A Cooperative Communication Model Tailored for Energy Balance in Wireless Sensor Networks

Camila F. Rêgo, Rodrigo R. Bezerra, Jacir L. Bordim

Departamento de Ciência da Computação,
Universidade de Brasília,
Campus Darcy Ribeiro, Asa Norte
70910-900, Brasília - DF, Brazil
{crego,rodrigorozario}@aluno.unb.br, bordim@unb.br

and

Ulisses R. Afonseca

Instituto Federal de Goiás - Campus Luziânia,
Rua São Bartolomeu, s/n, Vila Esperança,
72811-580, Luziânia - GO, Brazil
urafonseca@ifg.edu.br

Abstract

Wireless Sensor Networks (WSN) are characterized by their capacity of monitoring the environment, gathering and sharing information. Nodes in a WSN usually cooperate in the task of forwarding the sensed data to a sink node for later retrieval and analysis. The success of this task depends on the availability of efficient routes that meet the application requirements. As topology may change overtime, alternatives to improve and maintain network connectivity are highly desired. In this context, Cooperative Communication (CC) emerged as an alternative to improve network connectivity. Despite its benefits, CC-links are known to have higher energy demands as compared to traditional, direct, links. In particular, CC-links require the source node to expend more power than others nodes, shortening their life span. The main contribution of this paper is to propose a new Cooperative Communication model, capable of increasing the energy balance of the CC-links while improving network connectivity. Simulation results show that, compared to other CC schemes, the source node of a Cooperative Communication reduces the amount of expended energy by 68% in the evaluated settings.

Keywords: Wireless sensor networks, cooperative communication model, energy balance.

1 Introduction

A Wireless Sensor Networks (WSN) is a special kind of ad hoc network where sensor nodes are responsible for sensing and monitoring the environment. These nodes usually operate on batteries and have a single transceiver capable of communicating over short distances. In addition, the sensor nodes cooperate to perform more complex tasks, such as perform data gathering and fusion as well as passing on information obtained from the environment to a sink node. A WSN usually comprises of one or more sink nodes, which are responsible for issuing queries and collect the sensed data. The sink node may have a larger antenna capable of reaching the sensor nodes of interest. In some situations, the sensors are located in inhospitable places, making it difficult to replace batteries during network operation. Thus, battery power becomes a critical resource that must be carefully managed to extend sensor's lifetime. Given its importance, several alternatives to improve and optimize energy consumption are investigated in the literature [1].

WSNs can be applied in different contexts, such as seismological monitoring, checking the presence of toxic gases, help identifying and issuing tsunami alerts, monitoring river banks and potential areas of landslide risk. In such cases, the application may require that the sensors transmit the information to a sink node as

fast as possible. The need to maintain or re-establish effective routes to a sink node in such cases can be crucial to the success of the actions to be triggered. This scenario becomes even more critical in the case of events that pose risk to the population that may require immediate action. In a WSN, sensors can become inoperative due to battery depletion, hardware failure, or external events. Thus, alternatives to maintain or re-establish network connectivity has been investigated and proposed. Khelifa et al. [2] proposed the use of dormant nodes that are activated in the event of link failure. In the same line, Goyal et al. [3] proposed the use of limited mobility to recover and coordinated connectivity in similar situations. Li et al. [4] propose the addition of a minimum set of nodes that allow the resulting network topology to be connected. Recently, Guerriero et al. [5] proposed a centralized scheme to determine the best locations to position sensor nodes to improve connectivity. The above works rely on node movements or the capability of inserting additional nodes to the locations of need. Such alternatives, however, require previous knowledge of the affected areas and may take a considerable amount of time to regain connectivity. Hence, the search for mechanisms that allow the increase of connectivity without the need for inclusion or movement of nodes are of great interest. In this context, the Cooperative Communication (CC) has been considered a viable alternative to allow nodes to improve network connectivity. CC is a physical layer technique that allows devices with a single antenna to enjoy some advantages of MIMO (Multiple Input, Multiple Output) systems [6].

In contrast to a direct, point-to-point, communication where a single source transfers data to a single destination, Cooperative Communication allows neighboring nodes to aid the source node in the transfer. CC can be viewed as two-stage communication. In the first stage, the source node transfers the data to a set of neighboring nodes. This set is commonly referred to as *helper nodes*. Next, the source node and its helpers cooperatively transfer the data to a selected destination node.

The benefits of Cooperative Communication include improved signal quality, higher transmission rates and transmission range extension. Song et al. [7] studied the properties related to connectivity in sparse and dense networks when CC is used. Several studies have explored the use of CC along with topology control techniques to reduce energy consumption. Alternatives to increase connectivity, even before operation, have been investigated. Neves et al. [8] proposed a cooperative mechanism to increase the connectivity of a WSN allowing the use of directional cooperative links to improve the connectivity to the sink node.

A Cooperative Communication link, hereafter denoted as CC-link, usually has a higher energy demand when compared to a direct communication link [8, 9, 10]. Thus, the use of CC-links must be carefully evaluated in order to prevent premature battery depletion. In fact, the CC model considered in [8, 9, 10], the source node ends up using more energy than its helpers. This energy imbalance in the CC-links leads to a faster drainage of battery resources. This, in turn, may affect the network connectivity that relies on CC-links. Furthermore, the unbalanced energy consumption may shorten the life span of the network nodes that participate in a CC-link.

This paper proposes a Cooperative Communication model aiming to reduce the energy consumption of the source node and minimize the effects of energy imbalance of the CC-links and a preliminary version of this work appeared in [11]. In the proposed scheme, the source and helper nodes consume a similar amount of energy to establish a CC-link. By providing a better usage of the energy resources, the source node and its helpers may prolong the life span of the cooperative link. A direct benefit of this approach is to extend the lifetime of the network as well as improve its connectivity by prolonging the availability of the CC-links. The proposed model is compared to the traditional CC-model considered in [9, 10, 8]. These models are evaluated with three different topology control mechanisms: *CoopSink* [8], *CSC* and *CSC-HS* [12]. The evaluation results include the following yardsticks: energy consumption, network connectivity, number of transmissions, distance to reach the sink node and energy balance. When using the traditional CC model with *CoopSink*, the results show that the source node spends 40.71% more power than its helpers. In contrast, when the proposed CC model is used, the source node spends, on average, 34.26% less energy than its helpers. The results for *CSC* and *CSC-HS* show similar results, which denotes that the proposed scheme reduces the energy burden on the source node, improving the availability of the CC-links.

The remainder of this paper is organized as follows. Section 2 presents the network model and the traditional Cooperative Communication model. Also, this section presents a heuristic for selecting the best helpers to compose a CC-link with reduced energy consumption. Section 3 shows the formulation of the problem and details the proposed Cooperative Communication model. Section 4 details the evaluation scenario and metrics used to evaluate the proposed CC-model. Finally, Section 5 concludes this document.

2 Cooperative Communication

This section presents a brief overview of the correlate literature on Cooperative Communication models. More precisely, the Cooperative Communication model presented in the following sections are similar to those in [8, 9, 13].

2.1 Network model

The network topology is modeled as a planar graph $G = (V, E)$, where $V = \{v_1, v_2, \dots, v_n\}$ is a set of wireless nodes and E is the set of communication links. An edge $v_i v_j \in E$ denote that node v_i can transmit data to v_j . Each node $v_i \in V$ has a unique radio, runs on battery power and has 1-hop information. The set $N(v_i)$ is the direct neighbor set of v_i within its maximum transmission range R_{MAX} . For every $v_k \in N(v_i)$, there is $P_i \leq P_{MAX}$ such that $P_i(d_{i,k})^{-\alpha} \geq \tau$, following Inequality (1).

$$P_i(d_{i,j})^{-\alpha} \geq \tau \quad (0 \leq P_i \leq P_{MAX}), \quad (1)$$

where α is the path loss exponent, usually between 2 and 4, and represents the rate of signal fading with increasing distance; $d_{i,j}$ is the Euclidean distance between v_i and v_j ; and τ is the receiver sensitivity to correctly receive a packet, i.e., the threshold of the received power so that node v_j can correctly decode the signal and obtain the original message.

The following definitions are used throughout this paper:

Definition 1 (*Direct link*) A direct link $\overline{v_i v_j}$ is an edge in E representing that node v_i can transmit data to node v_j directly, that is, P_i is such that v_i can reach v_j when $P_i \leq P_{MAX}$. A solid horizontal line over the nodes denote a direct link.

For each link $v_i v_j \in E$, we define the link weight $w(v_i v_j)$ which represents the minimum total energy consumption (i.e., total transmission power) needed to maintain the link $v_i v_j$. The definitions of direct link weight and CC-link are shown next.

Definition 2 (*Direct link weight*) The weight of a direct link $\overline{v_i v_j}$ is defined as:

$$w(\overline{v_i v_j}) = \tau d_{i,j}^\alpha. \quad (2)$$

In this work, we assume a limited regime of interference, where the noise is small compared with the signal. Additionally, it is only considered the signal fading and its effect on a small scale is not considered in this model.

Cooperative Communication (CC) takes advantage of the physical layer design to combine partial signals to obtain complete information [14]. A CC-link between nodes v_i and v_j can be established if v_i transmits its signal jointly with a set of *helper* nodes $H_{i,j}$ and the sum of their transmission power satisfies Inequality (3).

$$\sum_{v_k \in v_i \cup H_{i,j}} P_k(d_{k,j})^{-\alpha} \geq \tau \quad (0 \leq P_k \leq P_{MAX}). \quad (3)$$

Hence, a helper node is a node that cooperatively retransmit the signal along with the transmitting node. The following definitions are applied for cooperative links:

Definition 3 (*Helper set*) $H_{i,j}$ is the set of helper nodes of v_i in a Cooperative Communication with v_j . It is assumed that all helper nodes need to be direct neighbors of v_i , that is, $H_{i,j} \subseteq N(v_i)$, where $N(v_i)$ is the set of all direct neighbors of v_i .

Definition 4 (*CC-link*) A CC-link $\widetilde{v_i v_j}$ is an edge of E that represents that node v_i can transmit data to v_j cooperatively by using a set of helper nodes $H_{i,j}$.

Definition 5 (*Network topology*) The direct communication graph and the CC communication graph are denoted as $\overline{G} = (V, \overline{E})$ and $\widetilde{G} = (V, \widetilde{E})$, respectively. The network topology $E = \overline{E} \cup \widetilde{E}$, in $G = (V, E)$ is the union of all direct links and CC-links.

2.2 Traditional Cooperative Communication Model

In a CC link from v_i to v_j , node v_i must: (i) send its data to its helper nodes in $H_{i,j}$; and then (ii) node v_i and its helpers must simultaneously send the same data to v_j . This way, the weight of the CC-link consists of the sum of the communication costs of these two moments: $w_d(H_{i,j})$ is the cost of the first moment and $w_{CC}(H_{i,j})$ is the individual node cost to transmit a data over a CC-link. The following definitions are used to compute the energy cost of a CC-link.

Definition 6 (*CC-link weight*): The weight of a CC-link $\widetilde{v_i v_j}$ is defined as:

$$w(\widetilde{v_i v_j}) = w_d(H_{i,j}) + (|H_{i,j}| + 1)w_{CC}(H_{i,j}), \quad (4)$$

where:

Figure 1: Steps of Cooperative Communication technique using traditional CC model

- $|H_{i,j}|$: is the number of elements in $H_{i,j}$;
- $w_d(H_{i,j}) = \left(\frac{\tau}{\max_{v_k \in H_{i,j}} (d_{i,k})^{-\alpha}} \right)$: is the minimum transmission power of node v_i to communicate with the most distant node in $H_{i,j}$;
- $w_{CC}(H_{i,j}) = \left(\frac{\tau}{\sum_{v_k \in v_i \cup H_{i,j}} (d_{k,j})^{-\alpha}} \right)$: is the minimum transmission power of node v_i to communicate with v_j , jointly transmitting with its helpers in $H_{i,j}$

Note that, according to Inequalities (1) and (3), a CC-link exists when the following relation holds:

$$\max(w_d(H_{i,j}), w_{CC}(H_{i,j})) \leq P_{MAX}. \quad (5)$$

In this work, the Cooperative Communication model is simplified assuming that the transmission power of v_i and its helper nodes $H_{i,j}$ are the same.

The above model, referenced as “traditional CC model” in the rest of the paper, was applied in [8, 9, 10]. Figure 1 shows an example of the traditional CC model discussed above. Figure 1(a) shows a topology such that node v_1 can reach two nodes, v_2 and v_3 with direct communication links and has one node v_4 outside its transmission range. Node v_1 selects nodes v_2 and v_3 as helper nodes to transmit to v_4 , that is $H_{1,4} = \{v_2, v_3\}$. Following the traditional CC-model, node v_1 send its data to v_2 and v_3 as presented in Figure 1(b). Next, these three nodes send the same data, cooperatively, to node v_4 , as represented on Figure 1(c). If the signal receiver by v_4 is greater than τ , it can decode and the data transmitted by v_1 is received. This final step is illustrated in Figure 1(d).

To show the energy requirements of each node to establish a CC link, the scenario in Figure 2 will be analyzed. Consider that $P_{MAX} = (R_{MAX})^2$. The transmission power needed to establish a CC link between v_1 and v_4 ($v_1 v_4$) using $H_{1,4} = \{v_2, v_3\}$ as helper nodes is calculated below based on Equation (3).

$$\begin{aligned} P_1(d_{1,4})^{-2} + P_2(d_{2,4})^{-2} + P_3(d_{3,4})^{-2} &\geq 1 \\ P_1[(d_{1,4})^{-2} + (d_{2,4})^{-2} + (d_{3,4})^{-2}] &\geq 1 \\ P_1 &\geq \frac{1}{\left(\frac{1}{2R}\right)^2 + \left(\frac{1}{1.2R}\right)^2 + \left(\frac{1}{1.6R}\right)^2} \\ P_1 &\geq 0.7490R^2 \end{aligned} \quad (6)$$

Figure 2: Cooperative Communication scenario

From Inequality 6, it is implied that in the second moment of CC, all the nodes (v_1, v_2 e v_3) operate with the same power, i.e., $P_1 = P_2 = P_3$. In this case, $0.7490R^2 = 0.7490P_{MAX}$ which is the minimum transmission power needed in each node to fulfill the CC ($P_1 < P_{MAX}$). Each node belonging to the CC-link will transmit with at least 74.9% of its maximum transmission power P_{MAX} . Since the CC-link using the traditional CC model is viable, its cost is calculated according to Inequality 4 and is presented below.

$$\begin{aligned}\widetilde{v_1v_4} &= P_{MAX} + (|H_{ij}| + 1) \times P_1 \\ \widetilde{v_1v_4} &= P_{MAX} + (2 + 1) \times 0.7490R^2 \\ \widetilde{v_1v_4} &= 3.2470R^2 = 3.2470P_{MAX}\end{aligned}\tag{7}$$

The cost of the source node is calculated by the sum of the power required in the two moments of CC, i.e., the power need to reach the most distant helper node and power of the second moment P_1 calculated previously. The cost of the source node is presented in Equation 8.

$$\begin{aligned}w_{source} &= P_{MAX} + P_1 \\ w_{source} &= P_{MAX} + 0.7490P_{MAX}\end{aligned}\tag{8}$$

In this scenario, the source node uses its maximum transmission power in the first moment of CC and 74.9% in the second moment. Furthermore, the cost of each helper node is equal to $P_1 = 0.7490P_{MAX}$.

In order to use cooperative links, it is required to select the set of neighboring nodes that will cooperate. The following section presents a heuristic to select the helper set.

2.3 Helper Set Selection

The selection of auxiliary nodes is crucial to the performance of the network as suitable choices can increase the diversity gain. Thus, the selection of helper nodes in CC determines the system performance for some routing objectives such as energy efficiency, throughput and delay. However, the selection of the auxiliary set with the objective of minimize the total energy consumption while maintaining connectivity is an NP-complete problem [10]. Some heuristics have been proposed in the literature in order to obtain a set of helper nodes in polynomial time.

The helper set selection algorithm used in this work is the *Greedy Helper Set Selection (GHSS)* proposed in [9]. The *GHSS* is a heuristic that computes a set of nodes auxiliary in polynomial time in order to reduce individual consumption of nodes. The algorithm takes as input a source node v_u ; a destination node v_v ; the set of neighboring nodes of origin, denoted $N(v_u)$. Distances $d_{u,v}$, $d_{u,i}$ and $d_{v,i}$ to $v_i \in N(v_u)$, should be known. The algorithm output is the estimated cost for the cooperative link $\widetilde{v_uv_v}$. Initially, the heuristic considers the transmission power needed by the source node, using a specific neighbor as helper, and the power required to send the data to the helper. Neighboring nodes are added to the auxiliary set if their inclusion does not incur an increase in communication power. The nodes use the same transmission power during cooperation phase. Thus, by adding more nodes to the set of auxiliary nodes, the individual transmission power is reduced.

2.4 Topology Control

Topology control is the activity of controlling the communication links on the network by adjusting the transmission power and the communication distance between nodes in order to maintain some global network property [15]. In this work we considered three topology controls proposed in the literature that are applicable to networks supporting Cooperative Communication:

- *CoopSink* [8]: centralized topology control technique for sensor networks that create efficient routes to the sink node. The traditional CC model is used to increase network connectivity and topology control reduces the energy consumption of nodes while maintaining energy-efficient routes to the sink;
- *CSC* [12]: centralized topology control technique for sensor networks that create routes that reduce the end-to-end delay to the sink node. The traditional CC model is used to increase the network connectivity and topology control is used to create routes with fewer hops to the sink, thus reducing the end-to-end delay;
- *CSC(HS)* [12]: centralized topology control technique for sensor networks that create routes that minimize the number of transmissions to the sink. Traditional CC model is used to increase the network connectivity and topology control is used to reduce the amount of required transmissions to reach the sink node to reduce power consumption and the end-to-end delay.

The aforementioned topology control mechanisms are illustrated in the Figure 3. Figure 3(a) presents the original topology with 70 randomly distributed nodes in an area of $500 \times 500\text{m}$ with direct and cooperative edges represented in black and gray, respectively. Figures 3(b), 3(c) and 3(d) present the resulting topology after applying *CoopSink*, *CSC* and *CSC(HS)*, respectively. We observed that the use of the traditional CC model increases network connectivity since isolated nodes become able to communicate and send data to sink node through cooperative edges. Additionally, *CoopSink* uses less cooperative links than *CSC* and *CSC(HS)*. The higher number of links result into a higher number of routes and the reduction of energy consumption by selecting more efficient routes.

Figure 3: (a) Original topology with 70 nodes distributed in a $500 \times 500\text{m}$ area with direct links in black and CC-links in gray. (b) *CoopSink*; (c) *CSC* and (d) *CSC(HS)*

3 Proposal

This work considers a WSN in which the sensor nodes cooperate to gather and relay information to a central unit, called sink node. The sink node is responsible to request and receive information from other nodes. Furthermore, each node in the network should be connected and its data should be transmitted to the sink as fast as possible and with minimum communication cost as possible. CC-links should be balanced such the source node and the helper nodes spend nearly the same amount of energy. To show the difference between how much transmission power is required by the source node and the helper node to establish a CC-link, let us consider the scenario in the Figure 2. In both moments of CC, the source node spend 174.9% and each helper node spend 74% of its maximum transmission power. In such case, the source node depletes its battery before the helper nodes, which makes the CC-link not viable and could disconnect part of the network. In order to avoid or minimize this problem, this work aims to:

- Propose a new CC model in order to increase the connectivity while maintaining the CC-links balanced.
- Compare the traditional CC model with the proposed CC model employing the topology control techniques presented in Section 2, namely *CoopSink*, *CSC* e *CSC(HS)*.

3.1 Proposed CC Model

The proposed CC model follows the concepts presented in the Section 2. Similar to the traditional CC model, in the first moment of CC, the source node sends the data to the helper nodes using the minimum power to reach the most distant node. The proposed CC model differs from the traditional CC model in the execution of the second moment of the CC. In the proposed model, the helper nodes send the data to the destination node, without the participation of the source node. Furthermore, the main difference to the traditional CC model is that the source node only participates in the first moment of CC, saving energy and improving the energy balance of the CC-link.

Similar to the traditional CC model, the proposed CC model the CC link is feasible only if the sum of the power of each helper node satisfies the Inequality 9.

$$\sum_{v_k \in H_{i,j}} P_k(d_{k,j})^{-\alpha} \geq \tau \quad (0 \leq P_k \leq P_{MAX}). \quad (9)$$

Figure 4(a) shows the first moment of CC, which is the same for both models, where the source node v_1 transmits the data to the helper nodes v_2 e v_3 . Figure 4(b) shows the second moment of CC which the helper nodes v_2 e v_3 transmit the data to the source node v_4 , without the contribution from the source node v_1 . As result of the modification on the second moment of CC, the cost of the CC-link is calculated according to Definition 7.

Figure 4: Scenario of Cooperative Communication using the proposed CC model

Definition 7 (*CC-link weight*): The weight of a CC-link $\widehat{v_i v_j}$ is defined as:

$$w(\widehat{v_i v_j}) = w_d(H_{i,j}) + (|H_{i,j}|)w_{CC}(H_{i,j}), \quad (10)$$

- $|H_{i,j}|$: is the number of elements in $H_{i,j}$;
- $w_d(H_{i,j}) = \left(\frac{\tau}{\max_{v_k \in H_{i,j}} (d_{i,k})^{-\alpha}} \right)$: is the minimum transmission power of node v_i to communicate with the most distant node in $H_{i,j}$;

- $w_{CC}(H_{i,j}) = \left(\frac{\tau}{\sum_{v_k \in v_i \cup H_{i,j}} (d_{k,j})^{-\alpha}} \right)$: is the minimum transmission power of node v_i to communicate with v_j , jointly transmitting with its helpers in $H_{i,j}$.

The transmission power needed to establish a CC link between v_1 and v_4 ($\widetilde{v_1 v_4}$) in the scenario analyzed in Figure 2 using the proposed CC model is calculated below based on Equation 9.

$$\begin{aligned} P_2(d_{2,4})^{-2} + P_3(d_{3,4})^{-2} &\geq 1 \\ P_2[(d_{2,4})^{-2} + (d_{3,4})^{-2}] &\geq 1 \\ P_2 &\geq \frac{1}{((\frac{1}{1.2R})^2 + (\frac{1}{1.6R})^2)} \\ P_2 &\geq 0.9216R^2 \end{aligned}$$

In the above inequality, it is implied that in the second moment of CC, the helper nodes (v_2 e v_3) operate with the same power, i.e., $P_2 = P_3$. In this case, $0.9216R^2 = 0.9216P_{MAX}$ which is the minimum transmission power needed in each node to fulfill the CC ($P_2 < P_{MAX}$). Each node belonging to the CC-link will transmit with at least 92.16% of its maximum transmission power P_{MAX} . Since the CC-link using the proposed CC model is viable, its cost is calculated according to Equation 10 and is presented below.

$$\begin{aligned} \widetilde{v_1 v_4} &= P_{MAX} + (|H_{ij}|) \times P_1 \\ \widetilde{v_1 v_4} &= P_{MAX} + (2) \times 0.9216R^2 \\ \widetilde{v_1 v_4} &= 2.8432R^2 = 2.8432P_{MAX} \end{aligned}$$

The cost of the source node is calculated by the power needed only in the first moment of CC, i.e., only the power need to reach the most distant helper node. The cost of the source node is presented in Equation 11.

$$w_{source} = P_{MAX} \quad (11)$$

Using the proposed CC model the power consumption of the source node decreased from $1.749 \times P_{MAX}$ to only P_{MAX} and energy consumption of the each helper node increased from 74.90% to 92.16%. In this work, the *energy balance* is defined as the ratio between the cost of the source node and the cost of each auxiliary node. Using the traditional CC model the energy balance is 2.23, meaning that the source node spend 2.23 times more energy than the helper nodes. Using the proposed CC model the energy balance is 1.08. In such scenario, the energy balance using the proposed CC model is closest to 1, meaning that the source node and its helpers expend a similar amount of energy.

4 Simulations Results

In order to evaluate the CC models as well as the topology control techniques, a simulator was developed in Matlab where the algorithms were implemented. Similar to [9, 10, 12], the simulation process uses the following parameters: $n = 20, 30, \dots, 100$ nodes randomly positioned in a 500×500 m area; sink node v_1 is fixed at position (250, 250). The fading coefficient is equal to 2; $P_{MAX} = 4900$ and $R_{MAX} = 70$ m. Additionally, every resulting topology has at least one CC-link, simulation results are drawn from an average of 500 simulations and the confidence interval is 95%. The following metrics were used to evaluate the presented algorithms:

- **M1 - Average number of hops to reach the sink node:** the CC, independently of the model utilized, occurs in two steps which can be seen as two virtual hops: in the first hop, the source node send the data to the helper nodes and in the second hop the data is sent to destination node;
- **M2 - Average number of transmissions to reach the sink node:** when node v_i with the helper set $H_{i,j}$ tries to reach a destination node v_j , a total of $|H_{i,j} + 2|$ transmissions are needed when using traditional CC model and $|H_{i,j} + 1|$ transmissions when using the proposed CC model. Thus, the average number of transmissions needed to reach the sink node shows the power consumption in each strategy;

- **M3 - Connectivity with sink node:** this metric present a comparison of the connectivity with the sink node in the original topology and using both CC models;
- **M4 - Average cost of cooperative links:** Usually, Cooperative Communication is more costly than traditional direct transmission and the number of CC-links tends to vary depending of the model and topology control utilized. This metric presents a comparison between the CC models and the topology control techniques: *CSC*, *CSC(HS)* and *CoopSink*;
- **M5 - Average cost of the source node:** this metric is defined as the sum of the cost of the first and second moment of CC to all source node divided by the total number of CC-links as shown in Equation 12.

$$C_{source} = \frac{\sum_{\widetilde{v_i v_j} \in \widetilde{E}} w_d(H_{i,j}) + w_{cc}(H_{i,j})}{|\widetilde{E}|}, \quad (12)$$

where w_d and w_{CC} are presented in Definition 6 for the traditional CC model and in Definition 7 for the proposed CC model. Additionally, $|\widetilde{E}|$ is the number of CC-links in a resulting topology.

- **M6 - Average cost of helper nodes:** the cost of each helper node belonging to a CC-link is given by $w_{CC}(H_{i,j})$ from Equation 4 for the traditional CC model and Equation 10 for the proposed CC model. Thereby, we can define the average cost of the helper nodes as the sum of the cost of each helper node in a CC-link divided by the total quantity of CC-links as shown in Equation 13

$$C_{aux} = \frac{\sum_{H_{i,j} \in \widetilde{E}} w_{CC}(H_{i,j})}{|\widetilde{E}|}, \quad (13)$$

where $w_{CC}(H_{i,j})$ is the cost of the second moment of CC to each helper node and $|\widetilde{E}|$ is the number of CC-links in the resulting topology.

- **M7 - Energy balance of the CC-link:** this metric presents the energy ratio between the average cost of the source node (C_{source}) and the average cost of the helper nodes (C_{aux}) in order to demonstrate the energy balance of the CC-link. This metric is calculated using the Equation 14.

$$\text{Energy Balance} = \frac{C_{source}}{C_{aux}} \times 100. \quad (14)$$

$$\text{M7} \begin{cases} = 1 & \text{ideal energy balance;} \\ > 1 & \text{source node spend more energy than helper nodes;} \\ < 1 & \text{helper nodes spend more energy than source node.} \end{cases} \quad (15)$$

- **M8 - Average cost of route to the sink node:** this metric consists in the average of power needed to each node $v_i \in G$ reach the sink node.

Figure 5: Example of average cost of route to the sink node

Figure 5 presents an example of the average cost of route to the sink node calculation. This scenario shows three sensor nodes: v_1 , v_2 and v_3 and sink node v_0 . The route from node v_1 to sink node is composed by the cooperative link CC1, the direct link D1 and the cooperative link CC2. The route from node v_2 to sink node is composed by the direct link D1 and the cooperative link CC2. Also, the route from node v_3 to sink node is composed only by the cooperative link CC2. The cost of the direct link D1 is given by Equation 2 so that the cost of D1 is $w(\overline{v_2 v_3})$. The cost of CC-links are given by

Equations 4 and 10 depending on the model. In that way, the cost of CC1 and CC2 are $w(\widetilde{v_1v_2})$ and $w(\widetilde{v_3v_0})$, respectively. Thus, the average cost of route to the sink node can be computed as follows:

$$\begin{aligned} \mathbf{M8} &= (r_{v_1,v_0} + r_{v_2,v_0} + r_{v_3,v_0})/3, \\ &= w(\widetilde{v_1v_2}) + 2 \times w(\widetilde{v_2v_3}) + 3 \times w(\widetilde{v_3v_0})/3, \end{aligned}$$

where r_{v_i,v_j} represents the route from node v_i to node v_j .

The average cost of route to the sink node is calculated by the sum of the cost of the links in each route to the sink node divided by the number of routes to the sink.

The following results present the combination of topology control techniques: *CSC*, *CSC(HS)* and *CoopSink* with traditional CC model and the proposed CC model. Additionally, the *GHSS* heuristic is used to select helper nodes in both models. This techniques and models are evaluated based on metrics M1 to M8.

4.1 Average number of hops to reach the sink node (M1) and Average number of transmissions to reach the sink node (M2)

Figure 6 presents the results for metrics M1 and M2. In Figure 6(a), the y-axis shows the number of hops that each technique needs to reach the sink node while Figure 6(b) shows the average number of transmissions to reach the sink node. In metric M1, among all the topology control techniques analyzed the *CSC* obtains a reduction in the number of hops, independently of the CC model used. More specifically, compared to *CoopSink*, *CSC* can reduce up to 54.15% the number of hops to reach the sink node which results in a reduction in the overall end-to-end delay. Regarding to metric M2, *CSC(HS)* reduces the number of transmissions to reach the sink node, which is more evident after 50 nodes. In the best case scenario, *CSC(HS)* reduces up to 40.04% the number of transmissions to reach the sink node compared to *CoopSink*.

Except from *CoopSink*, the traditional CC model was able to reduce the number of hops compared to the proposed CC model regardless of network density. This is due to the fact that this model creates more CC-links, which increases connectivity and allows to reduce the number of hops to reach the sink node. In the case of *CoopSink*, this technique aims to reduce the energy to reach the sink by creating short edges. Thus, with the increase of connectivity by the use of the traditional CC model, the nodes are further from the sink in terms of number of hops. The proposed CC model tends to use more helper nodes than the traditional model to create the same CC-link, which causes to increase the number of transmissions to reach the sink node as shown in Figure 6(b).

Figure 6: (a) Simulation results for the metric average number of hops to reach the sink node; (b) Simulation results for the metric average number of transmission to reach the sink node

4.2 Connectivity with the sink node (M3)

Figure 7 presents the results of the metric M3. The y-axis shows the amount of network nodes that have connectivity to the sink node in percentage. As the topology control techniques does not influence the

connectivity, only the comparative results of the traditional CC model and the proposed CC model are presented. Between 20 and 70 nodes, the traditional model shows better results than the proposed model, with connectivity gain up to 134% compared to the original topology which does not use cooperative links. After 70 nodes, the traditional and proposed models have similar results.

Figure 7: Connectivity with the sink node (M3)

4.3 Average cost of cooperative links (M4)

Figure 8 presents the simulation results of metric M4 and the y-axis shows the average energy cost. The proposed CC model provides a reduction of the average cost of cooperative links for both *CSC* and *CSC(HS)*. These techniques tend to use more CC-links and more helper nodes which results in CC-links with higher range. The exclusion of the source node from the first moment of CC and, consequently, an inclusion of helper nodes results in CC-links with lower average cost. However, *CoopSink* with the traditional model provides a lower cost of the CC-link since this technique aims to reduce the total energy cost to reach the sink node.

Figure 8: Average cost of cooperative links (M4)

4.4 Average cost of source nodes (M5) and average cost of helper nodes (M6)

Figure 9 presents the simulation results of metrics M5 and M6. The y-axis shows the average energy consumption for both metrics. As shown in Figure 9(a), the traditional CC model significantly reduces the average cost of the source node compared to traditional model which follows from the fact that the source node does not participate in the second moment of CC. In the best case, at 100 nodes, *CoopSink* combined with the proposed CC model can reduce the average cost of the source node in 68.69%. For all topology control techniques, the uses of the proposed model results in a reduction of the average cost of the source nodes. As shown in Figure 9(b) the average cost of helper nodes tends to reduce as the network density increases. From 20 to 40 nodes, i.e., in sparse networks, the average cost of helper nodes is superior when using the proposed CC model if compared to the traditional model. This occurs since the source node does

not participate in the second moment of CC and there is not many neighboring nodes available to act as helper nodes. From 40 nodes, analyzing each topology control technique separately, the proposed model provides a reduction in the cost of the helper nodes since the proposed model uses more helper nodes than the traditional model and thus better distributes the cost of the cooperative link between helper nodes.

Figure 9: Average cost of communication of (a) source nodes and (b) helper nodes

4.5 Energy balance of the CC-link (M7)

Figure 10 shows the simulation results of metric M6. The y-axis shows the ratio of the average cost of communication and the ideal ratio is shown as a horizontal green line that cuts the y-axis at 1. Above the green line are presented the techniques where the source node spends more energy than the helper nodes and below the green line are presented the techniques which source node spends less energy than its helpers. In the best case of the traditional CC model, i.e. *CoopSink*, the source node spends, on average, 40.71% more energy than the helper nodes. The proposed model with the topology control technique *CSC*, the source node spends 23.27% less energy than the helper nodes on average. The best case scenario at 30 nodes, the source node spends 19.89% less energy than the helpers nodes which is closer to the ideal energy balance. Note that the topology control techniques using the proposed CC model are closer to the energy balance because the source node only participates in the first moment of CC.

Figure 10: Energy balance of the CC-link (M7)

4.6 Average cost of route to the sink node (M8)

Figure 11 presents the simulation results of metric M8. Since *CoopSink* aims to reduce the total energy to reach the sink node, it has the lowest average cost to route the sink node. However, in the worst-case scenario, *CSC(HS)* spends only 13.35 more energy than *CoopSink*. For *CoopSink* and *CSC(HS)*, the results of the proposed CC model and traditional model are very similar. However, the use of the proposed model with *CSC* results in lower route cost to reach the sink node.

Figure 11: Average cost of route to the sink node (M8)

5 Conclusion

This work proposed a new Cooperative Communication energy model in the context of a Wireless Sensor Networks. This new model aims to reduce the energy consumption on the source node and promotes energy balanced CC-links. The proposed model was compared to the traditional CC model along with three topology control techniques: *CoopSink*, *CSC* and *CSC(HS)*. The traditional model presents higher connectivity gain in sparse networks, but as the network density increases, the traditional and the proposed models have similar results. Additionally, the difference in connectivity between the proposed model and the traditional model is approximately 1% at 100 nodes. The proposed CC model provides a reduction of the cost of the source nodes up to 68.69% when compared to the traditional model. The topology control techniques that use the proposed CC model are closer to the ideal energy balance than when using the traditional model. Furthermore, in the best case scenario, the source node will spend 19.89% less energy than the helper nodes when using CSC with the proposed CC energy model. Thus, the results show a compromise between connectivity and communication cost, and scenarios with higher density have better results in the application of the proposed CC model. The selection of topology control technique depends largely on the application of focus: energy conservation (*CoopSink*), delay (*CSC*), or energy and delay (*CSC(HS)*). This work serves as a resource for decision based on the needs of the application of which CC model and topology control technique is more adequate.

Acknowledgments

This work was partially supported by CAPES (Coordenadoria de Aperfeiçoamento de Pessoal de Nível Superior), CNPq (Conselho Nacional de Pesquisa) and University of Brasília (UnB).

References

- [1] P. Mohapatra and S. V. Krishnamurthy, *Ad Hoc Networks - Technologies and Protocols*. Springer Science + Business Media, Inc. chapters 1, 3, 6, 2005.
- [2] B. Khelifa, H. Haffaf, M. Madjid, and D. Llewellyn-Jones, "Monitoring connectivity in wireless sensor networks," in *2009 IEEE Symposium on Computers and Communications*, July 2009, pp. 507–512. [Online]. Available: <http://dx.doi.org/10.1109/ISCC.2009.5202236>
- [3] D. Goyal and J. Caffery, "Partitioning avoidance in mobile ad hoc networks using network survivability concepts," in *Proceedings ISCC 2002 Seventh International Symposium on Computers and Communications*, 2002, pp. 553–558. [Online]. Available: <http://dx.doi.org/10.1109/ISCC.2002.1021729>
- [4] N. Li and J. Hou, "Improving connectivity of wireless ad hoc networks," in *Mobile and Ubiquitous Systems: Networking and Services, 2005. MobiQuitous 2005. The Second Annual International Conference on*, July 2005, pp. 314–324. [Online]. Available: <http://dx.doi.org/10.1109/MOBIQUITOUS.2005.32>
- [5] F. Guerriero, A. Violi, E. Natalizio, V. Loscri, and C. Costanzo, "Modelling and solving optimal placement problems in wireless sensor networks," *Applied Mathematical Modelling*, vol. 35, no. 1, pp. 230 – 241, 2011. [Online]. Available: <http://dx.doi.org/10.1016/j.apm.2010.05.020>

- [6] J. Yu, H. Roh, W. Lee, S. Pack, and D. Z. Du, "Topology control in cooperative wireless ad-hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 9, pp. 1771–1779, October 2012. [Online]. Available: <http://dx.doi.org/10.1109/JSAC.2012.121022>
- [7] S. Song, D. L. Goeckel, and D. Towsley, "Collaboration improves the connectivity of wireless networks," in *Proceedings IEEE INFOCOM 2006. 25TH IEEE International Conference on Computer Communications*, April 2006, pp. 1–11. [Online]. Available: <http://dx.doi.org/10.1109/INFOCOM.2006.121>
- [8] T. Neves and J. Bordim, "Topology control in cooperative ad hoc wireless networks," *Electronic Notes in Theoretical Computer Science*, vol. 302, pp. 29–51, 2014. [Online]. Available: <http://dx.doi.org/10.1016/j.entcs.2014.01.019>
- [9] J. Yu, H. Roh, W. Lee, S. Pack, and D. Z. Du, "Cooperative bridges: Topology control in cooperative wireless ad hoc networks," in *2010 Proceedings IEEE INFOCOM*, March 2010, pp. 1–9. [Online]. Available: <http://dx.doi.org/10.1109/INFCOM.2010.5462126>
- [10] Y. Zhu, M. Huang, S. Chen, and Y. Wang, "Energy-efficient topology control in cooperative ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 8, pp. 1480–1491, Aug 2012. [Online]. Available: <http://dx.doi.org/10.1109/TPDS.2011.293>
- [11] C. F. Rêgo, R. R. Bezerra, U. R. Afonseca, and J. Bordim, "Modelos de comunicação cooperativa e equidade no consumo de energia em enlaces cooperativos aplicados à rssf," in *CLEI 2016 - SLIHS ()*, oct 2016. [Online]. Available: <http://www.clei2016.cl/>
- [12] C. Rego, T. Neves, U. Afonseca, and J. Bordim, "Exploring cooperative communication to establish energy-and-delay aware routes in wsns," in *Second International Symposium on Computing and Networking (CANDAR), 2014*, Dec 2014, pp. 205–211. [Online]. Available: <http://dx.doi.org/10.1109/CANDAR.2014.55>
- [13] Z. Zhou, S. Zhou, J. H. Cui, and S. Cui, "Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 8, pp. 3066–3078, August 2008. [Online]. Available: <http://dx.doi.org/10.1109/TWC.2008.061097>
- [14] A. K. Sadek, W. Su, and K. J. R. Liu, "Multinode cooperative communications in wireless networks," *IEEE Transactions on Signal Processing*, vol. 55, no. 1, pp. 341–355, Jan 2007. [Online]. Available: <http://dx.doi.org/10.1109/TSP.2006.885773>
- [15] P. Santi, "Topology control in wireless ad hoc and sensor networks," *ACM Comput. Surv.*, vol. 37, no. 2, pp. 164–194, Jun. 2005. [Online]. Available: <http://dx.doi.org/10.1145/1089733.1089736>