Link redundancy based connected topologies in ad-hoc networks

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Link Redundancy Based Connected Topologies in Ad-hoc Networks

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Abstract— **The topology of a wireless network can have a significant impact on the connectivity, fault tolerance and longevity of a network. Power optimised topology control algorithms including a Relative Neighbourhood Graph (RNG) and a Minimum Spanning Tree (MST) reduce the links in a network topology, while keeping a topology connected. Link redundancy may be critical to cope with faults such as node failures and link disruptions. In this paper, we analyse the fault tolerance of a number of topology control algorithms. We propose a new distributed mechanism to increase the fault tolerance of power optimised topology control algorithms. The proposed mechanism can be used in the case of node failures, where extra link redundancy may be crucial to provide a connected topology. We compare the connectivity, fault tolerance, transmission power and the hop diameter of the proposed approach against RNG, MST and the 'minimum node degree' graphs for different node degree values. Simulations indicates that the proposed approach provides a distributed mechanism to enhance the fault tolerance and connectivity of RNG and MST topology graphs for high node failure rates.**

I. Introduction

An ad-hoc network is a group of autonomous wireless nodes working together to form a network. Nodes in an ad-hoc network can be battery powered devices with limited transmission capabilities. Power conservation can be a critical factor to enhance the lifetime of a network.

The topology of a wireless network can have a significant impact on the available network resources including connectivity, power usage, network lifetime, bandwidth and delay. Power optimised topology control algorithms model a network topology as a Graph (V, E), where 'V' are the vertices and 'E' are the edges. The vertices represent the nodes in a networks and edges represent the links. A Minimum Spanning Tree (MST) and a Relative Neighbourhood Graph (RNG), reduce the number of links in a topology graph, while maintaining a connected topology. The total power usage in a MST or a RNG can be reduced by adjusting the transmission power to cover the link distance between two nodes, and using the minimum power routes to forward the data packets [1]. There are various application of MST and RNG graphs in power optimised routing and flooding [2].

The signal attenuation characteristics, node mobility and low battery power can make wireless links unreliable and result in frequent link disruptions and node failures. In the presence of node failures, a low link redundancy solution including a MST and a RNG may result in a disconnected network and introduce unnecessary delay in network communications.

A 'minimum node degree' graph [3] aims to maintains a minimum number of one hop neighbours by controlling the 'node degree' parameter. The 'node degree' of a node is equal to the nodes within it's transmission range or the number of edges incident at a vertex in a topology graph. Numerous node degree values have been proposed to establish a highly probable connected network [4] [5] [6].

A minimum node degree graph can be more fault tolerance than a MST and a RNG [7], however a 'minimum node degree' graph fails to provide a fully connected network and may result in 'isolated nodes' and 'disjointed clusters' [8][9]. Furthermore, average transmission power used by a 'minimum node degree' graph is significantly larger than a MST and a RNG graph [7].

In this paper we propose a new distributed mechanism to select and add extra link/s to the power optimised topology graphs. The link selection is based on a 'redundancy' metric, which utilises two hop neighbours and their local topology graph information. A collaborative procedure proposed in [9] is used in conjunction with the neighbour discovery protocol to provide a bidirectional topology graph. The proposed algorithm is applied to the MST and RNG graphs and their connectivity, fault tolerance, transmission power and hop diameter are evaluated for increasing network size and node failure rates.

Section II of the paper provides an overview of the topology control algorithms. Section III discusses the proposed approach. Section IV illustrates the operation of the proposed approach with an aid of a worked example. Section V provides a simulation based analysis of the proposed approach. Section VI concludes the paper.

II. Topology Control Algorithms

A MST of a graph defines the smallest subset of edges that keeps the graph in one connected component [10]. There are two main algorithms, (1) *Kruskal's Algorithm* [11] and (2) *Prim's Algorithm* [11] for computing a MST. *Kruskal's* algorithm chooses edges of the graph with minimum weight. *Prim's* algorithm builds the MST by putting an arbitrary node into a tree. This eliminates the search step required in the Kruskal's algorithm. The edges are added to the graph if they are smaller than the previous edges already in the graph.

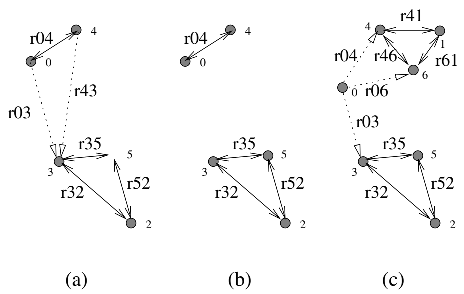


Fig. 1. [8](a) K-Neigh based topology graph with nd=2. (b) K-Neigh based bidirectional topology graph with nd=2. (c) Alone Soldier problem in K-Neigh based topology graph with nd=2.

The RNG of a N node network is exactly those pairs (i, j) of nodes, for which there is no node 'z' such that $\|r_i - r_z\| < \|r_i - r_j\|$ and $\|r_j - r_z\| < \|r_i - r_j\|$ where 'r_i' denotes the position vector of node 'i' [12] [13] [14]. Hence an edge between 'i' and 'j' is only valid if there is no other node between 'i' and 'j' that satisfies the condition stated above.

A '*minimum node degree graph*' is a topology graph where the edges incident at a node are equal to or lower than 'x', where 'x' is the target 'node degree' (nd) parameter. A number of topology control algorithms have been proposed to maintain a minimum node degree. Such algorithms include K-Neigh [15], Location Information No Topology (LINT) [16], and MobileGrid (MG) [17]. A 'minimum node degree' graph may not result in a connected network and the connectivity of a network can depend on numerous parameters such as node distribution pattern, node degree value and the size of a network. In order to illustrate the disconnected nature of 'minimum node degree' graphs, Figures 1(a), 1(b) and 1(c) are analysed.

Figures 1(a) and 1(b) are the plots of a 5 node network topology with a minimum node degree requirement of 2. A line represents a link and an arrow represents the direction of a link. When executing K-Neigh [15], the local unidirectional topology graphs of nodes 0, 4 and 3 comprises of links $\{r_{04}, r_{03}\}$, $\{r_{04}, r_{43}\}$, and $\{r_{35}, r_{32}\}$ respectively. After exchanging the local unidirectional topology graphs, the bidirectional links of nodes 0, 4 and 3 are $\{r_{04}\}$, $\{r_{04}\}$, and $\{r_{35}, r_{32}\}$ respectively. The bidirectional topology in Figure 1(b) is disconnected, since links 'r_{03}' and 'r_{43}' are unidirectional and are not included.

The fixed node degree approach may also create an 'alone soldier' problem [3], illustrated in Figure 1(c). This occurs when nodes 3, 4 and 6 have met their local node degree requirements and their local topology graphs do not contain a link to node 0, where as node 0 may have added unidirectional links to these nodes. There can be many topology distributions where the local node degree requirements may be met, but the bidirectional node degree requirements may not be satisfied. As the result of this, the bidirectional node degree graphs may be disconnected [8].

In [7] the connectivity, power usage and the hop diameter of 'minimum node degree' graphs is analysed for a range of node degree values and node failure rates. It was observed that in the case of node failures, a 'minimum node degree' graph has a better chance of maintaining a connected network as compared to a MST and a RNG [7]. However, the transmission power of 'minimum node degree' graphs is significantly larger than MST and RNG topology graphs [7].

III. Proposed Algorithm

The aim of the proposed algorithm, Link Redundancy (LR), is to add extra link/s to a power optimised topology in order to enhance it's fault tolerance. The links are added on the basis of their 'redundancy' value, which is calculated in a distributed manner by examining the one hop connectivity of a probable redundant link and comparing it with the 1^{st} and 2^{nd} hop connectivity of a node executing the LR algorithm. This allows a node to evaluate a redundancy parameter for each link which was not initially included in the topology graph. A high redundancy value implies a larger chance of providing connectivity with the 1^{st} and 2^{nd} hop topology control neighbours. This is different to the 'minimum node degree' graphs, where links are added on the basis of their distance from the reference node.

A topology graph is generated locally when executing a distributed topology control algorithm, including Distributed Relative Neighbourhood Graph (DRNG), Localised Minimum Spanning Tree (LMST) and K-Neigh or can be constructed and disseminated by a central node in the case of centralised algorithms, including RNG and MST.

The neighbour information is evaluated by exchanging "Hello" messages at the maximum power [18]. A "Hello" message contains the identification (ID) of the broadcasting node and is used to evaluate a list of unidirectional neighbouring nodes (N_i). The ID is a unique number assigned to a node to maintain its identity in a network, for example Internet Protocol (IP) address. A node's ID is used to construct a Topology Control Neighbour (TCN) list comprising of the nodes in the topology graph. A TCN list is generated by executing a particular topology control algorithm and is a subset of the maximum power neighbours (N_i).

Bidirectional TCNs are evaluated by appending the TCN list to a "Hello' packet and broadcasting it at the maximum power. Nodes receiving the broadcast are able to determine the bi-directional TCNs (BTCNs) by using the *Bidirectional-TCN()* function, where BTCNs are evaluated by performing a search between local TCNs and the one hop neighbouring TCNs.

The unique two hop TCNs of node 'i'' are depicted by set 'E_i' and is evaluated by calculating the set of nodes which are unique 1^{st} and 2^{nd} hop TCN neighbours of node 'i'. The two hop TCN list of node 'i' ($TCN_i \cup TCN(TCN_i)$), includes nodes which are TCNs of nodes 'i' and conjointly the set of nodes which are the TCNs of every TCN of node 'i', as shown in Equation 1.

$$E_i = TCN_i \;\cup\; TCN(TCN_i) \neq i, \notin E_i \qquad (1)$$

Each node calculates a set of possible links which are **not in** it's local topology graph but are within it's transmission range. This set is represented by set 'T_i' and is evaluated by removing the TCNs of node 'i' from 'N_i' ($T_i = \{N_i - TCN_i\}$). A *Construct-LR()* function is proposed, where each node initially calculates sets 'E_i' and 'T_i' and then calculated the **redundancy (R_j)** of each node $j \in T_i$. 'R_j' is calculated by evaluating the total number of nodes in set 'TCN_j' which are common to set E_i and dividing the total by the total number of nodes in E_i as depicted in Equation 2.

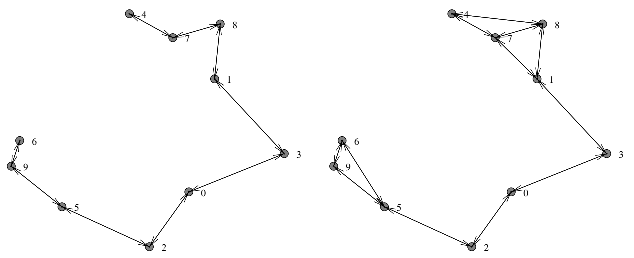
$$R_j = \frac{\sum TCN_j \cap E_i \cap j}{\sum E_i}, i \neq j, j \in T_i \quad (2)$$

In oder to add an extra redundant link, node 'i' executes the *Add-LR()* function and adds node '$j \in T_i$' which has the maximum redundancy value 'R_j', to the topology graph of node 'i'. In case of a deadlock where links may have equal redundancy values, link 'r_{ij}' with the least distance to node 'i' is chosen in order to conform with the power saving objectives of a power aware topology control algorithm.

Unidirectional TCNs are converted to BTCNs by using the *Convert-TCN()* function, which uses a search to evaluate the unidirectional TCNs and add a corresponding link. A node iterates through its neighbour's TCN list and adds the neighbour's ID to its local TCN list, if there is a unidirectional link from its neighbour to itself. The conversion of unidirectional TCNs to bidirectional TCNs does not require any message exchange apart from the "Hello" messages. We assume that all nodes are *Collaborative* and are willing to support such decisions. This procedure is critical as unidirectional links cannot be used for unicast communication and do not improve the bidirectional connectivity of a network.

Algorithm *Bidirectional-TCN()*
(∗ Find Bidirectional TCN list ∗)
TCN_i ←Local uni-directional TCN list of node i
$BTCN_i$ ←Local bi-directional TCN list of node i
if $TCN_i \neq 0$
  for each node k in TCN_i
    j ←Calculate node k's TCNs
    while $j \neq 0$
      if $j = i$
        then Add k to $BTCN_i$
  return $BTCN_i$

Algorithm *Construct-LR()*
(∗ Construct a R_j list ∗)
N_i ←1-hop unidirectional neighbours of node i, sorted in the order of their distance from i
$BTCN_i$ ←Local bi-directional TCNs of node i
T_i ←Set of nodes $\in \{N_i - BTCN_i\}$
E_i ←$BTCN_i \cup BTCN(BTCN_i) \neq i, \notin E_i$
Ei_{count} ←Total number of nodes in E_i
R_j ←Redundancy value of node j
$count$ ←Count of the common elements
for each node j $\in T_i$
  $BTCN_j$ ←Calculate node j's BTCN



(a) A RNG based network topology

(b) A LR-RNG based network topology

Fig. 2.

  for each node l $\in BTCN_j$
    if (l $\in E_i$ or $j \in E_i$)
      count=count+1
  $R_j = count/Ei_{count}$
  count =0
return R

Algorithm *Add-LR()*
(∗ Add a redundant link to the topology graph ∗)
N_i ←1-hop unidirectional neighbours of node i, sorted in the order of their distance from i
TCN_i ←Local uni-directional TCNs of node i
$BTCN_i$ ←Local bi-directional TCNs of node i
R_j ←Redundancy value of node j
T_i ←Set of nodes $\in \{N_i - BTCN_i\}$
R_{max} ←maximum redundancy value
R_{index} ←maximum redundancy index
r_{ij} ←Distance between node 'i' and 'j'.
$R_{max} = 0$
for each node j $\in T_i$
  if $(R_j > R_{max})$
    $R_{max} = R_j$
    $R_{index} = j$
  if $(R_j == R_{max}\ and\ R_{max} \neq 0)$
    if $(r_{ij} < r_{iT(R_{index})})$
      $R_{index} = j$
Add $T(R_{index})$ to TCN_i
return TCN_i

Algorithm *Convert-TCN()*
(∗ Convert unidirectional to bidirectional TCN ∗)
N_i ←1-hop unidirectional neighbours of node i
$BTCN_i$ ←Local bi-directional TCN list of node i
if $N_i \neq 0$
  for each node k in N_i
    j ←TCN of node k
    if i = j and k $\notin BTCN_i$
      then Add k to $BTCN_i$
  return $BTCN_i$

IV. Worked Example

Figure 2(a) is a RNG topology graph of a 10 node network. Figure 2(b) is a topology graph of LR applied to the RNG topology (LR-RNG) depicted in Figure 2(a). In Figure 2(b), a number of redundant links are included which were not preset in Figure 2(a). Example of such links include $\{1 \rightarrow 7\}$, $\{4 \rightarrow 8\}$, $\{5 \rightarrow 6\}$, $\{6 \rightarrow 5\}$, $\{8 \rightarrow 4\}$ and $\{7 \rightarrow 1\}$. The details of the LR-RNG calculation are as follows:-

Node 1: (i=1)
$TCN_1 = \{3, 8\}$
$E_1 = \{3, 8, 0, 7\}$, using equation 1
$T_1 = \{4, 7\}$, two redundant links to check.
Checking node 4: (j=4)
$TCN_4 = \{7\}$
$TCN_4 \cap E_1 \cap 4 = \{1\}$
$R_4 = \frac{1}{4} = 0.25$, using equation 2
Checking node 7: (j=7)
$TCN_7 = \{4, 8\}$
$TCN_7 \cap E_1 \cap 7 = \{8, 7\}$
$R_7 = \frac{2}{4} = 0.50$, using equation 2
Since $R_7 > R_4$, node 7 is added to the topology graph of node 1, and hence $\mathbf{TCN_1 = \{3, 7, 8\}}$

Node 4: (i=4)
$TCN_4 = \{7\}$
$E_4 = \{7, 8\}$, using equation 1
$T_4 = \{1, 8\}$, two redundant links to check.
Checking node 1: (j=1)
$TCN_1 = \{3, 7, 8\}$ Note that TCN_1 now includes node 7
$TCN_1 \cap E_4 \cap 1 = \{7, 8\}$
$R_1 = \frac{2}{2} = 1.00$, using equation 2
Checking node 8: (j=8)
$TCN_8 = \{1, 7\}$
$TCN_8 \cap E_1 \cap 8 = \{7, 8\}$
$R_8 = \frac{2}{2} = 1.00$, using equation 2
Since $R_8 = R_1$, node 8 is added to the topology graph of node 4, as the distance of node 4 to node 1 is greater than distance of node 4 to node 8 ($r_{41} > r_{48}$). Hence $\mathbf{TCN_4 = \{7, 8\}}$

Node 5: (i=5)
$TCN_5 = \{2, 9\}$
$E_5 = \{2, 9, 0, 6\}$, using equation 1
$T_5 = \{6\}$, one redundant links to check.
Checking node 6: (j=6)
$TCN_6 = \{9\}$
$TCN_6 \cap E_5 \cap 6 = \{6, 9\}$
$R_6 = \frac{2}{4} = 0.50$, using equation 2
Since R_6, is the only node to check, node 6 is added to the topology graph of node 5. A preprocessing phase can be introduced here to avoid the redundancy calculation if there is only one T node to check. Hence $\mathbf{TCN_5 = \{2, 6, 9\}}$. Similarly nodes 6, 7 and 8 have only one node in their T set ($T_6 = \{5\}, T_7 = \{1\}, T_8 = \{4\}$), and have added corresponding links to those nodes.

The topology in Figure 2(b) is more fault tolerant than Figure 2(a). For example, in case of the failure of nodes 7 and 9 the topology graph of LR-RNG will still be connected, where as in the case of RNG, nodes 6 and 4 will be be disconnected from the network. In the case of higher network densities, there can be many nodes in the 'T' and 'E' sets of a node, and worked examples can become complicated. The following section provides the simulation based analysis of the LR algorithm for increasing network size.

V. Simulation

A simulation of the topology graphs has been conducted to examine the performance of LR-MST, LR-RNG, Maximum Power Topology (MPT), RNG, MST and K-Neigh (nd=1,2,3,4,5,6,7,8) algorithms in a static network. In this study, the LR algorithm is executed locally to choose **one** additional redundant link per node. The nodes are distributed in a random manner in a 600m X 600m grid area and varied in number from 10 to 100. All nodes have a maximum transmission range of 200m. The simulation results are averaged over 500 random seeds. In order to model node failures due to an 'expired battery' or nodes being 'switched off', faults are introduced in a network by randomly removing a set of nodes from a topology graph.

The performance metrics studied are as follows:- (1) The **Average network connectivity**, is defined as the average of the 'mean connectivity'. The 'mean connectivity' of node 'i' is given by $c_i = \frac{x}{N}$, where 'x' is the number of nodes reachable by node 'i' and 'N' is the total number of nodes in a network. The average network connectivity of the entire network is evaluated by averaging the mean connectivity at every node and is given by $\frac{1}{N}\sum_{i=0}^{N-1} c_i$. (2) The **Average transmission power**, is defined as the average of the 'mean transmission power' per link, at each node. The 'mean transmission power' of node 'i' is given by $p_i = \frac{\sum_{j=1}^{L} p_{ij}}{L}$, where p_{ij} is the power required to reach link (i,j) and 'L' are the total number of links in local topology graph of node 'i'. The average transmission power of the entire network is evaluated by averaging the mean transmission power per link at every node and is given by $\frac{1}{N}\sum_{i=0}^{N-1} p_i$. (3) The **Average hop diameter**, is the mean of the maximum number of hops reachable by a node. (4) The **Average one hop neighbours**, are the mean one hop bidirectional neighbours in the topology graph.

A. Results

A study of the average network connectivity of the RNG, MST, MPT and LINT (nd=1,2,3,4,5,6) topology graphs has been conduced in [7]. Figure 3 is the plot of the average network connectivity against the number of network nodes. MPT, MST, RNG and LINT (nd=6,7,8) are able to reach ≈100% connectivity at ≈40 nodes [7]. The node degree values of 1, 2 and 3 show significantly lower connectivity than other node degree values examined. Since the node degree values of 1, 2, 3 and 4 illustrate connectivity below 95%, only node degree values of 5, 6, 7 and 8 are studied ahead.

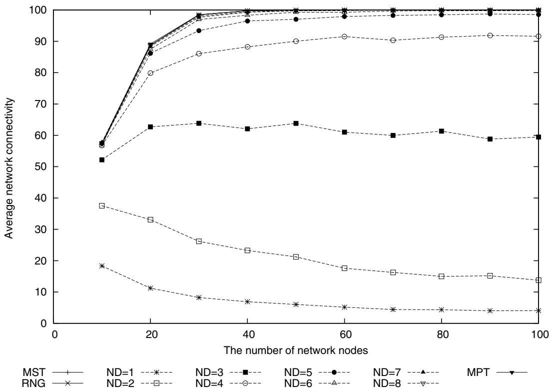


Fig. 3. [7] A comparison of the average network connectivity of the topology control algorithms.

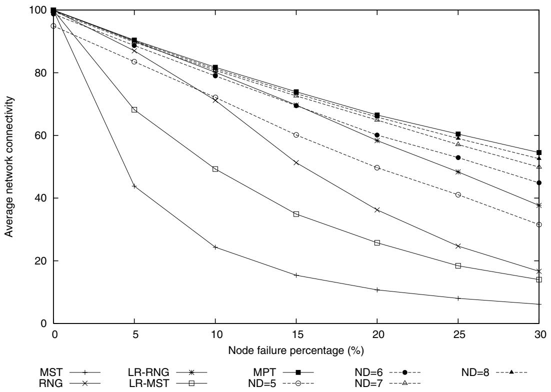


Fig. 4. A comparison of the fault tolerance of the topology control algorithms.

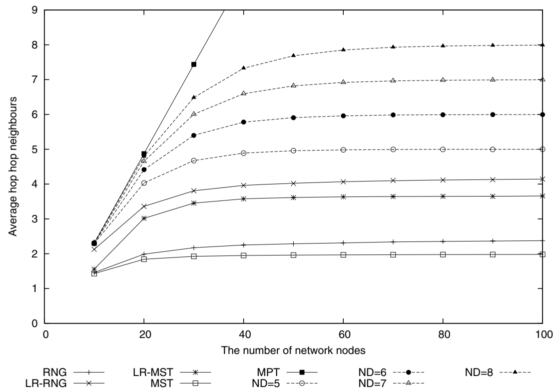


Fig. 5. A comparison of the average one hop bi-directional neighbours of the topology control algorithms.

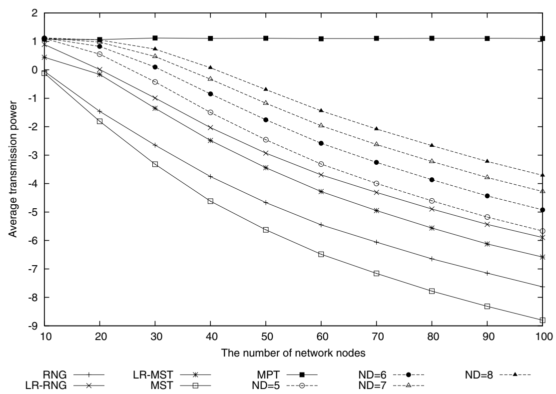


Fig. 6. A comparison of the average transmission power of the topology control algorithms.

Figure 4 is a plot of the average network connectivity for a 100 node network, against the node failure rate. LR-RNG, RNG, MST, LR-MST, MPT and K-Neigh (nd=5,6,7,8) illustrate a decrease in network connectivity with an increase in the failure rate. As expected, MST provides a least fault tolerant topology, and MPT provides the most fault-tolerant topology.

The average network connectivity of MST at 5% failure rate is ≈44%, where as the connectivity of LR-MST, LR-RNG, MPT, RNG and K-Neigh (nd=5,6,7,8) are ≈71% and ≈90% ≈90%, ≈87%, ≈ {88,89,90.3,90.4}% respectively. LR-MST illustrates a significant improvement in the connectivity of MST at the 5% node failure rate.

In the case of 15% node failure rate, the connectivity of LR-RNG and K-Neigh(nd=6) are ≈70%, where as the connectivity of RNG is ≈53%. The connectivity of LR-MST and MST are ≈34% and ≈15%.

In the case of a 30% node failure rate, the connectivity of LR-MST, LR-RNG, MPT, MST, RNG and K-Neigh (nd=5,6,7,8) are ≈14%, ≈38%, ≈54.6%, ≈7%, ≈22% and ≈ {40,44,52.7,53.7}% respectively. The connectivity of LR-MST, and LR-RNG are ≈2 and ≈1.7 times larger than MST and RNG respectively. The connectivity of LR-RNG is ≈6% lower than K-Neigh(nd=6) and ≈%16 lower than MPT in the case of 30% node failure rate.

In general the connectivity of MST and RNG is significantly improved by applying the LR algorithm. The connectivity of LR-RNG is now comparable to the connectivity of K-Neigh(nd=6) until the node failure rate of ≈20% and is only ≈3% lower than MPT.

Figure 5 is a plot of the average one hop bidirectional neighbours against the total number of network nodes. As expected MPT graph illustrates the maximum number of one hop neighbours where as a MST graphs shows the minimum number of one hop neighbours. In a 100 node network, the average one hop neighbours of RNG and MST are ≈2.4 and ≈2 respectively, whereas of LR-RNG and LR-MST are ≈4.1 and ≈3.7 respectively. As expected the number of one hop neighbours in LR-RNG and LR-MST are larger than RNG and MST topology graphs. The number of neighbours in the case of LR-RNG are ≈50% less than than one hop neighbours in the case of K-Neigh(nd=6).

Figure 6 is a plot of the average transmission power against the total number of network nodes. The average transmission power of MPT remains constant at ≈1.1 dBm/link. The average transmission power in the case of LR-MST, LR-RNG, RNG, MST and K-Neigh decreases with an increase in the number of nodes. In a 100 node network the average transmission power of LR-MST, LR-RNG, MST, RNG and

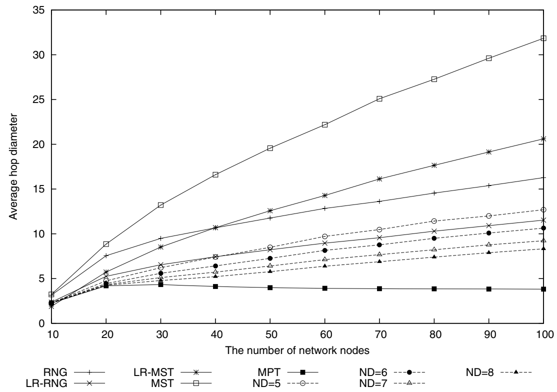


Fig. 7. A comparison of the hop diameter of the topology control algorithms.

K-Neigh (nd=5,6,7,8) are ≈-6.6dBm, ≈-5.9dBm, ≈-8.8dBm , ≈-7.6dBm and ≈ {0.86,-4.9,1.16,1.54}dBm respectively. The average transmission power of LR-RNG is ≈22% larger than RNG, and the power of LR-MST is ≈25% larger than MST. The power increase is due to the extra links added by executing the LR algorithm. However, the powers used by LR-MST and LR-RNG are ≈35%, ≈20% lower than K-Neigh (nd=6) and are significantly lower than MPT.

Figure 7 is a plot of the average hop diameter against the number of network nodes. The hop diameter increases with an increase in the number of nodes. MPT has the smallest hop diameter, where as MST has the largest hop diameter. The hop diameters of LR-MST, LR-RNG, MST, RNG, MPT and K-Neigh (nd=5,6,7,8), for a 100 node network are ≈20.6,≈11.5, ≈32, ≈16, ≈3.8 and ≈ {11.02,10.6,8.3,6.02} respectively. In a 100 node network the hop diameters of RNG and K-Neigh (nd=5,6,7,8) are ≈50% and ≈ $\{62 - 79\%\}$ lower than MST respectively. As expected the hop diameter of LR-MST and LR-RNG are lower than the hop diameters of MST and RNG respectively. The decrease in the hop diameter is due to the larger transmission power used in the LR based topology graphs.

In summary, the LR algorithm illustrates significant improvement in the connectivity of MST and RNG in the case of node failures. The connectivity of LR-RNG is comparable to the connectivity of K-Neigh and MPT until the node failure rate of 20%, as opposed to node failure rate of 5% observed in the case of RNG. The power usage of the LR-RNG algorithm is lower than the K-Neigh graph, and significantly lower than the MPT graph. Furthermore, K-Neigh cannot guarantee a connected network and the overall network connectivity value is dependant on various parameters such as the target 'node degree', maximum transmission range of the nodes and the network density [7]. The average one hop neighbours in the case of LR-RNG and LR-MST are lower than K-Neigh and significantly lower than MPT.

VI. Conclusion

In this paper we have proposed a new distributed approach (LR) to calculate the redundancy of links in a topology graph. We have applied the proposed algorithm to MST and RNG and have compared it with the topology graphs of MST, RNG and K-Neigh. A simulation based study has been conducted to examine the effects of network faults on the performance of the LR algorithm.

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