Analysis of Throughput Gain using Directional Antennae in Community Networks

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***Abstract*— As wireless networks evolve into the next generation to provide better services, a key technology, Wireless Mesh Networks (WMNs), has emerged recently. The capability of self-organization in WMNs reduces the complexity of network deployment and maintenance, and thus, requires minimal upfront investment. Popular implementations of WMNs include Community Networks which are clusters of linked, citywide networks. Current implementations of Community Networks use omni-directional antennae on all member nodes.**

In this research, we analyze the effect of using directional antennae on a subset of the nodes. We also present an algorithm which attempts to increase the throughput by reducing the number of exposed node cases by placing directional antennae on a subset of nodes. Simulations using our algorithm show an increase in throughput.

***Index Terms*— Wireless Mesh Networks, Community Networks, Exposed Nodes, Directional Antennae, Throughput**

I. Introduction

WMNs [3] consist of two types of nodes: mesh routers and mesh clients. A wireless mesh router contains routing functions to support mesh networking. Compared with a conventional wireless router, a wireless mesh router can achieve the same coverage with much lower transmission power through multi-hop communications. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). This feature brings many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage. Existing community network implementations benefit from these features and are thus fast gaining popularity. Some are being used to link to the wider Internet, particularly where individuals can obtain unmetered internet connections such as ADSL and/or cable modem at fixed costs and share them with friends. Where such access is unavailable or expensive, Community Networks can act as a low-cost partial alternative, as the only cost is the fixed cost of the equipment.

However considerable research efforts are still needed to fully exploit the potential of WMNs. The available MAC and routing protocols applied to WMNs do not provide enough scalability; the throughput drops significantly as the number of nodes or hops in a WMN increases. Similar problems exist in other networking protocols. Consequently, all existing protocols from the application layer to transport, network MAC, and physical layers need to be enhanced or re-invented. Even with exisiting protocols, there is a tremendous scope of improvement in the performance of WMNs. Application of directional antennae is one such possibility. Community networks so far use omni-directional antennae. There are no alignment requirements using omni-directional antenna and they also provide better coverage. However, the use of omni-directional antennae in dense mesh networks leads to greater interference which reduces the number of simultaneous transmissions and results in a reduction in the overall throughput of network.

Use of directional antennae results in better spatial re-use of spectrum and reduced interference. Apart from interference reducing capabilities, directional antennae also have lower error rates than omi-directional antennae. Placing directional antennae on calculated nodes to minimize interference would result in more simultaneous connections which would improve the overall throughput. Our research aims at finding the nodes at which the directional antenna should be placed and the corresponding antenna orientation directions to maximize throughput for any topology. We start by showing that interference is reduced on using directional antennae. We quantify interference with the number of exposed node cases for a given set of connections in a topology. Then we experimentally verify that directional antennae have lower packet error rates than omni-directional antennae. We then construct an algorithm for directional antenna placement on a subset of nodes and verify throughput enhancement by extensive simulations on The Enhanced Network Simulator (TENS)[11].

Our research into the application of directional antennae in community networks shows that it is a promising approach and can be utilized to improve throughput. More research is needed to look into the various facets of the problem which our work brings up. The remainder of this report is organized as follows. In Section II, we discuss some preliminaries related to wireless networks and the related work done in our field of research. In Section III, we present our approach towards the solution, starting with simple simulations and experimental work and then giving an algorithm for strategic node and direction selection for placing directional antennae in Section

Fig. 1. Cantenna [10]

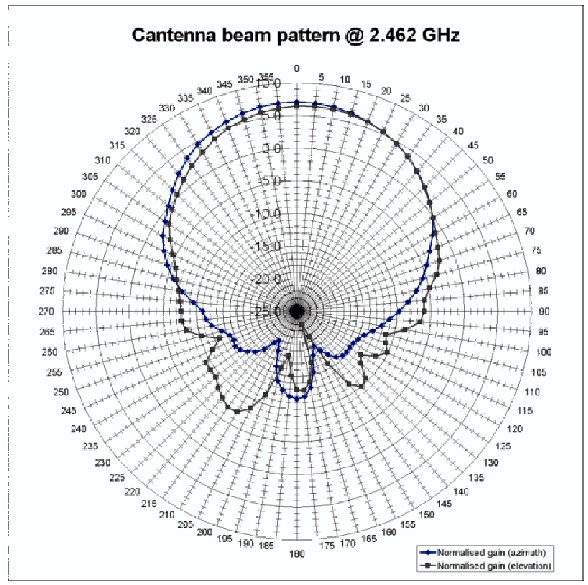

Fig. 2. Cantenna Radiation Pattern [10]

IV. Simulation results have been presented and explained in Section V. We conclude and present the scope of future work in Section VI.

II. Background

In this Section, we discuss the concepts and background necessary for understanding the experiments and simulations performed which have been detailed later. Community Network projects started to evolve in 1998 with the availability of 802.11 equipment, and are gradually spreading to cities and towns around the world. Such networks have a distributed rather than a tree-like topography and have the potential to replace the congested and vulnerable backbones of the wired internet in most places. An example of wireless community network is RoofNet Project [5] implemented by MIT. In the RoofNet project, each node has a single antenna and a single Ethernet port. Three of the 38 nodes have Yagi antennae on top of ten-story MIT buildings and act as gateways to MITs wired campus net. The other nodes are in apartment buildings, with roof-mounted omni-directional antennae. An omni-directional antenna radiates energy equally in all directions. This results in high degree of interference for nodes with a large number of neighbors in a community network. A directional antenna reduces interference because of a focused beam. It transmits and receives maximum power in a particular direction. The antenna radiation pattern depicts the variance of the transmit power or receive power of an antenna with direction. Fig 1 shows a typical cantenna and Fig 2 shows its corresponding radiation pattern.

Due to high degree of interference, an omni-directional antenna causes a large number of exposed nodes. The exposed node problem occurs when a node is prevented from sending packets to other nodes due to a neighboring transmitter. As shown in Fig 3, node A is sending data packets to node B. Node C lies in the interference range of node A so it senses the channel as busy and it does not communicate with node D which was possible without collisions. Hence node C is the exposed node. Directional antennae reduce the number of such exposed nodes by limiting interference. Some

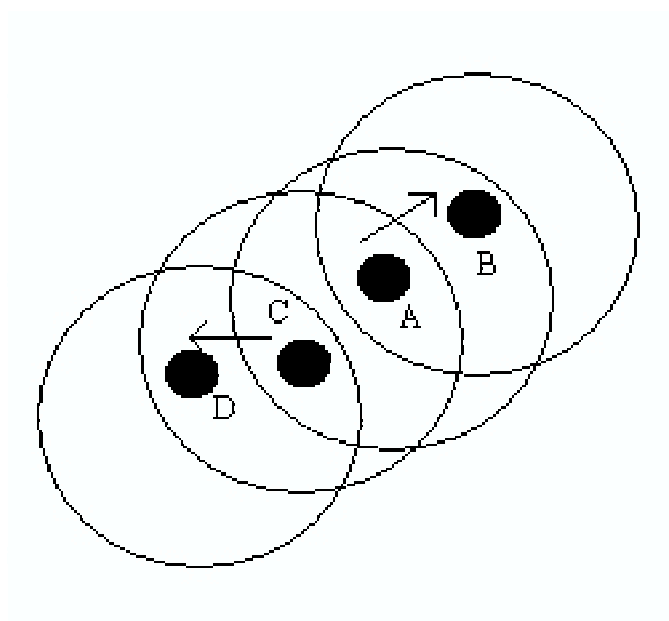

Fig. 3. The Exposed Node Problem

researchers in the past have addressed the challenges of using directional antennae in an attempt to improve wireless channel utilization. Substantial work has been done in the context of broadband and cellular networks (e.g. [4], [6]), literature in the context of directional antennae in ad hoc networks

is limited. [1] uses directional antennae to bridge network partitions for improving routing in mobile ad-hoc networks. It also uses directional antennae for maintaining connectivity in case a node moves out. However they primarily focused on connectivity and did not consider throughput improvement. [2] discusses the application of directional antennae in ad-hoc networks and identifies the challenges posed to physical, MAC and routing protocols but does not talk about any solution. [8] suggests a complete system solution with new routing and MAC protocols for ad-hoc networks which uses directional antennae. This solution is incompatible with existing hardware.

III. Solution Approach

As discussed in previous Sections, directional antennae have a potential to increase network throughput. In this Section, we try to quantify the impact of directional antennae on factors like exposed nodes and error rate as compared to omni-directional antennae. The results obtained from the analysis of the effect of directional antennae serve as the basis of the algorithm for strategic placement of directional antennae, which we propose in the next Section.

A. Simulations in JAVA for calculating exposed nodes

The topology of the RoofNet project (described in Section 2) is simulated using JAVA and the number of exposed node cases is calculated assuming a random number (8 to 12) of a pair of communicating nodes. For the directional topology, we mark some of the nodes as having a directional antenna and specify a direction. In the omni-directional case, all the nodes receiving the RTS/CTS from the communicating node pair are marked as exposed and then another node pair having both nodes unexposed is randomly chosen and the process repeated. Thus after the 8-12 node pairs have been chosen, we can infer the number of exposed nodes and communicating nodes in that state. In the directional case, the process is similar except that the set of nodes receiving the RTS/CTS change. This requires all nodes in the sector covered under the range of the corresponding directional antenna to be marked as exposed. The results shown in Fig 4 and Fig 5 depict that there is a substantial reduction in the number of exposed nodes and the number of simultaneous transmitting nodes increase on using directional antennae.

B. Experimental Work

Directional antennae reduce the error rate for a given receive signal strength due to reduced multi-path effects because of a focused beam. We verify this by taking packet error-rate measurements on campus for links ranging from 100m to 500m. An 8 dBi omni-directional antenna was chosen as the transmitter for all experiments and error rates were measured at the receiver using both an 8 dBi omni-directional antenna and an 8 dBi cantenna directed towards the transmitter. Vegetation and buildings obstructed the communicating nodes for some links. Data packets of size 1500 bytes at 120 Kbps were sent. Experiments were performed for 2 Mbps and 11 Mbps data rates. Fig 6 shows the variation of error rate

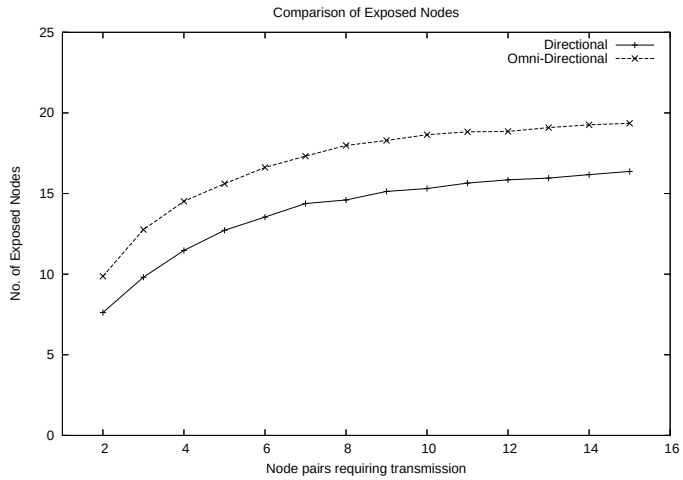

Fig. 4. Exposed Nodes on using Omni-directional and Directional antennae

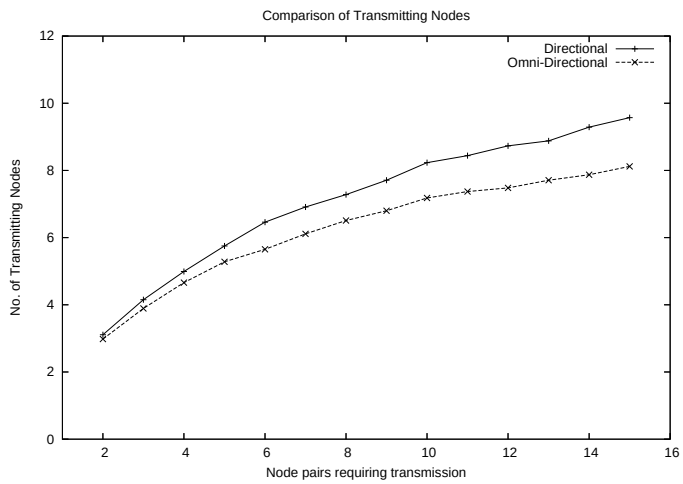

Fig. 5. Exposed Nodes on using Omni-directional and Directional antennae

with receive signal strength. For all links, the error rate was calculated keeping the receive signal strength constant for both the omni-directional antenna and the directional antenna. This was achieved by reducing the transmit power of the source when a directional antenna was used as the receiver and it provided higher signal strength. The error rate of the omni-directional antenna is higher than that of the directional antenna for all the points. The error rates are significantly high for some points which is because of the vegetation and the construction obstructions. In such cases too, directional antenna has better error rate characteristics. A lower error rate would result in more throughput due to lesser packet loss. This again favours the use of directional antennae instead of omni-directional antennae.

IV. Algorithm

The main idea on which we base our algorithm is the reduction in the number of exposed nodes which allows more simultaneous data transfers and hence better throughput. The

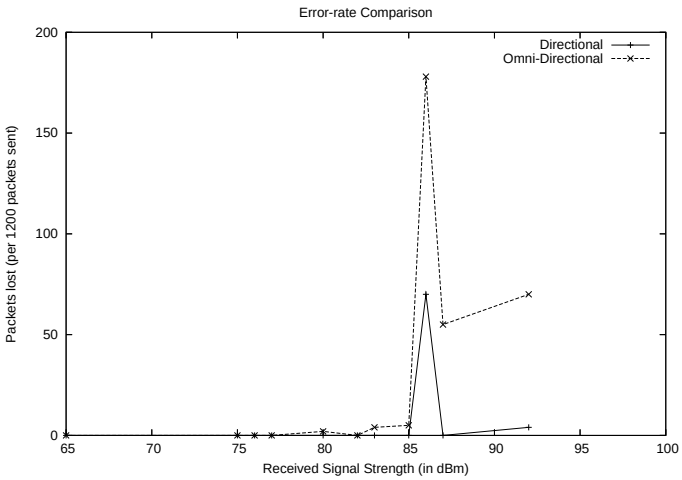

Fig. 6. Error rates using Omni-directional and Directional antenna

metric we choose to quantify exposed node cases is the exposed link. For a given node, the exposed link count gives the number of links in the network across which communication cannot occur when that node is communicating. In Fig 7, node

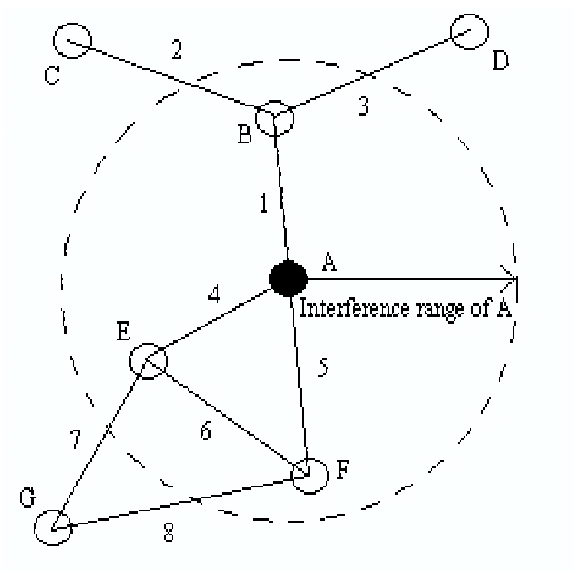

Fig. 7. Exposed Links

A has nodes B, E and F as neighbors (within its interference range). Nodes C and B are neighbors of node B while node G is a neighbor of both node E and node F. In this scenario, when node A starts communicating, nodes B, E and F would have to remain silent thus causing links 1, 4 and 5 to be exposed. In turn, links 2, 3, 7 and 8 which have one of these nodes as an end would be exposed because the nodes are exposed. The exposed link count for the above case scenario is 8. Our algorithm tries to place directional antennas on a subset of nodes such that the exposed link count is minimized faced to some restrictions. The algorithm can broadly be divided into two parts:

1) Selecting a subset of nodes to put directional antenna on
2) Direction determination for directional antennae to be put on these nodes

A. Node Selection

A neighbor discovery is initiated which identifies the nodes within the interference range for each node. The exposed link count for all the nodes in an omni-directional setup is calculated using the data obtained in neighbor discovery. Nodes with large exposed link counts are the ones which cause maximum interference. This results in lesser throughput because many possible simultaneous connections are blocked due to nodes being exposed. The nodes are sorted by their exposed link counts. Directional antennae should be placed on the nodes ranked highest in this sorted list. Since nodes with directional antennae within the interference range of each other could lead to poor performance, we choose nodes at least a certain threshold distace apart. This threshold distance depends on node density, antenna range and various other factors. In order to place directional antenna on k[1] nodes, top $k+t$ nodes are chosen from this sorted list. The t extra positions ensure conectivity. If placing directional antennae on any of the chosen nodes causes partitioning in the network, another node is chosen from the$t$ extra nodes.

B. Direction Selection

The direction of the directional antennae is to be decided next for the k selected nodes. For each of the nodes, a simulation is performed placing the antenna at an angle θ where $\theta = 30\ i$ for i ranging from 0 to 11 and the neighbor count is obtained for each of these angles. For a given node, an angle with high neighbor count implies strong connectivity which could lead to an increase in the exposed node count. However this also results in a more connected routing with shorter path lengths for many node pairs.The angles have to be chosen such that the directional antennas do not interfere with each other. The nodes having higher exposed link counts are given priority and their angles are chosen first. Then the angle for the node with the next highest exposed link cout is chosen. This minimizes interference while maintining the strongly connected property.

A low neighbor count implies poor connectivity which could lead to partitioning of the network on placing a directional antenna on the node. A better metric would be to choose the direction corresponding to the neighbor count which is the median in the list of neighbor counts. This direction would have sufficient connectivity and lesser exposed nodes. Out of the $k+t$ nodes obtained from the Node Selection step, the direction for the top k nodes is calculated according to the metric discussed previously. Once the directions have been chosen, we check if the network is still connected. If not,

[1]The number of antennae k to be used in a network depends on the topology. Determining the optimal number of antennae for a topology is another problem. We assume a reasonable constant depending on the topology we choose for simulations.

Given: Position of N nodes, Number of directional antennae k, Threshold distance D

Node Selection

- Probe each node from each node to determine neighbors
- Enumerate exposed links for each node
- Sort nodes by exposed links count
- Choose top-k nodes at least D apart

Direction Selection

- Calculate neighbors for each node obtained above placing antenna at angle $\theta = 30i$ for $i = 0$ to 11 and sort the list by number of neighbors for each direction.

a. *Maximum connectivity:*
For each node, choose the direction with maximum neighbors.

b. Median connectivity:
For each node, choose the direction with median neighbor count in the sorted neighbor count list

Check connectivity

Place directional antennae on selected nodes and check if network is connected, if not then go back to Direction Selection and choose different direction

Fig. 8. Node and direction determination algorithm

then we choose the highest ranking node in the *t* extra nodes selected and apply Direction Selection for it. This is repeated till a connected topology is obtained.

The required information regarding the topology is obtained from the steps above. Firstly, a simulation is performed to determine the neighbors of each node and thus form an adjacency matrix. This matrix is utilized to obtain a static routing for the topology using the Floyd-Warshall algorithm for finding the All-Pair Shortest Path. We thus obtain the complete information for performing a simulation using directional antennae on the nodes chosen by our algorithm.

V. Simulation Results

The simulations were performed on The Enhanced Network Simulator (TENS) on a network of N=38,50 nodes scattered on a 2-dimensional field of area A = 1000x1000 m^2 ,1500x1500 m^2. WLSTATIC was chosen as the routing protocol for the Node Selection and Direction Selection phases of the algorithm. Simulations for the topology thus obtained were performed using DSDV with a settling time of 100 seconds. Shadowing radio propagation model was used for the simulations. Packets were sent at a constant bit rate of 600 Kbps on UDP connections. The MAC layer data rate was taken as 11 Mbps whereas the base rate was 1 Mbps. We performed a number of simulations with different topologies and compared the performance of the directional antennae placement using our algorithm with the topology having all omni-directional antennae which serves as the base case.

A. Simulations for regular grid topology

Simulations were performed for a regular grid topology with 38 nodes evenly distributed in an area of 1000x1000 m^2. We apply our algorithm to this topology and choose 3 nodes for directional antenna placement. The nodes chosen are thus those with the highest exposed link count under the constraint that they are a threshold distance apart. We compare the performance of the topology obtained from our algorithm with the base case of all nodes having omni-directional antennae. Fig 9 and Fig 10 show the comparison of network throughput for 15 and 20 simultaneous connections respectively. Each connection was setup for a randomly chosen duration of up to 40 seconds. Throughput shown in Fig 9 and Fig 10 are the sum of throughputs for 15 and 20 connections respectively.

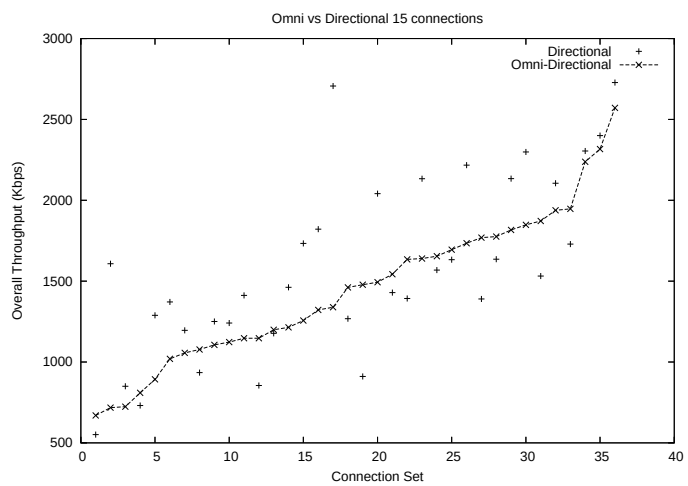

Fig. 9. Throughput Comparison for 15 connections

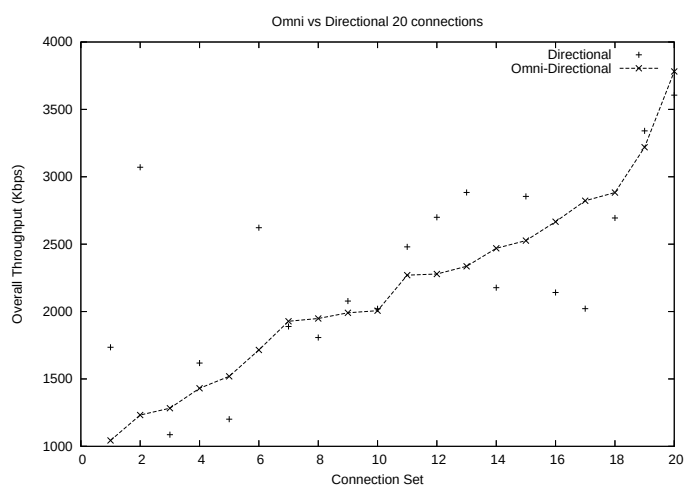

Fig. 10. Throughput Comparison for 20 connections

The average throughput for each connection of the connection sets shown in Fig 9 for topology from our algorithm comes out as 105.6 Kbps which is better than the throughput for the omni-directional topology which is 96.75 Kbps. For connections used in Fig 10 throughput from our algorithm is 115.07 Kbps while for the base case it is 108.37 Kbps. Hence we conclude that for a homogeneous node distribution, our algorithm outperforms the omni-directional topology in terms of network throughput. Next, we apply our algorithm on randomly generated topologies to analyze the impact of using directional antennae on more realistic setups.

B. Simulations for randomly generated topologies

Simulations were performed for randomly generated topologies each with 50 nodes scattered in an area of 1500x1500 m^2. The neighbor discovery starts with each node trying to send packets to each other node. This generated the neighbor count which is the input for the Node Selection phase. We choose 6 nodes in the Node Selection phase. Next we obtain the directions for antennas placed on these nodes. Our algorithm gives the angles for the two choices, the strong connectivity case and the median connectivity case. Finally, we select 4 directional antenna positions such that the interference is minimized for both the cases.

We perform simulations for maximum connectivity scenario as well as median connectivity scenario. For each simulation, 10 sets of connections were established with an interval of 150 seconds. Fig 11, Fig 12 and Fig 13 show the comparison of throughput when each connection set consisted of 15, 20 and 25 randomly chosen connections respectively for 7 randomly generated topologies. Each connection duration was chosen randomly for up to 40 seconds. The throughput obtained

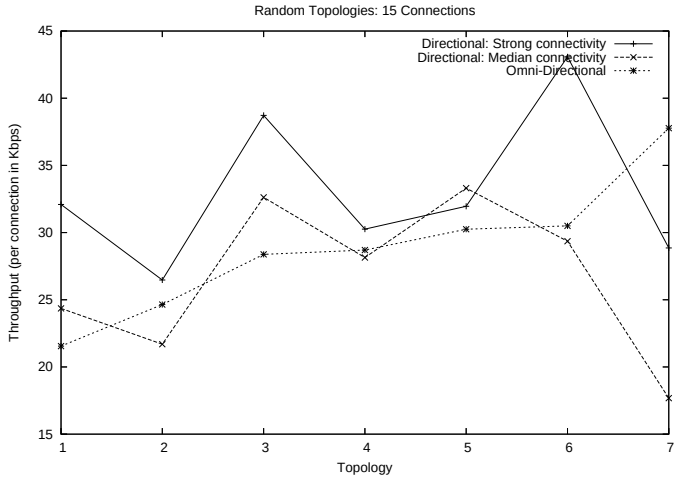

Fig. 11. Throughput Comparison for 15 connections in a random topology

for the simulation setup with the directional antennae placed so as to obtain maximum connectivity is the highest on an average. The simulation setup for directional antennae with median connectivity performs well for some topologies though it does not provide a conspicuous improvement in the overall throughput.

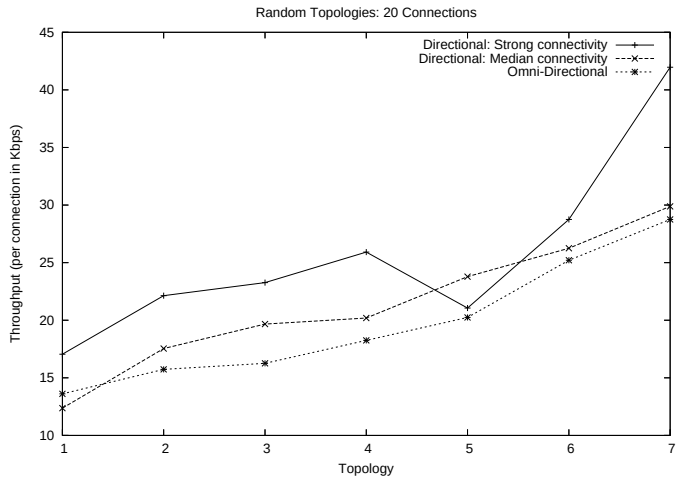

Fig. 12. Throughput Comparison for 20 connections in a random topology

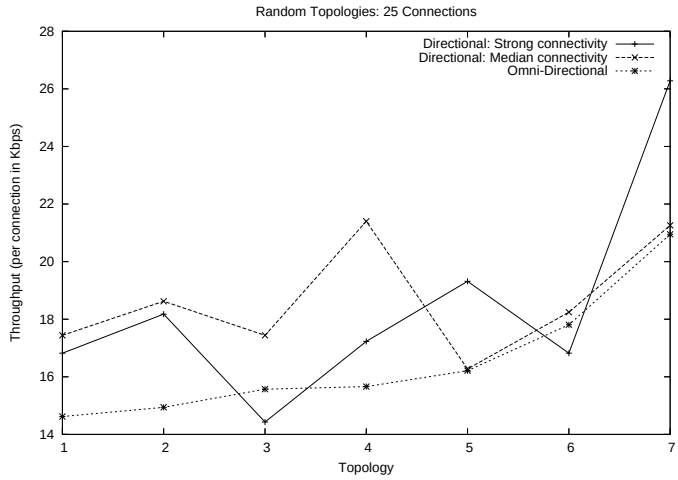

Fig. 13. Throughput Comparison for 25 connections in a random topology

The improvement obtained using directional antennae for maximum connectivity can be attributed to the reduced number of exposed nodes because of the first step of our algorithm where the nodes with maximum exposed links are chosen. Thus a number of nodes outside the interference range of the directional antenna would not be exposed. Apart from this, maximum connectivity also provides it with a strong routing support and cases of de-routing are minimized. The median connectivity case suffers due to an increase in de-routing because the paths to the node from its neighbors are very limited. Overall our algorithm chooses directional antenna such that the network throughput is better than that obtained by the omni-directional topology for similar connections.

C. Throughput comparison for maximum and median connectivity

To analyze the variation of throughput with the maximum connectivity and median connectivity choice in our algorithm, simulations were performed for 50 nodes randomly scattered on a 1500x1500 m^2 area. Directional antennas were placed on

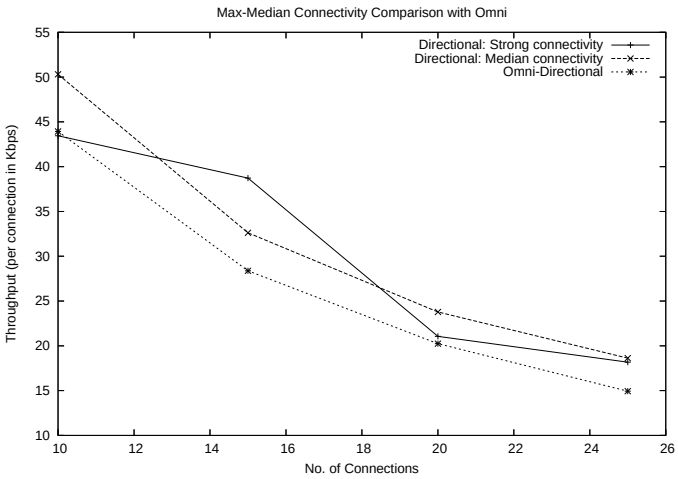

Fig. 14. Throughput dependence on degree of connectivity

4 nodes chosen by our algorithm. Simulations were performed for 10 sets of connections. A time gap of 150s was given after each connection set. Each simulation had 10, 15, 20 or 25 connections in the connection set. Each connection had randomly chosen source and destination pair with a duration of up to 40s. Fig 14 shows that the topologies with directional antenna perform better than the omni-directional antenna. The topologies chosen for strong connectivity and median connectivity perform better than the omni-directional antenna but the performance of one with respect to the other depends on the particular network and needs to be ascertained by doing simulations before making a choice.

VI. Conclusion and Future Work

In this report, we present an algorithm for determining the nodes, and the direction of the directional antennae to be placed on those nodes to improve network throughput. Our algorithm attempts to minimize the number of exposed nodes in the network while keeping the network connected. We compare the performance of our algorithm for the two options: median connectivity and maximum connectivity with the all omni-directional antennae case for different types of topologies including regular grid topology and randomly generated topologies. The application of our algorithm to the mesh topologies analyzed, improved the network throughput though the difference in the throughputs was not very high. In summary, directional antenna has the potential to improve the network throughput. Our algorithm presents a way of using directional antennae for doing so. More research needs to be done to fully exploit the capabilities of directional antennae.

In our research, we have assumed a campus peer to peer traffic pattern for a community network. Effect of other traffic patterns remains as future work. For a more realistic setup, an extensive error model needs to be applied and its effect observed. Finding the optimal number of directional antennas for a network is another possibility for research work. Our algorithm does not consider the effect of placing the directional antennae at nearby node positions at suitable angles. Carefully choosing directions for such positions can bring further improvement in throughput.

VII. Acknowledgement

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