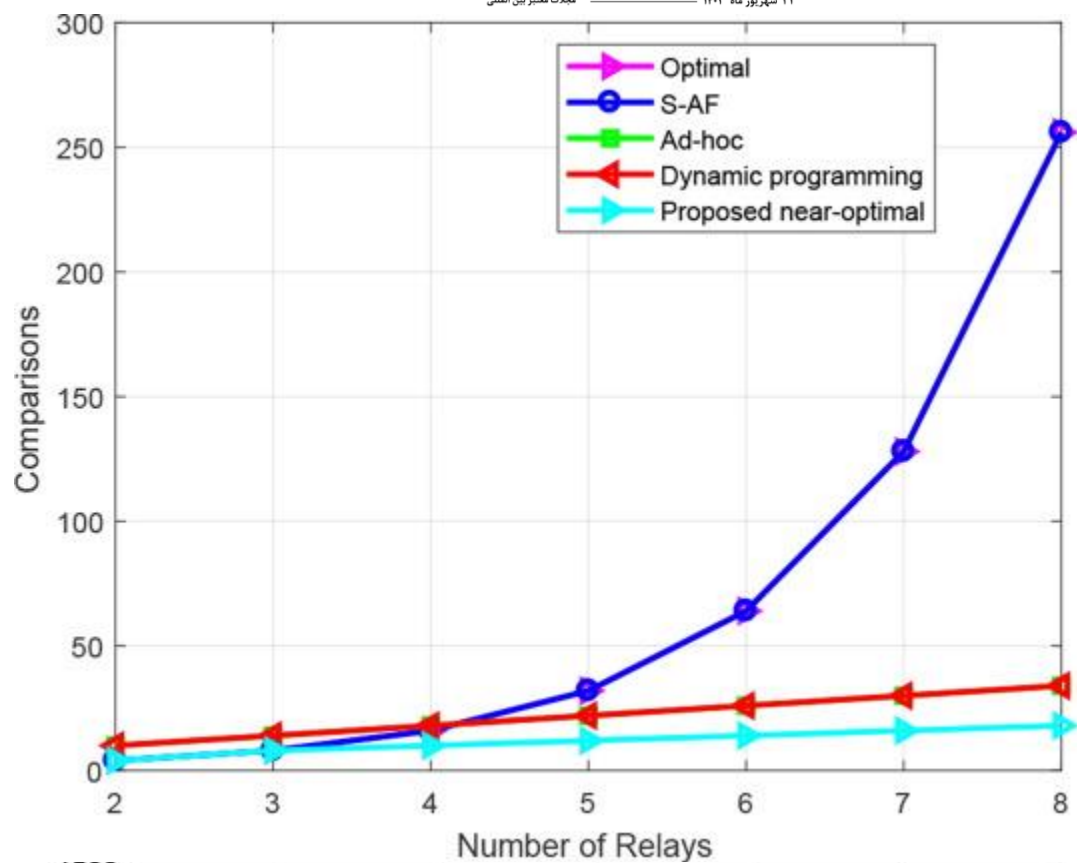
The proposed routing algorithm in this work provides close to optimal performance with much less complexity compared to traditional routing algorithms. Additionally, a low-cost power allocation scheme is also proposed to further improve the system's performance over traditional power allocation methods. The simulations show that the proposed methods in this work achieve significant improvement in terms of BER and outage probability compared to traditional relaying and power allocation algorithms. In this research, we have compared our results with four prior works in this field:

Selective Amplify-and-Forward (S-AF) Ding et al. (2010): It is a type of cooperative communication scheme where a relay node selectively amplifies and forwards only the signals with good quality to the destination, while discarding the signals with poor quality.

Ad-hoc Routing Gui et al. (2009): It aims to minimize the system error at each hop by selecting the path with the highest SNR.

Dynamic Programming Wang et al. (2013): The goal is to select the best route between a source node and a destination node in a multihop network as a dynamic programming problem and by breaking it down into smaller subproblems, and using the optimal solutions of these subproblems to construct the optimal solution for the original problem.

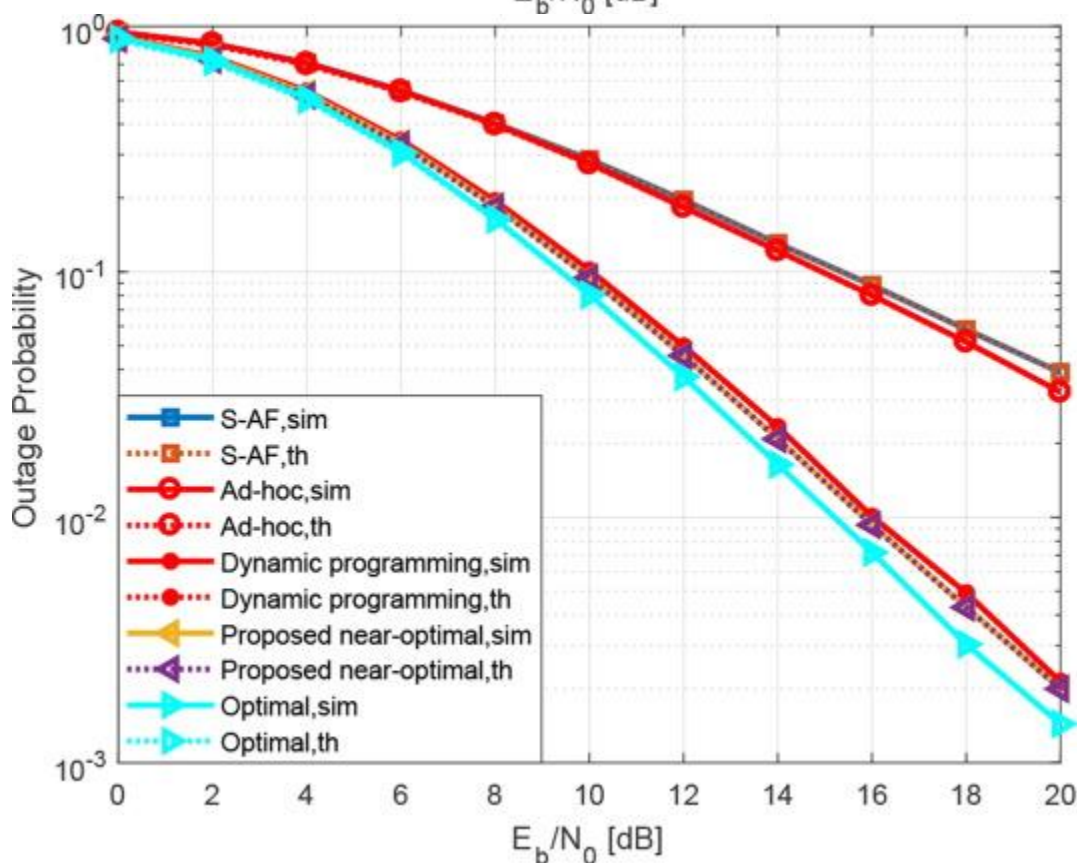
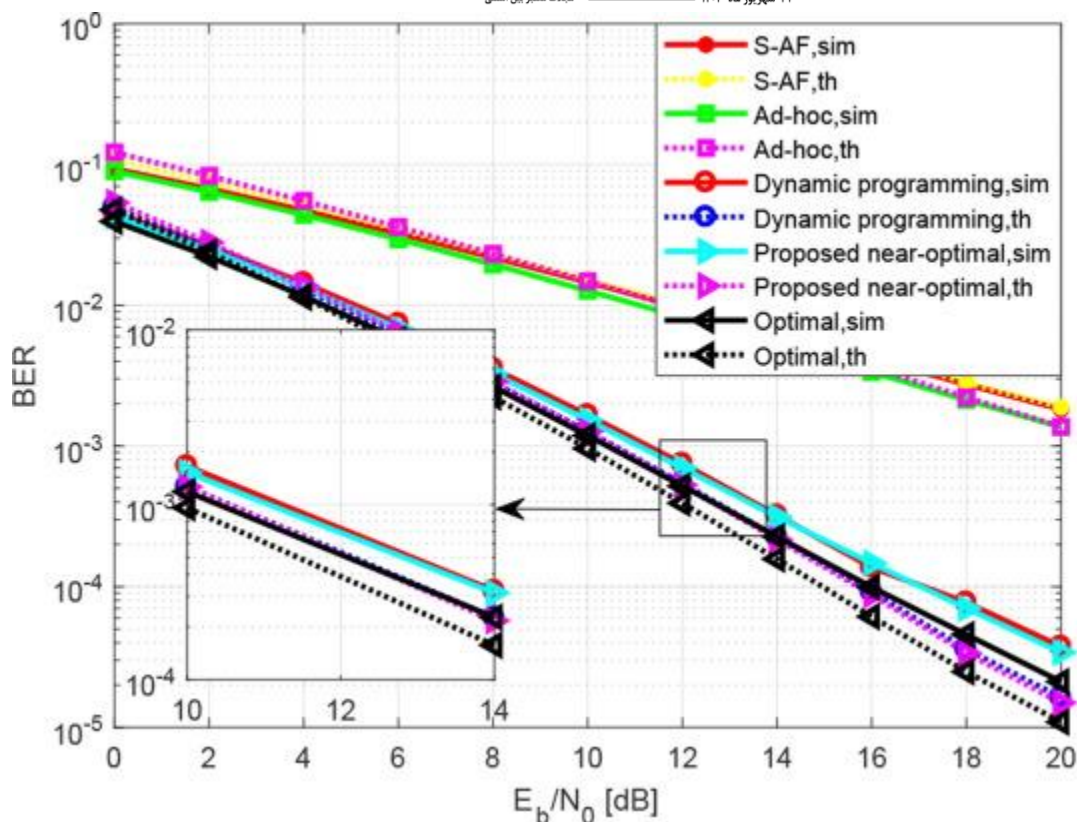
Optimal Relaying Dayarathna et al. (2022): It is a relay selection and routing scheme that maximizes the system performance of the multi-hop network by utilizing exhaustive search-based optimal routing.



Performance analysis

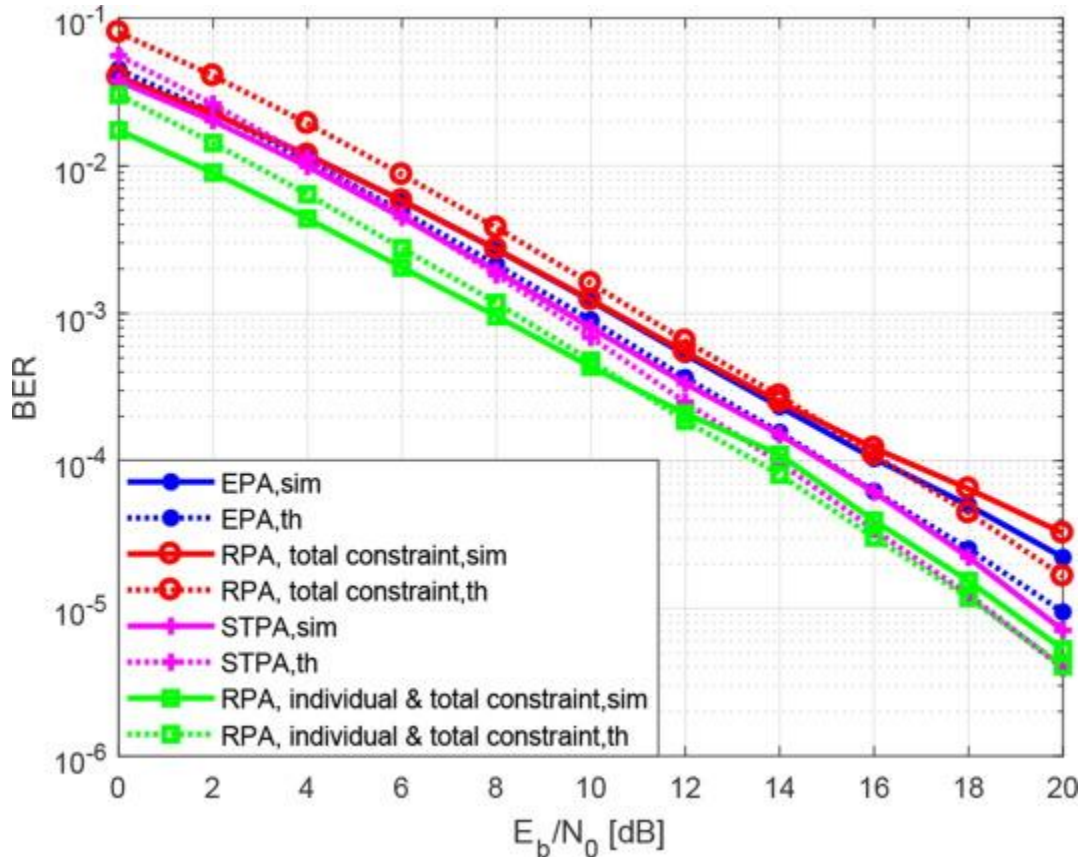
BER and outage performance with equal power allocation

presents the theoretical and simulation BER performance of the above network with equal power allocation in all relay nodes for 16-QAM for ad hoc, S-AF, dynamic programming, optimal, and our simplified near-optimal selection, respectively. The analytical BER for each channel selection has been calculated using , and the theoretical results match precisely the simulation results for all cases, which verifies the accuracy of both the theoretical derivations and the simulations. We can see that exhaustive search based optimal routing outperforms the BER performance while S-AF and ad hoc relay selection give the worst performance. Dynamic programming and near-optimal show very close BER performance in all regions. It is also observed that the two algorithms give very close performance compared to optimal selection. For example, dB and dB, the BERs for optimal selection are 0.0117 and 0.0005, for dynamic programming, 0.0130 and 0.0006, and for near-optimal selection, 0.0129 and 0.0006, respectively. Similarly, the analytical and simulated end-to-end outage performance of the above network for the above path selections are plotted and we find an exact agreement between simulated and theoretical outage curves for all path selection methods in the entire SNR region. For the analytical outage calculation, we used the approximation in for all cases. We can see that optimal path selection outweigh outage performance in all SNR regions while S-AF and ad hoc relaying show the worst performances. Simplified near-optimal relaying gives very close outage performance compared to optimal selection. For example, the outage probabilities of optimal selection are 0.5091 and 0.0388 while the outage probabilities for near-optimal selection are 0.5164 and 0.0438, respectively. The near-optimal scheme provides better outage performance than dynamic programming.

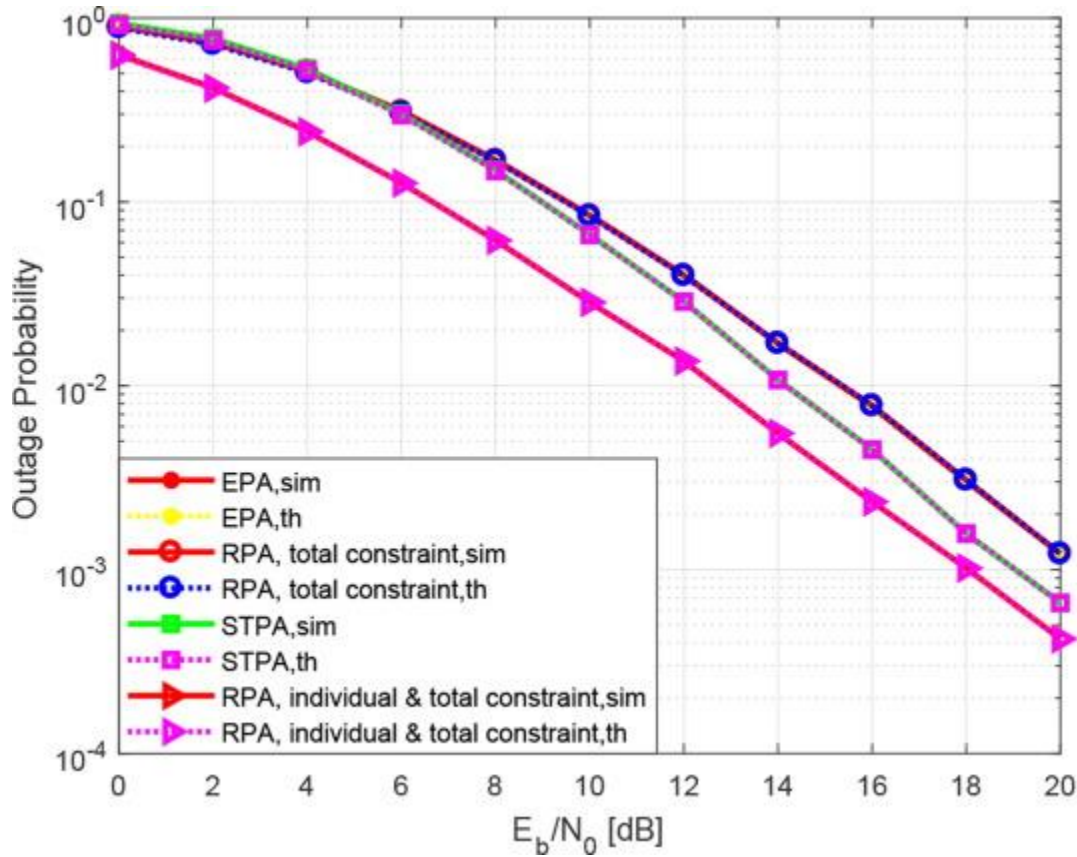


BER and outage performance with optimal power allocation

The rest of the power from all hops is assigned to the source node. The excessive power for the source node only boost the source signal strength and it does not have any effect on noise propagation. The ultimate goal of RPA with individual and total constraint is to amplify the source signal and limit the hop-to-hop noise propagation. Therefore, RPA with individual and total power constraint gives the best performance over other techniques. Similarly, the simulated and analytical outage performance for the four power allocations of the system are plotted. There is an exact curve for theoretical and simulation investigation for all cases. The analytical outage probability has been found by for the system with the above power allocations. The results show that our proposed RPA with individual and total power constraint outperforms RPA with total power constraint.



BER as a function of the SNR for L -hop optimal routing with various transmission schemes.



Outage performance of L -hop optimal routing for various transmission schemes.

and show that BER and outage performances for RPA with total power constraint are similar to EPA. This is because EPA at total power constraint assigns higher values for any and as a result we see SNR variations even at fixed with different channel excitations. On the other hand, RPA with both individual and total power constraint limits the values of and assigns more value for which means it resists noise propagation from all previous hops. Therefore, we see excellent system performances (both BER and outage) for RPA with both individual and total power constraints.

Conclusion

This paper showed that the proposed near-optimal relay selection scheme gives very close BER and outage performances compared to optimal path selection at much lower complexity than other algorithms, in particular dynamic programming. This scheme may have an excellent application in medium to large scale complex relay networks. It was also shown that the proposed RPA with individual and total power constraint outperforms the other power allocation techniques at a lower cost. Instead of sending a signal through all available paths, selecting the best path reduces the network design complexity and save transmission power that increases the network life-time. Another important issue is that the single searching algorithm is able to provide a unique path for both minimum BER and minimum system outage performances, and no separate operation is required. This indicates the importance of our work when the number of hops is very large. The findings of our work may have very interesting applications in advanced wireless communications.



However, it needs more extensive research in the case of CSI mismatch and this can be interestingly recommended for future works. We may also recommend a joint investigation of low-cost optimal path selection and total optimal power allocation simultaneously to further enhance system performances.

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