Fault Tolerance in Strongly Minimum Energy Topology with MLD: A Distributed, Energy Efficient yet Simple Protocol

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Abstract. *Wireless Sensor Networks (WSN) have been the subject of extensive research due to their wide range of applications. A sensor node should have the longest lifetime possible, since we need to build a system that performs its functions effectively and, at the same time, spends the least amount of energy, allowing the battery to last longer. One of the functions that consumes more energy in a WSN is the wireless data transmission. In this context, it becomes interesting to determine a setting of transmission powers for the network sensor nodes so the network remains connected while nodes' transmission powers remain minimum. The problem of minimizing the total energy consumption in a network is known in the literature as Strongly Minimum Energy Topology (SMET) and its decision version is known to be an NP-Complete problem. In this work, we evaluate the cost of adding fault tolerance through redundant paths to the SMET Minimum Spanning Tree (MST) topology, creating a redundant MST, a non-practical fault tolerant baseline algorithm. Next, we propose a practical redundant algorithm, Minimum Link Degree (MLD), which does not need any localization information and can be implemented in a distributed fashion. Our results show that the MLD topology is a promising approach, performing better than the redundant MST with respect to number of survived nodes' faults.*

1. Introduction

The great advance, in the past couple of decades, in areas such as micro-controllers, sensors/actuators and wireless communication protocols, have led to the development of intelligent sensing systems for physical, chemical and biological quantities, among others. These systems have a huge number of applications in many areas of study and are known as Wireless Sensor Networks (WSNs).

The basic component of a WSN is the sensor node, a computational element with processing, storage, wireless communication and sensing capacities [Silva et al. 2004]. Eventually, sensor nodes may also have some actuators when the application demands some sort of control. Usually, finite energy batteries are used as energy sources of sensor nodes. Therefore, aspects related to the sensor node's energy consumption are extremely important in WSNs [Min et al. 2002, Pottie and Kaiser 2000].

One strategy to reduce the consumption of sensor nodes is to reduce the transmission power of each node in a way that they remain interconnected to each other (throughout a given path), transmitting at the lowest possible power. Cheng et al. [Cheng et al. 2003] proved that the problem of minimizing the sum of nodes' transmission powers, keeping the network fully connected is, in its decision version, an NP-Complete

problem known as Strongly Minimum Energy Topology (SMET). Due to the relevance of this problem, it is necessary to propose approximation algorithms and heuristics to generate satisfactory solutions in practicable time.

Most of existing heuristics are restricted to the theoretical aspect of SMET problem, ignoring important features of WSNs, such as network nodes' instability or how the heuristic would be implemented in a distributed way, in order to be actually used. This work proposes a fault-tolerant approach to the SMET problem, building redundant topologies in which a node fault will not compromise the network connectivity. To summarize, among the contributions of this paper, it is worth to highlight:

- Proposition of a non-practical, fault tolerant version of the Minimum Spanning Tree (MST) approximation algorithm, namely Redundant MST. We show that, as a consequence of fault tolerance, energy consumption in the network is, in average, two times larger.
- We provide a Minimum Link Degree (MLD), practical and distributed algorithm, and propose its use as a redundant topology generation algorithm. We show that MLD has an increase of less than 50% in the network total power consumption, when compared to non-practical Redundant MST.
- Using two different failure models, we show that the network fault tolerance degree, with MDL topology, is two times larger than MST topology. Finally, comparing the number of tolerated faults and power expenditures, we argue that MLD has a better cost benefit than the baseline Redundant MST.

The paper will be presented according to the following structure: Section 2 review some of the related work and discuss the corresponding contributions to power savings in WSNs. Section 3 formalizes the SMET problem. The baseline, MST approximation algorithm, its fault tolerant version and MLD algorithm are presented. Section 4 describes the experiments' methodology and Section 5 presents the results and discussion. Section 6 discusses final remarks and future work.

2. Related Work

This section presents the main proposals related to this work.

Cheng et al. [Cheng et al. 2003] defined the *Strongly Minimum Energy Topology* problem and proved its NP-Completeness. The problem consists of defining a set of transmission powers for the nodes of a WSN, in such way that the sum of transmission powers is minimum and the resultant nodes' connectivity graph is a *Strongly Connected Component*. Many other research efforts emerged from their results, proposing approximation algorithms and heuristics for the SMET Problem. In their work, Cheng et al. also proposed two strategies for solving the SMET Problem. The first one is an approximation algorithm, with approximation factor of two, based on the computation of the *Minimum Spanning Tree* in the complete graph in which edges represent distance between nodes. The second is a greedy algorithm that had similar results, when compared to the first strategy. These two strategies were stated as baselines for SMET. Further discussion about the first strategy is presented in section 3.

Wattenhofer et al. [Wattenhofer et al. 2001] proposed a distributed algorithm in which each node makes local decisions about its transmission power and those local decisions guarantee global connectivity. Based on direction information, each node increases

its own transmission power until a neighbor is found in each direction. As result, a network with a longer lifetime is obtained. Moreover, interference is reduced due to shorter transmission powers. The algorithm was validated through simulation, in statical scenarios with stable nodes.

Ye et al. [Ye et al. 2005] proposed a clustering scheme for WSNs, which is suitable for collecting periodical data, found in typical sensing applications. In this strategy, *cluster heads* are elected based on remaining energy capacity. A novel method for balancing data load between cluster heads was introduced. Their results show an increase of 35% in the sensor network's longevity.

Cheng and Cardei [Cheng et al. 2004] explored SMET considering approximated solutions. The authors present an optimization algorithm that improves the results of any topologies based on *Minimum Spanning Trees*. The presented approximation algorithms have polynomial time and can be applied to low mobility or static scenarios.

More recent efforts [Zhao and Gurusamy 2008, Yan et al. 2013] investigate methodologies to increase network lifetime. In the present work, our purpose is to investigate the extra cost of nodes' fault tolerance to the network energy consumption and also to verify its impact in the network survivability. We first propose a Redundant MST algorithm, which is not a practical algorithm for real-time topology generation, but will be used as baseline for comparison purpose. Later, we propose a MLD algorithm, a practical distributed approach. We compare MLD with the baseline, Redundant MST, with respect to energy consumption and number of tolerated nodes' faults.

3. WSNs, SMET Problem and Algorithms

WSNs have great importance due to their wide range of applications. This kind of network has been successfully used in military applications [Arora et al. 2004, He et al. 2004], environmental [Mainwaring et al. 2002] and home [Boonsawat et al. 2010, Nunes et al. 2015] monitoring, robotics [Sibley et al. 2002, LaMarca et al. 2002], among others. Most of the WSN applications, sensor nodes are supplied by batteries that have a finite energy capability.

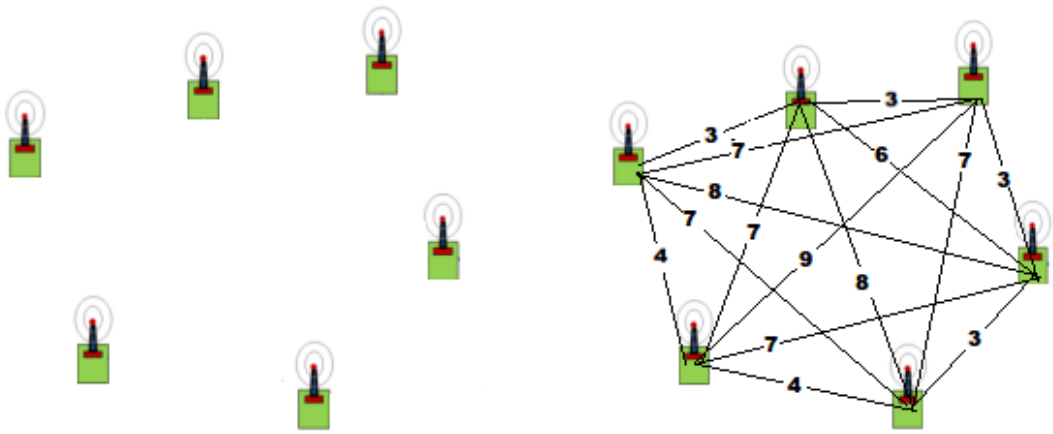
In this scenario, it is very important to reduce the node consumption. To make it possible, many technologies have been improved. Firstly, energy-efficiency micro-controllers have become crucial [Vieira et al. 2003]. Together with the advancements in micro-controllers, low consumption communication protocols were designed [Gutierrez et al. 2001, Yu et al. 2012] and evaluated [Lee et al. 2007].

A third approach to save energy in WSNs is to search for topologies that allow wireless connectivity among nodes, saving the maximum possible amount of power. Following this direction, the theoretical problem SMET [Cheng et al. 2003] was proposed. In this section, we formalize the SMET Problem and its baseline approximation MST algorithm. Moreover, we propose a redundant version of this algorithm, as a fault-tolerant topology generator. Finally, we propose MLD, a practical and distributed approach to generate fault-tolerant, energy efficient topologies.

3.1. Strongly Minimum Energy Topology

Considering a WSN in which nodes positions are known (Figure 1.a), it is possible to represent it by a complete, undirected graph. In this case, each vertex in the graph cor-

responds to a sensor node and each edge weight corresponds to the distance between a given pair of nodes (Figure 1.b).



(a) (b)

Figure 1. Distances between nodes represented as a graph

The relation between the transmission power of a sensor node and the range of this sensor node transmission is given by Eq. 1.

$$Thr = Pt/d^{\alpha}, \tag{1}$$

$$\sum_{i=0}^{n} Pt_i. \tag{2}$$

where Thr represents the minimum signal strength, at the destination, for the message to be successfully received, d represents the distance between the transmitting and receiving nodes, according to the graph in Figure 1.b, Pt corresponds to the power with which the message is transmitted, α is a constant that depends on the propagation medium. In general, α assumes values from two to six. Propagation medium with no obstacles has α close to two. Based on the graph in Figure 1.b and Equation 1, it is possible to determine the needed power for one node to reach another node in the WSN. The SMET problem can be defined as the problem of finding the set of transmission powers (one Pt for each node) in such way that the connectivity graph is a *Stronlgly Connected Component* (SCC) and, at the same time, the sum of nodes' transmission powers (Eq. 2) is minimum. SMET decision version is an NP-Complete problem.

3.2. A Baseline for SMET Problem

A trial and error approach to the SMET problem is not feasible for networks with any number of nodes, since each node can be assigned to an infinite number of real values for transmission power. Cheng et al. [Cheng et al. 2003] proposed an approximation algorithm that generates solutions with consumptions of, at most, two times the minimum. In the present work, this algorithm will be used as a baseline to compare fault-tolerant algorithms with not fault-tolerant ones. In other words, it will be used to find out the extra cost, in terms of power consumption, and fault tolerance.

This baseline algorithm is simply based on the computation of the *Minimum Spanning Tree* (MST), i.e., the distance graph (Figure 1.b). Next, transmission powers are assigned according to the generated tree, in such way that every edge in the tree exists in the WSN connectivity graph. Henceforth, for simplicity, this algorithm will be referred as MST_SMET. MST_SMET has the time complexity of Minimum Spanning tree computation, that is O($V^2 log(V)$), for an implementation using the Kruskal algorithm [Ahuja et al. 1988]. Although it has polynomial time complexity, this is not a practical algorithm, because it requires a very large (at least $\Omega(E + Vlog(V))$ [Faloutsos and Molle 1995]) number of messages in the network. It also needs the location of every node in the network, which, in most WSNs, is not available. Figure 2 shows the complete graph and the generated topology for a network with 50 sensor nodes. Notice that, in the topology of Figure 2, any fault node (except for a leaf node) will cause loss of connectivity. Algorithm 1 presents the definition of MST_SMET. It is important to notice that nodes' positions are necessary in MST_SMET input data.

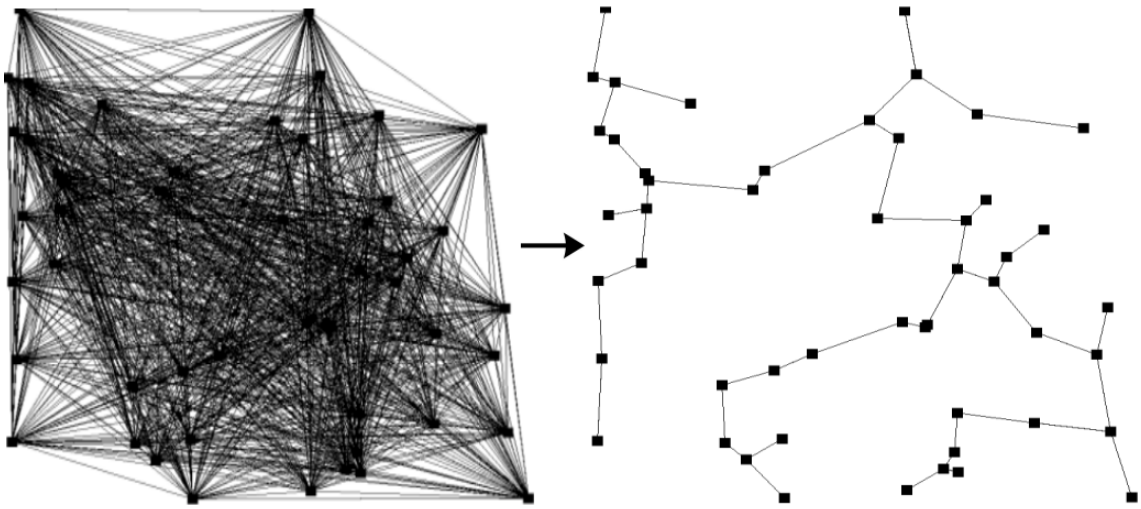


Figure 2. Connectivity topology generated by MST_SMET

Data: A Set of nodes $N[Vu(x, y)]$
Result: A setting for the N nodes transmission powers that generates an SCC
Generate the distances complete Graph Gc from $N[Vu(x, y)]$;
Compute The Kruskal Algorithm in the complete Graph Gc resulting in T_{MST};
For each node $Vu(x, y)$: Set Pu to the minimum value that makes node $Vu(x, y)$ reach everyone of its T_{MST} neighbors;

Algorithm 1: MST_SMET

The notation $N[Vu(x, y)]$ represents a vector of N nodes $Vu(x, y)$, in which x and y are the geographical coordinates of each node Vu.

3.3. Introducing Fault Tolerance with Redundant MST

Faults in WSN nodes are extremely common in real scenarios. Due to the importance of fault tolerance in a WSN topology for real deployment, we here propose a MST-based algorithm that generates fault-tolerant topologies with low energy consumption,

namely Redundant MST. Since MST_SMET presented good results in reducing the energy consumption [Cheng et al. 2003], we provide a variation of this algorithm for redundant topologies. First, the algorithm computes the MST in the complete distances' graph Gc, generating T_{MST}. Next, the edges of T_{MST} are removed from the original distances' graph Gc obtaining $Gc' = Gc - T_{MST}$. Finally, the algorithm computes another MST, T_{MST2}, now in Gc'. Notice that T_{MST} and T_{MST2} are completely edge-independent. The redundant topology will then consist of $T_{MST} \cup T_{MST2}$. Thus, transmission powers are assigned according to $T_{MST} \cup T_{MST2}$ topology, in such way that every edge in T_{MST} $\cup$ T_{MST2} exists in the WSN connectivity graph. Figure 3 presents the topology generated by Redundant MST. Algorithm 2 presents the definition of Redundant MST. As in MST_SMET, Redundant MST time complexity is upper bounded by the Kruskal algorithm and, thus, is equal to O($V^2 log(V)$).

Although Redundant MST introduces fault tolerance to the WSN, it must be understood as a baseline for redundant minimum energy topologies, because it suffers from the same practical shortcomings of MST_SMET (e.g., no viable distributed implementation and need of position awareness). With that in mind, we proceed to the proposition of a practical distributed algorithm that will have its performance compared to Redundant MST with evaluation purpose.

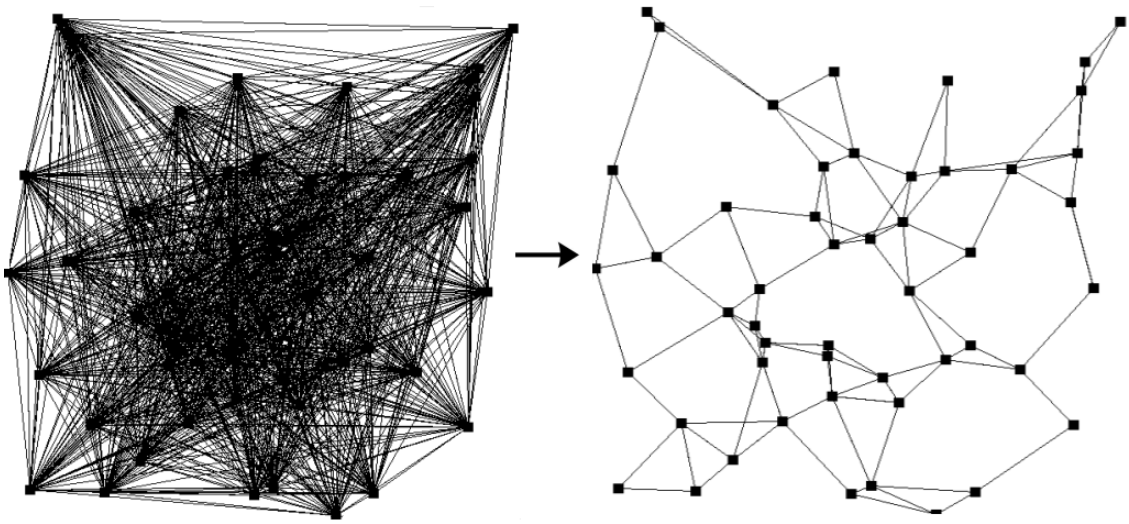


Figure 3. Connectivity topology generated by Redundant MST

Data: A Set of nodes $N[Vu(x, y)]$.
Result: A setting for the N nodes transmission powers that generates an SCC.
Generate the distances complete Graph Gc from $N[Vu(x, y)]$;
Compute Kruskal Algorithm in the complete Graph Gc resulting in T_{MST};
Generate $Gc' = Gc - T_{MST}$;
Compute Kruskal Algorithm in the Graph Gc' resulting in T_{MST2};
For each node $Vu(x, y)$: Set Pu to the minimum value that makes node $Vu(x, y)$ reach everyone of its T_{MST} U T_{MST2} neighbors;

Algorithm 2: Redundant MST

3.4. Introducing Feasibility with MLD

As the name may indicate, the Minimum Link Degree approach consists of defining a constant parameter K that will be the minimum number of neighbors a node must have in the network topology.

Xue and Kumar [Xue and Kumar 2004] show that it is possible to statistically guarantee that, for sufficient large values of K, MLD generates fully connected topologies. They proved that, given a graph $G(N)$, with N randomly distributed nodes within a given area, $\lim_{N\to\infty} P_{connected}(G(N)) = 1$ if $K > 2/log(4/e) \times log(N)$. $P_{connected}(G(N))$ denotes the probability of $G(N)$ being a connected graph. To complement this asymptotic result, the authors experimentally evaluate the effect of K on the probability of connectivity for different values of N. Their experimental results show that for $K = \lceil log(N) \rceil$, $P_{connected}(G(N)) \approx 1$.

In all of our experiments, presented in Section 5, we set $K = 4$. We fixed this value after empirical evaluation, because it always resulted in connected and fault-tolerant topologies.

As mentioned before, a great advantage of MLD is that it can be easily implemented in a distributed way. To do so, each node just needs to send beacon messages with gradually higher transmission powers until K nodes answer with "I've heard you!" messages. Moreover, in MLD there is no need for nodes' geo-location awareness (notice Algorithm 3 input). It can even be periodically applied to scenarios with mobility to generate connected topologies over time. Consequently, it is a much more practicable algorithm. The definition of MLD is presented in Algorithm 3. The algorithm has O(V^2) time complexity. Its distributed version has O(D), where D is the maximum distance between a pair of nodes, in the WSN. Figure 4 shows an MLD topology.

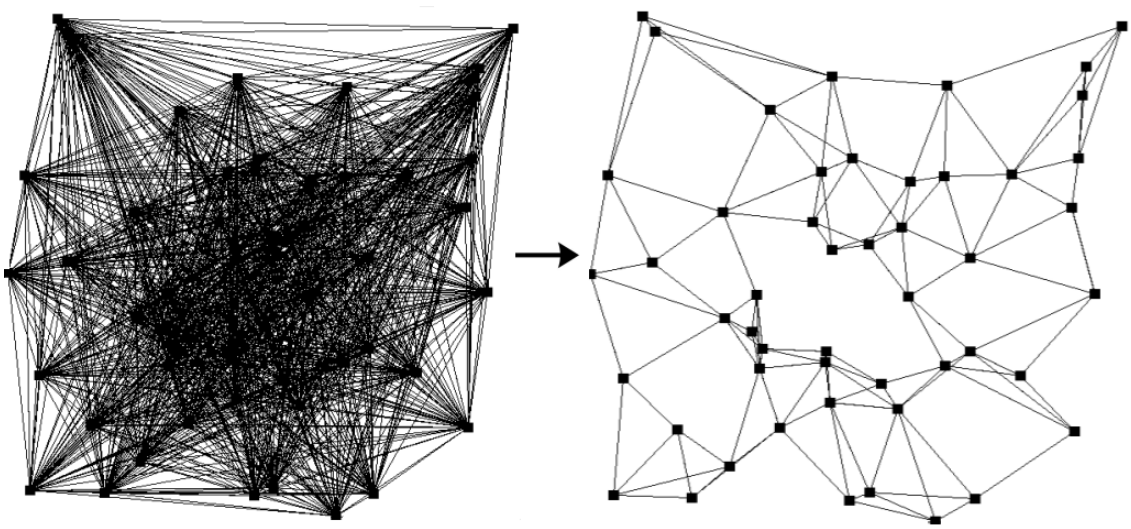


Figure 4. Connectivity topology generated by MLD

Data: A Set of nodes $N[Vu]$; An integer K
Result: A setting for the N nodes transmission powers that generates an SCC.
Initialization: Set $Pu = 0$, for every node u;
For each node Vu: Set Pu to the minimum value that reaches at least K nodes in $N[Vu]$;

Algorithm 3: Minimum Link Degree

4. Methodology

To evaluate the performance of MLD in comparison with MST and Redundant MST, these algorithms were implemented in the Sinalgo network simulator [EDC_Group 2008].

The comparison of algorithms consider three metrics: sum of transmission powers of all nodes (Equation 2, Section 3); highest node consumption in the network (Equation 3); and standard deviation between network nodes' transmission powers (Equation 4). In Equations 3 and 4, Pu corresponds to the transmission power of node u, $\overline{P}$ is the average consumption and N is the total number of nodes in the network.

$$max(Pu); u = 1, ..., N, \tag{3}$$

$$\sum_{u=1}^{n} \sqrt{\frac{(Pu - \overline{P})^2}{(n-1)}}. \tag{4}$$

Although the minimization of the first metric is the main goal, the second metric (maximum consumption of a node) indicates how fast the failure of the first node will happen, that is, in a not fault-tolerant topology, represents the network lifetime itself. The third metric shows how uniformly distributed between nodes, the transmission powers are. A small standard deviation means that nodes' batteries are more equally consumed extending the lifetime of a fault-tolerant network.

The simulation space consisted of a 500m $\times$ 500m plane. The algorithms were tested in networks that have from 20 to 100 nodes (less than four nodes per $100m^2$, referred as sparse) and from 100 to 800 nodes (more than four nodes per $100m^2$, referred as dense). Five scenarios, with nodes randomly distributed in a two-dimensional space, were conducted for each node cardinality. The graphics in Section 5 show the average results with confidence intervals. The confidence intervals have a 95% confidence probability.

As a final experiment, we compare the fault tolerance of generated topologies by analyzing the number of node faults survived at each topology, according to two very different fault models. The first one models faults caused by total consumption of a node battery supply. In this case, nodes are removed from the network in order of their consumption, i.e., the network node with the highest consumption is the first one to be removed and so on. In the second model, the goal is to simulate nodes' faults due to natural causes in the sensed environment (e.g., node damaged because of high temperature or smashed by an animal). In this case, the fault node is randomly selected in the topology. In both models, nodes are deactivated until the network loses connectivity, i.e., until there exists a given pair of alive nodes with no path between one another. In this last experi-

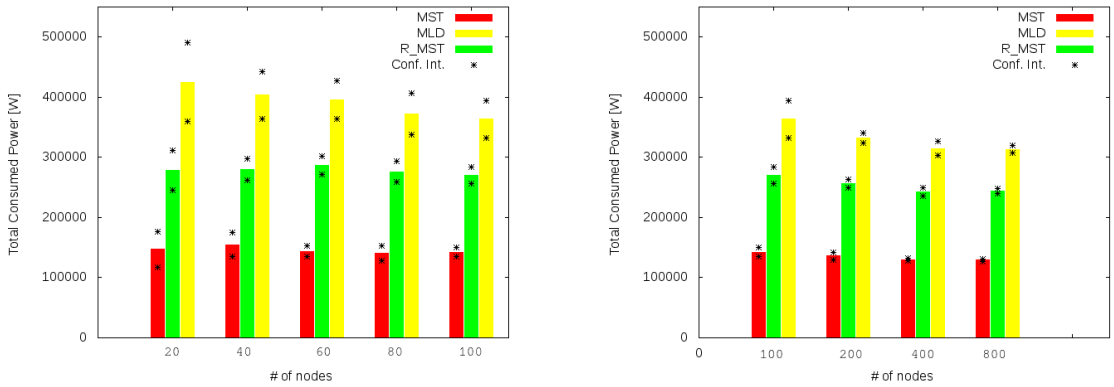
ment, the algorithms were compared to each other in 10 different position sets for each kind of node density, sparse and dense.

5. Simulation and Results

In this section, we discuss our simulation results. Transmission powers were computed according to Equation 1 (Section 3) with $\alpha = 2.0$ and $Thr = 0.7$, usual values for free-space modeling [Cheng et al. 2003].

5.1. Energy Consumption

The first desired property in our topologies is the low energy consumption. Since our experiments were made with randomly positioned nodes, tests with fewer nodes have less precise confidence intervals due to the lower probability of similarities in the geographical distribution of nodes.



(a) Sparse (less than 4 nodes/$100m^2$)

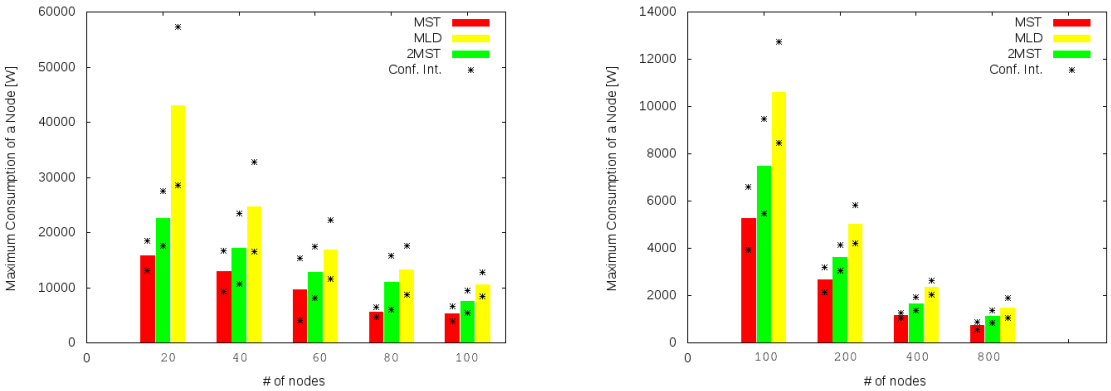
(b) Dense (more than 4 nodes/$100m^2$)

Figure 5. Total network consumption in generated topologies

Figure 5 shows a comparison between algorithms, considering the total energy consumption in sparse and dense networks. The first interesting result from this experiment is that the Redundant MST consumes around two times more energy than MST_SMET. This may be understood as the extra cost of adding fault tolerance to a low energy topology. Moreover, results show that this double cost does not seem to change with the increase of the node density, remaining approximately constant.

Turning our attention to the practical aspect of the topology generation, the results show that MLD has an average increase of less than 50% in energy consumption, in sparse scenarios, when compared to non-practical Redundant MST. In addition, it is possible to notice that, with MLD topology, the energy consumption decreases with the node density. For instance, with 20 nodes the MLD consumption is 52% higher than Redundant MST. With 800 nodes, the extra consumption decreases to 28%. In fact, with more than four nodes per $100m^2$, the difference is less than 35%.

Figure 6 shows the maximum consumptions at nodes. As we can see, the maximum consumption decreases exponentially with the node density. This metric indicates in which topology the first fault of a node will occur. MST_SMET has the best results, i.e., the lowest consumption. However, the first fault in MST_SMET will cause the network

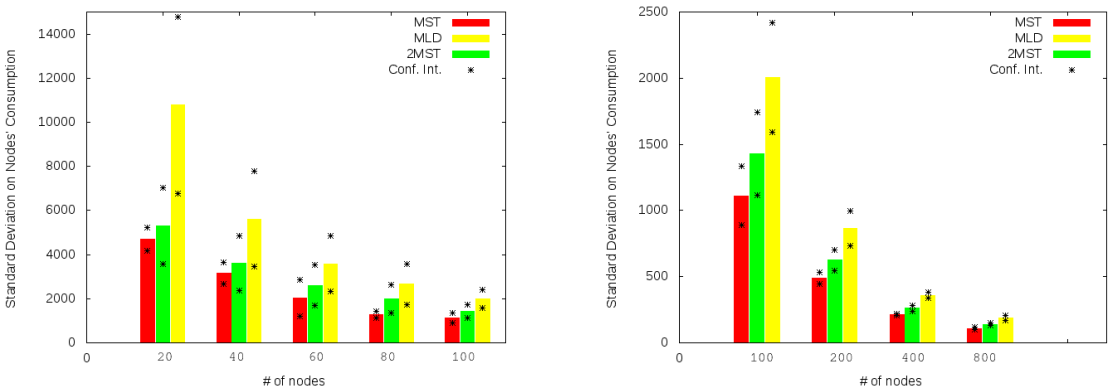


(a) Sparse (less than 4 nodes/$100m^2$)

(b) Dense (more than 4 nodes/$100m^2$)

Figure 6. Maximum consumption at a node in generated topologies

disconnection, because every node is extremely important for the MST_SMET topology. Redundant MST and MLD have higher maximum consumptions. Since Redundant MST always includes MST_SMET topology, Redundant MST nodes will always have higher consumptions than MST_SMET nodes. The difference decreases with node density. The maximum consumptions in the three algorithms become very similar in dense networks.



(a) Sparse (less than 4 nodes/$100m^2$)

(b) Dense (more than 4 nodes/$100m^2$)

Figure 7. Standard deviation between nodes' power consumption in generated topologies

Figure 7 presents the standard deviation of the power transmission for the nodes. As in the maximum consumption, the performance difference decreases with the node density. All three metrics present this behavior. This is an indication that MLD results get better, in comparison with the baselines, with the increase of the node density.

Looking back at the total network consumption (Figure 5), with 800 nodes, MLD consumed 2.5 times more than MST_SMET. Considering the MST_SMET approximation rate of two, this result shows that MLD generates fault-tolerant topologies with at most five times more consumption than the minimum possible, not fault tolerant, energy topology (i.e., the optimal solution for SMET).

When we visually inspect the generated topologies (Figures 3, 4 and 5), one may

notice that MLD topology seems to be more redundant, i.e., this network may survive to more node faults than the other two. This observation motivated our next experiment that analyses the number of tolerated faults until the network loses connectivity.

5.2. Fault-Tolerance Analysis

Our first analysis of the fault tolerance considers faults caused by the lack of battery. At each time, the alive node with the highest consumption is removed from the network. Nodes are removed until the topology becomes disconnected. Figure 8 shows boxplots of the results in sparse (20 nodes, less than $1/100m^2$) and dense (100 nodes, $4/100m^2$).

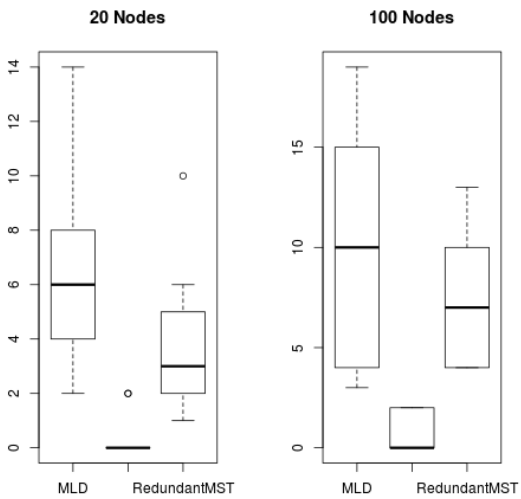


Figure 8. Number of faults until the network disconnects for each algorithm in sparse and dense scenarios. Battery fault model

The result shows that MLD presents the best performance, being two times more fault tolerant in sparse scenarios and 60% more fault tolerant in dense, when compared with Redundant MST considering average results.

Figure 9 presents results for the random fault tolerance. In this case, MLD presents even better results when compared to the Redundant MST.

In both Figures 8 and 9, we can see MST_SMET results in the center of the images. As expected, the number of tolerated faults is zero, except for rare cases in which the fault occurs in a leaf of the MST topology.

The results show that the practical algorithm MLD presents a better performance than the baseline, the Redundant MST, with respect to the number of tolerated faults in both, sparse and dense scenarios with both fault models.

6. Conclusions and Future Works

In this work, we investigate aspects of the *Strongly Minimum Energy Topology* problem, which has its decision version known to be NP-Complete. Specifically, we discuss the importance of fault tolerance in WSNs. Based on the MST_SMET, an algorithm for not fault-tolerant topologies, we propose a non-practical algorithm, Redundant MST, to be

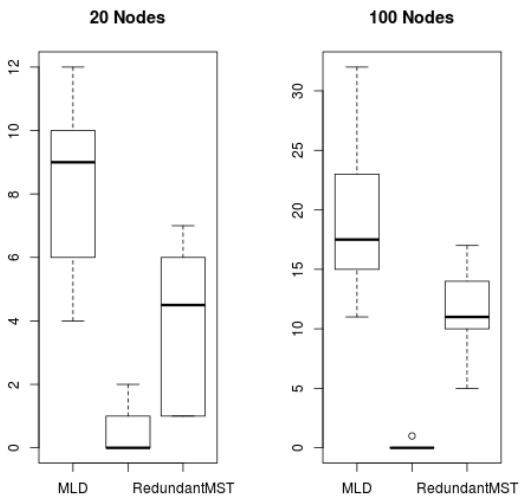


Figure 9. Number of faults until a network disconnection occurs for each algorithm in sparse and dense scenarios. Random fault model

used as a baseline for fault-tolerant topologies. Next, we directed our attention to the practical aspect, proposing the *Minimum Link Degree*, a practical, distributed and fault-tolerant algorithm.

All three algorithms were implemented in the Sinalgo platform and compared with respect to energy consumption and fault-tolerance degree. Simulation results show that MLD is a good strategy for creating fault-tolerant topologies. It consumes around 50% more energy than the Redundant MST in sparse scenarios and 35% more in dense scenarios. Because of a higher redundancy in MLD topologies, the number of survived faults is, on average, two times larger than in Redundant MST. If, in a given WSN, the low energy consumption and the fault tolerance are equally important, we may define a cost-benefit function BC as $BC = WSN_{faultsSurvived}/WSN_{totalConsumption}$. In all experimented scenarios, $BC(MLD) > BC(Red.MST) > BC(MST\_SMET)$. This results shows that MLD has a great potential of use because, in many sensing applications, the fault tolerance of the network can be even more important than the total energy consumption. To summarize, Table 1 presents a qualitative comparison among the evaluated algorithms.

	Time Complexity	Fault Tolerant	Distributed?	Consumpt. (at most)	Survived Faults
MST_SMET	O($V^2 log(V)$)	No	Not viable	2 x Min.	None
Red. MST	O($V^2 log(V)$)	Yes	Not viable	4 x Min.	Good
MLD	O(V^2)	Yes	Viable	6 x Min.	Better

Table 1. Qualitative comparison between algorithms

Some interesting future extensions would be: (i) evaluate MLD in a WSN scenario with mobility; (ii) apply MLD to generate low-power and fault-tolerant topologies in real WSNs; (iii) design specific routing algorithms to work on an MLD topology; and (iv) study MLD variations for environments with physical obstacles.

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