Optimal and Near-Optimal Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks

Fatemeh Mansourkiaie, *Student Member, IEEE*, and Mohamed Hossam Ahmed, *Senior Member, IEEE*

***Abstract*— Cooperative communication has gained much interest due to its ability to exploit the broadcast nature of the wireless medium to mitigate multipath fading. There has been considerable research on how cooperative transmission can improve the performance of the physical layer. Recently, researchers have started to consider cooperative transmission in routing, and there has been a growing interest in developing cooperative routing protocols. Most of the existing cooperative routing algorithms are designed to reduce the energy consumption; however, packet collision minimization using cooperative routing has not yet been addressed. This paper presents an optimization framework to minimize collision probability using cooperative routing in wireless sensor networks. We develop a mathematical model and formulate the problem as a large-scale mixed integer non-linear programming problem. We also propose a solution based on the branch-and-bound algorithm augmented with reducing the search space. The proposed strategy builds up the optimal routes from each source to the sink node by providing the best set of hops in each route, the best set of relays, and the optimal power allocation for the cooperative transmission links. To reduce the computational complexity, we propose a near-optimal cooperative routing algorithm, in which we solve the problem by decoupling the power allocation problem and the route selection problem. Therefore, the problem is formulated by an integer non-linear programming, which is solved using the branch-and-bound space reduced method. The simulation results reveal that the presented algorithms can significantly reduce the collision probability compared with the existing schemes.**

***Index Terms*— Cooperative routing, collision minimization, mixed-integer optimization, wireless sensor networks.**

I. Introduction

COOPERATIVE communication has emerged as a promising approach for mitigating wireless channel fading and improving the reliability of wireless networks by allowing nodes to collaborate with each other. Nodes in cooperative communication help each other with information transmission by exploiting the broadcasting nature of wireless communication [1]. In a cooperative transmission scheme, neighboring nodes are exploited as relay nodes, in which they cooperate with the transmitter-receiver pair to deliver multiple copies of a packet to the receiver node through independent fading channels. The idea behind cooperative transmission is shown in Fig. 1. This figure illustrates a simple cooperative transmission scheme where two nodes (one source node and one relay node) communicate with the same destination node. Each node has one antenna and does not individually have spatial diversity. However, it may be possible for one node to overhear the signal of other nodes and forward them to the destination node. Because the fading paths from the two nodes are statistically independent, this generates spatial diversity. Combining multiple copies of the same signal at the destination node leads to several advantages, including a better signal quality, reduced transmission power, better coverage, and higher capacity [2]–[4].

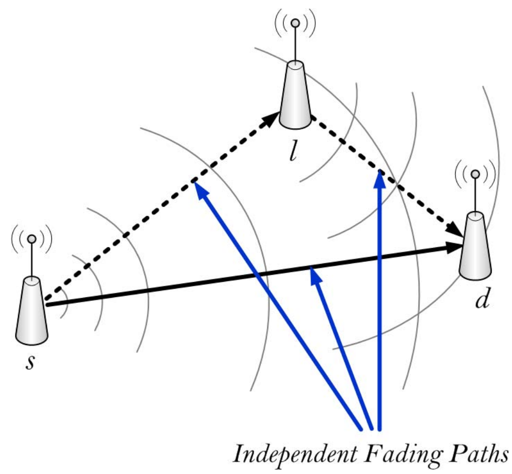


Fig. 1. A simplified cooperative transmission model.

Routing algorithms that take into consideration the advantages of cooperative transmission are known as cooperative routing. Therefore, cooperative routing is a cross-layer design approach that combines the network layer and the physical layer to transmit packets through cooperative links. This cross-layer design approach effectively enhances the performance of the routing protocols in wireless networks.

In general, a cooperative route is a concatenation of cooperative-transmission and direct-transmission links. Fig. 2 shows an example of cooperative routings. The direct-transmission (DT) block is represented by the link (a, b), where node a is the transmitter node and node b is the receiver node. The cooperative-transmission (CT) block is

Manuscript received August 18, 2015; revised October 19, 2015; accepted October 21, 2015. Date of publication October 27, 2015; date of current version February 4, 2016. The associate editor coordinating the review of this paper and approving it for publication was Prof. Okyay Kaynak.

The authors are with the Department of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL A1B3X5, Canada (e-mail: fmk847@mun.ca; mhahmed@mun.ca).

Digital Object Identifier 10.1109/JSEN.2015.2495329

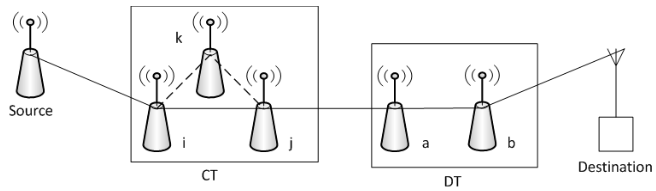


Fig. 2. A sample cooperative routing.

represented by the links (i, j), (i, k), and (k, j), where i is the transmitter node, k is a relay node, and j is the receiver node. In cooperative transmission, in addition to the direct link from the transmitter node to the receiver node, one or more relay nodes can be used to forward the signal to the receiver node. Therefore, the definition of the traditional link, which includes only two nodes, should be revised.

Cooperative routing was introduced by Khandani *et al*. [5] and the authors also showed that the problem of finding the optimum cooperative route is *NP-Hard*. In the past few years, significant progress has been made on the design and development of cooperative routing protocols. In [6], we presented a comprehensive survey of existing cooperative routing techniques together with the highlights of the performance of each strategy. While many efficient sub-optimal cooperative routing algorithms are proposed in the literature, only a few studies have focused on optimal cooperative routing. Sub-optimal cooperative routing algorithms can be divided into two categories. The first category of cooperation-based routing algorithms, namely Cooperative Along Shortest-Path (such as the proposed algorithms in [5], [7], and [8]) is implemented by finding the shortest-path route first, and then building the cooperative route based on the shortest path. The main idea of algorithms in this category is to use cooperative transmission to improve performance along the selected non-cooperative route. However, the optimal cooperative route might be completely different from the non-cooperative shortest path. Therefore, the merits of cooperative routing are not fully exploited if cooperation is not taken into account while selecting the route. One of the heuristic cooperative routing algorithms presented in [5] is called the Cooperative Along Non-cooperative (CAN-L) algorithm with the objective of minimizing total transmitted power. The basic idea is to run a non-cooperative shortest path first, and then to use cooperative transmission by the last L nodes along the non-cooperative path. To deal with the outage problem, the authors in [8] proposed k-shortest path cooperative routing (OKCR) algorithm. The OKCR algorithm first runs k non-cooperative shortest path (which minimize total transmission power) and then in each link of non-cooperative paths, the best relay that minimizes the outage probability is assigned. After constructing all the cooperative links over each path, the path that requires less total power is chosen. The algorithms in the second category, Cooperative Based Path (e.g., the proposed algorithms in [9]–[11]), address the above problem by exploiting cooperative routing during the route selection process. However, the algorithms in this category are not optimal due to the following reasons: (1) they employ sub-optimal approaches in the relay node selection [10], power allocation [9], [11], or route selection [12] and (2) they utilize optimal relay node selection, resource allocation, and route selection but not jointly (as will be discussed in detail in Section IV), such as the algorithm in [2]. Authors in [9] presented an algorithm called Minimum Power Cooperative Routing (MPCR). The algorithm finds the route that minimizes the total transmission power. MPCR makes routing decisions by assuming the cooperative transmission is also available for each link. In [10] the authors proposed the EP-H1 algorithm. The EP-H1 algorithm considers the two-stage cooperation model to find the route that consumes minimum energy. In the fist stage the transmitter node broadcasts the message to its neighbors. In the second stage every node that has successfully decoded the message will joint the transmitter node to form a cooperative transmitting set. The transmitting set cooperatively transmits the message to a receiver node using equal power. The power allocation vector minimizes the total amount of consumed energy.

Most of the existing cooperative routing algorithms, such as [5], [9], and [10], focused on the algorithm design and performance analysis without addressing implementation issues; only a few proposed algorithm, in [11] and [13], deal with the practical aspects of cooperative routing. The authors in [13] used parametric programming in an off-line manner to reduce the computational requirements for the sensor nodes to very simple operations during network functioning. In [11], the authors take practical system parameters into consideration, such as, channel codes, modulation, data rate, frame error rate, retransmissions, and hardware energy consumption. The author proposed two cooperation routing algorithms to minimize energy consumption. The first proposed algorithm, namely cooperation over non-cooperative shortest path is in the first category of cooperative routing (cooperation along non-cooperative path) and the second proposed algorithm, namely cooperative cost based shortest path routing is in the second category of cooperative routing (cooperative based routing algorithm).

The main objective of cooperative routing in all proposed schemes, either the optimal or sub-optimal cooperative routing algorithms, is to save energy while guaranteeing a certain QoS. However, packet collision minimization has not been taken into account in existing cooperative routing algorithms.

Interactions among multiple neighboring flows may lead to the hidden and exposed node problems which cause packet collision. In general, cooperative routing can improve the performance due to the more robust links and less power consumption. However, cooperative routing causes extra packet transmission by the relays. Therefore, the gain of a cooperative routing algorithm with multiple flows is different from the one with a single flow, especially in terms of the packet collision probability. There are only a few papers, such as [14]–[16], that considered multiple flows in cooperative routing. In [14] collision is brought into attention by defining a contention graph, where a set of transmitting nodes coordinates their transmissions to a set of receiving nodes. However, the final objective of the routing protocol in [14] is minimizing the total transmission power, and the algorithm approaches the non-cooperative protocol when network congestion emerges.

Moreover, to avoid collision in the proposed algorithm in [14], each flow is transmitted in a certain time slot. The collision problem of cooperative routing in [15] is solved in the MAC layer, and the objective of the cooperative routing is maximizing the network flow. In [16], we proposed Minimum Collision Cooperative Routing (MCCR) algorithm by combining cooperative transmission, optimal power allocation, and route selection. In the MCCR algorithm, firstly, each node calculates the collision probability caused by transmitting a signal from that node to the other nodes in the network. The calculation is done using the initial transmission power (for the source and relay), which is assumed to be 0 dBm, the standard value in IEEE 802.15.4 devices [17]. Since the optimum relay location in decode-and-forward relaying technique is at the middle point between i and j of a cooperative link [18], we select a relay node (k) which is the closest to the middle point of each link. In the second step, Bellman-Ford algorithm is applied to find the route which has the minimum cost function of the entire route. Therefore, the route which causes the minimum collision probability to all nodes in the network is selected. In the third step, optimal power is allocated to all nodes (sources of direct transmission links and sources and relays of cooperative transmission links for all hops of the selected route) in the selected route. The optimal transmission power is obtained using the Lagrange Multipliers method. The MCCR algorithm is a sub-optimal routing due to the following reasons; (1) the optimal power allocation technique is decoupled from the optimal route selection and (2) a sub-optimal approach is employed in the relay node selection and relay nodes are selected as the node closest to the middle point of the transmitter and receiver nodes of each link.

In Wireless Sensor Networks (WSNs), upon the detection of an event, packet traffic load in some spots may get intensified, resulting in a high packet collision rate and consequently, packet loss. To solve this problem, we develop a mathematical characterization for the collision probability in cooperative routing. The presented framework demonstrates the exact formulation for the optimal relay node and optimal power allocation set, and the joint use of optimal power, relay node allocation, and path selection. The final problem formulation is in the form of Mixed Integer Non-linear Programming (MINLP). We propose a solution procedure based on the Branch-and-Bound method augmented with the effective space reduction method. The computational complexity of the algorithm for solving these problems grows exponentially with the number of binary variables. Due to the high complexity of the problem, one cannot obtain optimal solutions within reasonable time for the large network topologies. Therefore, one needs to resort to the heuristic approach. We present a sub-optimal algorithm for the formulated problem by decoupling the optimal transmission power allocation from the route selection. We solve the Integer Non-linear Programming (INLP) in the first phase and apply optimum power in the second phase; therefore, the cooperative routing using INLP, is a sub-optimal algorithm.

To the best of our knowledge, there is no framework which can accurately characterize the collision probability in the cooperative network and minimize the collision problem employing cooperative routing. Overall, the main contribution of this paper includes the following:

1) The collision problem in WSNs is formally defined and formulated. The traffic load per node in cooperative transmission is also explored.
2) An MINLP model, employing the cooperative routing, is presented to minimize the collision problem subject to the outage probability constraint.
3) The MINLP solution serves as a benchmark for evaluating the quality of the solutions obtained by any sub-optimal algorithm for this problem.
4) The obtained solution applies a joint optimization approach for power allocation, relay node assignment, and path selection which are the main optimization issues in cooperative routing.
5) Moreover, sub-optimal algorithms are proposed by separating one of the optimization variable decision, i.e., optimal transmission power, from the other optimization variables.
6) Our proposed algorithms find good solutions which reduce the collision probability compared to the existing cooperative routing algorithms.

The remainder of this paper is organized as follows. In Section II, we illustrate the system model and formulate our optimization task. In Section III, we develop a mathematical model and we formulate the problem to minimize collision probability by optimizing the relay node assignment, power allocation and path selection jointly. In Section IV, we propose the optimal solution to the problem. In Section V, a sub-optimal cooperative routing algorithm is presented. Simulation results and performance evaluations are given in Section VI. Finally, we conclude the paper in Section VII.

II. System Model

We consider a WSN, where source nodes communicate with the destination nodes (or sink nodes) via cooperative routing. The notations that will be used through this paper are summarized in Table I.

We assume that the distance-based attenuation follows the generic exponential path-loss model with an exponent γ [9]. In direct transmission, where a source (s) transmits its signal directly to the next destination (d), the received signal at d is given by

$$y_{sd} = \sqrt{p_s^D K r_{sd}^{-\gamma}}\, h_{sd} u + n_{sd}, \tag{1}$$

where p_s^D is the transmission power from the source in the direct transmission mode, K is a constant that depends on the characteristics of the transmitter, the receiver, and channel (e.g., the frequency and the antenna gain), r_{sd} is the distance between the two nodes (s and d), and u is the transmitted data with a unity power.

The criterion for a good detection is that the received signal-to-noise ratio (SNR) must be greater than the detection threshold (β). Outage is defined as the status when the receiver is unable to detect data u. Hence, a link is considered to be in outage if the received SNR falls below β. Thus, the outage probability, when direct transmission is only used, Pr_{out}^D, is

TABLE I
NOTATION

Symbol	Definition
$\mathbb{N}$	Set of nodes in the network
$\mathbb{N}_s$	Set of source nodes
$h_{i,j}$	Complex Gaussian channel coefficient of link $i \to j$
N_o	Additive white Gaussian noise power
γ	Path-loss exponent
u	Transmitted data with the unity power
p_i	Transmission power of node i
β	Detection threshold
$r_{i,j}$	Distance between node i and j
Pr_{out}	Outage probability
y_{ij}	Signal received from node i at node j
$Con_{i,j}$	Connectivity indicator
Pr_{tx}	Probability of being transmitting
Pr_{rx}	Probability of being receiving
$E_{i,n}$	Binary indicator of the link $i \to j$
$F_{i,j}^{n}$	Binary indicator of the relay node n of link $i \to j$
$I_s(n)$	Interference from s by n
$I_{th}^{C}oll.$	Interference threshold
$\Lambda_t(n)$	Total packet transmission by node n
$\Lambda_0(n)$	Packet generated by node n
Λ_t	Total packet transmission
T_p	Packet time duration
$P_{t_{max}}$	Maximum transmission power level
H	Total number of hops in the route

defined as $Pr(SNR_{sd} < \beta)$. It can be easily shown that the power that minimizes the collision probability subject to the outage probability constraint ($Pr_{out}^{D} \leq Pr_{out}^{*}$) is given by

$$p_s^D = -\frac{\beta N_o r_{sd}^{\gamma}}{K \ln(1 - Pr_{out}^{*})}, \tag{2}$$

where Pr_{out}^{*} is the maximum acceptable outage probability and N_o represents the noise power.

In cooperative transmission, the employed system model is similar to that used in [9]. As shown in Fig. 1, a cooperative link consists of three nodes: source (s), destination (d), and a potential relay node (l). The relaying technique used in this study is the incremental adaptive decode-and-forward. With this technique, the source sends its signal to the destination using the direct link. If the destination is unable to detect the signal using the direct link, the relay forwards the signal to the destination (provided that the relay was able to detect the signal). If the relay is unable to detect the signal, it remains silent and the destination will rely on the direct signal only. For cooperative transmission, the received signals from s at d and l can be respectively expressed as

$$y_{sd} = \sqrt{p_s^C K r_{sd}^{-\gamma}}\, h_{sd} u + n_{sd}, \tag{3}$$

$$y_{sl} = \sqrt{p_s^C K r_{sl}^{-\gamma}}\, h_{sl} u + n_{sl}, \tag{4}$$

where p_s^C is the transmission power from the source in the cooperative transmission. If the relay forwards the signal to the destination, the received signal at the destination from the relay node can be expressed as $y_{ld} = \sqrt{p_l^C K r_{ld}^{-\gamma}}\, h_{ld} u + n_{ld}$, where p_l^C is the transmission power of the relay node. In this case, the destination detects the signal using the relay signal only. Although combining schemes such as maximum ratio combining are more efficient, they require storage of the direct signal until the indirect signal is received. Also, combining schemes require more signal processing and perfect knowledge of the channel state information. Due to the limited power and processing capabilities in WSNs, such combining techniques are not employed in this work.

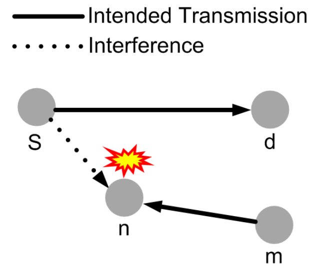


Fig. 3. Collision Problem.

III. Problem Formulation

In this section, we present a mathematical model for our joint routing, relay node assignment, and power allocation. Denote $\mathbb{N}$ as the set of nodes in the network, with $|\mathbb{N}| = N$. In set $\mathbb{N}$, there are three subsets of nodes, namely, (i) the set of source node, $\mathbb{N}_s = \{s_1, s_2, ..., s_{N_s}\}$, with $|\mathbb{N}_s| = N_s$, (ii) the set of destination nodes, $N_d = \{d_1, d_2, ..., d_{N_d}\}$ with $\mathbb{N}_d = |N_d|$, and (iii) the set of remaining nodes that are available for serving either as intendant nodes in the route, or as relay nodes. Moreover, nodes i and j are disconnected from each other, $Con_{i,j} = 0$, if $r_{ij} \geq R_d$, where Con is the connectivity indicator and R_d is the connection distance threshold. Otherwise, node i and j are connected and $Con_{i,j} = 1$. As illustrated in Fig. 3, a source node, s, will cause a collision to another node, n, if s is sending while n is simultaneously receiving (from another node, m), provided that the interference from s at n is high enough to cause a collision. As a result, in direct transmission, the probability that s will cause collision at n, given that m was unable to sense the transmission of s, $Pr(Coll._s^D(n)$, can be expressed as

$$Pr\left(Coll._s^D(n)\right) = Pr_{rx}(n) Pr(I_s(n) > I_{th}^{Coll.}), \tag{5}$$

where $Pr(I_s(n) > I_{th}^{Coll.})$ is the probability that the received interference from s by n, $I_s(n)$, is greater than the interference threshold, $I_{th}^{Coll.}$, above which the interference causes a collision and the desired signal is undetectable and $Pr_{rx}(n)$ is the probability that n will be receiving. A node will be in the receiving mode if it is selected either as an intermediate node in the route or as a relay. Hence, the probability of receiving, $Pr_{rx}(n)$ is given by

$$Pr_{rx}(n) = \sum_{i \in \mathbb{N}}^{i \neq n} Pr_{tx}(i)\, E_{i,n} + \sum_{v \in \mathbb{N}}^{v \neq n} \sum_{w \in \mathbb{N}}^{w \neq n, w \neq v} Pr_{tx}(v)\, F_{v,w}^{n}, \tag{6}$$

where $E_{i,n}$ is a binary variable to specify whether the link between i to n is in the routing solution, i.e.,

$$E_{i,n} = \begin{cases} 1 & \text{if node } n \text{ is used as the next node in its route to destination,} \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

$F^n_{i,j}$ is another binary variable to specify whether n is used as a relay node for the link between i to j in the routing solution, i.e.,

$$F^n_{i,j} = \begin{cases} 1 & \text{if node } n \text{ is used as the relay node on hop } i, j, \\ 0 & \text{otherwise.} \end{cases} \quad (8)$$

$Pr_{tx}(n)$ is the probability that n is transmitting; hence, $Pr_{tx}(n) = \Lambda_t(n)\, T_p$, where T_p is the packet time duration and $\Lambda_t(n)$ is defined as the total packet transmission rate of node n. Therefore, $\Lambda_t(n)$ is the sum of the packet generation rate of node itself, $\Lambda_0(n)$, and the transmission rate of packets that node n forwards either as a next hop or a relay node, thus,

$$\Lambda_t(n) = \Lambda_0(n) + \sum_{m\in\mathbb{N}}^{m\neq n} \Lambda_t(m)\Big\{E_{m,n}\big(Pr\,(SNR_{mn} > \beta) + Pr\,(SNR_{mn} < \beta) \sum_{l\in\mathbb{N}}^{l\neq n, l\neq m} Pr\,(SNR_{ml} > \beta)\,Pr\,(SNR_{ln} > \beta)\big) + \sum_{k\in\mathbb{N}}^{k\neq n, k\neq m} F^n_{m,k} Pr\,(SNR_{mk} < \beta)\,(SNR_{mn} > \beta)\Big\}, \quad (9)$$

where SNR_{mn} is the SNR of the link between node m and node n.

Employing Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism for channel access, nodes that are within the sensing range of a transmitter are inhibited from transmitting. Therefore, the probability that s will cause a collision to one or more nodes in the network is given by

$$Pr(Coll._s^D) = \Big(1 - \prod_{n\,\in\,\mathbb{N}} \Big(1 - Pr\,\Big(Coll._s^D\,(n)\Big)\,Pr\,(NST_s)\Big)\Big), \quad (10)$$

where $Pr(NST_s)$ is the average probability of not sensing transmission of s by a node that has traffic to send to n, thus,

$$Pr\,(NST_s) = \sum_{m\in\mathbb{N}} Pr(I_s(m) < I_{th}^{Sens.}) \times \big(Pr_{tx}(m)E_{m,n} + \sum_{k\in\mathbb{N}}^{k\neq m,n} Pr_{tx}(k)F^k_{m,n} \times Pr(SNR_{mn} < \beta)\,Pr\,(SNR_{kn} > \beta)\big), \quad (11)$$

where $I_{th}^{Sens.}$ is the carrier sensing threshold above which the channel is deemed busy.

Since incremental relaying is used, the average collision probability caused by the cooperative link to all other nodes in the network is equal to the collision probability caused by the source, $Pr(Coll._s^D)$, if the direct signal (from the source) is detectable at the destination or if the relay node is unable to detect the source signal. Otherwise, collision happens by either the source or the relay; hence, the collision probability is the probability of the union of two events: 1) collision caused by the source and 2) collision caused by the relay. Thus, the per node collision probability caused by the cooperative transmission (from s and l) to all other nodes in the network is given by

$$Pr\,\Big(Coll._{s,l}^C\Big) = Pr(Coll._s^D) \times \Big[Pr\,(SNR_{sd} > \beta) + Pr\,(SNR_{sd} < \beta)\; Pr\,(SNR_{sl} > \beta)\Big] + \Big[1 - \Big(1 - Pr(Coll._s^D)\Big)\Big(1 - Pr(Coll._l^D)\Big)\Big] Pr(SNR_{sd} < \beta)Pr(SNR_{sl} > \beta). \quad (12)$$

Since the received signal envelop follows the Rayleigh distribution, the SNR is exponentially distributed. Thus, Eq. (12) can be rewritten as in Eq. (13), as shown at the bottom of this page.

$$\begin{aligned} Pr\,\Big(Coll._{s,l}^C\Big) = {} & \left(1 - \prod_{i\in\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\,(i)\,exp\left(-\frac{I_{th}\,r_{si}^{\gamma}}{K\;p_s}\right)\sum_{j\in\mathbb{N}}^{j\neq s, j\neq i} Pr_{tx}\,(j)\left(1 - exp\left(-\frac{I'_{th}\,r_{sj}^{\gamma}}{K\;p_s}\right)\right)\right]\right) \\ & + \left(1 - \prod_{i\in\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\,(i)\,exp\left(-\frac{I_{th}\,r_{si}^{\gamma}}{K\;p_l}\right)\sum_{j\in\mathbb{N}}^{j\neq s j\neq i} Pr_{tx}\,(j)\left(1 - exp\left(-\frac{I'_{th}\,r_{sj}^{\gamma}}{K\;p_l}\right)\right)\right]\right) \\ & \times \left(1 - exp\left(-\frac{N_o\,\beta_d\,r_{sd}^{\gamma}}{Kp_s}\right)\right) * exp\left(-\frac{N_o\,\beta_d\,r_{sl}^{\gamma}}{Kp_s}\right) \\ & - \left(1 - \prod_{i\in\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\,(i)\,exp\left(-\frac{I_{th}\,r_{si}^{\gamma}}{K\;p_s}\right)\sum_{j\in\mathbb{N}}^{j\neq s, j\neq i} Pr_{tx}\,(j)\left(1 - exp\left(-\frac{I'_{th}\,r_{sj}^{\gamma}}{K\;p_s}\right)\right)\right]\right) \\ & \times \left(1 - \prod_{iin\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\,(i)\,exp\left(-\frac{I_{th}\,r_{si}^{\gamma}}{K\;p_l}\right)\sum_{j\in\mathbb{N}}^{j\neq s, j\neq i} Pr_{tx}\,(j)\left(1 - exp\left(-\frac{I'_{th}\,r_{sj}^{\gamma}}{K\;p_l}\right)\right)\right]\right) \\ & \times \left(1 - exp\left(-\frac{N_o\,\beta_d\,r_{sd}^{\gamma}}{Kp_s}\right)\right) * exp\left(-\frac{N_o\,\beta_d\,r_{sl}^{\gamma}}{Kp_s}\right) \end{aligned} \quad (13)$$

Therefore, the probability that the entire route causes collision can be expressed as

$$Pr(Coll._{route}) = 1 - \prod_{h=1}^{H}\left(1 - Pr\left(Coll._{s_h,l_h}^{C}(h)\right)\right), \quad (14)$$

where h is the hop number, H is the total number of hops in the route, and $Pr\left(Coll._{s_h,l_h}^{C}(h)\right)$ is defined as the collision probability caused by source and relay nodes (s and l) of the h-th hop.

In a cooperative transmission link with incremental adaptive decode-and-forward relaying, outage probability is given by

$$\begin{aligned} Pr_{out}^{C} = & Pr(SNR_{sd} < \beta)Pr(SNR_{sl} < \beta) \\ & + Pr(SNR_{sd} < \beta)Pr(SNR_{sl} > \beta)Pr(SNR_{ld} < \beta). \end{aligned} \quad (15)$$

Employing the exponential SNR in Eq. (15), outage probability of a cooperative link can be expressed as

$$\begin{aligned} Pr_{out}^{C} = & 1 - exp\left(-\frac{k1}{p_s}\right) - exp\left(-\frac{k2}{p_s} - \frac{k3}{p_l}\right) \\ & - exp\left(\frac{k1+k2}{p_s} + \frac{k3}{p_l}\right), \end{aligned} \quad (16)$$

where $k1 = \frac{N_o\beta r_{sd}^{\gamma}}{K}$, $k2 = \frac{N_o\beta r_{sl}^{\gamma}}{K}$, and $k3 = \frac{N_o\beta r_{ld}^{\gamma}}{K}$.

In addition to that, the end-to-end outage probability of a certain route is defined as the probability that outage takes place in one of the H hops of the route, i.e.,

$$Pr_{out}(route) = 1 - \prod_{h=1}^{H}\left(1 - Pr_{out}^{C}(h)\right), \quad (17)$$

where $Pr_{out}^{C}(h)$ is the outage probability of the h-th link in the route.

The goal of the algorithm is to find the route from each source to the sink such that each route minimizes the collision probability per node due to the route to other nodes in the network, while satisfying the end-to-end outage probability constraint. Therefore, the optimization problem can be formulated as below

$$\underset{p_{s_h},\, p_{l_h},\, E_{i,j},\, F_{i,j}^{k}}{Min.} \quad Coll_T, \quad (18)$$

$$s.t. \; Pr_{out}(route_r) \le Pr_{out}^{*}, \quad \forall r \in \mathbb{N}_s$$

$$C1\colon N_s \le \sum_{i\in\mathbb{N}}\sum_{j\in\mathbb{N}}^{j\neq i} E_{i,j} + \sum_{i\in\mathbb{N}}\sum_{j\in\mathbb{N}}^{j\neq i}\sum_{k\in\mathbb{N}}^{k\neq i,k\neq j} F_{i,j}^{k} \le 2N_s(N-1),$$

$$C2\colon E_{i,j} - F_{i,j}^{k} \ge 0, \quad \forall i,j,k \in \mathbb{N} \quad i \neq j \neq k$$

$$C3\colon E_{i,j} - \sum_{k\in\mathbb{N}}^{k\neq i} E_{j,k} \ge 0,$$

$$C4\colon \sum_{i\in\mathbb{N}}^{i\neq D} E_{i,D} \ge 1,$$

$$C5\colon \sum_{i\in\mathbb{N}}^{i\neq S} E_{S,i} \ge 1,$$

$$C6\colon \sum_{i\in\mathbb{N}}^{i\neq j} E_{i,j} + \sum_{i\in\mathbb{N}}^{i\neq j}\sum_{k\in\mathbb{N}}^{k\neq i,k\neq j} F_{i,k}^{j} \le 1,$$

$$0 \le p_{s_h} \le P_{t_{max}}, \quad 0 \le p_{l_h} \le P_{t_{max}}$$

$$E_{i,j} \in \{0,1\}, \quad F_{i,j}^{k} \in \{0,1\}$$

where p_{s_h}, p_{l_h}, $E_{i,j}$, and $F_{i,j}^{k}$ are the optimization decision variables. $P_{t_{max}}$ is the maximum transmission power level for the IEEE 802.15.4 devices. $Pr_{out}(route_r)$ is defined as the total outage probability of route r and $Coll_T$ is the objective function, which is the total collision probability per node in the network and can be expressed as

$$Coll_T = 1 - \prod_{r=1}^{N_s}(1 - Pr(Coll._{route_r})). \quad (19)$$

where, $Pr(Coll._{route_r})$ is defined as the total collision probability caused by route r.

As explained earlier, each node in a cooperative routing can receive data from the previous node and can work either as the relay node or the next hop. Constraint $C1$ in Eq. (18) forces the range for the number of links involved in the source-destination paths in the network with N_s source nodes (i.e., N_s flows in the network). A cooperative relay node may be assigned to hop (i, j) only if the hop is included in the path solution. Otherwise, no relay node will be assigned to that hop (i, j); $C2$ in Eq. (18) characterizes this constraint. Constraint $C2$ also holds when j is not a next hop and in that case all E variables in Eq. (18) are equal to zero. Constraint $C3$ formulates the flow balance at an intermediate node along the path between each source, s_i, and the destination node, D. Moreover, the destination node must be reach and each source node must transmit data to some other nodes. These constraints are expressed by $C4$ and $C5$, respectively. Our model assumes that the node can be selected either as the next node in the route (such as nodes i, j, a, and b in Fig. 2 or as a relay node (such as node k in Fig. 2). Thus, we added constraint $C6$ to ensure that the node cannot be selected as a next node in the route and a relay node at the same time.

Obviously, Eq. (18) is a *Mixed Integer Non-Linear Programming* problem, since the binary variables ($E_{i,j}$, $F_{i,j}^{k}$) and real variables (p_{s_h}, p_{l_h}) are involved in the non-linear objective and the constraints.

Lemma 1: The minimum collision cooperative routing problem is NP-Hard.

The proof of lemma 1 is given in the Appendix.

IV. Proposed Solution Procedure

The Branch-and-Bound algorithm is by far the most widely used tool for solving integer optimization problems. Obviously, the optimal value of cost function in a continuous linear relaxation of a problem will always be a lower bound on the optimal value of the cost function. Moreover, in any minimization, any feasible point always specifies an upper bound on the optimal cost function value. The idea of the Branch-and-Bound is to utilize these observations to subdivide MINLP‘s feasible region into more-manageable subdivisions and then, if required, to further partition the subdivisions.

TABLE II
COOPERATIVE ROUTING USING BRANCH-AND-BOUND SPACE REDUCED PSEUDOCODE

Input: An arbitrarily located set of nodes, $\mathbb{N}$,
set of source nodes, N_s, and a destination node, D
1: define set Ω of sub-problems;
2: $\Omega \leftarrow \omega 0; B_U \leftarrow \infty$;
3: solve linear relaxation of $Coll_T$ and denote its minimum cost function by B_L;
4: **while** $\Omega \neq \emptyset$ **do**
5: select a problem $\omega \in \Omega$ with the minimum B_{L_ω};
6: let $B_L \leftarrow B_{L_\omega}$;
7: set B_{U_ω} a feasible solution for ω via local search;
8: **if** $B_{U_\omega} < B_U$ **then**
9: $B_U \leftarrow B_{U_\omega}$, $\Omega^* \leftarrow \Omega$
10: **if** $B_L \geq (1-\epsilon)B_U$ **then**
11: **return** B_{U_ω};
12: **else**
13: remove all problems $\omega i \in \Omega$ with $B_{L_\omega} \geq (1-\epsilon)B_U$;
14: **end if**
15: **end if**
16: remove all problems that includes disconnected link;
17: select two sub-problem $\omega 1$ and $\omega 2$;
18: solve linear relaxation of $\omega 1$ and $\omega 2$ and denote their optimal cost functions by $B_{L_{\omega 1}}$ and $B_{L_{\omega 2}}$;
19: **if** $B_{L_{\omega 1}} \leq (1-\epsilon)B_U$
20: $B_L \leftarrow B_L \cup \{\omega 1\}$
21: **end if**
22: **if** $B_{L_{\omega 2}} \leq (1-\epsilon)B_U$
23: $B_L \leftarrow B_L \cup \{\omega 2\}$
24: **end if**
25: **end while**
26: **Output** the $(1-\epsilon)$ optimal solution B_U.

These subdivisions make a so-called enumeration tree whose branches can be pruned in a systematic search for the global optimum.

A. Branch-and-Bound Space Reduced Algorithm

We enhance the Branch-and-Bound algorithm and develop a *Branch-and-Bound Space Reduced* algorithm to solve the MINLP. This proposed algorithm reduces the Branch-and-Bound area of a search and implements the Branch-and-Bound relaxation and separation strategy to solve the problem.

The pseudocode of the proposed framework, using the Branch-and-Bound Space Reduced, is described in Table II. In this algorithm, Ω represents optimization problem set and Ω^* denotes the global minimum of the cost function $Coll_T$. Therefore, the algorithm provides a $(1-\epsilon)$ optimal solution Ω_ϵ, which means Ω_ϵ is close enough to Ω^* such that $\Omega^* \geq (1-\epsilon)\Omega$. Initially, Ω includes the original problem, i.e., $Coll_T$ denoted by $\omega 0$. A lower bound of the cost function is first derived through solving a linear relaxation of $Coll_T$ denoted by (B_L) (line 3 in Table II). Construction of the linear relaxation is described in the next subsection. Since any feasible solution of ω can serve as an upper bound, the one obtained by rounding under the satisfaction of all constraints is used and denoted as B_U.

The process of finding the lower and upper bound for the cost function, is called *bounding*. If the derived upper and lower bounds are within the ϵ-vicinity of each other, the algorithm terminates (line 10, 11). Otherwise, it divides the feasible region of the problem into two narrower subsets (*branching* step), and the problem ω will be replaced with two subproblems $\omega 1$ and $\omega 2$ constructed by branching binary variable $E_{i,j}$, respectively (see line 17). Simultaneously, other variables are fixed according to the constraints in Eq. (18). After dividing the original problem into two new subproblems, the algorithm performs relaxation and local search on these two new subproblems. Now, we have lower bounds $B_{L_{\omega 1}}$ and $B_{L_{\omega 1}}$ for subproblems $\omega 1$ and $\omega 2$, respectively. Since the relaxation in subproblems $\omega 1$ and $\omega 2$ are both tighter than that in ω, we have $min\{B_{L_{\omega 1}} B_{L_{\omega 2}}\} \geq B_{L_\omega}$ and $min\{B_{U_{\omega 1}} B_{U_{\omega 2}}\} \leq B_{U_\omega}$. For minimizing the collision probability (minimization problem), the lower bound of the original problem is updated from $B_{L_\omega} = B_{L_{\omega 1}}$ to $B_{L_\omega} = min\{B_{L_{\omega 1}}, B_{L\omega 2}\}$. Also, the upper bound of the original problem is updated from $B_{U_\omega} = B_{U_{\omega 1}}$ to $B_{U_\omega} = min\{B_{U_{\omega 1}}, B_{U\omega 2}\}$.

The developed feature of Branch-and-Bound, reduces the feasible integer variable space. In this phase of the algorithm, all subsets that include the disconnect integer variables (i.e., disconnected next hop $\left(E_{i,j} = 1 \ \& \ Con_{i,j} = 0\right)$ or disconnected relay node $\left(F_{i,j}^k = 1 \ \& \ Con_{i,k} = 0 \text{ or } Con_{k,j} = 0\right)$ are removed and the subsets area of search is reduced.

Through an iterative branching procedure, subsets are further divided into smaller ones to build the enumeration tree. The structure of the enumeration tree allows the algorithm to remove some branches and search for the solution in a very effective way. Moreover, narrowing down the subsets of the optimization variables makes the linear relaxations tighter (i.e., increases B_L) and provides the next local search processes with a closer starting point to the optimal solution (i.e., reduces B_U). Hence, the gap between B_L and B_U is reduced as the process continues. More precisely, the global lower bound B_L is updated in each iteration, in order to contain the minimum of the lower bounds of all subsets (lines 5, 6). The global upper bound B_U is also updated at each iteration (lines 8, 9) and the branches with a lower bound greater than $(1-\epsilon)B_U$ are pruned (line 13). This approach is continued until the difference between the global lower and upper bounds satisfy the accuracy ϵ (lines 10, 11). Clearly, we may lose the global optimum by pruning the branches. However, if the global optimum in a pruned branch with the lower bound is B_{L_ω}, then $\Omega^* \geq B_{L_\omega}$, and consequently, $\Omega^* \geq (1-\epsilon)B_U$. Therefore, the current best feasible solution with objective value B_U is already an $(1-\epsilon)$ optimal solution, and the optimality is still guaranteed $(1-\epsilon)$. In fact, this guarantee is the key feature of the algorithm, which makes it very effective in solving the MINLP.

B. A Lower Bound for the Collision Problem

To obtain the exact solution using a Branch-and-Bound algorithm in a reasonable computation time, computation of the lower bound of the cost of each branch are important. The stronger bound decreases the number of enumerations for searching the most promising branch. In order to derive the lower bound of the collision problem the linearization technique along with relaxation of the integer variables are used and the non-linear objective and constraint are replaced by the linear-relaxed form. Firstly, we approximate the exponential expression in the objective function $(Coll_T)$ and constraint in Eq. (17) using a first order Taylor polynomial approximation. Then, due to the fact that the logarithm function can transfer the multiplication and divisions operations of the variables into linear form, we define the new variable θ and we apply the logarithmic operation to the non-linear functions. Therefore, the following operations are used for linearisation and relaxation of the non-linear functions ($Coll_T$ and Pr_{out}).

$$exp(-z_{i,j}) = 1 - z_{i,j} \tag{20}$$

$$\theta_{i,j} = \ln(v_{i,j} * w_{i,j}) = \ln v_{i,j} + \ln w_{i,j} \tag{21}$$

where z, v, and w are the optimization variables. For instance, using Eq. (20), the term $exp\left(-\frac{I_{th} r_{si}}{K p_s}\right)$ in Eq. (13), can be written as $\left(1 - \frac{I_{th} r_{si}}{K p_s}\right)$, and doing a simple change of variable $\frac{I_{th} r_{si}}{K p_s} = K' X_s$, the term can be rewritten as $\left(1 - K' X_s\right)$ which is in a linear expression.

C. Complexity

The worst case computational complexity of the MINLP grows exponentially with the number of integer variables. In other words, a problem with n_b binary variable requires solving 2^{n_b} non-linear programming problems [13]. Although actual run-time is reduced, due to the search space reducing, the complexity of the algorithm remains exponential. Therefore, low-complexity sub-optimal approach is provided in the next section.

V. Sub-Optimal Cooperative Routing for Collision Minimization

In order to reduce the computational complexity, we propose a new algorithm in which the optimal transmission power (for the source and relay nodes of each link) is allocated separately. Then, the optimal allocated power is used in the optimal route search problem.

TABLE III

Cooperative Routing Using INLP Pseudocode

Input: An arbitrarily located set of nodes, $\mathbb{N}$,
set of source nodes, N_s, and a destination node, D;
1: $p_s \leftarrow 0$ dBm, $p_l \leftarrow 0$dBm ;
2: $Coll'_T = \{Coll_T \mid p_s = p_l = 0dBm\}$;
3: solve the relaxed problem using Branch-and-Bound space reduce Algorithm in Table II and denotes its results as $P^*_{N_s}$;
4: apply Lagrange Multiplier function on $P^*_{N_s}$;
5: obtain optimal power allocation for each transmitter and relay node from Eqs. (24)-(26);
6: **Output** Optimal path with optimal power allocation.

Assumption: The algorithm uses equal, fixed transmission power in the objective function and the constraints. This value is assumed to be 0 dBm, that is the standard value in IEEE 802.15.4 devices [17]. Therefore, the problem is simplified to an INLP problem. The cost function of the algorithm is defined as $Coll_T\ |_{p_s=p_l=0\ dBm}$.

The Branch-and-Bound Space Reduced algorithm, which is discussed in subsection IV.A, is employed to solve the INLP problem as well (line 3). After optimal path selection using Branch-and-Bound Space Reduced algorithm, the optimal power allocation is obtained by solving a constrained optimization problem using the Lagrange Multipliers method.

The constraint optimization problem for each selected cooperative link can be formulated as follows.

$$\begin{aligned} &\underset{p_s, p_l}{Min} \quad Pr\left(Coll.^C_{s,l}\right), \\ &s.t.\ Pr^C_{out} \le Pr^*_{out}. \end{aligned} \tag{22}$$

In a cooperative transmission link, the constrained optimization problem can be solved using the Lagrange Multipliers method as follows

$$\begin{aligned} &\frac{\partial}{\partial\ p_s}(\,Pr(Coll.^C_{s,l}) + \lambda\, Pr^C_{out}) = 0, \\ &\frac{\partial}{\partial\ p_l}(\,Pr(Coll.^C_{s,l}) + \lambda\, Pr^C_{out}) = 0, \\ &Pr^C_{out} = Pr^*_{out}\ ,\ \ \lambda > 0, \end{aligned} \tag{23}$$

$$\begin{aligned} &\sum_{n\in\mathbb{N}}\left[\frac{I_{th}^{Coll.} r_{sn}^{\gamma}}{K p_s^2}\,\phi\left(p_s,n\right) - \theta\left(p_s,n\right)\right]\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right]\left[1-\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(exp\left(-\frac{k2}{p_s}\right) - exp\left(-\frac{k1+k2}{p_s}\right)\right)\right] \\ &-\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(\frac{k1}{p_s^2}\right)exp\left(-\frac{k1+k2}{p_s}\right) + \left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(exp\left(-\frac{k2}{p_s}\right) - exp\left(-\frac{k1+k2}{p_s}\right)\right)\frac{k2}{p_s^2} \\ &+\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_s,n\right)\right]\right)\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(\frac{k1+k2}{p_s^2}exp\left(-\frac{k1+k2}{p_s}\right) + \frac{k2}{p_s^2}exp\left(-\frac{k2}{p_s}\right)\right) - \frac{\lambda k1}{p_s^2}exp\left(-\frac{k1}{p_s}\right) \\ &-\frac{\lambda k2}{p_s^2}exp\left(-\left(\frac{k2}{p_s}+\frac{k3}{p_l}\right)\right) - \frac{\lambda\left(k1+k2\right)}{p_s^2}exp\left(-\frac{k1+k2}{p_s} - \frac{k3}{p_l}\right) = 0 \end{aligned} \tag{24}$$

$$\begin{aligned} &\sum_{n\in\mathbb{N}}\left\{\frac{I_{th} r_{sn}^{\gamma}}{K p_l^2}\,\phi\left(p_l,n\right) - \theta\left(p_l,n\right)\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_l,m\right)\right]\right\}\times\left[exp\left(-\frac{k2}{p_s}\right) - exp\left(-\frac{k1+k2}{p_s}\right)\right]\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right] \\ &-\frac{\lambda k3}{p_l^2}\left[exp\left(-\frac{k2}{p_s}-\frac{k3}{p_l}\right) + exp\left(-\frac{k1+k2}{p_s}-\frac{k3}{p_l}\right)\right] = 0 \end{aligned} \tag{25}$$

$$1 - exp\left(-\frac{k1}{p_s}\right) - exp\left(-\frac{k2}{p_s}-\frac{k3}{p_l}\right) - exp\left(\frac{k1+k2}{p_s}+\frac{k3}{p_l}\right) = Pr^*_{out} \tag{26}$$

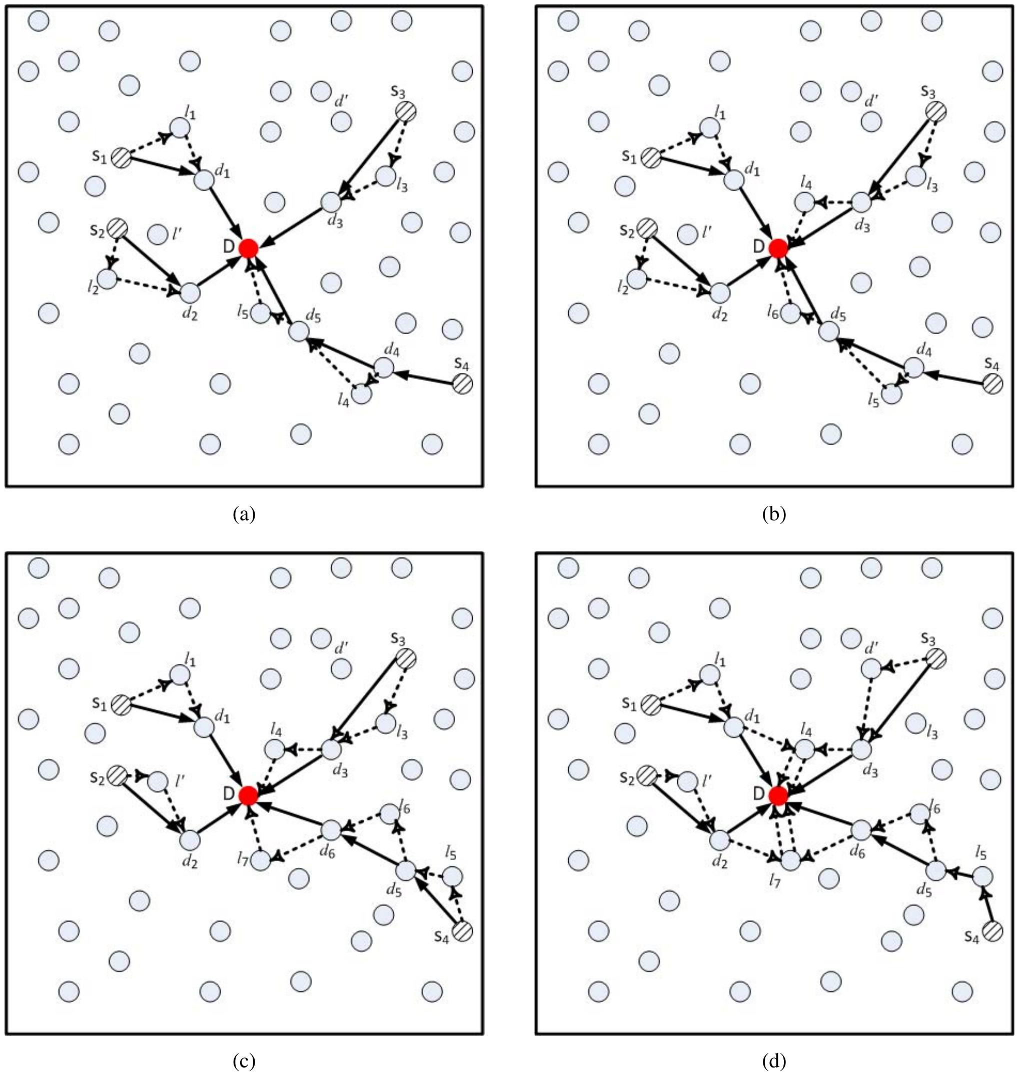


Fig. 4. Selected routes of the proposed algorithms for the 50-node network with 4 flows. (a) Cooperative routing using MINLP. (b) Cooperative routing using INLP. (c) MCCR. (d) MPCR [9].

where λ is the Lagrange multiplier. By substituting Eqs. (13), (14), (16), and (17) in Eq. (23), we get Eqs. (24)-(26), as shown at the bottom of previous page, where $\phi(p,n)$ and $\theta(p,n)$ are defined as follows

$$\phi(p,n) = Pr_{rx}(n)\,exp\left(-\frac{I_{th}^{Coll.} r_{sn}^{\gamma}}{K\,p}\right) Pr(NST_s),$$

$$\theta(p,n) = Pr_{rx}(n)\,exp\left(-\frac{I_{th}^{Coll.} r_{sn}^{\gamma}}{K\,p}\right) \times \sum_{m\in\mathbb{N}} \frac{I_{th}^{Sens.} r_{sm}^{\gamma}}{K\,p^2} Pr(NST_s).$$

These three expressions (Eqs. (24)-(26)) are solved simultaneously to determine p_s and p_l.

VI. Performance Evaluation

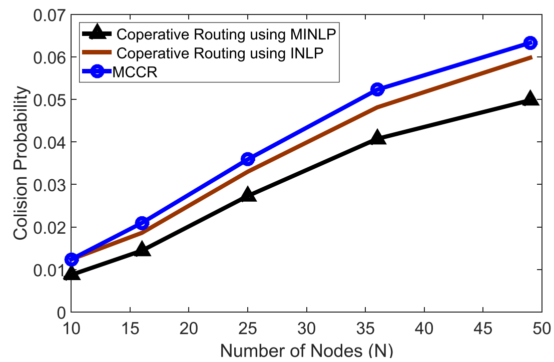
In this section, we evaluate the performance of the proposed algorithms.

Assumptions: We consider a random topology consisting of 10 to 50 sensor nodes (i.e., N varies from 10 to 50) and 3 or 4 flows, with randomly selected sources. The evaluation scenario is similar to the one used in [14]. We assume that the path-loss exponent (γ) equals 4, the noise power (N_o) equals -103.8 dBm, and the detection SNR threshold (β) equals 10 dB. The interference threshold equals αN_o, where α is a design parameter. In this paper we assume $\alpha = 1$, which means the collision interference threshold is equal to the noise power ($I_{th}^{Coll.} = N_o$). We also assume the sensing threshold equals the noise power, i.e., $I_{th}^{Sens.} = N_o$ [17]. The packet generation rate (Λ_0) at each source node follows Poisson traffic model with a rate of 4 pkt/s. The end-to-end outage probability constraint (Pr_{out}^{*}) is set to 0.1. To compare and evaluate the total collision probability caused by each cooperative routing algorithm, Eq. (19) is used.

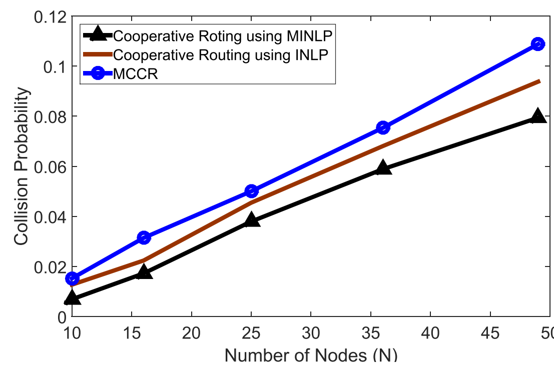
The proposed routing solutions: cooperative routing solution using MINLP, cooperative routing using INLP, the MCCR algorithm presented in [16], and the MPCR algorithm [9] are compared in Fig. 4 (a)-(d), respectively for a network with 50 sensor nodes. As shown in this figure, there are 4 source nodes, $N_s = 4$, and one sink node in the network. It can be seen that the proposed routing solution avoids selecting the more active nodes. The more active nodes are the nodes that have higher transmission/reception probability (compared to the other nodes in the network) and are located at the high traffic area. The high traffic load area (or active area) is the area around (and includes) the more active nodes. In other words, the proposed routing solutions select the nodes as far as possible from the high traffic load areas. For example, as can be seen in the Fig. (4) (a)-(d), unlike MPCR, in MCCR, cooperative routing using MINLP, and cooperative routing using INLP, next hop and the relay nodes (node l_4 and l_7) are not selected by multiple flows in the network, since it increases the collision probability. Moreover, in the cooperative routing solution using the MINL and INLP algorithms, unlike MCCR and MPCR, the selected relay nodes are also located far from the more active nodes or high traffic load areas. In the MCCR algorithm (which is a sub-optimal cooperative routing to minimize collision probability) the relay node is assumed to be the closest node to the middle node. Therefore, it is not selected as the optimal relay node to minimize collision probability. Moreover, in the MPCR algorithm (in which the objective of cooperative routing is minimizing total transmission power) the relay node is selected to minimize total transmission power, regardless of the amount of collision caused by the selected relay node. Therefore, the assigned relay node in MCCR and MPCR might be located near to more active area. In addition to that, as can be seen in Fig (4) (a) and (b), node l', which is near more active nodes, is not selected as the relay node in MINLP and INLP routing algorithms. Thus, the Figures illustrate that the proposed routing algorithms avoid selecting the nodes that are located at the high traffic area, i.e., the area that contains more active nodes. By doing this, the algorithm avoids involving the nodes that can cause packet collision problem.

A. Comparison Between the Proposed Collision Minimization Cooperative Routing Algorithms

The Collision probability caused by optimal cooperative routing using MINLP solution and that of INLP, and the MCCR algorithm are compared in Fig. 5 (a) and (b), respectively. From this figure, it is evident that cooperative routing using MINLP solution outperforms the other schemes and has the lowest collision probability. It can be seen that, at $N = 50$ and 4 flows in the network, the collision probability of cooperative routing using MINLP solution is reduced by 21%, and 43% compared with INLP and MCCR, respectively. This collision probability reduction is expected because in cooperative routing using MINLP, unlike INLP and MCCR, optimum power allocation is involved (from the initial routing decision process) in the routing selection to minimize collision probability. Moreover, unlike MCCR, the cooperative routing algorithms using MINLP and INLP assign the optimal relay node to each cooperative link. The results also show that the performance of cooperative routing using INLP is very



(a)



(b)

Fig. 5. Comparing collision probability of the proposed routing with (a) 3 flows in the network and (b) 4 flows in the network.

close to optimal; therefore, it can be considered a near-optimal cooperative routing algorithm. In the MINLP, the collision probability is the cost function during the route selection and power is allocated to the transmitters, in each hop, to minimize the collision probability caused by selected links across the route. However, the price for achieving optimal performance is the higher computational complexity of MINLP.

B. Evaluating the Effect of Cooperative Routing Parameters

To investigate the effect of each of the cooperative routing parameters (cooperative path selection, relay selection, and cooperative power allocation) separately in minimizing the collision probability (i.e., one technique is used, while the other two are not employed), we developed two additional routing algorithms. In the first one, called Cooperative Along Minimum Collision Direct path (CAMCD), cooperation is employed after constructing the route with the minimum collision probability using direct links only. Therefore, it does not take into account the possibility of using cooperative links during route selection. However, after route selection, it may use cooperative transmission over the links of the selected route. The second algorithm, called Minimum Collision Non-cooperative (MCN), considers only direct links during both the route selection and signal transmission. CAMCD and MCN use optimal power allocation, as explained in Section V.

As shown in the Fig. 6, taking into account the possibility of using cooperative link during the route selection in cooperative

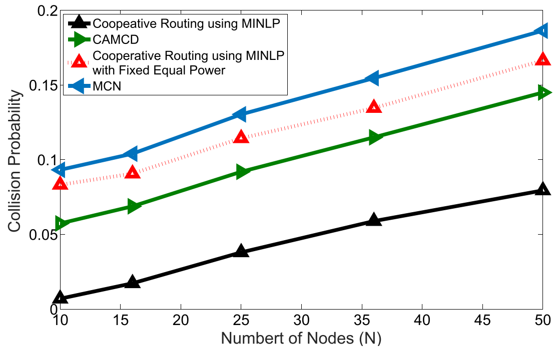


Fig. 6. Evaluating the contribution of the cooperative routing parameters.

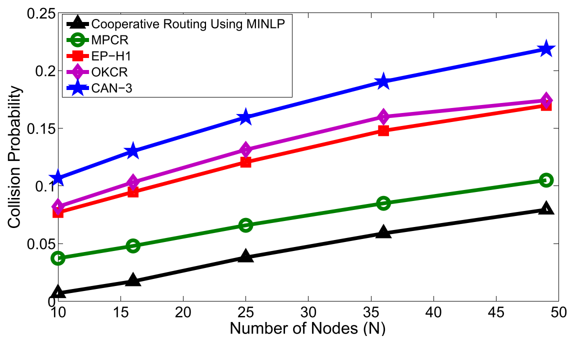


Fig. 7. Comparing collision probability of the proposed cooperative routing and that of minimum power cooperative routing algorithms.

routing using MINLP contributed 42% in minimizing collision probability. Moreover, comparing the performance of cooperative routing using MINLP and MCN to minimize collision reveals that cooperation transmission (employing relay node for transmission) contributes 57% in collision reduction of the cooperative routing using MINLP algorithm.

Furthermore, in order to gain insight into the effect of the optimal power allocation to minimize the caused collision probability with cooperative routing using MINLP, we compare the performance of the algorithm with optimal power allocation with that of the algorithm with equal power allocation (i.e., $p_s = p_l = 0$ dBm for all nodes in the route). As shown in Fig. 6, the contribution of optimal power allocation in the collision probability reduction ranges from 39% to 47% for $N = 9$ to 50.

C. Comparison Between the Proposed Cooperative Routing and Minimum Power Cooperative Routing Algorithms

We compare the performance of the proposed cooperative routing using the MINLP solution algorithm with that of OKCR [8], EP-H1 [10], MPCR [9], and CAN-L [5]. These algorithms are the common and well-known cooperative routing algorithms, in which the assuming scenario is compatible with our proposed cooperative routing algorithm. The objective of the OKCR, EP-H1, MPCR and CAN-L algorithms is to minimize total transmission power in cooperative routing. Fig. 7 compares the collision probability caused by cooperative routing using the MINLP solution algorithm and that of the OKCR, EP-H1, MPCR and CAN-3 algorithms versus the number of nodes in the network. It is evident that the cooperative routing using the MINLP solution algorithm outperforms the other schemes and has the lowest collision probability. At N = 49, the collision probability of cooperative routing using MINLP solution is reduced by 82%, 78%, 56%, and 93% compared with OKCR, EP-H1, MPCR, and CAN-3, respectively. This collision probability reduction is expected because cooperative routing using MINLP solution selects the cooperative route that minimizes the collision probability by employing the collision probability as the cost function during the route selection and also by allocating the power (in each hop) to minimize the collision probability caused by the selected links across the route. By doing that, the cooperative routing using MINLP solution avoids selecting nodes that can cause high collision probability either because of the large number of neighbors or because some of these neighbors have a high probability of being used as the receiver or transmitter.

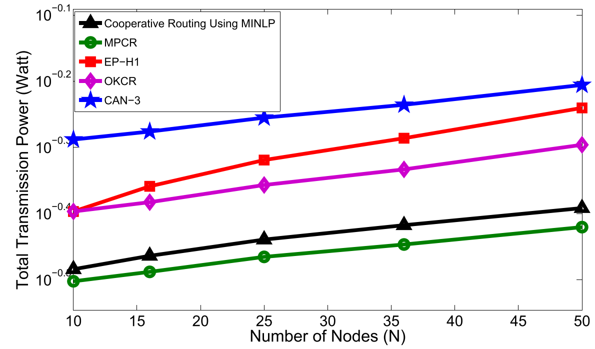


Fig. 8. Comparing total transmission power of the proposed cooperative routing and that of minimum power cooperative routing algorithms.

The required transmission power of the selected routes by different routing algorithms, in the network with 4 flows, is shown in Fig. 8. A larger number of nodes increases the distance between source-sink nodes; therefore, the total transmission power increases. On the contrary, the CAN-3 algorithm first constructs the shortest-path route then it applies the cooperative transmission on the last 3 links of the established route. Therefore, the CAN-3 algorithm is limited in applying the cooperative transmission on a certain number of nodes, while the other algorithms can consider any node in the network to be a part of cooperative routing. Thus, the CAN-3 algorithm consumes more transmission power than the other algorithms in Fig 8. Moreover, the objective in MPCR is to minimize transmission power; therefore, MPCR is slightly more energy efficient than cooperative routing using MINLP solution. Comparing Figs. 7 and 8 show that minimizing the transmission power does not necessarily minimize the collision probability in the cooperative routing.

D. Evaluating the Total Power Consumption, Considering Retransmission of Collided Packets

It was shown in the previous subsection that, although the algorithm that minimizes the collision probability requires more transmission power than the minimum-power

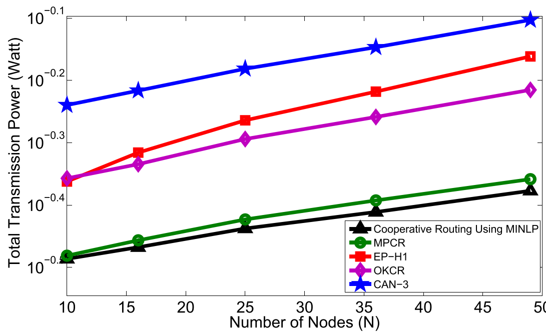


Fig. 9. Comparing total transmission power of the proposed cooperative routing and that of minimum power cooperative routing algorithms, taking retransmission into consideration.

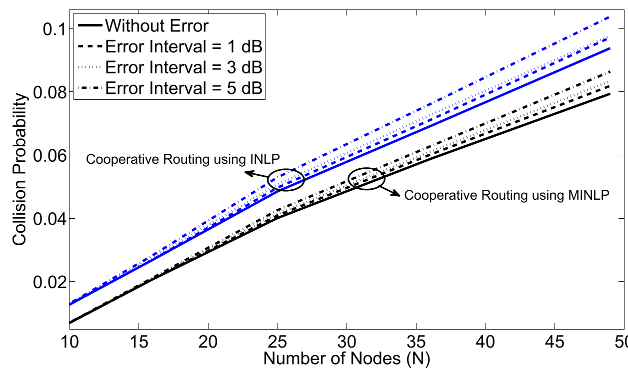


Fig. 10. Evaluating the performance of the proposed algorithms assuming the existence of a random error in SNR.

cooperative routing, the former algorithm has significantly less collision probability. Therefore, the collision probability in minimum-power cooperative routing leads to frequent packet retransmissions. In the previous subsection, the total transmission power was calculated without taking the packet retransmission into account. In this section, we consider packet retransmission into consideration. The packet is retransmitted, if it is collided in the first round of transmission. We assume that the collided packet can be retransmitted for three times at most (after that the packet is dropped). This number is the default retransmission times for the IEEE 802.15.4 devices [17]. Therefore, the total transmission power is can be calculated as

$$P_T^{re} = P_T \left(1 + Coll_T + Coll_T^2 + Coll_T^3\right), \tag{27}$$

where P_T^{re} is the total transmission power by taking the retransmission into consideration.

The required transmission power of the selected routes by different routing algorithms, in the network with 4 flows and considering retransmission of collided packets, is shown in Fig. 9. It is evident that by considering the retransmission of collided packet, our cooperative routing scheme that minimizes collision probability saves considerably more energy compared to EP-H1, CAN-3, and OKCR and saves slightly more energy than the MPCR algorithms.

E. Implementation Challenges of the Proposed Algorithms

One of the main challenges to implement the proposed cooperative routing algorithms is the computational complexity of the algorithms. The worst case computational complexity of Branch-and-Bound space reduction algorithm which is used to solve MINLP and INLP is $O(2^{n_b})$, where n_b is the number of binary variable and 2^{n_b} is the number of combinations for the binary variables. The second important challenge of proposed cooperative routing implementation is the availability of the required information. The proposed algorithms require the complete knowledge of the network, such as the channel state information, noise power, path loss, and the node location information. This information can be stored in a high-capacity sensor node or the sink node. To deal with these practical implementation issues of the presented framework, the algorithms can be implemented in an off-line manner during the network design and planning phase. Moreover, we investigate the performance degradation of the proposed algorithms, considering the existing of errors in the knowledge of the network model parameters. The existing errors in the knowledge of the network model parameters, such as noise power, channel, transmitter gain, and path loss can be integrated as an error in SNR. Simulation results for a network with 4 flows in the network and assuming the SNR error follows a random uniform variable in the intervals (a) (−0.5 dB, +0.5 dB), (b) (−1.5 dB, +1.5 dB), and (c) (−2.5 dB, +2.5 dB) are shown in Fig. 10. As can be seen, the proposed algorithms are relatively robust to the error in SNR and the performances of the proposed algorithms are degraded slightly by increasing the existing error in SNR. As can be seen in Fig 10, at $N = 49$, the collision probability of cooperative routing using MINLP increased by 3.8%, 4.7%, and 7.8% for the error intervals equal to 1 dB, 3 dB, and 5 dB, respectively. The range of increase in the collision probability is slightly higher for the cooperative routing using INLP and as can be seen at N = 49, the collision probability of cooperative routing using MINLP increased by 4.3%, 5.1%, and 10.3% for the error intervals equal to 1 dB, 3 dB, and 5 dB, respectively.

VII. Conclusion

In this paper, we presented the optimal cooperative routing to minimize collision probability in wireless sensor networks by joint use of optimal power, relay node allocation, and route selection. This optimization problem is inherently hard due to its mixed-integer nature, non-linearity of the problem, and a very large solution space. We developed an efficient solution procedure based on the Branch-and-Bound technique augmented with a space reduction algorithm to speed up the computation. Then, we proposed the heuristic sub-optimal cooperative routing algorithms to speed up the computational complexity by decoupling transmission power allocation in the cooperative routing algorithm from the optimal route selection. Results reveal that cooperative routing using MINLP outperforms the heuristic routing algorithm. The performance of the proposed routing algorithms is compared with existing cooperative routing algorithms and the results demonstrate the significant rate gains that can be achieved by incorporating cooperative transmission in route selection for minimizing collision in wireless sensor networks. There are several directions for future work, including development of a flexible cooperative routing algorithm with multiple cost functions (for example collision probability and energy consumption) to optimize multiple routing objectives, simultaneously. In addition to that, further investigation and improvements to the current implementation approaches are identified as an area for future work. For instance, to deal with practical challenges of the proposed algorithms, parametric programming in an off-line manner to reduce the computational requirements for the sensor nodes to very simple operations during network functioning can be investigate in future work. For the dynamic networks which are programmed in an off-line manner, in order to follow the changes in the networks, the operations can be updated in implementation based on the change in the status of the network; therefore, the routing is updated upon detecting a change in the network parameters.

APPENDIX

In [19], for a given source-destination pair with N nodes in the network, the number of possible broadcasting trees from the source node to the destination node with zero transmitters and zero relaying nodes (i.e., only the source node is transmitting the packet) is given by

$$R(0) = \binom{N}{N} = 1, \quad (28)$$

The number of possible broadcasting trees with one relay node is given by

$$R(1) = \binom{N}{1} \sum_{i=1}^{N-1} \binom{N-1}{i}, \quad (29)$$

the above formula means that we first need to pick one node as the relay node and then decide how many nodes are reached directly by the relay node (the remaining nodes are directly reached by the source node). The case of possible broadcasting trees with two relay nodes is more complicated and is given by

$$R(2) = \binom{N}{2} \sum_{i=1}^{N-2} \left(\binom{N-1}{i} \sum_{j=1}^{N-2} \binom{N-1-i}{j} \right), \quad (30)$$

therefore, the number of possible broadcasting trees with i relay nodes is given by

$$R(i) = \binom{N}{i} \sum_{k_1=1}^{N-i} \left(\binom{N-1}{k_1} \sum_{k_2=1}^{N-1} \left(\binom{N-1-k_1}{k_2} \right. \right. \\ \left. \left. \ldots \sum_{k_j=1}^{N-i} \left(\binom{N-1-\sum_{j=1}^{i-1} k_j}{k_i} \right) \right) \ldots \right). \quad (31)$$

The above formula means that we first need to pick i nodes as the relay nodes with a number of possibilities of $(\binom{N}{i})$ and then decide how many nodes are reached directly by the relay node (the remaining nodes are directly reached by the source node). Therefore, the total number of possible broadcasting trees in the network is given by

$$T = \sum_{i=0}^{N-1} R(i). \quad (32)$$

For example, for $N = 15$ (15 nodes in the network), the number of broadcasting trees is more than 8.7 billion [19]. Since cooperative paths are mapped as broadcasting trees, for the network with N_s there are $N_s T$ possible cooperative paths from the source nodes to the destination node. Therefore, selecting the best path out of all possible paths is *NP-hard*.

REFERENCES

[1] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] R. Madan, N. B. Mehta, A. F. Molisch, and J. Zhang, "Energy-efficient decentralized cooperative routing in wireless networks," *IEEE Trans. Autom. Control*, vol. 54, no. 3, pp. 512–527, Mar. 2009.

[3] W. Zhuang and M. Ismail, "Cooperation in wireless communication networks," *IEEE Wireless Commun.*, vol. 19, no. 2, pp. 10–20, Apr. 2012.

[4] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[5] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[6] F. Mansourkiaie and M. H. Ahmed, "Cooperative routing in wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 604–626, May 2015.

[7] C. Pandana, W. P. Siriwongpairat, T. Himsoon, and K. J. R. Liu, "Distributed cooperative routing algorithms for maximizing network lifetime," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2006, pp. 451–456.

[8] P. Ahmadi and B. Jabbari, "An outage-aware power saving cooperative routing algorithm in wireless networks," in *Proc. Wireless Telecommun. Symp. (WTS)*, Apr. 2013, pp. 1–5.

[9] A. Ibrahim, Z. Han, and K. J. R. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[10] M. Dehghan, M. Ghaderi, and D. Goeckel, "Minimum-energy cooperative routing in wireless networks with channel variations," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3813–3823, Nov. 2011.

[11] A. M. Akhtar, A. Behnad, and X. Wang, "Cooperative ARQ based energy efficient routing in multi-hop wireless networks," vol. 64, no. 11, pp. 5187–5197, Nov. 2015.

[12] J. Zhang and Q. Zhang, "Contention-aware cooperative routing in wireless mesh networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2009, pp. 1–5.

[13] J. Habibi, A. Ghrayeb, and A. G. Aghdam, "Energy-efficient cooperative routing in wireless sensor networks: A mixed-integer optimization framework and explicit solution," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3424–3437, Aug. 2013.

[14] J. Zhang and Q. Zhang, "Cooperative routing in multi-source multi-destination multi-hop wireless networks," in *Proc. IEEE 27th Conf. Comput. Commun. (INFOCOM)*, Apr. 2008, pp. 306–310.

[15] B. Han, J. Li, J. Su, and J. Cao, "Self-supported cooperative networking for emergency services in multi-hop wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 450–457, Feb. 2012.

[16] F. Mansourkiaie and M. H. Ahmed, "Joint cooperative routing and power allocation for collision minimization in wireless sensor networks with multiple flows," *IEEE Wireless Commun. Lett.*, vol. 4, no. 1, pp. 6–9, Feb. 2015.

[17] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Standard 802.15.4, 2011.

[18] B. Han, J. Li, and J. Su, "Optimal relay node placement for multi-pair cooperative communication in wireless networks," in *Proc. IEEE WCNC*, Apr. 2013, pp. 4724–4729.

[19] F. Li and I. Nikolaidis, "On minimum-energy broadcasting in all-wireless networks," in *Proc. 26th Annu. IEEE Conf. Local Comput. Netw. (LCN)*, Nov. 2001, pp. 193–202.

Fatemeh Mansourkiaie received the B.Sc. and M.Sc. degrees in electronics and communications engineering from Iran in 2004 and 2008, respectively. She is currently pursuing the Ph.D. degree in electrical and computer engineering with the Memorial University of Newfoundland, St. John's, Canada. Her research interests are in the area of wireless communications, with a focus on cooperative communication, resource allocation, collision minimization, and wireless sensor networks.

Mohamed Hossam Ahmed (SM'07) received the B.Sc. and M.Sc. degrees in electronics and communications engineering from Ain Shams University, Cairo, Egypt, in 1990 and 1994, respectively, and the Ph.D. degree in electrical engineering from Carleton University, Ottawa, in 2001. He was a Senior Research Associate from 2001 to 2003. In 2003, he joined the Faculty of Engineering and Applied Science, Memorial University of Newfoundland, where he works currently as a Full Professor. He has authored over 120 papers in international journals and conferences. His research interests include radio resource management in wireless networks, multi-hop relaying, cooperative communication, vehicular ad-hoc networks, cognitive radio networks, and wireless sensor networks. He serves as an Editor of the IEEE COMMUNICATION SURVEYS AND TUTORIALS and an Associate Editor of the *International Journal of Communication Systems* (Wiley) and *Wiley Communication and Mobile Computing*. He served as a Guest Editor of the Special Issue on Fairness of Radio Resource Allocation of the *EURASIP Journal on Wireless Communications and Networking* in 2009, and the Special Issue on Radio Resource Management in Wireless Internet of the *Wireless and Mobile Computing Journal* (Wiley) in 2003. He served as the Co-Chair of the Signal Processing Track in ISSPIT'14 and the Transmission Technologies Track in VTC'10-Fall, and the Multimedia and Signal Processing Symposium in CCECE'09. He won the Ontario Graduate Scholarship for Science and Technology in 1997, the Ontario Graduate Scholarship in 1998, 1999, and 2000, and the Communication and Information Technology Ontario (CITO) Graduate Award in 2000. His research is sponsored by NSERC, CFI, Bell/Aliant, and other governmental and industrial agencies. He is a Registered Professional Engineer in the province of Newfoundland, Canada.