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Abstract

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Power Efficient Connected Topologies in Ad-hoc Networks

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Abstract—Power efficient topologies in an ad-hoc network can reduce battery usage and increase the lifetime of a network. Topology control algorithms including a Local Minimum Spanning Tree (LMST), Distributed Relative Neighbourhood Graph (DRNG) and K-Neigh graphs are computed by using the location or the distance information of the network nodes. Inaccurate distance or location information *can* lead to disconnected topology graphs. Furthermore, a distance based topology graph may not necessarily be connected due to wireless signal attenuation and propagation characteristics. In a realistic scenario, a small link distance may correspond to a large transmission power as the signal may need to transverse through obstacles. Hence it is imperative to include the environment characteristics when generating power efficient connected topology graphs.

In this paper we identify the topology construction procedures that may lead to disconnected network topologies. We propose a new procedure that can work in conjunction with the neighbour discovery protocol to provide a better connected and power efficient network topology. Simulations indicate that the proposed algorithm provides a significant improvement in the connectivity of power base DRNG graphs.

I. INTRODUCTION

An Ad-hoc network is a collection of cooperative wireless nodes working together to form a network. Nodes in an ad-hoc network can work in an autonomous manner and act as routers to forward network traffic. There are numerous applications of ad-hoc networks including sensor networks, which may consist of thousands/millions of ad-hoc nodes dispersed in sensor fields, disaster recovery scenarios and military networks. Power conservation is critical in an ad-hoc network, as wireless nodes may be portable battery operated devices with limited transmission capabilities and power saving strategies can increase the longevity of a network.

Topology control algonthms model a network topology as a Graph(V, E), of 'vertex' set V and 'edge' set E. The vertices represent the nodes in a network and edges represent links. The location information of nodes is used to construct a network topology graph, where the cost of an edge is proportional to the distance of the link. Examples of the distributed topology control algonthms include Distributed Relative Neighbourhood Graph (DRNG) [1], Local Minimum Spanning Tree (MST) [2] and K-Neigh [3] graphs. The distance and location estimates can be either achieved by Global Positioning Services (GPS) [4] devices or using signal strength of the received broadcast [5][6][7][8][9]. A network topology graph can be used to evaluate a power efficient communication topology, where nodes adjust the transmission power to cover a link distance, and use minimum power routes to forward the data packets [10].

The network topology graphs generated by using GPS location information, may give an inaccurate estimate of the physical connectivity/topology of a network, as nodes may be separated by obstacles and the signal strength may not be large enough to penetrate the obstacles. Furthermore, a smaller link distance may not necessarily correspond to a low transmission power as the signal may need to transverse a number of objects before reaching the destination.

The topology control algorithms such as DRNG and LMST rely on accurate location information to create the topology graphs. The topology graphs based on the power of a received signal broadcast can provide a more accurate representation of the connectivity of a network. The 'Free Space' or a 'Two Ray' signal attenuation models can be used to evaluate the distance information of network nodes by evaluating the pathloss [8] [9]. 'Free Space' and 'Two Ray' signal attenuation models result in symmetrical local topology graphs as the signal attenuation along a particular link is the function of the separation distance only [1]. In the case of multi-path propagation, the signal attenuation or pathloss may not be the same for a particular link distance and may be distorted due to the reflection from objects and other phenomenas such as scattering and shadowing [8]. As a result of the asymmetrical pathlosses, the local topology graphs created by using the pathloss information may not be symmetrical, as the link distance estimates may differ. Therefore, the DRNG or LMST neighbours of one node may not be the same from another node's prospective and may result in a number of unidirectional links in the local topology graphs.

The topology construction procedures proposed in literature, disregard the unidirectional links for unicast communications as the acknowledgements for a receiver are not available. For example the working of the 802.11 [11] Medium Access Channel (MAC) protocol relies on Clear-To-Send (CTS) and ACK packets transmitted by a receiver to coordinate transmission of a data packet. Therefore a bidirectional links is essential to coordinate the transmission of a unicast data packet in a 802.11 based network. Discarding all unidirectional links can

[1]Assuming a constant gain and height of the transmitter and the receiver antennas.

further reduce the bidirectional connectivity of a network and introduce 'isolated nodes' and 'disjointed clusters'.

We propose a distributed topology construction procedure that is integrated as a part of the neighbour discovery protocol to enhance the bidirectional connectivity of the power based topology graphs. The rest of the paper is organised as follows. Section II provides a background on the topology construction procedures and the pathloss models. It also describes the topology construction problem and the disconnected nature of the distance and power based topology graphs. Section III describes the proposed approach. Section IV, provides a simulation analysis of the proposed approach and Section V concludes the paper,

11. BACKGROUND

A. Topology Construction

Topology control algorithms rely on the location information of nodes to construct a topology graph. For example the DRNG of node 'i' are exactly those pairs (i, j) of nodes, for which there is no node '$z \in N.$' such that $\|r. - r.\| < \|r. - r.\|$ and $\|r. - r.\| < \|r. - r.\|$ where '$r.$' denotes the position vector of node 'i' and '$N.$' are the one hop neighbours of node 'i' [12].

Neighbour discovery protocols assist in constructing the topology information by dissemination link-state information in a network. The topology information is used by the routing protocols to discover and construct routes in a network [13]. An example of a distributed neighbour discovery protocol is "Hello" messages. Nodes broadcast a "Hello" packet which is an Internet Protocol (IP) packet, and includes a node's IP address. Nodes receiving a "Hello" broadcast are able to evaluate their surrounding neighbours by staring the IP addresses. Nodes can determine a bidirectional or unidirectional link by exchanging the neighbour information. When constructing routes only bidirectional links are included as unicast packets require acknowledgements from a receiver node. Examples of receiver based acknowledgements include Clear-To-Send (CTS) and Acknowledgement (ACK) packets in 802.11 MAC protocol based networks [11].

The power of a received broadcast has been used to predict the distance between a transmitter and a receiver node by using a particular pathloss model [5][6][7][8]. The pathloss of a signal is defined as the difference in the effective transmitted power and the received power. The average large-scale path loss for an arbitrary transmitter and receiver separation is expressed as a function of distance by using the path loss component 'n' and is given by Equations 1 and 2 [8].

$$\bar{PL}(dB) = \bar{PL}(d_0) + 10nlog(\frac{d}{d_0}) \tag{1}$$

$$\bar{PL}(d_0)(dB) = 10logP. - 10logP(d_0) \tag{2}$$

Where '*do*' is the close-in reference distance which is determined from the measurements close to the transmitter, and 'd' is the separation between the transmitter and the receiver. The value of 'n' depends on the propagation environment and '$P.$' is the transmission power of a transmitter.

The 'Free Space' signal attenuation model is used to predict receiver signal strength when transmitter and a receiver have a clear unobstructed line of sight and is given by Equation 3 [8].

$$P. = P.G.G.\frac{\lambda^2}{4\pi^2 L d^2} \tag{3}$$

Where '$P.$' is the received power, 'G.' and '$G.$' are the gains of the transmitter and the receiver respectively, 'λ' is the wavelength and 'L' is the system loss factor not related to propagation.

The 'Two Ray' signal attenuation model is used to predict the receiver signal strength, in the case of direct path and ground reflection path, and is represented by Equation 4 [8].

$$P. = P.G.G.\frac{h.^2 h.^2}{d4}$$

Where '$h.$' and 'h.' are the heights of the transmitter and the receiver respectively.

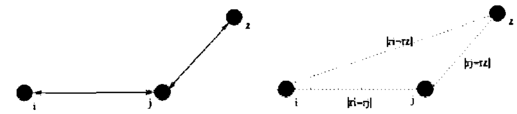
Both 'Free Space' and 'Two Ray' signal propagation models indicate that the average received signal power decreases with distance, whether indoor or outdoor channels [8], and thus the pathloss factor increases with distance. In a realistic scenario the signal strength can vary considerably in indoor and outdoor environments due to multi-path effects such as reflection, diffraction and scattering. The signal attenuation due to reflection, diffraction and long distance pathloss is known as shadowing [14]. The surrounding environment clutter may differ for different locations for the same distance separation 'd'. The measured signal may be significantly different from the average value predicted by Equations 1 and 2. It was shown in [14][15] that the pathloss 'PL(dB)' at a particular location is random and distributed log-normally about the mean distance dependent value and is given by Equation 5 [8].

$$PL(d)[dB] = \bar{PL}(d) + X. = \bar{PL}(d_0) + 10nlog(\frac{d}{d_0}) + X. \tag{5}$$

Where '$X.$' is the zero mean Gaussian distribution random variable (in dB) with standard deviation 'σ' (in dB). The log-normal distribution describes the shadowing effect which occurs over a large number of measurements with the same separation distance 'd'.

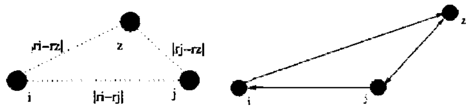
B. Connected Topology Construction Problem

Topology control algorithms such as DRNG and LMST, rely on accurate distance information to construct the topology graphs. When using the 'Free Space' or 'Two Ray' signal attenuation models, the pathloss can be directly linked to the separation distance between a transmitter and a receiver by using Equations 1 and 2. According to Equations 3 and 4, the pathloss from one node to another node and vice-versa, is only dependent on the separation distance (provided that nodes have



(a) **Distance based DRNG topology graph**

(b) **Physical** link **distance based topology** of **node 'i'**



(c) **Pathloss based topology of node 'i'**

(d) **Pathloss based DRNG topology graph**

Fig. 1.

a common maximum transmission power and similar antenna height and gains).

A DRNG graph generated on the basis of the received signal power or pathloss results in ***symmetrical DRNG neighbours*** when using the 'Free Space' or 'Two Ray' signal attenuation models. Symmetrical neighbours implies that if node 'i' is **a** DRNG neighbour of node 'j' then node 'j' is also **a** DRNG neighbour of node 'i'.

Figure 1(a) illustrates a three node DRNG based network topology graph calculated from the location information of the network nodes. The lines in the figure represent links and the arrows represent the direction of the links. Figure 1(b) is the physical link distance representation of the network topology and is used in computing the DRNG topology. The dotted lines represent the physical link distances. When using the 'Free Space' or the 'Two Ray' signal attenuation model, all three nodes maintain the same link distance information and thus compute symmetrical DRNG neighhours and result in the DRNG topology graph depicted in Figure 1(a).

If the log-normal shadowing effects are introduced by using Equation 5, the pathloss from **'z'** to 'i' may be lower than the pathloss from 'j' to **'i'**, contrary to *the* physical distance measurements. In this case the physical topology formed in Figure 1(b) may appear as shown in Figure 1(c). Node 'i' may add node **'z'** as **a** DRNG neighbour, where as node 'j' may still view the physical topology as shown in Figure 1(b) and add node 'i' **as a** DRNG neighbour. **As** a result of this, node 'i' will establish a unidirectional link with node 'z' and node 'j' will establish a unidirectional link with node 'i' and produce a DRNG topology graph shown in Figure 1(d). The DRNG neighhours in Figure 1(d) are no longer symmetrical and include two unidirectional links, one from node 'i' to node 'z' and the other from node 'j' to node 'i'. Discarding the unidirectional links from the topology graph can further reduce the connectivity of **a** DRNG graph and result in network partitioning and clusters. To illustrate this point visually, we examine the DRNG topology graphs in Figures 2(a) 2(b) 2(c) which are generated by simulating the 'Free Space' and the 'log-normal shadowing pathloss' models. The details on the simulation are outlined in Section IV.

Figure 2(a), is **a** DRKG based bidirectional topology graph of **a** 20 node network. The topologies have k e n generated by using a 'Free Space' signal attenuation model. The lines in the figure represent the link and the arrows represent the direction of **a** link. The topology graph in 2(a) is connected and is equivalent to a distance based DRNG.

Figure 2(b) is a DRNG based topology graph of the **same** node distribution as in Figure 2(a), however the signal attenuation model is based on long-normal shadowing and the pathloss are asymmetrical. The dotted lines represent unidirectional links between nodes. The bidirectional topology graph of Figure 2(b) is illustrated in Figure 2(c), where only bidirectional links are included. The topology graphs in Figure 2(c) is disconnected as **all** the unidirectional links are discarded. Furthermore, due to the asymmetric pathlosses, there have been **a** number **of** links which are included in Figure 2(c), and were not included in Figure 2(a). Examples of such links includes nodes $\{10, 19\}$, $\{10, 1\}$ and $\{6, 14\}$.

III. PROPOSED ALGORITHM

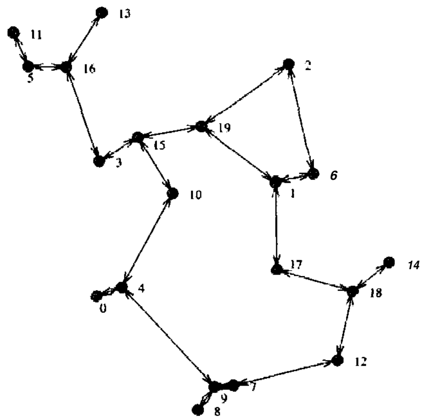
In order to construct the local topology graphs, we propose ***Construct-TCN()***, ***Bidirectional-TCN()*** and ***Convert-TCN()*** functions. The three functions proposed are distributed and rely on one-hop neighbour information. The aim of the functions is to construct symmetrical local power based topology graphs. **A** neighbour discovery mechanism similar to "Hello" messages is used to evaluate the one hop neighbours of **a** node. Nodes receiving **a** "Hello" broadcast, store the IP address of **a** "Hello" packet and the power of the received broadcast to construct the one hop neighbour list '$N_{.}$'.

The ***Construct-TCN()*** function is executed to construct a local DRNG topology graph from '$N_{.}$' **and** can be modified to evaluate **a** MST or a K-neigh graph [2]. **A** Topology Control Neighbour (TCN) list, **is** used to store the local DRNG neighbours. In order to construct **a** local DRNG, a node relies on the IP address of a node and the power of **a** received "Hello" packet exchanged among themselves. **A** node 'i' checks where the power to reach another node 'z', ($P_{..}$) satisfies the condition that $\|P_{..}\| < \|P_{..}\|$ and $\|P_{..}\| < \|P_{..}\|$. **If** this condition is true then link (i,j) **is** not included in the local DRNG graph of node **'i'**.

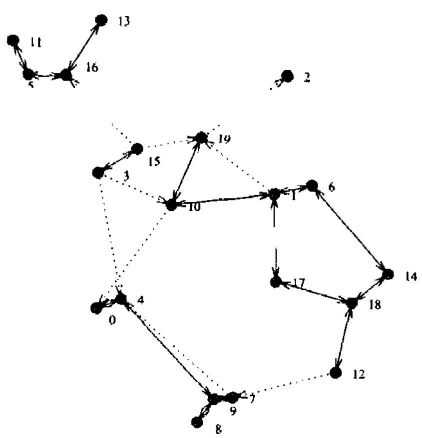
The **TCN** list is exchanged at the maximum power by appending it to a "Hello" message. The exchange of TCN list is used to evaluate bidirectional and unidirectional TCNs. The ***Bidirectional-TCN()*** function is used to evaluate the bidirectional links in the local topology graph. by performing a search on **a** neighbour's TCNs.

Due to multipath propagations, the local power based DRNG graphs may not he symmetrical. The unidirectional TCN links may be critical to maintain a connected graph. **A** unidirectional TCN link between two nudes is converted

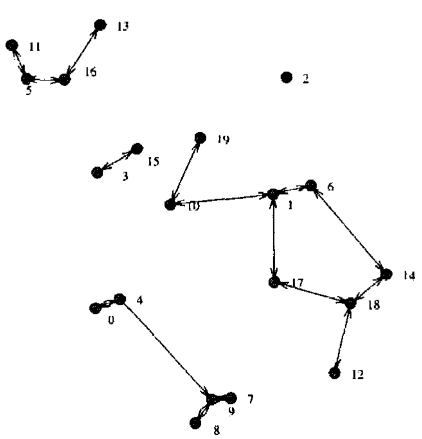
[2]**Due to the space limitations we have only considered DRNG in this paper**



(a) Power based DRNG topology. assuming a 'Free Space' signal attenuation model



(b) Power based DRNG topology. assuming log-normal shadowing



(c) Power based bidirectional **DRNG** topology, assuming log-normal shadowing

Fig. *2.*

into a bidirectional link by a collaborative procedure (*Convert-TCN()*), where nodes are willing to convert a neighbour's unidirectional link into a bidirectional link. In *Convert-TCN()*, a node iterates through it's neighbour's TCN list and adds the neighbour's IP address to it's local TCN list if there is a unidirectional link from it's neighbour to itself.

Algorithm *Construct-TCN()*

```
(* Construct a TCN list *)
N. ←1-hop unidirectional neighbours of node i, sorted
   in the order of their power from i
TCN. ←Local uni-directional TCNs of node i
if N. ≠ 0
    for each node j ∈ N.
        P.. ←Transmission Power of node i re-
            quired to reach node j
        for each node k ∈ N. AND k ≠ j
            if P.. ≥ P..
                then Pmax = P..
            if P.. ≥ P..
                then Pmax = P..
            if Pmax < P.. ←Check if a node
            exists
                then COND = TRUE
        if COND ≠ TRUE ←If there is no such
        node
            then Add j to TCN.
return TCN.
```

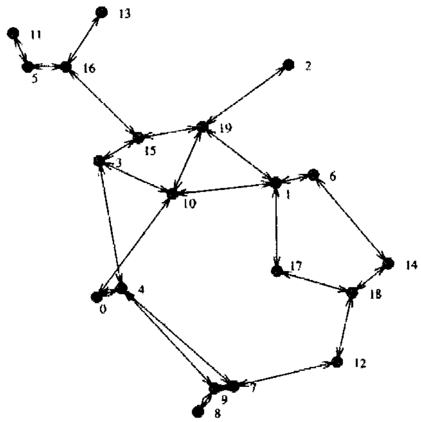
Algorithm *Bidirectional-TCN()*

```
(* Find Bidirectional TCN list *)
TCN. ←Local uni-directional TCN list of node i
BTCN. ←Local bi-directional TCN list of node i
if TCN. ≠ 0
    for each node k in TCN.
        j ←Calculate node k's TCNs
        while j ≠ 0
            if j = i
                then Add k to BTCN.
return BTCN.
```

Algorithm *Convert-TCN()*

```
(* Convert unidirectional to bidirectional TCNs *)
N. ←1-hop unidirectional neighbours of node i
BTCN. ←Local bi-directional TCN list of node i
if N. ≠ 0
    for each node k in N.
        j ←TCN of node k
        if i = j and k ∉ BTCN.
            then Add k to BTCN.
    return BTCN.
```

Figure 3(a) is the topology graph of the topology initially discussed in Figure 2(c). However, the topology is connected as the unidirectional links have been converted to bidirectional link by executing the *Convert-TCN()* function.



(a) Power based bidirectional DRNG topology with Convert-TCN(), assuming log-normal shadowing

Fig. 3.

IV. SIMULATION AND ANALYSIS

A. Scenurio

A simulation of the topology graphs has been conducted to examine the connectivity of a DRNG graph in the case of log-normal shadowing pathloss model. Nodes are distributed in a random manner in a 600m X 600m grid area and vaned in number from 10 to 100. The simulation results are averaged over 500 random seeds. All nodes have a maximum transmission range of 200m(5db).

In order to model pathloss due to log-normal shadowing, each link in the topology graph is randomly assigned a pathloss error factor ranging from 0-25% of the received power. The receiver power is calculated by using the signal attenuation model proposed in Equation **3.**

The performance metrics studied are as follows:- (1) The ***Average network connectivity,*** is defined as the average of the mean connectivity, seen by each node. 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 nctwork is evaluated by summing the mean connectivity of every node and is given by $\frac{1}{N}\sum_{i=0}^{N-1} c_i$. (2) The ***Average one hop bidirectional neighbours,*** arc the mean one hop bidirectional neighbours of the entire nctwork. *(3)*The ***Average transmission power.*** **is** defined as the average of the mean transmission power per link, seen by 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 summing the mean transmission power of every node and is given by $\frac{1}{N}\sum_{i=0}^{N-1} p_i$.

B. Results

Figure 4(a) is the plot of the average bidirectional network connectivity of a power based DRNG, DRNG-CA (power based DRNG with the proposed collaborative approach) and a Maximum Power Topology (MPT). Figure 4(a) illustrates that the connectivity of a power based DRNG graph **is** significantly lower than the MPT and the DRNG-CA based topology graphs. In a 100 node network, the connectivity of DRNG is ≈59% lower than DRNG-CA and MPT. The connectivity of DRNG can be improved significantly by applying the ***Convert-TCN()*** where unidirectional links in a topology graph **are** converted into bidirectional links.

Figure 4(b) is the plot of the average number of bidirectional one hop neighbours against the number of network nodes. The MPT based network topology has the largest number of neighbours as compared to the DRNG based network topology. In a 100 node network, the number of one hop bidirectional neighbours in the case of DRNG-CA are ≈1.7 times larger than DRNG, however there **is** a significant improvement in the connectivity over DRNG.

Figure 4(c) is the plot of the average transmission power against the number of network nodes. MPT illustrates a fixed average transmission power of approx ≈-9.5dB. The transmission power of DRNG and DRNG-CA decreases with an increase in the number of network nodes as nodes adjust the transmission power to cover the link distance of a DRNG neighbour. In a 100 node network, the power usage of DRNG is 10% lower than DRNG-CA. The power used in DRNG-CA **is** ≈78% lower than MPT. As expected the average transmission power of DRNG-CA is larger than DRNG, since additional power **is** consumed when converting the unidirectional links into bidirectional links. However, the connectivity of MPT and DRNG-CA are comparable wheres the connectivity of DRNG is significantly lower than DRNG-CA.

V. CONCLUSION

In this paper we have shown that a power based topology graph such as DRNG may be disconnected in the case of log-normal-shadowing pathloss model. A distributed mechanism to improve the connectivity of a power based DRNG graph **is** proposed in conjunction with the neighbour discovery protocol. The proposed mechanism shows significant improvement in the connectivity of the topology graphs.

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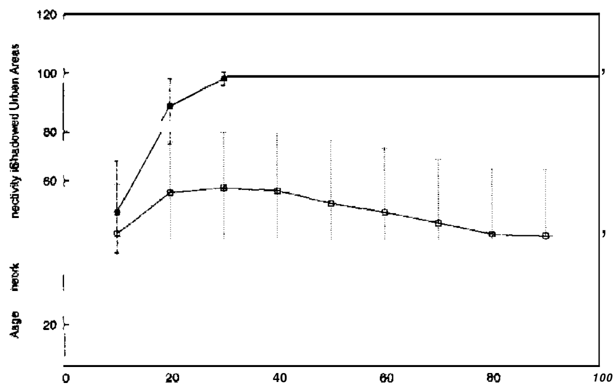

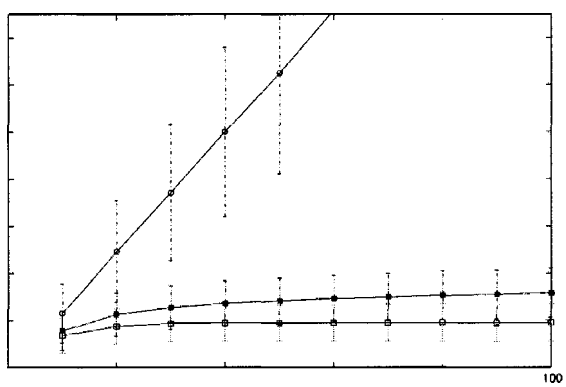

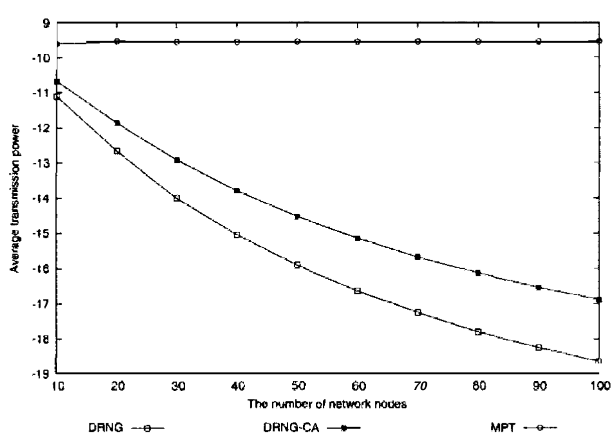

(c)

Fig. 4.

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