Outage Analysis of Myopic Multi-hop Relaying: A Markov Chain Approach

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Abstract—In this paper, a cooperative protocol is investigated for a multi-hop network with buffers of finite size at the relay nodes. The protocol is based on the myopic decode-and-forward coding strategy, where each node of the network cooperates with a limited number of neighboring nodes for the transmission of the signals. Each relay stores in its buffer the messages that were successfully decoded, in order to forward them through the appropriate channel links. A complete theoretical framework is investigated that models the evolution of the buffers as a state Markov chain (MC). We analyze the performance of the proposed protocol in terms of outage probability and diversity gain by using the state transition matrix and the related steady state MC. Our results show that the proposed protocol outperforms the conventional multi-hop relaying scheme and the system's outage probability as well as the achieved diversity order depend on the degree of cooperation among neighboring nodes.

Index Terms—Cooperative networks, multi-hop relaying, myopic coding, outage probability, diversity, Markov chain.

I. INTRODUCTION

Although the initial deployment of 5G networks has commenced and the research in academia and industry has already made some first steps towards the beyond 5G (B5G)/6G-era, the challenge of denser communications that will require higher rates still exists. Cooperative networks with multiple relays that can assist the transmission of information from a source to a destination is a promising technology that can address these issues [1]. Especially in B5G/6G networks, research needs to satisfy the challenging demands of ultra-reliable low-latency communications for massive connectivity in various environments. Cooperative relay communications is a low-cost solution with high flexibility, which can help the connection of trillions of devices with enhanced reliability and low energy consumption.

Numerous studies have investigated the performance of cooperative networks with multiple relays over a single transmission path (multi-hop relaying). More specifically, the end-to-end performance of a dual-hop network was analyzed in [2], while [3] extended the classical dual-hop relaying to a generalized model with hardware impairments. Other studies extended this approach to multi-hop schemes. In [4], the outage probability performance of a multi-hop system over Nakagami fading channels was studied. In addition, the authors in [5] presented a new protocol for half-duplex multi-hop relaying networks based on the concept of buffer-aided relaying and investigated the corresponding achievable rates.

Cooperative diversity is another relaying technique that has received a lot of attention by the researchers, as it enables broadcast transmission and spatial diversity of the participating nodes. In [6], Laneman et al. proposed several techniques of cooperative communication, such as selection relaying and incremental relaying, and investigated their outage performance. Moreover, the authors in [7] studied general cooperating setups, consisting of multiple transmission paths that include an arbitrary number of cooperating hops, and derived asymptotic expressions for the average symbol error probability. These setups consisted of either a single relay or multiple relays in parallel transmission paths. A cooperation scenario for multi-hop networks was introduced in [8], where the authors suggested that the spatial diversity gain could be achieved by combining at each node the signals that have been concurrently sent by all the preceding terminals along a single transmission path. However, full cooperation of the nodes in such networks exhibits a number of practical difficulties in its implementation. To overcome these issues, the authors in [9] proposed the myopic coding strategy as an information theory concept. In this strategy, each node of the network cooperates with a limited number of subsequent neighboring nodes. They showed that the achievable rate increases considerably, while the complexity of its implementation remains low.

In this paper, we propose a cooperative protocol over a multi-hop network, where each relay has a buffer of finite size. The protocol is based on the myopic decode-and-forward (DF) coding strategy [9] and the transmission of the decoded signals to the appropriate nodes is adapted according to the status of the buffers. Through this paper, we extend the work presented in [9] by studying the performance of myopic coding in terms of outage probability and diversity gain. To our knowledge, no previous work in the literature analyzes myopic coding from that perspective. Therefore, the main contribution of this work is the investigation of a theoretical framework to analyze such cooperative networks. For the analysis of the system in terms of outage probability, we model the evolution of the buffers as a state Markov chain (MC). Through this
formulation, we study the long-term outage performance of the system, where the system’s status reaches a stationary distribution, and we provide the achieved diversity order. Our results demonstrate that as the number of cooperating nodes increases, the performance of the system is enhanced both in terms of outage probability and diversity gain.

II. System Model

A. Network topology

A wireless network topology is considered, which consists of a source $S$, $N$ intermediate relays $R_1, R_2, \ldots, R_N$, and a destination $D$. For ease of notation, we let node $i$ correspond to the relay $R_i$, $1 \leq i \leq N$, and nodes $0$ and $N+1$ correspond to the source $S$ and destination $D$, respectively. At the relays, the DF scheme is employed for forwarding the signals. Moreover, time is assumed to be slotted and $x(t)$ is used to denote the signal that $S$ sends to $R_1$ at time-slot $t$. Each transmitter (the source $S$ or a relay $R_i$) transmits with the same fixed power $P$. The destination $D$ receives data based on a $k$-hop myopic DF coding [9], $1 \leq k \leq N+1$, where $k$ represents the maximum number of nodes that a transmitter can forward data to. More specifically, node $i$ ($0 \leq i \leq N$) can send data to $L_i = \min(k, N-i+1)$ subsequent nodes. As such, at each time-slot, the transmitter $i$ splits its power to $L_i$ partitions. Therefore, a signal is sent through the link $i \rightarrow j$ with transmit power $a_{i,j}P$, where $a_{i,j}$ denotes the power splitting parameter, such that $\sum_{j=i+1}^{\min(i+k,N+1)} a_{i,j} = 1$. However, at a given time-slot $t$, only the successfully decoded signals can be transmitted to the appropriate nodes. For this reason, each relay $R_i$ has a data buffer (data queue) $b_i$ of finite size $L_i$, where it can store the decoded signals for forwarding\(^1\), based on the proposed protocol (see Section II-C). An example of this topology is presented in Fig. 1, for $k = 2$ hops and $N = 3$ relays.

B. Channel model

For the analysis, we consider independent and identically distributed (i.i.d) channel links that experience propagation path loss, which is assumed to follow the power law of $d_{i,j}^{-\eta}$, where $d_{i,j}$ is the distance between the nodes $i$ and $j$ and $\eta$ denotes the path loss exponent. Without loss of generality, we assume the ordering $d_{i,j} < d_{i,j+1} \forall i,j, i < j$. Furthermore, all wireless links exhibit fading modeled as frequency-flat Rayleigh block fading. This signifies that the fading coefficients $h_{i,j}$ remain constant during one time-slot, but they change independently for different time-slots, by following a circularly symmetric complex Gaussian distribution with zero mean and unit variance i.e., $h_{i,j} \sim CN(0,1)$. We assume that during one time-slot the relays of the system can receive and transmit data simultaneously. For the sake of simplicity, we assume the interference caused by other relayed signals can be fully canceled out through sophisticated signal processing and equalization techniques [5], [8]. Therefore, the instantaneous signal-to-noise ratio (SNR) at a receiver $j$ during one time-slot, assuming that the transmission at every link is coherent is given by

$$\text{SNR}_j = \frac{1}{\sigma^2} \left( \sum_{i=0}^{N} \mathbb{1}_{i,j} |h_{i,j}| \sqrt{d_{i,j}^{-\eta}a_{i,j}P} \right)^2,$$

where $\sigma^2$ is the variance of the additive white Gaussian noise (AWGN) at the receiver, $|h_{i,j}|$ is a random variable that follows a Rayleigh distribution with unit scale parameter and $\mathbb{1}_{i,j}$ equals to one if node $i$ transmits a signal to node $j$ at the current time-slot, otherwise it is equal to zero.

C. k-hop myopic protocol

We now present our proposed protocol based on the $k$-hop myopic DF coding [9]. Firstly, we assume that a signal at the receiver $j$ is successfully decoded if the instantaneous $\text{SNR}_j$ is not below a predefined threshold $\gamma$ i.e., $\text{SNR}_j \geq \gamma$, otherwise an outage occurs. Each relay keeps in its buffer the signals that were successfully decoded, in order to forward them through the appropriate channel links. For this, the buffer of each relay is used as an one-dimensional array with indexed elements, where the element $b_i[w]$, $1 \leq w \leq L_i$, refers to the $w$-th most recently received signal.

At an arbitrary time-slot $t$, the flow of information from $S$ to $D$ follows the procedure described below:

- The node $S$ sends the signals $x(t-j+1)$ to the nodes $j = 1, \ldots, k$, respectively. Moreover, each relay forwards the same signals $x(t-j+1)$ to the corresponding nodes $j = i+1, \ldots, \min(i+k,N+1)$, if and only if its buffer element $b_i[j-i]$ is not empty i.e., the signal at the specific index was previously decoded by the relay.
- After the transmission of the $x(t-j+1)$ signals, each relay prepares its buffer for the next time-slot by shifting the elements one position to the right. In other words, $b_i[2]$ will get the data of $b_i[1]$, $b_i[3]$ the data of $b_i[2]$, etc. Therefore, the first element of each buffer becomes unassigned for the decoding of $x(t-j+1)$. This shifting operation is important for the transmission of the appropriate signals to the corresponding nodes at the next time-slot ($t+1$).
- Every relay combines all the received signals and attempts to decode the message. The first element of its buffer $b_i[1]$ is used for the outcome of the decoding process: it stores the signal if it is successfully decoded, otherwise it becomes an empty element. It is important to note that, in case the signal is not decoded, an empty

\(^1\)Note that each node sends data to the subsequent $L_i$ nodes concurrently. Therefore, a storage space of the same size is required in order to hold the data that will be forwarded.
element is still used to denote this condition so that the relay will not be able to forward the signal.

- Finally, the destination D combines the received signals and if the message is not successfully decoded i.e., SNR_{N+1} < \gamma, then the system is in outage and the message is lost.

According to the above procedure, it is clear that some of the elements at the buffers might be empty due to the shifting operation. Consequently, the proper transmission of the successfully decoded signals to the appropriate nodes relies on the contents of each relay's buffer that evolve with time.

III. STATE MARKOVIAN CHANNEL MODEL

For the analysis of this system we investigate a theoretical framework that models the evolution of the relays’ buffers as a MC. In this section, the state transition matrix construction and the derivation of the stationary distribution of the MC are presented, which will be used for the computation of the system’s outage probability in Section IV.

Recall from Section II-C that, as a result of the decoding process and the shifting operation, each buffer’s elements can be found in two possible conditions: either to have the \( w \)-th most recently received signal or to be empty. To assist with the analysis, we introduce an one-dimensional array \( \beta_i \), with its elements defined as

\[
\beta_i[w] = \begin{cases} 
0, & \text{if } b_i[w] \text{ is empty;} \\
1, & \text{otherwise,}
\end{cases}
\]  

in order to indicate the non-empty elements of the buffer\(^2\) \( b_i \). A state of the MC is formed by the concatenation of all the arrays \( \beta_i \). The number of the states is given by all the possible combinations that can be derived by each \( \beta_i \)'s element. Thus, each state is a vector of finite size \( L_V = \sum_{i=1}^{N} L_i = (2N - k + 1)k/2 \) that represents which elements in each buffer have decoded signals. Thus, with a slight abuse of notation, we let

\[
s_m \triangleq (\beta_{1,m}, \beta_{2,m} \ldots, \beta_{N,m}),
\]

denote the \( m \)-th state of the MC, \( 1 \leq m \leq M \), where \( M \) is the number of the states and is equal to \( M = 2^{L_V} \). Since this concatenation results in a binary representation of a decimal number, the states are predefined and arranged in a numerical ascending order, such that the states \( s_1 \) and \( s_M \) are denoted by the \( 1 \times L_V \) binary vectors \((00 \ldots 0)\) and \((11 \ldots 1)\), respectively.

A. State transition matrix construction

The state transition matrix is a square matrix containing information on the transition probabilities between the states of the MC. Specifically, it defines how the system evolves with time and indicates which of the available links will be used at each time-slot. Let \( A \) denote the \( M \times M \) state transition matrix of the MC, where the entry \( p_{r,q} = \mathbb{P}(s_q \rightarrow s_r) = \mathbb{P}(X_{t+1} = s_r|X_t = s_q) \) is the probability of the transition from state \( s_q \) at time \( t \) to state \( s_r \) at time \( (t + 1) \). The calculation of these probabilities rely on the status of the buffer of each relay, and consequently from the corresponding arrays \( \beta_i \).

Algorithm 1 shows the proposed procedure for the construction of the state transition matrix \( A \), given the number of relays \( N \) and the number of hops \( k \). We first need to detect all the possible transitions between the states of the MC. Thus, for each pair of states \( (s_q, s_r) \), we examine if the variations at the elements of each array \( \beta_i \) are consistent with the evolution of the buffers as in the proposed protocol. Each array \( \beta_{i,m} \) can be extracted by the vector of a state \( s_m \) by taking all the elements of the vector from the index \( s_m[\sum_{j=1}^{i-1} L_j + 1] \) to the index \( s_m[L_i] \). A transition from \( s_q \) to \( s_r \) exists, if the contents of all the arrays shift one position to the right. This is equivalent to the equality \( \beta_{i,q}[w] = \beta_{i,r}[w + 1], 1 \leq w \leq L_i - 1 \), for all the arrays \( \beta_i, i = 1, \ldots, N \). If at least one of these equalities does not hold, then the transition is not possible. The first element of each array at the new state \( \beta_{i,r}[1] \) indicates if an outage occurred at the corresponding relay. As the decoding is handled separately by each relay, these probabilities are independent and therefore the transition probability is given as their product. The entries of the state transition matrix are then given by

\[
p_{r,q} = \begin{cases} 
\prod_{i=1}^{N} \left[ \beta_{i,r}[1](1 - P_o(T_{i,q})) \right], & \text{if } s_q \rightarrow s_r \text{ exists;} \\
(1 - \beta_{i,r}[1]) P_o(T_{i,q}), & \text{otherwise,}
\end{cases}
\]

where \( P_o(\cdot) \) is the probability of having an outage event, and \( T_{i,q} \) is the set of nodes that transmit a signal to the relay \( i \) given that \( s_q \) was the previous state. Note that, due to the two possible values the elements \( \beta_{i,r}[1] \) can take, the aggregate
number of all possible transitions from every state are $2^N$. The analytical expressions of these probabilities are given in Section IV.

B. Steady state distribution

We now derive the stationary distribution of the MC, which is denoted as $\pi$. In this case, the interpretation of the stationary distribution gives an insight to the long-term use of the available channel links in the system, as it indicates how the signals are being transmitted across the relays until they reach the final destination. We first introduce some properties of the state transition matrix $A$, required in order to have a unique stationary distribution, while the calculation of the steady states is given in Lemma 1.

**Proposition 1.** The state transition matrix $A$ of the defined MC is a column stochastic matrix$^3$, which is irreducible$^4$ and aperiodic$^5$.

**Proof.** See Appendix A.

**Lemma 1.** The column stochastic matrix $A$ of the defined MC has a unique stationary distribution, which is given by [11]

$$\pi = (A - I + B)^{-1}b,$$

(5)

where $\pi$ is the stationary distribution, $b = (1 \ldots 1)^T$ and $B_{r,q} = 1, \forall r, q$.

C. Illustrative example

We provide an example of the proposed framework that refers to a network topology with $N = 2$ relays and $k = 2$ hops. In this case, the size of the buffers $b_1$ and $b_2$ (and therefore of the arrays $\beta_1$ and $\beta_2$) is $L_1 = 2$ and $L_2 = 1$, respectively. The concatenation of the arrays $\beta_1$ and $\beta_2$ results in a binary vector of finite size $L_V = 3$, which represents a state of the MC. In this example, there are $M = 2^3 = 8$ different states, which are presented in Fig. 2. By following the aforementioned algorithm, the state transition matrix $A$ is derived as

$$A = \begin{pmatrix}
    P_{1,1} & P_{1,2} & P_{1,3} & P_{1,4} & 0 & 0 & 0 & 0 \\
    P_{2,1} & P_{2,2} & P_{2,3} & P_{2,4} & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & P_{3,5} & P_{3,6} & P_{3,7} & P_{3,8} \\
    0 & 0 & 0 & 0 & P_{4,5} & P_{4,6} & P_{4,7} & P_{4,8} \\
    P_{5,1} & P_{5,2} & P_{5,3} & P_{5,4} & 0 & 0 & 0 & 0 \\
    P_{6,1} & P_{6,2} & P_{6,3} & P_{6,4} & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & P_{7,5} & P_{7,6} & P_{7,7} & P_{7,8} \\
    0 & 0 & 0 & 0 & P_{8,5} & P_{8,6} & P_{8,7} & P_{8,8}
\end{pmatrix},$$

(6)

where the entries $p_{r,q}$ denote the probabilities of the existent transitions and are given by

$^3$A column stochastic matrix is a square matrix of non-negative terms in which the elements in each column sum up to one [10].

$^4$An irreducible matrix is a non-negative matrix such that every pair of states can communicate [10].

$^5$The period of a state $s_q$ is the greatest common divisor of the set \( \{ t \in \mathbb{N} : p_{q,t} > 0 \} \); if the period is 1, the state is aperiodic. The transition matrix is aperiodic if all the states are aperiodic [10].

![Fig. 2. The possible states of the MC for a network topology with $N = 2$ relays and $k = 2$ hops. For each state, the contents of the arrays $\beta_1$ and $\beta_2$ are presented below the corresponding relay, as well as which of the available links are used.](image)

IV. OUTAGE PROBABILITY & DIVERSITY ANALYSIS

In this section, we provide our main results for the performance analysis of our proposed protocol. We consider two performance metrics for the evaluation of the protocol, namely, the outage probability and the diversity order. In the proposed protocol, at each time-slot the SNR of the $j$-th receiver is calculated based on the set $T_{j,q}$ of the nodes that send a signal to the receiver, given that $s_q$ was the previous state. Since the signals are transmitted coherently, the outage probability achieved at the $j$-th node is given as follows.

**Theorem 1.** The probability of having an outage event at the $j$-th node is

$$P_o(T_{j,q}) = \frac{1}{2} - \frac{1}{\pi} \int_0^{\infty} \frac{1}{t} z \left[ \exp \left( -jt\gamma_0 \right) \times \prod_{i=\xi}^{j-1} \phi_{i,j}(t) \right] dt,$$

(8)

where $z(x)$ returns the imaginary part of $x$, $\xi = \max(0,j-k)$, $\gamma_0 = \sqrt{\gamma\sigma^2 P^{-1}}$ and $\phi_{i,j}(t)$ is the characteristic function of $|h_{i,j}|$ and is equal to

$$\phi_{i,j}(t) = 1 + 2jt \sqrt{\frac{\pi a_{i,j}}{2d_{i,j}}} \exp \left( -\frac{a_{i,j}t^2}{2d_{i,j}} \right) \left[ 1 - Q \left( \sqrt{\frac{\pi a_{i,j}}{2d_{i,j}}} \right) \right].$$

(9)

**Proof.** See Appendix B.

The outage probability of the system $P_{out}(\gamma)$ can be calculated by using the steady state of the MC along with the
Appendix C.

Proof. The investigated model can achieve diversity order equal to the number of hops.

Proposition 2. The investigated model can achieve diversity order equal to the number of hops.

V. NUMERICAL RESULTS

In this section, we provide simulation and numerical results to demonstrate the system performance of our proposed myopic protocol. For the simulations, the following parameters are considered. The distance between $S$ and $D$ is set to a fixed value of $d_{0,N+1} = 3$ m and the distance between two consecutive nodes is the same for all nodes i.e., $d_{i,i+1} = d = d_{0,N+1}/(N+1)$ for $i = 0, \ldots, N$. In addition, the path loss exponent is equal to $\eta = 2$ and the variance of the AWGN is normalized to $\sigma^2 = 1$. Finally, the SNR threshold is set to $\gamma = 0$ dB. Our results are numerically optimized with respect to the power splitting parameters $a_{i,j}$. We use as a benchmark the conventional multi-hop model used in [4], where each node sends a signal only to its subsequent node through orthogonal channels. The outage probability in this case is given by

\[ P_{\text{out}}(\gamma) = \sum_{m=1}^{M} \pi_m P_o(T_{N+1,m}). \]  

(10)

The power splitting parameters $a_{i,j}$ are significant for the system’s outage performance. It is therefore essential to optimize the outage probability with respect to these elements. We formulate the system’s outage probability minimization problem as follows

\[
\min_{\{a_{i,j}\}} P_{\text{out}}(\gamma) \quad \text{subject to} \quad \sum_{j=i+1}^{M} a_{i,j} = 1, \quad i = 0, \ldots, N, \quad 0 \leq a_{i,j} \leq 1, \quad i = 0, \ldots, N. \]  

(11)

The aforementioned minimization problem can be solved using numerical tools, such as the NMinimize function of Mathematica. Below, we provide the proposition which specifies the diversity order that the proposed protocol can achieve.

**Proposition 2.** The investigated model can achieve diversity order equal to the number of hops.

Proof. See Appendix C.

VI. CONCLUSIONS

In this paper, we presented a new protocol over a multi-hop cooperative network with finite buffers at the relay nodes, based on the myopic coding strategy. A general methodology that captures how the contents of each relay’s buffer evolve with time was proposed by using a MC formulation. Under this framework, we derived the outage probability of the system and the diversity order that can be achieved. We demonstrated that as the number of hops in the proposed protocol increases, the system’s performance is enhanced both in terms of outage probability and diversity gain. This theoretical framework can be extended by considering multi-hop networks with multiple paths, which is left as future work.
The probability of having an outage event at the $j$-th node can be expressed as

$$P_o(T_{j,q}) = \mathbb{P}\left( \sum_{i=\xi}^{j-1} [h_{i,j} - \frac{\alpha_i \sqrt{P}}{\sigma}] I_i (j-i) < \gamma_0 \right),$$

where $\gamma_0 = \sqrt{\gamma^2 P - 1}$. To simplify the analysis, the characteristic function approach is used for the derivation of the outage probability. Each term of the above sum follows a Rayleigh distribution, hence its characteristic function is

$$\phi_{i,j}(t) = 1 + 2jt \sqrt{\frac{\alpha_i \sqrt{P}}{2I_i}} \exp\left( -\frac{\alpha_i \sqrt{P} t^2}{2I_i} \right) \left[ 1 - Q\left( j \sqrt{\frac{\alpha_i \sqrt{P}}{2I_i}} \right) \right].$$

Since the sum is a linear combination of independent random variables, its characteristic function is the product of each individual’s characteristic function. Using the Gil-Pelaez inversion theorem [12], we can obtain $P_o(T_{j,q})$ as (8).

### C. Proof of Proposition 2

By considering $P \to \infty$, we notice that the outage probability at each relay and for every received signal converges to zero. This implies that the stationary distribution of the transition matrix is given by $\pi_{m} \to 0$, $m = 1, \ldots, M-1$, and $\pi_M \to 1$, as all the buffers are full. Therefore, the system’s outage probability is approximated by

$$\lim_{P \to \infty} P_{out} \approx P_o(T_{N+1,M})$$

where $\xi = N - k + 1$. The expression in (15) is derived by applying a Taylor series expansion to the exponential term and considering that $\int_{0}^{\infty} \frac{z}{e^{\xi \phi(N-1, M)}} \, dz = \frac{\pi}{2}$, while for (16), we take into account that the first $(2k-1)$ terms of the sum are zero. This is validated in Fig. 5 which compares the expressions (15) and (16) and shows that by omitting the first $2k-1$ terms the outage probability remains the same. In (16), the term corresponding to $z = 2k$ dominates the other terms; hence the diversity order equals $\lim_{P \to \infty} \log(P_{out}) = k$.

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