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Topology Control in Cooperative Ad Hoc Wireless Networks

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**Abstract**

Cooperative communication (CC) is a technique that exploits spatial diversity allowing multiple nodes to cooperatively relay signals to the receiver so that it can combine the received signals to obtain the original message. CC can be combined with topology control to increase connectivity at the cost of a small increase in energy consumption. This work focuses on exploring CC to improve the connectivity with a sink node in ad hoc wireless networks. More precisely, this work proposes a new technique, named CoopSink, that combines CC and topology control techniques to increase connectivity to a sink node while ensuring energy- eﬃcient routes. Simulation results show that connectivity and routing to the sink cost can be improved up to 6*.*8 and 2*.*3 times, respectively, when compared with other similar strategies.

*Keywords:* Topology Control, Wireless Networks, Network Protocols, Cooperative Communication.

# 1 Introduction

Ad hoc wireless networks are networks where the nodes can communicate with each other without resorting to a centralised infrastructure. These networks have a large number of civil and military applications, ranging from communication sup- port in battlefield, search and rescue operations to object monitoring and tracking. One of the major challenges in ad hoc networks is to reduce energy consumption as these nodes are often powered by batteries [[2](#_bookmark26)]. As battery replacement may not be a feasible option during operation, alternatives to improve and optimize energy expen- diture in wireless networks are of great interest. This facts have driven the quest for power saving strategies aiming to extend the network lifetime [[25](#_bookmark50),[5](#_bookmark30)]. These energy saving proposals can be grouped in two main categories: (*i*) techniques that allow the nodes to alternate between active/idle operational modes; and (*ii*) techniques that allow the nodes to adjust their transmission power. Recent works in the first

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category can be found in [[34](#_bookmark57),[9](#_bookmark34),[30](#_bookmark55)]. Topology control strategies fall in the second category and have been largely explored in the literature [[22](#_bookmark47),[8](#_bookmark33)]. Topology control consists in allowing wireless nodes to select a subset of neighbouring nodes and/or adjust the transmission power with the objective of reducing energy consumption while maintaining network connectivity [[7](#_bookmark31),[3](#_bookmark27),[23](#_bookmark48)].

In traditional multiple-hop wireless networks, intermediate nodes cooperate with each other to assist in the task of relying data packets from a source node to the desired destination. Note that this process occurs at the network layer. Cooperative communication (CC), on the other hand, is a physical layer technique that allows single antenna devices to benefit from some advantages of Multiple-Input Multiple- Output (MIMO) systems by exploring the spatial diversity [[28](#_bookmark53)]. This technique allows nodes to improve signal quality and transmission range. In CC, when a

source node transmits a packet, a set of *helper nodes* in the vicinity of the source

overhear the signal and, simultaneously, relay independent copies of the same signal to the destination node. The destination node then combines the received signals to obtain the original packet.

Recent works have explored CC with topology control techniques to reduce en- ergy consumption [[5](#_bookmark30)]. Ways to increase network connectivity and improve network lifetime has been investigated [[35](#_bookmark58),[33](#_bookmark59)]. However, to the best of our knowledge, no work so far explored CC to increase the connectivity to the sink in ad hoc wireless networks. Link failure due to battery depletion and node failure may prevent wire- less nodes to reach the sink. In this context, CC can be explored to improve network connectivity and to allow the establishment of alternative routes to the sink node.

This work presents a new technique, named CoopSink, that combines CC and topology control in an ad hoc wireless network to increase connectivity to the sink while ensuring energy efficient routes. This proposal could be applied to the envi- ronment described in [[4](#_bookmark29)], where there is a sink node equipped with a large range radio for query broadcast and the nodes cooperate to overcome link failures and report information to the sink. This scenario is similar to that found in the Amazon Tall Tower Observatory (ATTO) project, where the objective is to position a high central tower in the middle of the Amazon forest and, with the help of smaller and strategically placed sensors, to obtain reliable estimates of sources of greenhouse gases like *CO*2, *CH*4 and *N*20 [[24](#_bookmark49)]. The proposed technique has been evaluated through simulation and the results have confirmed that CoopSink is able to improve network connectivity and provide energy-efficient routes to the sink. More precisely, the simulation results show that connectivity and routing to the sink improved up to 6*.*8 and 2*.*3 times, respectively, as compared with other similar strategies.

The remaining of this paper is organised as following. Section [2](#_bookmark2) makes an overview of related works on topology control and cooperative communication. Sec- tion [3](#_bookmark4) describes the communication and network models and formalises the main problem addressed in this work. Section [4](#_bookmark14) describes the CoopSink protocol and Section [5](#_bookmark16) presents the simulation results that compares the proposed scheme with other similar and prominent strategies. Section [6](#_bookmark25) concludes the work.

This section presents a brief review of the closely related works that explore topology control and cooperative communication in wireless networks.

* 1. *Topology Control*

Topology Control is a technique that alters the network topology based on some given conditions. For instance, topology control can be used to optimize network power consumption, reduce routing cost and the number of control messages, im- prove throughput or meet certain QoS requirements [[5](#_bookmark30),[15](#_bookmark40),[11](#_bookmark35)].

According to [[5](#_bookmark30)], topology control protocols can be classified as: (*i*) centralised; or (*ii*) distributed. Centralised protocols consider that global information is avail-

able, such as topological information, routing information, global memory status, and so on. However, even when global information is at hand, it has been proven that finding strongly connected topologies with minimum total energy consumption is a NP-complete problem [[6](#_bookmark32)]. Among centralised protocols, Ramanathan et al. [[27](#_bookmark51)] proposed alternatives to optimize network connectivity while improving network lifetime. Distributed protocols consider *k*-hop neighbouring information, where *k* is typically one or two. Li et al. [[20](#_bookmark45)] propose a cone-based algorithm for TC that aims to optimize energy consumption while maintaining network connectivity. To achieve this, each node adjusts its transmitting power to cover a number of neighbouring nodes, under the condition that they lay at most *α* degrees apart from each other.

The authors show that a degree of *α* = 5*π* is enough to preserve network connec-

6

tivity. Several optimized solutions of the basic algorithm are also discussed and a beacon-based protocol is defined for topology maintenance. In a more recent work, Li et al. [[21](#_bookmark46)] proposed a Localised Minimum Spanning Tree (LMST) algorithm. The LMST works by having each node building a localised MST based on 1-hop neigh- bouring information. The final topology is constructed so that the maximum node degree is 6. Comprehensive surveys can be found in [[22](#_bookmark47),[14](#_bookmark36)].

* 1. *Cooperative Communication (CC)*

Cooperative communication (CC) is a technique introduced by [[19](#_bookmark44)] and [[26](#_bookmark52)] that allow single antenna devices to explore characteristics of MIMO systems. In coopera- tive communication, a set of nodes transmit independent copies of the original signal. The intended receiver obtain independent versions of the transmitted signal which reduces the fading effect through multi-path propagation. In this communication model, each wireless node is assumed to transmit data and to act as a cooperative agent, relaying data from other users. CC was previously used in energy efficient broadcasting [[1](#_bookmark28)], constructing connected dominating sets [[32](#_bookmark60)], routing [[17](#_bookmark42)], among others applications.

CC techniques can be classified as *amplify-and-forward* and *decode-and- forward* [[19](#_bookmark44)]. In the former, a node that receives a noise version of the signal, amplify and relay this noisy version. The receiver then combines the information

sent by both sender and relay nodes. When decode-and-forward is employed, a relay node must first decode the signal before retransmitting it. As the cost of a CC-link area usually higher than conventional links, ways to select suitable nodes is usually employed. Among the techniques used to identify the best set of relay nodes are received Signal-to-Noise Ratio (SNR) and/or remaining battery energy.

This work considers cooperative communication employing *decode-and- forward* approach where the relay nodes are selected based on the SNR of the received

signal. This technique requires each node to have a dedicated memory to store data packet and a signal processor that can estimate the SNR of each received packet as in [[19](#_bookmark44)].

* 1. *Topology Control in Cooperative Ad Hoc Networks to Extend the Link Coverage*

Few works in the literature have considered the use of topology control and CC to improve network coverage in ad hoc networks. The possibility of link coverage extension using CC was investigated in [[18](#_bookmark43),[31](#_bookmark56)]. In this context, Cardei et al. [[5](#_bookmark30)] studied the use of topology control combined with CC with the objective of obtain- ing strongly connected topologies with minimum energy consumption. The authors showed that this problem is NP-complete and two localised and distributed algo- rithms were proposed. Both algorithms take as input the result of a traditional topology control algorithm (without CC). The first algorithm uses a distributed de- cision process where each node uses information of neighbours with at most two hops. The second algorithm iteratively assigns transmission power to the nodes, using one hop neighbour information.

Yu et al. [[33](#_bookmark59)] proposed a centralised topology control scheme aiming to increase network connectivity and reduce transmission power. To minimise the number of cooperative communication links (CC-links) and to reduce transmission cost, a poly- nomial and an exponential (but optimal) helper decision algorithms were proposed. Zhu et al. [[35](#_bookmark58)] consider the problem of selecting energy efficient paths when CC-links are used. The authors propose two topology control algorithms to build cooperative energy spanners in which the energy efficiency of individual paths are guaranteed. Both algorithms can be executed in a distributed or localised fashion. The work in [[33](#_bookmark59)] focus on maintaining network connectivity with the objective of minimising global energy consumption. Similarly, the work in [[35](#_bookmark58)] focused on reducing energy consumption by selecting efficient routes.

In ad hoc settings, link failure due to battery depletion and node failure may prevent wireless nodes to reach the desired destination. In this context, CC can be explored to improve network connectivity and to allow the establishment of more efficient routes. This work addresses this problem. To the best of our knowledge, this is the first work to explore the use of CC-links to improve network connectivity to a sink node in a wireless ad hoc networks.

# Network Model and Problem Definition

This section first describes the CC model and the corresponding network model that are used in this work. In a second moment, the model is exemplified and the main problem of this work is formalised. The model defined in this section is similar to that used in [[5](#_bookmark30),[33](#_bookmark59),[35](#_bookmark58)].

* 1. *CC model*

Consider a wireless ad hoc network where each node *vi* can adjust its transmission power *Pi* with values within the interval [0*, PMAX* ]. When *Pi* = 0, the node’s radio is off and, when *Pi* = *PMAX* , the node’s radio operates with maximum power. In traditional cooperative communication models, a sender node *vi* can directly communicate with a receiver node *vj* only if the transmission power of *vi* satisfies Equation [1](#_bookmark5).

*Pi*(*di,j*)*−α ≥ τ* (0 *≤ Pi ≤ PMAX* )*,* (1)

where: *α* is the path loss exponent, usually between 2 and 4, and represents the rate of signal fading with increasing distance; *di,j* is the Euclidian distance between *vi* and *vj*; and *τ* is the minimum Signal-to-Noise Ratio (SNR) received by *vj*, so that *vj* can decode the signal and obtain the original message.

CC takes advance of the physical layer design to combine partial signals to obtain complete information [[28](#_bookmark53)]. This way, a communication between the nodes *vi* and *vj* can be achieved with CC if *vi* transmits its signal jointly with a set of *helper* nodes *Hi,j* and the sum of its transmission power satisfies Equation [2](#_bookmark6). In CC, a helper node is a node that cooperatively retransmit the signal along with the transmitting node.

*v ∈*Σ*v ∪H*

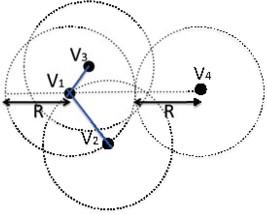
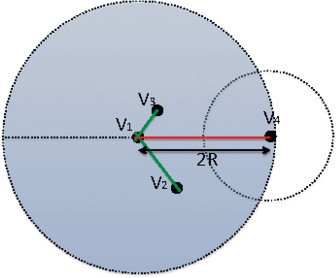
*k i i,j*

*Pk*(*dk,j*)*−α ≥ τ* (0 *≤ Pi ≤ PMAX* ) (2)

Figures [1a](#_bookmark7) and [1b](#_bookmark8) exemplify a scenario where CC could be used to increase connec-

tivity in an ad hoc network. In Figure [1a](#_bookmark7), there are three nodes (*v*1, *v*2 e *v*3), which are close to each other, and one distant node (*v*4). The transmission radius, that is, the transmission power of *v*1 allows it to reach nodes *v*2 and *v*3 directly. Node *v*2 and *v*3 have a single neighbouring node, in this case, node *v*1. Node *v*4 is outside radio range of the other nodes.

When CC is employed, node *v*1 could select the nodes *v*2 and *v*3 as its helpers to transmit to *v*4, that is, *H*1*,*4 = *{v*2*, v*3*}*. After selecting these nodes as helpers, *v*1, in a first moment, transmit its data to *v*2 and *v*3. In a second moment, *v*1 and its helpers transmit the same data to *v*4, amplifying the *v*1 transmission radius. If the combined SNR received in *v*4 is greater than *τ* , the node is able to decode the signal and obtain the original data from *v*1, as illustrated in Figure [1b](#_bookmark8). When node *v*1 transmits its data for its helper nodes *v*2 and *v*3, in a first moment, *v*4 also receives partial data from *v*1. In some CC models, such partial data is used by *v*4 in the signal decoding process, during the second moment of the CC. In this work, such partial data is ignored for simplicity (as in [[33](#_bookmark59)] and [[35](#_bookmark58)]). Physical layer techniques to implement CC can be find in [[13](#_bookmark37)].

(a) (b)

Fig. 1. (a) Scenario with three nodes (*v*1, *v*2 e *v*3) within radio reach of each other and one distant node (*v*4). (b) Node *v*1 uses nodes *v*2 and *v*3 as helper nodes to increase radio range thus reaching node *v*4.

* 1. *Network model*

Consider an ad hoc network with *n* nodes that are capable to receive and combine partial, received data, in agreement with the CC model. The network topology is modelled as a planar graph *G* = (*V, E*), where *V* = *{v*1*, v*2*, ..., vn}* is a set of wireless nodes and *E* is the set of communication edges. An edge *vivj ∈ E* symbolises that node *vi* can transmit data to *vj* directly and/or using CC. *N* (*vi*) is the direct neighbour set of *vi* within its maximum transmission range *RMAX* , for every *vk ∈ N* (*vi*), there is *Pi ≤ PMAX* such that *Pi*(*di,k*)*−α ≥ τ* , following Equation [1](#_bookmark5). In other words, *vi* can directly communicate with its neighbours in *N* (*vi*). Each node *v**i ∈ V* has an unique ID and knows its own location information. Node IDs and location information are exchanged among the nodes. Each node *vi ∈ V* has an unique radio and runs on battery power. Given the previous information, we define several important concepts, similar to those in [[35](#_bookmark58)].

**Definition 1** *(Direct edge): A direct edge vivj is an edge in E representing that node vi can transmit data to node vj directly, that is, Pi is such that vi can achieve vj when Pi ≤ PMAX. A solid horizontal line over the nodes denote a direct edge.*

**Definition 2** *(Helper node set): Hi,j symbolises the set of helper nodes of vi in a co- operative communication with vj. It is assumed that all helper nodes need to be direct neighbours of vi, that is, Hi,j ⊆ N* (*vi*)*, where N* (*vi*) *is the set of all direct neighbours of vi. In other words, all the elements in N* (*vi*) *are helper nodes candidates.*

**Definition 3** *(CC edge): A CC edge vivj is an edge of E that represents that node vi can transmit data to vj cooperatively by using a set of helper nodes Hi,j. A wavy horizontal line is used to denote a CC edge.*

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**Definition 4** *(Helper edge): A helper edge is an edge from vi to one of its helper nodes in Hi,j. For example, in Figure* [*1b*](#_bookmark8)*, node v*1 *uses the nodes v*2 *and v*3 *as helper nodes to create a CC edge between v*1 *and v*4*, that is, H*1*,*4 = *{v*2*, v*3*}, this way, the edges v*1*v*2 *and v*1*v*3 *are considered helper edges.*

**Definition 5** *(Network topology): The union of all direct edges and CC edges are E and E, respectively. Similarly,* *the dire* *ct communication graph and the CC com- munication graph are denoted as G* = (*V, E*) *and G*˜ = (*V, E*˜)*, respectively. Note that*

˜

*E* = *E E. Following the notation, note that, if vivj ∈ E, then: vivj* = *vivj if vivj*

*is a direct edge; and vivj* = *vivj if vivj is a CC edge.*

˜

˜

**Definition 6** *(Direct edge weight): The weight of a direct edge vivj is defined as:*

*w*(*vivj*)= *τdα .*

*i,j*

**Definition 7** *(CC edge weight): The weight of a CC edge v*˜*ivj is defined as:*

*|H |* + 1)*w* (*H* )*,*

*where:*

*w*(*v*˜*ivj*)= *wd*(*Hi,j*)+(

*i,j*

*CC i,j*

* *|Hi,j|: is the number of elements in Hi,j;*

*d i,j*

* *w* (*H* )= *τ*

(max*vk∈Hi,j di,k* )

*−α* *: is the minimum energy consumption of node vi*

*to communicate with the most distant node in Hi,j;*

* *wCC*(*Hi,j*)= Σ

*vk∈vi*

*τ*

*Hi,j* (*dk,j* )

*−α* *: is the minimum energy consumption of node*

*vi to communicate with vj, jointly transmitting with its helpers in Hi,j*

Note that, according to Equations [1](#_bookmark5) and [2](#_bookmark6), the following relation must be true to exist an CC edge:

max (*wd*(*Hi,j*)*, wCC*(*Hi,j*)) *≤ PMAX*

In a CC from *vi* to *vj*, the node *vi* must, in a first moment, send its data to its helper nodes in *Hi,j* and, in a second moment, node *vi* and its helpers must simultaneously send the same data to *vj*. This way, the weight of the CC edge consists in the sum of the communication costs of these two moments. *wd*(*Hi,j*) is the cost of the first moment while *wCC*(*Hi,j*) is the individual node cost to transmit a data with CC, that is, it must be multiplied by (*|Hi,j|* + 1), that is, the number of nodes that are involved in the CC between *vi* and *vj*. In this work, the CC model is simplified assuming that the transmission power of *vi* and its helper nodes are the same. Furthermore, it is only considered the power consumption in each sender node.

**Definition 8** *(Directional path cost): Given a source node vi and a destination node vj in a graph G* = (*V, E*)*, there is a directional path between vi and vj if, and only if, there is a sequence of vertex:*

*such that:*

*vi, vi*1 *, vi*2 *, ..., vik−*1 *, vik , vj ∈ V,*

(*vivi*1 )*,* (*vi*1 *vi*2 )*, ...,* (*vik−*1 *vik* )*,* (*vik vj*) *∈ E.*

*The directional path cost between vi and vj in a graph G is defined as:*

*πG*(*vi, vj*)=

*w*(*vivi*1 )+ *w*(*vi*1 *vi*2 )+ *...* + *w*(*vik−*1 *vik* )+ *w*(*vik vj*)*.*

*That is, the sum of the weight of all the edges, both direct edges and CC edges, that belong to the path between vi and vj. The cost of the shortest path in G between vi and vj is defined as:*

min(*πG*(*vi, vj*))*.*

**Definition 9** *(ESF - Energy Stretch Factor): Let Gj* = (*V, Ej*) *be a subgraph of G* = (*V, E*)*, Ej ⊆ E, Gj e G are connected graphs. The ESF of a pair of nodes vi and vj in Gj with respect to the same nodes in G is defined as:*

*G′* min(*πG′* (*vi, vj*))

*ρG* (*vi, vj*)= min(*π*

*,*

(*v ,v* ))

*G i j*

*Consider the ESF of Gj with respect to G as:*

*ρG′* = max

*G vi,vj ∈V*

*′*

*ρG* (*vi, vj*)*.*

*G*

*That is, the greatest ESF between any pair of nodes in V in Gj with respect to*

*G. Figure* [*2*](#_bookmark12) *illustrates this concept.*

**Definition 10** *(CE-t-S - Cooperative Energy t-Spanner): Let Gj* = (*V, Ej*) *be a subgraph of G* = (*V, E*)*, Ej ⊆ E, G and Gj are connected graphs. Gj is a CE-t-S with respect to G if its ESF is less than a constant t, that is:*

*ρG′ ≤ t.*

*G*

**Definition 11** *(COE-t-S - Cooperative Oriented Energy t-Spanner): COE-t-S is a specific case of the CE-t-S. Let Gj* = (*V, Ej*) *be a subgraph of G* = (*V, E*)*, Ej ⊆ E, Gj and G are not necessarily connected (unlike the COE-t-S). Consider a particular node vo ∈ V and constant t. Gj is a COE-t-S with respect to G and vo if:*

*where:*

⎧ *G′*

max *μ*(*vi, vo*) *≤ t,*

*vi∈V*

⎨ max *ρGP* (*vi, vo*)*, if there is a path from vi to vo;*

*μ*(*vi, vo*)=

*P*

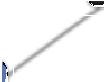
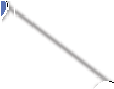
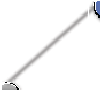
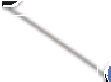
⎩ 0*, otherwise.*

* 1. *Computing the CC cost*

To exemplify the described model, consider the graph represented by Fig- ure [1a](#_bookmark7). This is a direct graph *G* = (*V, E*), where *V* = *{v*1*, v*2*, v*3*, v*4*}* and *E* = *{v*1*v*2*, v*1*v*3*, v*2*v*1*, v*3*v*1*}*. Consider, just for exemplification, that *α* = 1, *τ* = 1 and that *Rmax* = *R*. Note that *α* = 1 is not practical in real situations, but it makes the calculation easier in an example. Thus, we can compute the maximum transmission power of each node *vi ∈ V* based on Equation [1](#_bookmark5):

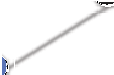
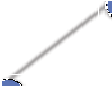
G G'

Vi Vi



uG(vi,vj)

Vj



uG'(vi,vj)

Vj

(a) (b)

Fig. 2. (a) Example of graph *G* = (*V, E*). (b) Example of graph *G′* = (*V, E′*), *E′ ⊆ E*. *πG*(*vi, vj* ) is the path cost from *vi* to *vj* in graph *G*. The ESF of a pair of nodes *vi, vj ∈ V* of *G′* with respect to *G* is equal

to *ρG'* (*v ,v* )= min(*πG'* (*vi,vj* )) .

*G i j*

min(*πG* (*vi,vj* ))

*PMAX* (*dMAX* )*−α* = *τ, PMAX* (*R*)*−*1 = 1*,*

*PMAX* = *R.*

Note that each node *vi ∈ V* has a maximum transmission power of *R* with the provided settings. In *G*, nodes *v*2 and *v*3 are neighbours of node *v*1, that is, *N* (*v*1)= *{v*2*, v*3*}*. This way, node *v*1 could select any non-empty subset of *N* (*v*1) as its helper nodes to create a CC edge from *v*1 to *v*4, that is *H*1*,*4 *⊆ N* (*v*1), following Definition [2](#_bookmark9). The new graph with the CC edge that comes from *v*1 to *v*4 is illustrated in Figure [1b](#_bookmark8).

Consider that, for the proposed example, *d*12 = *R*, *d*13 = *R* , *d*14 = 2*R*, *d*24 =

2

1*.*73*R* and *d*34 = 1*.*80. From Equation [2](#_bookmark6), we can compute the transmission power that node *v*1 needs to achieve node *v*4 using nodes *v*2 and *v*3 as helper nodes:

*vk∈v*1*∪{v*2*,v*3*}*

Σ

*Pk*(*dk,*4)*−*1 *≥* 1*,*

= *P*1(*d*14)*−*1 + *P*2(*d*24)*−*1 + *P*3(*d*3*,*4)*−*1 *≥* 1*,*

1

= *P*1 *≥*  1

+ 1 + 1 *,*

2*R* 1*,*73*R* 1*,*80*R*

= *P*1 *≥* 0*.*612*R.*

Note that all the involved nodes (*v*1, *v*2 e *v*3) operate with the same transmission power, that is, *P*1 = *P*2 = *P*3. Thus, the minimum transmission power for *v*1 to achieve *v*4 with CC is equal to *P*1 = 0*.*612*R*. This transmission power is bellow the previous seen maximum transmission power that is equal to *PMAX* = *R*. To compute the CC edge weight for the edge *v*˜1*v*4 we use Definition [7](#_bookmark10):

1 (*|H*1*,*4*|* + 1)

*w*(*v*˜1*v*4)= *R−*1 + Σ

*vk∈v*1

*{v*2*,v*3*}*

(*dk*4

)*−*1

Table 1

Weight of the CC edge *v*˜1*v*4 (graph in Figure [1b](#_bookmark8)) for different helper node sets *H*1*,*4.

*w*(*v*1*v*4)

|  |  |  |
| --- | --- | --- |
| *H*1*,*4 | *P*1 |  |
| *{v*2*, v*3*}* | 0*.*612*R* | 2*.*8˜36*R* |
| *{v*2*}* | 0*.*928*R* | 2*.*855*R* |
| *{v*3*}* | 0*.*947*R* | 2*.*395*R* |

= *R* + (*|H*1*,*4*|* + 1) *∗* 0*.*612*R,*

= 2*.*836*R.*

Note that the weight of the CC edge *v*1*v*4, using nodes *v*2 and *v*3 as helpers, is equal to *w*(*v*1*v*4) = 2*.*836*R*. Likewise the previous example, we use Equation [2](#_bookmark6) to compute the transmission power that node *v*1 needs to achieve *v*4 using just node *v*2 as a helper node and using just node *v*3 as a helper node. Table [1](#_bookmark13) summarises all the calculus made for this example.

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Analysing the *w*(*v*1*v*4) column in table, one can verify that the weight of the CC edge *v*1*v*4 is lower using just node *v*3 as a helper node. This happens because, as can be observed from Definition [7](#_bookmark10), the weight of a CC edge is the sum of the cost to send a data packet from the source node to its helpers and the cost to transmit collaboratively with its helpers. As, in the example, node *v*2 is farther away from from *v*1 than *v*3, respectively distances of *R* and *R* . Hence, node *v*1 spends more power to reach node *v*2 than to reach *v*3. So, using just node *v*3 as its helper, allows for grether battery savings. The problem of efficient helper set selection in CC is a challenging issue and has been addressed in other works [[12](#_bookmark38),[29](#_bookmark54)].

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* 1. *Problem formulation*

Consider an ad hoc network, where the nodes are scattered in a fixed area and there is an unique sink in the network border. The sink node is responsible for collecting and requesting information from the other nodes. The nodes are fixed, that is, no mobility is assumed, and the underline network graph can get disjoint due to link failures, battery depletion and so on. This work’s proposal consists in exploring CC communication to improve network connectivity while keeping energy expenditure as low as possible. Using the defined notation, given a network topology *G* = (*V, E*), where *vo ∈ V* is a sink node, the goal of this work is to propose a technique that uses CC to create a graph *G* and a subgraph *Gj*, *Gj ⊆ G*, such that *Gj* is a COE-t-S with respect to *G* and the node *vo*, following the Definition [11](#_bookmark11). In the following section, this work’s proposal is described.

# Proposal

In this section, it is described the *CoopSink* (short for Cooperative Sink), a topology control technique for cooperative ad hoc networks. This technique aims to

improve node connectivity to the sink while the energy consumption of the routes to the sink are minimised. In a first moment, a greedy heuristic for the helper set selection problem is described, then the CoopSink technique is described as a sequence of four steps. The formulation and algorithms of this section are based on the definitions of Section [3](#_bookmark4) and it is assumed a central computing unit.

* 1. *Greedy Helper Set Selection Algorithm (GHSS)*

Algorithm [1](#_bookmark0) describes a greedy heuristic, proposed by [[33](#_bookmark59)] and adapted for this work. This heuristic is used to select the most efficient helper nodes for CC and can be used in both directional and bi-directional graphs. The algorithm’s inputs are: a transmitter node *vi*; a set *N* (*vi*) of *vi*’s neighbours; and a receiver node *vj*. The output is the set of helper nodes *Hi,j*, such that the weigh of the CC-links *vivj* is minimised (although optimal solutions are not guaranteed). Consider the function prototype *GreedyHelperSetSelection*(*vi,N* (*vi*)*, vj*) to refer to Algorithm [1](#_bookmark0). In the following, the algorithm and the gaining function is described.

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* + 1. *Algorithm general description*

Algorithm [1](#_bookmark0) has three main steps:

* + - * **Step 1 (lines 1-11)**: this step consists on sorting the neighbour nodes from *vi* (*N* (*vi*)) according to a gain heuristic. The greater the gain that a node in *N* (*vi*) brings, according to the heuristic, up ahead it will be positioned in the vector *B*. The following functions are used in this step: the function *head*(*X*) returns the first element from a vector or a set *X*; the function *remove*(*X, Y* ) removes the element *Y* from the set *X*; the function *SortDescending*(*X*) receives the vector *X* and returns the same vector but sorted in descending order; while

function *indexTerms*(*X*), where *X* = [ *bk*1 *, bk*2 *, ..., bk|N* (*vi*)*|* ], returns the vector

*ck*1

*ck*2

*ck|N* (*vi*)*|*

*Y* = [*vk*1 *, vk*2 *, ..., vk|N* (*v* )*|* ]. The gain function is described in section [4.1.2](#_bookmark15).

*i*

* + - * **Step 2 (lines 12-21)**: This step consists on adding the elements from vector *C* to the helper set *Hi,j* so that *vi* and its helpers should have the minimum transmission power to create the CC-link *vivj*, according to Equation [2](#_bookmark6). If, after adding all the elements in *C*, the coupled power from these nodes is not enough to create the CC-link *vivj*, an error message is returned (lines 16-18);

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* + - * **Step 3 (lines 22-31)**: This step consists on adding the maximum number of helper nodes to the set *Hi,j* so that the inclusion of the next node does not increase the CC-link weight. In the case of the inclusion of a CC-link increases the CC-link weight or all the elements in *C* were already tested, the function returns the set *Hi,j* (lines 23-24). The function *WeightCC*(*vivj,* Ω), where *vivj ∈ Et* and Ω *⊆ V* , returns the CC-link weight of the link *vivj* using the nodes in Ω as helper nodes.
    1. *Gain function*

The gain function in Algorithm [1](#_bookmark0) (Step 1) is used to sort the nodes in *N* (*vi*)

in order of greater gain in terms of energy consumption to create a CC-link *v*˜*ivj*.

Consider, for each node *vk ∈ N* (*vi*), the following values:

* *bk → τ −α −* Σ

(*di,j* )

*τ*

*vl∈{vi,vk}*(*dl,j* )

*−α* : the amount of power that node *vi* can save if it

adds node *vk* as a helper. Note that the first element in the subtraction is the cost for *vi* directly communicate with *vj* and the second element of the subtraction is the power for *vi* cooperatively communicate with *vj* using node *vk* as a helper;

* *ck* = *τ −α* : The energy cost for *vi* to directly communicate with the helper *vk*.

(*d* )

*i,k*

As the objective here is to reduce the weight of the CC-link, the values for *bk*, that represents the gain, should be maximised while the values of *ck*, that represents the cost to communicate with the helper node, should be minimised. This way, the

gain function considers the ratio *bk*

*c*

*k*

as a metric that indicates which node brings

greater gain, that is, if *bk* is maximum for *k* = *h*, so the inclusion of the helper node

*c*

*k*

*vh* will bring a greater gain than other helper nodes.

* 1. *CoopSink: Proposal Description*

This section describes the steps of CoopSink technique. The CoopSink consists on the execution in sequence of the following four steps:

* **Step 1**: Create a topology graph, where each node creates as much edges as its maximum transmission power allows;
* **Step 2**: Use CC to create as much CC-links as possible in the network;
* **Step 3** From previous step’s graph, use topology control to cut edges such that energy efficient routes to the sink are kept;
* **Step 4**: Adjust the transmission power of the nodes, to minimise the energy consumptions but maintaining the network connectivity.

The following sub-sections better describe each of previous steps.

* + 1. *Step 1: Construction of graph GP*

Algorithm [2](#_bookmark0) describes the CoopSink’s first step. This step consists on creating all the possible direct edges in a graph topology, since all nodes operates with its maximum transmission power *PMAX* . Algorithm [2](#_bookmark0) takes as input: the node set

*V* = *{v*1*, v*2*, ..., vn}* and its information in the map; the maximum transmission

power *PMAX* . As output, we have the direct graph *GP* . Figures [3a](#_bookmark17) and [3b](#_bookmark18) show an input graph and the computed *G* graph. In Figure [3a](#_bookmark17) we have a 500x500m area with *n* = 50 nodes no edges, that is, *E* = *∅*. Figure [3b](#_bookmark18) illustrates the resulting

graph when nodes create edges based on its maximum transmission power. In this example, *PMAX* = 4900 and *RMAX* = 70. Note that the resulting graph is not necessarily connected.

* + 1. *Step 2: Construction of graphs G and G*

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Algorithm [3](#_bookmark0) describes the CoopSink’s second step. This step consists on cre- ating all the possible CC edges taking as input the graph *G* = (*V, E*) from the previous step and returning the graph *G*, which has both direct and CC edges. As

**Algorithm 1** : *GreedyHelperSetSelection*(*vi,N* (*vi*)*, vj*)

**Require:** *vi,N* (*vi*)*, vj*

**Ensure:** *Hi,j*;

1: # (Step 1)

2: Set: *A → N* (*vi*);

3: vector: *B →* [], *C →* [];

4: **while** (*vk → head*(*A*)) */*= *∅* **do**

5: *bk → τ −α −* Σ

(*di,j* )

6: *ck* = *τ −α* ;

(*d* )

*i,k*

7: *B →* [*B, bk* ];

*c*

*k*

8: *remove*(*A, vk*);

9: **end while**

*τ*

*vl∈{vi,vk}*(*dl,j* )

*−α* ;

10: *B → SortDescending*(*B*);

11: *C → indexTerms*(*B*)

12: # (Step 2)

13: *k →* 0, Ω *→ vi*;

**while** Σ*v ∈*Ω *MAX k,j* **do**

14: ( *P* (*d* )*−α*) *< τ*

*k*

15: *k → k* + 1;

16: **if** *k > |C|* **then**

17: return error;

18: **end if**

19: *Hi,j → Hi,j ∪ A*[*k*];

20: Ω *→* Ω *∪ Hi,j*

21: **end while**

22: # (Step 3)

23: **while** (*k ≤ |N* (*vi*)*|*) **do**

24: **if** (*k* = *|N* (*vi*)*|*) **or**

(*WeightCC*(*vivj,* Ω) *< WeightCC*(*vivj,* Ω

˜ ˜

25: return *Hi,j*;

26: **else**

27: *k → k* + 1;

28: *Hi,j → Hi,j ∪ C*[*k*];

29: Ω *→* Ω *∪ Hi,j* ;

30: **end if**

31: **end while**

32: return *Hi,j*;

*∪ C*[*k* + 1])) **then**

described in Subsection [2.3](#_bookmark3), the efficient helper set selection in CC is a challenging problem, since it is computationally costly. Therefore, heuristics can be used to handle this problem. In this work we consider the greedy heuristic proposed in [[33](#_bookmark59)]. This heuristic, which has the *GreedyHelperSetSelection*(*vi, vj*) prototype, receive as input: the source node *vi*; and the destination node *vj*. The output is the helper set *Hi,j*. As an example, consider the graphs represented in Figures [3b](#_bookmark18) and [3c](#_bookmark19). The graph in Figure [3b](#_bookmark18) is the output graph from Step 1 and the input graph of Step

**Algorithm 2** : *CoopSinkStep*1(*V, PMAX* )

**Require:** *V* e *PMAX* ;

### Ensure: *G*;

1: *G* = (*V, ∅*);

2: **for** (*vi, vj ∈ V* ) **do**

3: **if** (*PMAX* (*dij*)*—α ≥ τ* ) **then**

4: Add *vivj* to *GP* ;

5: **end if**

6: **end for**

2. Graph in Figure [3c](#_bookmark19) is the output from Step 2. In these graphs, direct edges *vivj ∈ E* are shown in blue, CC edges *vivj ∈ E* are shown in red and helper edges *Hi,j* are shown in green. Note that, in this example, a large number of CC edges were created, however, these are direct edges, that is, the existence of *vivj ∈ E* does not imply *v*˜*jvi ∈ E*.

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* 1. *Step 3: Removing edges from G*

Algorithm [4](#_bookmark0) describes the CoopSink’s third step. This step consists on creating a graph *Gj* such that the graph is a COE-t-S with respect to *G* and a node *vo ∈ V* . It receives as input: a graph *G*; a constant *t*; and a node *vo ∈ V* . It returns a graph *Gj*. Figures [3c](#_bookmark19) and [3d](#_bookmark20) illustrate what happens in this step. The graph in Figure [3c](#_bookmark19) is a graph with several direct and CC edges and is one of the inputs of Step 3. The other inputs are, in this example, *t* = 1*.*4 and *vo* on location (0*,* 0) in the cartesian plane. The resulting graph from Step 3, illustrated in Figure [3d](#_bookmark20), is a COE-t-S with respect to the graph in Figure [3c](#_bookmark19). The resulting graph is a direct graph oriented to the node *vo*, that is, all the connected nodes have direct routes to *vo*. Note that previously unconnected nodes on Figure [3b](#_bookmark18) now have a path to the sink node *vo*. One may note that some nodes area still disconnected in the final stage. Figure [3d](#_bookmark20) shows a node that failed in establishing CC links to its neighbouring nodes.

* + 1. *Step 4: Adjusting the transmission power*

Algorithm [5](#_bookmark0) describes the CoopSink’s last step. This step consists on adjusting the transmission power of all the nodes in the input graph *Gj* such that the COE-t-S property is maintained and the energy consumption is minimised.

In the following section, the CoopSink technique is compared with other tech- niques from the literature.

# Simulation Results

In the previous section, it was proposed a new technique for topology control in cooperative ad hoc networks, which focus on increasing connectivity while main- taining efficient routes to the sink. In this section, it is used simulation to compare the proposal to others in the literature. The following techniques were chosen for comparison: CoopBridges [[33](#_bookmark59)] and MST-Kruskal [[16](#_bookmark41)]. CoopBridges starts from the

**Algorithm 3** : *CoopSink Step*2(*G*)

### Require: *G*;

**Ensure:** *G*;

1: *G*˜ = (*V, ∅*);

2: **for** (*vi, vj ∈ V* ) **do**

3: *Hij → GreedyHelperSetSelection*(*vi, vj*);

4: **if** (*wCC*(*Hi,j*) *≤ PMAX* ) **then**

˜ ˜

5: Add *vivj* to *G*;

6: **if** (*vivj ∈ G* and *w*(*vivj*) *> w*(*vivj*)) **then**

˜

7: Remove *vivj* from *G*;

8: **end if**

9: **end if**

10: **end for**

11: *G* = *G* + *G*˜;

**Algorithm 4** : *CoopSink Step*3(*G, t, vo*)

**Require:** *G* = (*V, E*); **Ensure:** *Gj* = (*V, Ej*); 1: *Gj → G*;

2: *k →* 1;

3: vector *A →* receives all the edges in *E* ordered by weight;

4: **while** (*k ≤ |B|*) **do**

5: *vivj → A*[*k*];

*P*

6: *Gj*

*P*

*→ Gj*

*— vivj*;

7: **if** (max*vi∈V μ*(*vi, vo*) *≤ t*) **then**

8: # The deletion of edge *vivj* will harm the ESF;

*P*

9: *Gj*

*P*

*→ Gj*

+ *vivj*;

10: **if** (*vivj* = *vivj*) **then**

˜

11: Remove all the edges from *vi* to all the nodes in *Hi,j* from B;

12: **end if**

13: **end if**

14: *k → k* + 1;

15: **end while**

**Algorithm 5** : *CoopSink Step*4(*Gj*)

**Require:** *Gj* = (*V, Ej*);

1: **for** *vi ∈ V* **do**

2: *a →* max*vivj∈G′* 3: *b →* max*v*˜*ivj ∈G′* 4: *Pi* = max*{a, b}*;

*P*

*P*

5: **end for**

*wd*(*Hi,j*);

*wCC* (*Hi,j* );

direct graph *G* (output from CoopSink Step 1) and splits all connect components into clusters. Creates as much bi-direction CC edges as possible within clusters.

500

450

400

350

300

AREA (m)

250

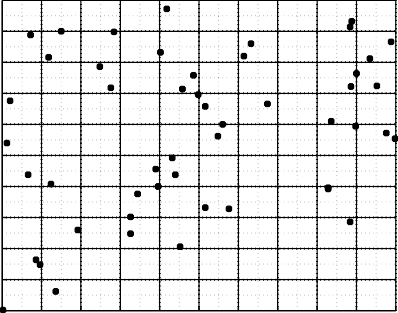
200

150

100

50

0



0 50 100 150 200 250 300 350 400 450 500

AREA (m)

(a)

500

450

400

350

300

AREA (m)

250

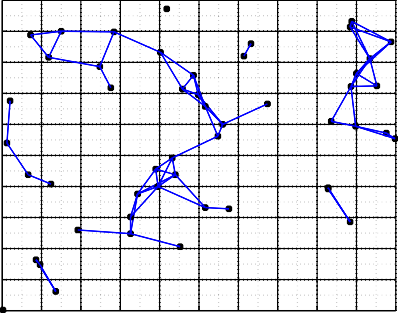
200

150

100

50

0



0 50 100 150 200 250 300 350 400 450 500

AREA (m)

(b)

500

450

400

350

300

AREA (m)

250

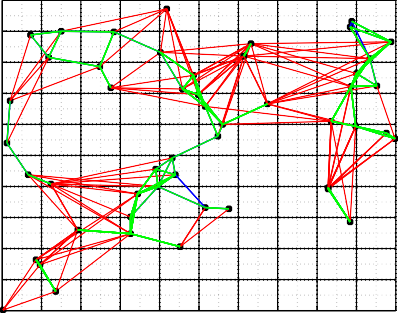
200

150

100

50

0



0 50 100 150 200 250 300 350 400 450 500

AREA (m)

(c)

500

450

400

350

300

AREA (m)

250

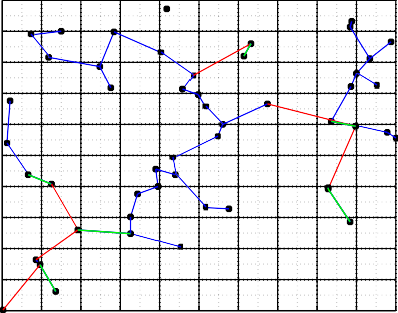
200

150

100

50

0



0 50 100 150 200 250 300 350 400 450 500

AREA (m)

(d)



Fig. 3. (*a*) Network topology example with *n* = 50 nodes and *|E|* = 0. (*b*) Direct graph *G* created from (*a*) when nodes operate with maximum power *PMAX* . (*c*) Graph *G*, created from the graph in (*b*), by adding all the possible CC edges. (*d*) COE-t-S created from (*c*).

Finally, uses a distributed MST algorithm to remove inter-clusters edges and intra- clusters latter. MST-Kruskal grows a minimal spanning tree (MST) one edge at a time by finding an edge that connects two trees in a forest of growing MSTs, receives as input the graph *G*.

Initially, it was our intention to compare the proposal also with the Greedy- (Add/Del)-Link technique [[35](#_bookmark58)], however, this technique assumes that the topology created, after adding the CC edges, would be necessarily connected. This hypothesis is not considered in both CoopSink and CoopBridges. Here, a resulting topology is the topology created after the application of a topology control algorithm. To evaluate the CoopSink performance, it is considered the following metrics:

* M1 - Connectivity to the sink: The percentage of nodes that have a route to the sink in the resulting topology;
* M2 - Average transmission power: The average of transmission power assigned to each node in the resulting topology;
* M3: ESF to the sink: Consists on creating a subgraph *Gj* = (*V, Ej*) from *G* = (*V, E*), *Ej ⊆ E*, and to verify the value for the constant *t* when it is considered

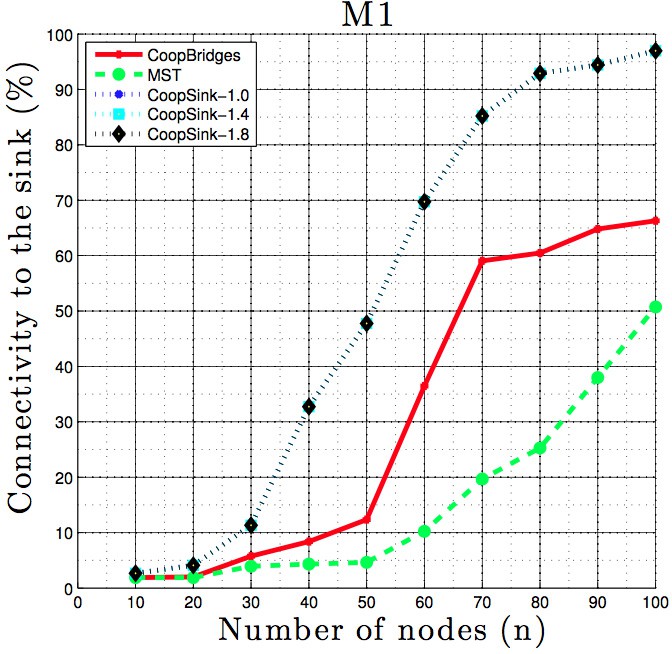


Fig. 4. Simulation results for M1.

that *Gj* is a COE-t-S with relation to *G*;

* + M4: Number of CC edges: The number of CC edges in the resulting topology.

The reason to consider M1 is to evaluate the connectivity improvements that CoopSink can bring to the network. M2 is justified once minimising energy con- sumption is a basic concern in ad hoc networks. M3 is used to verify the goodness of the routes connecting to the sink when compared with another proposals. M4 enumerates the average number of CC edges in the resulting topology. M4 is also useful to better understand the average energy cost, as CC edges consume more power than direct links.

In order to perform the evaluation, a simulation was developed in Matlab [[10](#_bookmark39)], following the steps described in Section [3](#_bookmark4) for CoopSink and the algorithm described in [[33](#_bookmark59)] for CoopBridges. The MST-Kruskal implementation is already present in Matlab. The CoopBridges implementation was validated with the original results. Similarly to other works [[33](#_bookmark59),[35](#_bookmark58)], the simulation process takes the following param- eters: *n* = 10*,* 20*, ...,* 100 nodes are randomly positioned in a 500x500m area; the sink node is always node *v*1 at position (0*,* 0); The PLE is equal to 2 (*α* = 2); *PMAX* = 4900; SNR is equal to 1 (*τ* = 1); and *t* = 1*.*0*,* 1*.*4*,* 1*.*8 are the values for con- stant *t*. The simulation results have been drawn from an average of a 100 simulations. The compared proposals are: CoopBridges, MST, CoopSink-1.0, CoopSink-1.4 and CoopSink-1.8, where the last three are the CoopSink technique with *t* assuming val- ues of 1*.*0, 1*.*4 and 1*.*8, respectively. The following subsections present and analyse the simulation results for each metric considered.

2000

Average transmission power (P¯ )

1800

1600

M2

CoopBridges MST



CoopSink−1.0 CoopSink−1.4 CoopSink−1.8

1400

1200

1000

800

600

400

200

0

10 20 30 40 50 60 70 80 90 100

## Number of nodes (n)

Fig. 5. Simulation results for M2.

* 1. *M1: Connectivity to the sink*

Figure [4](#_bookmark21) presents the simulation results for metric M1. The *x*-axis shows the number of network nodes and the *y*-axis shows the percentage of the nodes that have a route to the sink. The figure shows that the parameter *t* had no impact on the CoopSink connectivity to the sink. As can be seen in the figure, CoopSink allows for greater connectivity than CoopBridges and MST. Indeed, with 80 nodes, the connectivity to the sink using CoopSink exceeds 90%. The CoopSink’s connectivity to the sink was up to 3*.*8 times better than CoopBridges and up to 6*.*8 times better than MST.

* 1. *M2: Average transmission power*

Figure [5](#_bookmark22) presents the simulation results for metric M2. The *x*-axis shows the number of network nodes and the *y*-axis shows the average transmission power for each node. As the MST does not create CC edges, the energy consumption in this technique is lower that that in CoopSink and CoopBridges. For this reason, the average transmission power of the nodes in CoopSink tend to be greater. However, using CoopSink-1.4 and CoopSink-1.8, the energy consumption is not very far from CoopBridges (up to 30% in the best case scenario). CoopSink, on the other hand, provides better connectivity. For smaller *t* values, the energy consumption tends to

2.5

M3

CoopBridges MST



CoopSink−1.0 CoopSink−1.4 CoopSink−1.8

2

ESF to the sink

1.5

1

10 20 30 40 50 60 70 80 90 100

## Number of nodes (n)

Fig. 6. Simulation results for M3.

increase as the freedom to remove edges from the graph reduces.

* 1. *M3: ESF to the sink*

Figure [6](#_bookmark23) presents the simulation results for metric M3. As before, the *x*-axis shows the number of nodes while the *y*-axis presented the ESF values to the sink for each of the simulated techniques. As the ESF is measured comparing two graphs, the following graphs are used in the comparison:

* CoopSink-(1.0/1.4/1.8): Graph *Gj* (output of CoopSink’s Step 3) with graph *G*

(output of CoopSink’s Step 2);

* CoopBridges: Resulting graph from CoopBridges technique with the graph *G*

(output of CoopSink’s Step 2);

* MST: Resulting graph from MST with graph *G* (output of CoopSink’s Step 1). The results show that:
* The CoopSink variations obey the ESF to the sink, established during configu- ration. This means that the observed values for the ESF to the sink must be smaller or equal to 1*.*0 for CoopSink-1.0, smaller or equal to 1*.*4 for CoopSink-1.4

and smaller or equal to 1*.*8 for CoopSink-1.8.

* Both CoopBridges and MST have no commitment with the ESF to the sink. This mean that some of the routes to the sink can be quite inefficient in terms of energy

M4

12



CoopBridges MST

CoopSink−1.0 CoopSink−1.4

10 CoopSink−1.8

Number of CC edges

8

6

4

2

0

10 20 30 40 50 60 70 80 90 100

## Number of nodes (n)

Fig. 7. Simulation results for M4.

consumption;

* CoopBridges obtained a ESF to the sink up to 2*.*34 times greater than CoopSink, while the MST obtained a ESF to the sink up to 2*.*29 greater. The greater the ESF difference is, the less efficient the routes are. From the above, it can be verified that CoopSink presented routes up to 2*.*34 times better with relation to other proposals in the scenario considered in this work;
* Note that, for smaller values to constant *t*, we have very efficient routes in CoopSink at the price of a greater energy consumption, as can be observed in the results for metric M2. Clearly, striking a sensitive balance between these con- flicting parameters is not an easy task and may depend on the application. In high throughput environments without severe energy restrictions, it would be desirable to keep *t ≈* 1, while in environments with energy restrictions, the *t* values should be higher.
  1. *M4: Number of CC edges*

Figure [7](#_bookmark24) presents the simulation results for metric M4. The *x*-axis presents the number of network nodes while the *y*-axis shows the number of CC edges in the resulting topology. It should be noted that:

* + - CoopSink has more CC edges when the values for constant *t* are smaller. This happens because, with smaller values for *t*, greater is the restriction to remove

edges in the CoopSink algorithm. These results are consistent with the results from metric M2, once the energy consumption for CoopSink-1.0 was substantially greater that CoopSink-1.4 and CoopSink-1.8;

* + - * With less than 60 nodes, the CoopBridges has less CC edges than CoopSink-1.4 and CoopSink-1.8, and this number increases and surpass CoopSink later. This happens because the connectivity to the sink in CoopBridges improves with *n ≥* 50 nodes, explaining this increase in the number of CC edges;
      * From 60 nodes, the CoopBridges remains with basically the same number of CC edges than CoopSink-1.4 and CoopSink-1.8. However, the CoopBridges still has less connectivity to the sink. This shows that CoopSink is able explore CC links more efficiently than CoopBridges when the connectivity to the sink is considered.

# Conclusion

In this work, it was presented a new technique, named CoopSink, that can be used to perform topology control in cooperative ad hoc networks. More specifically, CoopSink is a technique developed for ad hoc networks where there is the necessity to create efficient routes to a sink node. With this purpose, CC is used to increase connectivity and reduce energy consumption while maintaining efficient routes to the sink. When compared to other similar proposals, CoopSink was able to improve network connectivity to the sink up to 6*.*8 times while routes are up to 2*.*3 times better when the ESF to the sink is considered. Future works aim to analyse the impact of the required node synchronisation that is necessary for CC communication.

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