Minimum Power Allocation for Cooperative Routing in Multihop Wireless Networks

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Abstract—Due to the limited energy supplies of nodes, in many applications like wireless sensor networks, energy-efficiency is crucial for extending the lifetime of these networks. We study the routing problem for multihop wireless ad hoc networks based on cooperative transmission. The source node wants to transmit messages to a single destination. Other nodes in the network may operate as relay nodes. In this paper, we propose a cooperative multihop routing for the purpose of power savings, constrained on a required outage probability at the destination. We derive two efficient power allocation schemes, which only depend on the statistics of the channels. It is shown that energy savings of 90% are achievable in line networks with 10 relays for 10^{-4} outage probability constraint at each receiving node.

I. INTRODUCTION

Energy consumption in multihop wireless networks is a crucial issue that needs to be addressed at all the layers of a communication system, from the hardware up to the application. In this paper, we focus on energy savings in routing problem in which messages may be transmitted via multiple radio hops. After substantial research efforts in the last several years, routing for multihop wireless networks becomes a well-understood and broadly investigated problem [1], [2]. Nevertheless, with the emergence of new multiple antennas technology, existing routing solutions in the traditional radio transmission model are not efficient anymore. For instance, it is feasible to coordinate the multiple transmissions from multiple transmitters to one receiver simultaneously. As a result, transmitting signals with the same channel from several different nodes to the same receiver simultaneously are not considered collision but instead could be combined at the receiver to obtain stronger signal strength. In [3], the concept of multihop diversity is introduced where the benefits of spatial diversity are achieved from the concurrent reception of signals that have been transmitted by multiple previous terminals along the single primary route. This scheme exploits the broadcast nature of wireless networks where the communications channel is shared among multiple terminals. On the other hand, the routing problem in the cooperative radio transmission model over static channels is studied in [4], where it is allowed that multiple nodes along a path coordinate together to transmit a message to the next hop as long as the combined signal at the receiver satisfies a given SNR threshold value.

In this paper, a cooperative multihop routing scheme is proposed for Rayleigh fading channels. The investigated system can achieve considerable power savings compared to non-cooperative multihop transmission, when there is an outage probability QoS requirement at the destination node. We derive two power allocation schemes by minimizing the transmission power given a constraint on the outage probability at each phase. Simulation results show that, using the proposed power allocation strategies, considerable gains are obtained comparing to the non-cooperative multihop transmission.

II. SYSTEM MODEL AND PROTOCOL DESCRIPTION

We consider an arbitrary N-relay wireless network, where information is to be transmitted from a source to a destination (see Fig. 1). Due to the broadcast nature of the wireless channel, some relays can overhear the transmitted information, and thus, can cooperate with the source to send its data. The wireless link between any two nodes in the network is modeled as a Rayleigh fading narrowband channel. The channel fades for different links are assumed to be statistically independent. The additive noise at all receiving terminals is modeled as zero-mean complex Gaussian random variables with variance $N_0$. For medium access, the relays are assumed to transmit over orthogonal channels, thus, no interrelay interference is considered in the signal model.

Following [4], we also assume that each transmission is either a broadcast transmission where a single node is transmitting the information, and the information is received by multiple nodes, or a cooperative transmission where multiple nodes simultaneously send the information to a single receiver. Various scenarios for the cooperation among the relays can be implemented. A general cooperation scenario, m-cooperation, (1 ≤ m ≤ N + 1), can be implemented in which each relay

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Fig. 1. Wireless multihop network under m-cooperation.
combines the signals received from the previous relays and along with that received from the source.

For a general scheme \(m\)-cooperation, \((1 \leq m \leq N+1)\), each receiving node decodes the information after combining the signals received from the previous \(m\) transmitting nodes. Fig. 1 shows a wireless multihop network consisting of a source node \(s\), \(N\) relays, and a destination node \(d\), which is operating under \(m\)-cooperation scenario. The cooperation protocol has \(N+1\) phases. In Phase 1, the source transmits the information, and the received signal at the destination (node number \(N+1\)) and the relays can be modeled as

\[
y_{0,i} = \sqrt{P_0} h_{0,i} s + v_i, \text{ for } i = 1, 2, \ldots, N+1,
\]

where \(P_0\) is the average total transmitted symbol energy of the source, since we assume the information bearing symbols \(s\)'s have zero-mean and unit variance, \(v_i\) is complex zero-mean white Gaussian noise at the \(i\)th receiving node. The channel coefficients \(h_{i,j}\), \(i = 0, 1, \ldots, N, j = 1, 2, \ldots, N+1\), are complex Gaussian random variables with zero-mean and variances \(\sigma_i^2\). In Phase 2, relay nodes are sorted based on their received SNR, such that relay number 1 has the highest received SNR. Generally, in Phase \(n\), \(2 \leq n \leq N+1\), the previous \(\min\{m, n\}\) nodes are transmitting their signal toward the next node. Similar to [4], we assume that transmitters are able to adjust their phases in such a way that the received signal at the \(n\)th receiving node in Phase \(n\) is

\[
y_n = \sqrt{P_0} h_{0,n} |u(m-n) s + \sum_{i=\max(1,n-m)}^{n-1} \sqrt{P_i} |h_{i,n} s_i + v_n|,
\]

where the function \(u(x) = 1\), when \(x \geq 0\), and otherwise is zero and the symbol \(s_i\) is the re-encoded symbol at the \(i\)th relay.

III. OUTAGE PROBABILITY-BASED LINK COST FORMULATION

In this section, our objective is to find the optimal power allocation required for successful transmission from a set of transmitting nodes to a receiving node.

A. Non-Cooperative Multihop Link Cost

First, we consider the simplest case where only one node is transmitting within a time slot to a single target node. Now, we investigate how the transmitter node should decide the value of its transmit power \(P_1\) to satisfy the target SNR, \(\gamma_{th}\), at the destination with a target outage probability of \(\rho_0\). We consider that the receiver can correctly decode the source data whenever

\[
\text{SNR}_d = \frac{P_1 |h_{1-1,i}|^2}{N_0} \geq \gamma_{th}.
\]

That is

\[
\text{Pr}\left\{ \frac{P_1 |h_{1-1,i}|^2}{N_0} \geq \gamma_{th} \right\} = \exp \left( \frac{-\gamma_{th} N_0}{P_1 \sigma_{1-1,i}^2} \right).
\]

Therefore, the required transmit power can be calculated as

\[
P_1 = \frac{-\gamma_{th} N_0}{\sigma_{1-1,i}^2 \ln(1-\rho_0)}, \tag{4}
\]

Now, assume a connection from the source node to the destination via \(N\) intermediate nodes. For decoding the message reliably, the outage probability must be less than the desired end-to-end outage probability \(\rho_{max}\). The probability of correct reception is

\[
P_e(N) = \prod_{n=1}^{N+1} \text{Pr}\left\{ \frac{P_n |h_{n-1,n}|^2}{N_0} \geq \gamma_{th} \right\} = \prod_{n=1}^{N+1} \exp \left( \frac{-\gamma_{th} N_0}{P_n \sigma_{n-1,n}^2} \right).
\]

Thus, in the multihop case, a target outage probability \(\rho_0 = 1 - N^2 \sqrt{1-\rho_{max}}\) is required at each hop. Since \(\ln(1-\rho_{max}) = (N+1) \ln(1-\rho_0)\), the total power in this case, and hence, the non-cooperative multihop link cost is given by

\[
P_{T}(\text{non-coop}) = \sum_{n=1}^{N+1} C(n-1, n) = \sum_{n=1}^{N+1} -\gamma_{th} N_0 (N+1) \ln(1-\rho_{max}),
\]

where \(C(n-1, n)\) is the point-to-point link cost when the \((n-1)\)th node transmits to the \(n\)th node, which is given in (4).

B. Cooperative Multihop Link Cost

In this case, a set of multiple nodes \(T_{x_n} = \{x_{n,1}, x_{n,2}, \ldots, x_{n,m}\}\) cooperate to transmit the same information to a single receiver node \(r_x\). Assuming coherent detection at the receiving node, the signals simply add up at the receiver, and acceptable decoding is possible as long as the received SNR becomes larger than \(\gamma_{th}\). Using (2), the received SNR at the receiving node can be written as

\[
\gamma_{rec} = \sum_{i=1}^{m} \gamma_i,
\]

\[
\gamma_i = \frac{P_i |h_{i-1,i}|^2}{N_0}.
\]

For the notational simplicity, we skipped the index \(i\). Our objective is to find the minimum value of function \(C(T_{x_n}, n) = \sum_{i=1}^{m} P_i\) such that the outage probability at the receiving node become less than the target value \(\rho_0\). In this case, the probability of outage can be calculated as

\[
\text{Pr}\{\text{\{\sum_{i=1}^{m} \gamma_i < \gamma_{th}\}}\}
\]

Now, we are going to derive a tractable outage probability formula at the receiving node \(r_x\). For calculating \(\text{Pr}\{\gamma_{rec} < \gamma_{th}\}\), we first derive the moment generating function (MGF) of the random variable \(\gamma_{rec}\). Since \(\gamma_i\)'s are independent exponential random variables, the MGF of \(\gamma_{rec}\), i.e., \(M_{\gamma_{rec}}(-s) = \mathbb{E}\{e^{-s\gamma_{rec}}\}\), can be written as

\[
M_{\gamma_{rec}}(-s) = \prod_{i=1}^{m} \frac{1}{1 + \frac{P_i \sigma_{i}^2 s}{N_0}}.
\]

Using partial fraction expansion, and by assuming that all links have different variances, (7) can be decomposed into

\[
M_{\gamma_{rec}}(-s) = \sum_{i=1}^{m} \frac{\alpha_i}{1 + \frac{P_i \sigma_{i}^2 s}{N_0}},
\]

where

\[
\alpha_i = \frac{P_i \sigma_{i}^2}{N_0}.
\]

Since each term in the summation in (8) is corresponding to the MGF of an exponential distribution, \(\text{Pr}\{\gamma_{rec} < \gamma_{th}\}\) can be written as

\[
\text{Pr}\{\gamma_{rec} < \gamma_{th}\} = \sum_{i=1}^{m} \alpha_i \left( 1 - e^{-\frac{\gamma_{th} N_0}{P_i \sigma_{i}^2}} \right).
\]
where $y_i$ is the number of nodes with equal variance $\sigma^2_{h_i}$ and $\beta_i$ is a constant which is a function of transmit powers and the links' variances. The summation terms in (11) are corresponding to the MGF of an gamma distribution distribution [5, Eq. (2.21)], and thus, $Pr\{y_i < y_{th}\}$ can be written as

$$Pr\{y_i < y_{th}\} = \sum_i \beta_i \gamma \left( \frac{y_{th} N_0}{P_i \sigma^2_{h_i}} \right).$$

(12)

where $\gamma(k, x)$ is incomplete gamma function of order $k$ [6, Eq. (8.350)]. Since in practice relay nodes are located in different positions, from now on, we consider the outage probability obtained in (10).

Now, we formulate the problem of power allocation in the cooperative multihop networks. The link cost or total transmitted power for the multipoint-to-point case is $C(Tx_m, n) = \sum_{i=1}^{m} P_i$. Therefore, the power allocation problem, which has a required outage probability constraint on the receiving node, can be formulated as

$$\min \sum_{i=1}^{m} P_i,$$

s.t.

$$\sum_{i=1}^{m} \alpha_i \left( 1 - e^{-\frac{y_{th} N_0}{P_i \sigma^2_{h_i}}} \right) \leq \rho_0,$$

$$P_i \geq 0, \text{ for } i = 1, \ldots, m.$$

(13)

Before deriving the optimal solution for the problem given in (13), the following theorem is needed.

**Theorem 1:** Assuming high SNR conditions, the optimum power coefficients $P_1, \ldots, P_m$ in the optimization problem stated in (13) are unique.

**Proof:** The objective function and the second set of constraints in (13) are linear functions of the power allocation coefficients, and thus, they are convex functions. Assuming high SNR conditions, the first constraint in (13) can be approximated as

$$f(P_1, \ldots, P_m) \approx \sum_{i=1}^{m} \alpha_i \frac{y_{th} N_0}{P_i \sigma^2_{h_i}} - \rho_0,$$

(14)

with $D_f = \{P_i \in (0, \infty), i \in \{1, \ldots, m\}; f(P_1, \ldots, P_m) \leq 0\}$, $f : D_f \rightarrow \mathbb{R}$. From [7], it can be verified that $f(P_1, \ldots, P_m)$ is a posynomial function, which is a convex function. Hence, since the objective function and the constraint are convex, the optimum power allocation coefficients in the optimization problem stated in (13) are unique.

The optimal power allocation strategy for high SNRs is found in the following. However, since the approximate outage probability expression derived in (13) is an upper-bound on the outage probability, this result can be used reliably for all SNR scenarios.

The Lagrangian of the problem stated in (13), with the approximation given in (14), is

$$L(P_1, \ldots, P_m) = \sum_{k=1}^{m} P_k + \lambda f(P_1, \ldots, P_m).$$

(15)

For nodes $k = 1, \ldots, m$ with nonzero transmitter powers, the Kuhn-Tucker conditions are

$$\frac{\partial}{\partial P_k} L(P_1, \ldots, P_m) = 1 + \lambda \frac{\partial}{\partial P_k} f(P_1, \ldots, P_m) = 0,$$

(16)

where

$$\frac{\partial}{\partial P_k} f(P_1, \ldots, P_m) = \frac{\gamma_{th} N_0}{k^2 \sigma^2_{h_k}} + \sum_{i=1}^{m} \frac{\partial \alpha_i}{\partial P_k} \frac{\gamma_{th} N_0}{P_i \sigma^2_{h_i}}.$$

(17)

By assuming that the constraint in (13) is satisfied, the first term in (17) can be expressed as

$$\frac{\gamma_{th} N_0}{k^2 \sigma^2_{h_k}} = \rho_0 - \sum_{i=1}^{m} \frac{\gamma_{th} N_0}{P_i \sigma^2_{h_i}}.$$

(18)

The second and third terms in (17) can be calculated as

$$\frac{\partial \alpha_i}{\partial P_k} = \sum_{i=1}^{m} \frac{\alpha_i \gamma_{th} N_0}{P_i \sigma^2_{h_i}} - P_i \sigma^2_{h_i},$$

$$\frac{\partial \alpha_i}{\partial P_k} = \frac{P_k \sigma^2_{h_k} - P_i \sigma^2_{h_i}}{P_k \sigma^2_{h_k} - P_i \sigma^2_{h_i}} \text{ for } i \neq k.$$

(19)

(20)

Substituting (18)-(21) into (16), we have the following set of equations

$$P_k = \lambda \left[ \rho_0 - \sum_{i=1}^{m} \frac{P_i \sigma^2_{h_i}}{P_k \sigma^2_{h_k} - P_i \sigma^2_{h_i}} \left( \frac{\alpha_i}{P^2 \sigma^2_{h_i}} + \frac{\alpha_k}{P^2 \sigma^2_{h_k}} \right) \right],$$

(21)

for $k = 1, \ldots, m$. Since the strong duality condition [7, Eq. (5.48)] holds for convex optimization problems, we have $\lambda f(P_1, \ldots, P_m) = 0$ for the optimum point. If we assume Lagrange multiplier has a positive value, we have $f(P_1, \ldots, P_m) = 0$, which is equivalent to

$$\rho_0 = \sum_{i=1}^{m} \alpha_i \frac{\gamma_{th} N_0}{P_i \sigma^2_{h_i}},$$

(22)

Combining (21) and (22), we can find the optimum value of power coefficients $P_k$, $k = 1, \ldots, m$.

**C. Suboptimal Cooperative Multihop Link Cost**

Since it is not possible to derive a closed-form solution for power coefficients $P_k$, we can find the suboptimal closed-form solution. Define $\gamma_{max} \triangleq \max \{\gamma_1, \gamma_2, \ldots, \gamma_m\}$. The total SNR can be approximated by its upper bound as $\gamma_{rec} \leq \gamma_{max}$. Thus, we have the following approximation for the cumulative density function (CDF) of $\gamma_{rec}$ as

$$Pr\{\gamma_{rec} < \gamma_{th}\} \approx \prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_{th} N_0}{P_i \sigma^2_{h_i}}} \right).$$

(23)

where order statistics is used to derive the CDF of $\gamma_{max}$, which is shown on the right side of (23).
The total transmitted power for the multipoint-to-point case is \( \sum_{i=1}^{m} P_i \). Therefore, the power allocation problem, which has a required outage probability constraint on the receiving node, can be formulated as

\[
\begin{align*}
\min & \quad \sum_{i=1}^{m} P_i, \\
\text{s.t.} & \quad \prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_h N_0}{m P_i^2 \sigma_h^2}} \right) \leq \rho_0, \\
& \quad P_i \geq 0, \text{ for } i = 1, \ldots, m.
\end{align*}
\]

(24)

The solution of the power allocation problem given in (24) is found in the following theorem:

**Theorem 2:** For the set of \( m \) transmitters, which send a common signal toward the destination, the optimum transmit power coefficients of the problem stated in (24) satisfy the following equations

\[
P_k = \frac{-\gamma_h N_0}{\sigma_h^2} \left[ 1 - \frac{\rho_0}{\prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_h N_0}{m P_i^2 \sigma_h^2}} \right)} \right],
\]

(25)

for \( k = 1, \ldots, m \).

**Proof:** For the problem stated in (24), we redefine the constraint function of \( f(P_1, \ldots, P_m) \) as

\[
\begin{align*}
f(P_1, \ldots, P_m) &= \prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_h N_0}{m P_i^2 \sigma_h^2}} \right) - \rho_0, \\
\text{and its corresponding derivative can be calculated as }
\end{align*}
\]

\[
\frac{\partial}{\partial P_k} f(P_1, \ldots, P_m) = \frac{-\gamma_h N_0}{m P_k^2 \sigma_h^2} e^{-\frac{\gamma_h N_0}{m P_k^2 \sigma_h^2}} \prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_h N_0}{m P_i^2 \sigma_h^2}} \right).
\]

(27)

Combining (16) and (27), we have

\[
\lambda^{-1} = \frac{-\gamma_h N_0}{m P_k^2 \sigma_h^2} e^{-\frac{\gamma_h N_0}{m P_k^2 \sigma_h^2}} \prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_h N_0}{m P_i^2 \sigma_h^2}} \right).
\]

(28)

By assuming that the equality in the first constraint in (24) is satisfied, we have

\[
\rho_0 = \prod_{i=1}^{m} \left( 1 - e^{-\frac{\gamma_h N_0}{m P_i^2 \sigma_h^2}} \right).
\]

(29)

Dividing both sides of equalities (28) and (29), we can find the Lagrange multiplier as

\[
\lambda = \frac{m P_k^2 \sigma_h^2}{\gamma_h N_0 \rho_0} \left( e^{-\frac{\gamma_h N_0}{m P_k^2 \sigma_h^2}} - 1 \right).
\]

(30)

Substituting \( \lambda \) into (23), we get (25). Moreover, using (29), it can be verified that the arguments of the logarithm in (25) are between zero and one, and thus, \( P_k \) in (25) are positive. Hence, the second set of constraints in (24) are satisfied.

The optimal power allocation scheme proposed in Theorem 2 can be easily solved with initializing some positive values for \( P_i, i = 1, \ldots, m \), and using (25) in a fixed-point iteration.

**IV. ENERGY SAVINGS VIA COOPERATIVE ROUTING**

The problem of finding the optimal cooperative route from the source node to the destination node can be mapped to a Dynamic Programming (DP) problem [4]. As the network nodes are allowed only to either fully cooperate or broadcast, finding the best cooperative path from the source node to the destination has a special layered structure. In [4], it is shown that in a network with \( N + 1 \) nodes, which has \( 2^N \) nodes in the cooperation graph, standard shortest path algorithms have a complexity of \( O(2^N) \). Hence, finding the optimal cooperative route in an arbitrary network becomes computationally intractable for larger networks. For this reason, we restrict the cooperation to nodes along the optimal noncooperative route. That is, at each transmission slot, all nodes that have received the information cooperate to send the information to the next node along the minimum energy noncooperative route [4]. Therefore, with the help of the link cost expressed in Subsection III-A, the minimum-energy non-cooperative route is first selected, which has \( N \) intermediate relays. Then, nodes along the optimal non-cooperative route cooperate to transmit the source information toward the destination. That is, at each transmission slot, all nodes that have received the information cooperate to send the information to the next node along the minimum energy non-cooperative route. In the \( n \)th transmission slot of full-cooperation scheme, the reliable set is \( T_{n} = \{ s, r_1, \ldots, r_{n-1} \} \), which includes the source node and the previous relays \( r_i, i = 1, \ldots, n - 1 \). The link cost associated with the nodes in \( T_n \), which cooperate to send the information to the next node, is given by \( C(T_n, n) = \sum_{i=1}^{n} P_i(n) \), where \( P_i(n) \) is the transmit power from the source node in the \( n \)th phase, and \( P_i(n), i = 1, \ldots, n \) are the transmit power from \( r_{i-1} \)th node, and they can be estimated with the optimization problems stated in Subsection III-B and C. Note that the \( n \)th node denotes the \( n \)th relay when \( n \leq N \), and the destination node when \( n = N + 1 \). Therefore, the total transmission power for the cooperative multihop system is

\[
P_T(coop) = \sum_{n=1}^{N+1} C(T_n, n) = \sum_{n=1}^{N+1} \sum_{i=1}^{n} P_i(n). \quad (31)
\]

For the case of \( m \)-cooperation scheme, in which just previous closest nodes cooperate to transmit along the non-cooperative route, \( P_T \) (cooperative) in (31) can be modified to

\[
P_T(m-coop) = \sum_{n=1}^{N+1} C_m(T_n, n) = \sum_{n=1}^{N+1} \sum_{i=1}^{m} P_i(n). \quad (32)
\]

The energy savings for a cooperative routing strategy relative to the optimal non-cooperative strategy is defined as

\[
\text{Energy Savings} = \frac{P_T(\text{non-coop}) - P_T(\text{coop})}{P_T(\text{non-coop})}, \quad (33)
\]

where \( P_T(\text{coop}) \) is computed in (31) and (32) for the case of full-cooperation and \( m \)-cooperation routings, respectively.
We denote the required outage probability at the nth phase as $P_T(n)$, which must be less than the desired end-to-end outage probability $P_{\text{max}}$. This guarantees that by using the power allocation term of end-to-end desired outage probability $P_{\text{max}}$, the outage probability at each hop, i.e., $P_{\text{max},n}$, occurs even if an intermediate node experiences an outage. This is achieved by using the power allocation strategy derived in Section III. The outage probability $P_{\text{max}}$ at the nth node is affected by all previous $n-1$ hops and can be iteratively calculated according to the recursion

$$P_{\text{max},n} = 1 - (1 - P_{\text{max},n-1}) \prod_{i=\max\{1,n-m\}}^{n-1} (1 - P_{\text{max},i})$$  \hspace{1cm} (34)

with $P_{\text{max},0} = 0$, where $P_{\text{max},n-1}$ is the outage probability of the $n$th transmission phase and can be calculated as $\rho_0$.

The end-to-end outage probability at the destination is given by using $n = N + 1$ in (34). If the power allocation strategy derived in Section III is used, (34) can be rewritten as

$$P_{\text{max}} = 1 - (1 - \rho_0) \prod_{i=\max\{1,n-m\}}^{n-1} (1 - \rho_i)$$  \hspace{1cm} (35)

To get an insight into the relationship between the end-to-end outage probability $P_{\text{max}}$, we have $P_{\text{max}} = 1 - (1 - \rho_0)^N$, when full cooperation is used. Thus, the target outage probability at each hop, i.e., $\rho_0$, can be represented in terms of end-to-end desired outage probability $P_{\text{max}}$.

It is important to note that based on (34), outage at the destination occurs even if an intermediate node experiences an outage. This guarantees that by using the power allocation strategies investigated in Section III, the outage probability QoS at the destination is satisfied.

### V. Simulation Results

In this section, we present some simulation results to quantify the energy savings due to the proposed cooperative routing scheme. We consider a regular line topology where nodes are located at unit distance from each other on a straight line. The optimal non-cooperative routing in this network is always to send the information to the nearest node in the direction of the destination. Assume $\gamma_0 = 1$ and noise power $N_0$ is normalized to 1. From (6), and by assuming $\sigma_n^2$ is proportional to the inverse of the squared distance, the total power required for non-cooperative transmission can be calculated as $P_T(\text{non-coop}) = \frac{(N+1)}{\ln(1-\rho_0)}$. Since we restrict the cooperation to nodes along the optimal non-cooperative route, the total transmitted power for full-cooperation and $m$-cooperation in line networks can be obtained from (31) and (32), respectively.

In Fig. 2, we compare the achieved energy savings of the proposed cooperative routings with respect to the non-cooperative multihop scenario, in which satisfying the required outage probability $\rho_0$ at each step. For $\rho_0 = 10^{-7}$, it can be observed that using the full cooperation scheme around 90% saving in energy is achieved when 10 relays are employed.

### REFERENCES


