UNIDIRECTIONALITY IN AD-HOC NETWORKS: A SIMULATION STUDY

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ABSTRACT

This paper is to study the impact on performance on using unidirectional links, in addition to bi-directional links, in ad-hoc networks. The study offers a better understanding on the future routing protocol design for ad-hoc networks. By using unidirectional links in addition to bi-directional links, the routing performance will improve greatly. To accurately evaluate the use of unidirectional links, both unidirectional and bi-directional links in the Random graph and the Euclidean graph approaches are investigated. The Random graph approach, where node connection and link direction are the only concerns, serves as a theoretical benchmark for the study. The Euclidean graph approach, where the dynamics of the wireless network are captured, examines the ability of the networks to transmit messages to most, if not all, of the nodes within a small number of hops on the provision of the minimal network connectivity. The simulation results show the presence of a significant proportion of unidirectional links and the improvement of network performance by increasing network connectivity and reducing path length

Keywords: ad-hoc networks, unidirectionality, routing protocol, Random graph, Euclidean graph.

1 INTRODUCTION

The existing routing protocols developed for ad-hoc networks assume all wireless links are bi-directional, influenced by the traditional wired Internet. Either the table-driven routing protocols [11, 17, 21] or the on-demand routing protocols [3, 4, 10, 12, 13, 18, 20] tend to perform poorly in unidirectional ad-hoc networks, as exhibited in [19]. Unidirectionality, defined as a one-way communication between any two nodes, is very common in ad-hoc networks.

1.1 UNIDIRECTIONALITY

According to The Internet Engineering Task Force (IETF), a "mobile ad-hoc network" (MANET [5]) is an autonomous system of mobile routers (and associated hosts) connected by wireless links – the union of which forms an arbitrary graph. The routers are free to move randomly and organized themselves arbitrarily; thus, the network topology may change rapidly and unpredictably. Such a network may operate in a stand-alone fashion, or may be connected to the Internet. A stand-alone ad-hoc network can be further structured into multi-tiered hybrid ad-hoc networks.

Unidirectionality is simply caused by different radio capabilities, signal interference, wide-area information broadcast and EMCON operations. Unidirectionality can be temporary or permanent. It can make the whole network unidirectional, by having just one unidirectional link.

- Different radio capabilities.

Radio devices within a network can have different transmission power or receiver sensitivities. Moreover, power consumption rate and power conservation policy temporally affect the radio transmission and reception capabilities.

- Signal Interference.

Even a network of identical radio transmission and reception capabilities will have unidirectional links. Interference, either by hostile jammers or by friendly "co-site" will reduce a nearby receiver's sensitivity. One classical example is the "hidden terminal" problem [2].

- Wide-area information broadcast.

Satellite-based transmitters (GBS) essentially provide high bandwidth links over large geographical areas. It has been used for the forward links from a satellite to ground receivers while the return routes use alternative paths, due to high cost of satellite up-link devices.

- Emission-controlled (EMCON) operations.

An extreme instance—applicable only in military networks—is when one cannot transmit due to impending threat. In such case, it may be necessary to have some other node to provide a comparable route in response to a route discovery request. (Obviously, an EMCON node cannot participate in bi-directional communications, but it still needs to receive information.)

1.2 RELATED WORK

In order to use unidirectional links, in addition to bi-directional links, in routing decision in ad-hoc networks, several approaches have been proposed, which can be mainly categorized into two groups, namely the tunneling mechanism and the existing protocol modification. However, they impose additional communication and storage overheads.

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1.2.1 TUNNELING MECHANISM

The idea is to emulate bi-directional links through existing unidirectional links, as explained in [9] for traditional wired networks, and in [16] for ad-hoc networks. In other words, it is to add a virtual layer between the link layer and the network layer, functioning as a tunnel transparent to the routing module at the network layer. Upon detecting the existence of unidirectional links with the use of ACKs at the link layer, a sink, towards which a unidirectional link is directed, periodically sends out encapsulated *link_inform* messages destined to a source, i.e. node on the other end of the unidirectional link. The *link_inform* message is to notify the source about the existence of the unidirectional link towards the sink. When this packet is received by the source, the network layer and the data link layer make a note of the unidirectional property of the link. Hence, both the source and the sink of the unidirectional link are aware of its existence. The tunneling modifications are transparent to the routing module, thereby allowing any routing protocol to be used.

By emulating bi-directional links, Nesargi's approach for ad-hoc networks [16] is based on the tunneling mechanism at the link layer proposed for traditional wired networks in [9]. Benassy-Foch, et. al. [1] suggested applying the tunneling mechanism on DVMRP [21].

1.2.2 PROTOCOL MODIFICATION

To support unidirectional links in ad-hoc networks, one short-term solution is to modify existing routing protocols. With minimal routing algorithm modification, DSR [12] can work on unidirectional links by establishing two directional paths (forward and backward) between the source and the destination. Prakask [19] suggested the use of additional data structures and algorithms to DSDV [17] and AODV [18]. These modifications incur higher communication and storage overheads.

1.3 CONTRIBUTIONS

The objective of this paper is to study the impact on performance on using unidirectional links, in addition to bi-directional links, in ad-hoc networks. Although unidirectionality in ad-hoc networks has been a concern, no performance analysis has been carried out. The study offers a better understanding on the future routing protocol design for ad-hoc networks. By using unidirectional links, in addition to bi-directional links, the routing performance will improve greatly.

In order to accurately perform the evaluation, unidirectional links in the Random graph approach and the Euclidean graph approach are investigated. The Random graph approach, where node connection and link direction are the only concerns, serves as a theoretical benchmark for the study. The Euclidean graph approach, where the dynamics of the wireless networks including mobility and transmission power are captured, shows the ability of the networks to transmit messages to most, if not all, of the nodes within a small number of hops on the provision of the minimal network connectivity.

We will investigate the improvement of the routing performance with the use of unidirectional links, in addition to bi-directional links, in ad-hoc networks by examining the following questions:

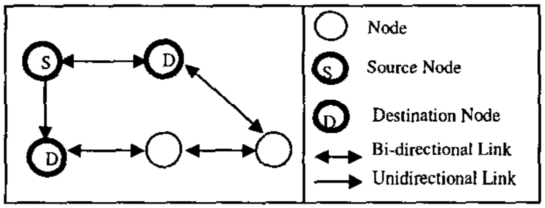
- What is the portion of unidirectional links in the network?
- How can the use of unidirectional links, in addition to bi-directional links, improve the routing performance?

1.4 ORGANIZATION OF THE PAPER

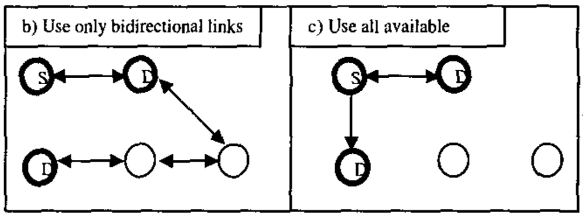
The paper is organized as follows. Section 2 describes two approaches in the performance analysis methodology, where the Random graph approach serves as a benchmark and the Euclidean graph approach shows the dynamics of the networks. In Section 3, simulation results are discussed. And lastly, conclusion and future work are in Section 4.

2 PERFORMANCE ANALYSIS METHODOLOGY

To study the impact on performance on using unidirectional links, in addition to bi-directional links, a set of experiments has been carried out to quantitatively measure the advantages of the use of all available links (both bi-directional and unidirectional links) over the use of bi-directional links only. An example is illustrated in Figure 1. In a connected ad-hoc network, depicted in Figure 1(a), where both unidirectional and bi-directional links exist, routing over only bi-directional links is likely to establish non-optimal paths, as in Figure 1(b). On the other hand, routing over all possible links (both bi-directional and unidirectional links) can give out an optimal path, which is the shortest path, as in Figure 1(c).



a) A Simple Network



b) Tree using Bidirectional Links c) Tree using Unidirectional Links

Figure 1: Unidirectionality Effect on Optimal Path

To measure the impact, two separate approaches, namely the Random graph and the Euclidean graph are employed. The Random graph approach serves as a theoretical benchmark for the study. Only node connection and link directionality are considered. The Euclidean graph approach simulates wireless network scenarios and captures the network dynamics including node mobility and transmission power. The basic idea is to apply to a 100-node network, with a variety of network density and connectivity, and generate connections between nodes and a shortest-path tree. A connection between two nodes (i.e. i and j) of n hops is denoted as d(i, j: n) where $d(i, j: n+1) = \min\{d(i, k,: n) + d(k, j:1)\}$ and $i \neq j \neq k$. The shortest-path tree is defined as a tree network topology, rooted at one node, connects to most, if not all, of the nodes, within a smallest number of hops. The rationale is that in ad-hoc networks where connectivity is highly transient and evidently unidirectional, the ability to transmit data to all the nodes within a small number of hops on the provision of the minimal network connectivity is crucial.

The evaluation metrics are normalized measured values for the purpose to compare networks with different number of nodes. They are defined as follows:

- Link Density (LD) is defined as the percentage of directional links from the underlying fully connected network. A fully connected network has a link from every node to every other node. A bi-directional link consists of two directional links in forward and backward direction. Link Density can be written as

$$LD = \frac{L}{N(N-1)} \text{ x } 100\,\%$$

  where L is a number of directional links,
  N is a number of nodes in the network.

- Unidirectional Link Density (ULD) is defined as the percentage of unidirectional links from the underlying fully connected network.

$$ULD = \frac{L_u}{N(N-1)} \text{ x } 100\,\%$$

  where L_u is a number of unidirectional links,
  N is a number of nodes in the network,
  $L = L_u + L_b$, and LD = NLD + BLD.

- Bi-directional Link Density (BLD) is defined as the percentage of bi-directional links from the underlying fully connected network.

$$BLD = \frac{L_b}{N(N-1)} \text{ x } 100\,\%$$

  where L_b is a number of bi-directional links,
  N is a number of nodes in the network,
  $L = L_u + L_b$, and LD = NLD + BLD.

- Node reachability (NR) level is defined as the percentage of all reachable nodes included in a shortest-path tree.

$$NR = \frac{N_r}{N} \text{ x } 100\,\%$$

  where N_r is a number of all reachable nodes included in a shortest-path tree,
  N is a number of nodes in the network.

- Depth of the shortest-path root-based tree (D) is defined as the maximum number of hops it takes from a root node to most, if not all, of the other nodes on the provision of the minimal network connectivity. It can also be referred as the height of the shortest-path tree.

- Pairs Connected (PC) is defined as the percentage of all connections between nodes, if reachable.

$$PC = \frac{C_{ij}}{N(N-1)} \text{ x } 100\,\%$$

  where Cij is a number of connections between node
  and node j such that $d(i, j: n+1) =$
  $\min\{d(i, k,: n) + d(k, j:1)\}$ and $i \neq j \neq k$.

- Average Path Length (APL) is defined as the average length of connections between nodes in hops.

2.1 RANDOM GRAPH APPROACH

A Random graph is a graph in which properties such as the number of graph vertices, graph edges, and connections between them are determined in some random way. In order to serve the study purposes, the randomness of its properties is limited with respect to directionality and connection mode.

Directed graph (G) which is theoretically defined in [22] as a triple consisting of a vertex set V(G), an edge set E(G), and a function assigned each edge an ordered pair of vertices. For instance, (A, B) denotes a directed link from node A to node B. A bi-directional link between node A and node B requires both (A, B) and (B, A).

Random graphs are generated in two modes, namely the randomly connected and the weakly connected. For a randomly connected Random graph, a directed link between any two nodes is randomly generated such that the number of links generated fulfills the specified link density. A node may be detached from the rest. A weakly connected graph has an additional constraint that its underlying graph is connected, regardless of the link direction.

Then, two shortest-path trees are constructed; one with only bi-directional links, and the other with both link types. To ensure the best possible shortest-path tree, the selected root node is the node that yields the minimum tree depth, where all nodes are examined.

2.2 EUCLIDEAN GRAPH APPROACH

Euclidean graphs are generated, where its points have coordinates in a Cartesian grid. Each point corresponds to a node. Each edge between points represents associated parameters of a link between the two corresponding nodes. The link parameters include link existence and link directionality. Link existence depends on transmission power, receiver sensitivity and distance between two corresponding nodes. To make the graph directed, every link is transformed to two opposite (directed) links.

We consider a wireless network with 100 stationary wireless nodes. Each node with omni-directional antennas is randomly placed in a square area (A), and assigned transmission power (TP). Then, network size, area and transmission power parameters are denoted as network density (ND) and relative transmission power (RTP). For example, network A has one node with TP of 1, located in a one unit area and network B has four nodes, each with TP of 2, located in a four unit area. Both networks yield the same ND (= 1) and RTP (= 1).

Formally, the network density (ND) and relative transmission power (RTP) can be defined as follows.

- Network Density (ND) is normalized as an average number of nodes ($\bar{n}$) per area unit, which can be written as

  $ND = \frac{\bar{n}}{A}$; where A = the area of coverage

  e.g. A 100-node network with node density of 1 is placed in a 10 unit by 10 unit region.
- Relative Transmission Power (RTP) is defined as the normalized transmission power with respect to an area length, which can be written as

  $$RTP = \frac{TP}{AL}$$

  where TP is the transmission power in diameter,

  AL is the length of the coverage region, $= \sqrt{A}$.

  e.g. A node with TP of 2 in a 10 unit by 10 unit region has a RTP of 0.2.

3 SIMULATION RESULTS

With 15 runs on different random seeds, simulation experiments were carried out to determine the impact when unidirectional links, in addition to bi-directional links, are used, where two approaches have been used. Interestingly, both approaches show the similar outcome. This section comparatively demonstrates the network performance when all links, not only bi-directional links, are used, under the Random graph approach and the Euclidean approach. Performance metrics are the unidirectional link density, bi-directional link density, node reachability, depth of the shortest-path root-based tree, percentage of pairs connected, and average path length.

With 100 nodes, more than 1,500 directed Random graphs have been generated in two modes, namely the randomly connected and the weakly connected. A Random graph is constructed with link densities between 1 and 60. Then, node connections and shortest-path root-based trees of each mode are constructed using both unidirectional and bi-directional links and only bi-directional links.

Of the same number of nodes, 500 Euclidean graphs have been generated. Nodes are randomly placed with various network densities and relative transmission powers. Two different power transmission modes are used, namely the fixed transmission power at the maximum transmission power, and the uniformly distributed transmission power in the range (0, max Tx power * 2], whose mean value is the maximum transmission power.

3.1 UNIDIRECTIONAL LINK DENSITY VS. BI-DIRECTIONAL LINK DENSITY

The proportion of unidirectional links is significant enough such that the use of unidirectional links, in addition to bi-directional links, will greatly improve the routing performance. The portions of unidirectional links and bi-directional links used from all generated directional links are shown in Figures 2 and 3.

Figure 2 shows no significant differences between the randomly connected graphs and the weakly connected graphs. When the link density is less than 20 percent, most directional links are unidirectional, whereas bi-directional links constitute less than 5 % out of all links considered. The bi-directional links show up at a higher probability when the graph gets more connected. With 60% link density, half of the directional links are bi-directional.

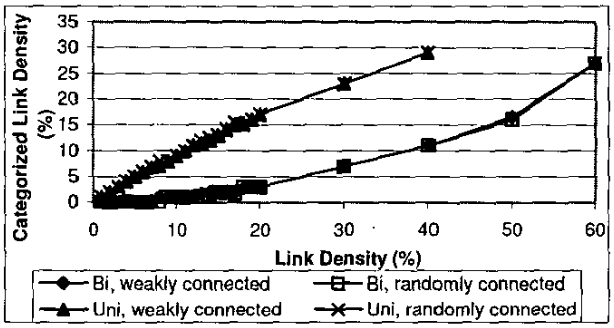


Figure 2: Unidir. and Bi-directional Link Densities from Random Graph

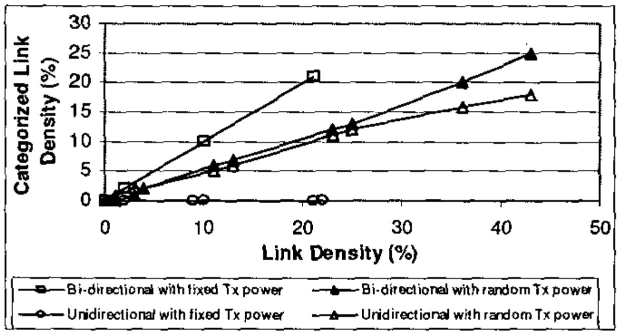


Figure 3: Unidir. & Bi-directional Link Densities from Euclidean Graph

Assuming the use of omni-directional antenna in the Euclidean graph, Figure 3 shows that nodes with identical transmission power produce a completely bi-directional network. Networks of nodes with the fixed maximum transmission range contain only bi-directional links. Network of nodes with random transmission power has unidirectional links almost as much as bi-directional links. Due to the uniform distribution of the transmission power level, the disparity in the transmission power level of a source node and of a sink node, which causes unidirectional links, occurs as equally as the similarity, which creates bi-directional links, does.

The different results between two approaches can be explained. The unidirectional link density from the Random graph approach is twice as much as the unidirectional link density of network of nodes with the random transmission power using the Euclidean graph approach. The bi-directional link density of network of nodes with the random transmission power from the Euclidean graph approach is twice as much as that using the Random graph approach. This is due to the nature of omni-directional transmission range. With a directional antenna, where the transmission range can be beamed in one particular direction, the bi-directional link density of such network will be lower.

3.2 NODE REACHABILITY

As the link density increases, more nodes are connected, that results in higher node reachability. Figure 4 illustrates that all nodes from the Random graph approach can be reached via unidirectional links, in addition to bi-directional links, at the mere 4% link density. One with both links in the weakly connected mode performs slightly (1 percent) better than that in the randomly connected mode. Formed by only bi-directional links, a network is able to cover all the nodes at 20 percent link density. For bi-directional links, there is no difference between the weakly connected and randomly connected modes.

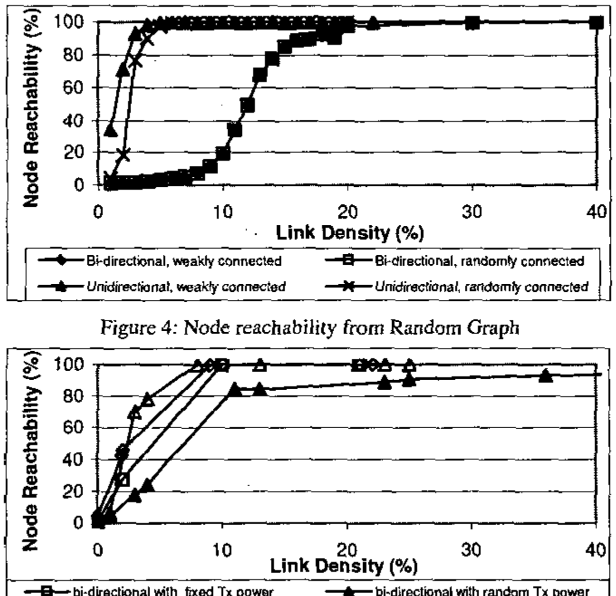


Figure 4: Node reachability from Random Graph

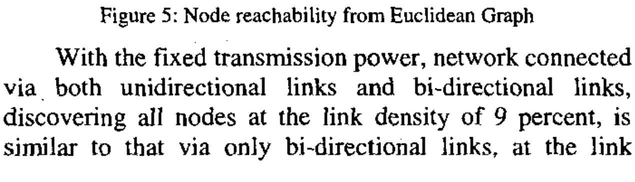


Figure 5: Node reachability from Euclidean Graph

With the fixed transmission power, network connected via both unidirectional links and bi-directional links, discovering all nodes at the link density of 9 percent, is similar to that via only bi-directional links, at the link density of 10 percent. With the random transmission power level, unidirectional network reaches all nodes at the link density of 8 percent, while bi-directional network may be able to approach all nodes with the link density of higher than 40 percent. Random transmission power levels among nodes can greatly worsen bi-directional node reachability, but considerably improve unidirectional node reachability.

Based on Figure 4 and 5, the use of unidirectional links, in addition to bi-directional links, can ease routing, as most nodes can be reachable with minimal network connectivity. This is crucial in ad-hoc network where the link connectivity is unstable. In order to reach 90 percent of the network for both approaches, the connection using both unidirectional and bi-directional links needs only 3 – 8 percent link density, while the connection using only bi-directional links requires 8 – 25 percent link density.

3.3 DEPTH OF SHORTEST-PATH TREE

The depth level of shortest-path tree (SPT) gives an idea of how fast a message can propagate across a network. The higher the depth of shortest-path tree is, the more the number of hops it takes a message to traverse across the network. However, a depth level of SPT before its peak is meaningless, due to insufficient node reachability, as exhibited in Figure 4 and 5. With the insufficient node reachability level, only a subset of network is reachable. Therefore a shortest-path tree constructed from only a subset of nodes does not represent the whole network. A node is considered as reachable, if there exists a path from a root node onto the node itself. The peak depth level indicates a maximum number of hops to reach most, if not all, of the nodes with the least link density.

Even though the weakly connected graph has a relatively lower depth level than the randomly connected graph does, the use of unidirectional links, in addition to bi-directional links, has much more impact on the depth of the SPT than on the use of bi-directional links only. As demonstrated in Figure 6, with both unidirectional and bi-directional links, the peak depth level of around 10 is reached at 2 percent link density and at 4 percent link density for the weakly connected graph and the randomly connected graph, respectively. Whereas, with only bi-directional connection, the peak depth level of 10 is reached at 13 percent and 18 percent link densities for the weakly connected graph and the randomly connected graph, respectively. In order to reach the depth level of 4 to reach most, if not all, of the nodes, unidirectional connection achieves at 8 percent link density, while bi-directional connection gets there at 30 percent. With more than 30 percent link density, no significant difference among all, as the depth level converges down to 3.

Figure 7 illustrates how the transmission mode, in addition to link directionality, affects the depth level. At the link density of about 4 percent, each tree reaches its peak depth level, at different depth levels. The shortest path trees with both links and with only bi-directional links, of the fixed transmission power mode, have their peak depth levels at around 9. Ones with both links and with only bi-directional links, of the random transmission power mode, have their peak depth levels at 11 and 7, respectively. In order to reach the depth level of 4 to reach most, if not all, of the nodes, a tree with the random transmission power and unidirectional connection achieves at 15 percent link density. A tree with the random transmission power and bi-directional connection gets there at 35 percent. The rest arrives at around 25 percent link density. At more than 30 percent link density, there is no significant difference, as the depth level converges to 3.

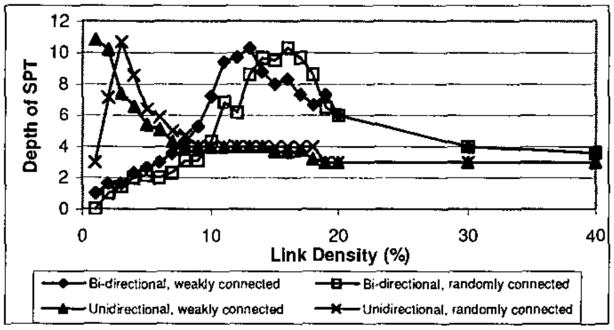


Figure 6: Depth of Shortest Path Tree from Random Graph

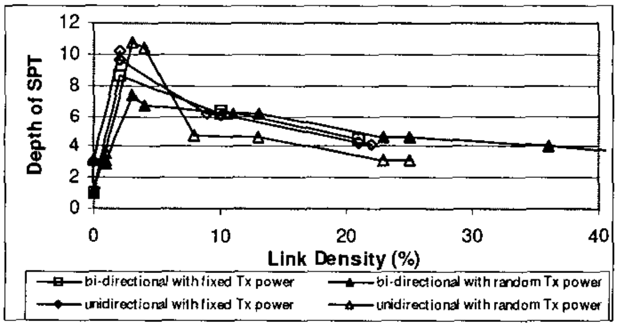


Figure 7: Depth of Shortest Path Tree from Euclidean Graph

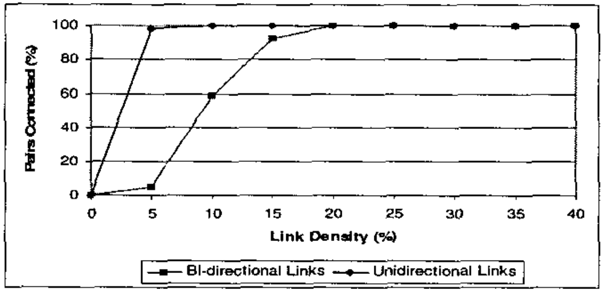


Figure 8: Percentage of Pairs Connected from Random Graph

Both approaches show similar results as link density increases. The peak depth level of one with unidirectional links is almost 11, and one with bi-directional links is about 10. Figure 6 and Figure 7 illustrate that both approaches have a depth level of 3 at convergence.

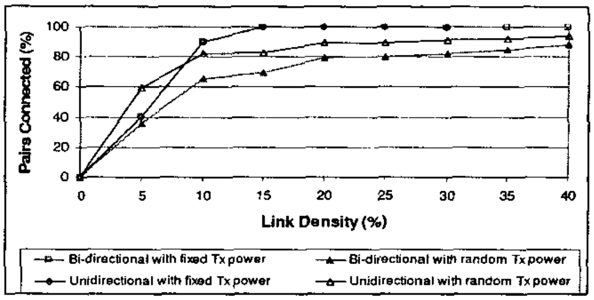


Figure 9: Percentage of Pairs Connected from Euclidean Graph

3.4 PERCENTAGE OF PAIRS CONNECTED

The percentage of pairs connected indicates how well a node can reach all other nodes. Figure 8 shows that in the Random graph approach a node can reach 90% of all nodes at 5 and 15 percent link densities with both links and with only bi-directional links respectively. The Euclidean graph in Figure 9 illustrates networks with identical transmission power, regardless of directionality, pair up at less than half of the link density that those with random transmission power do. In order to reach 90% of all nodes, it takes 10%, 20% and 30% link densities, for networks with identical transmission power, unidirectional networks with random transmission power, and bi-directional networks with random transmission power respectively. Figures 8 and 9 confirm that using unidirectional links, in addition to bi-directional links, expedites network connectivity by 50%.

3.5 AVERAGE PATH LENGTH

In addition to how many connections nodes paired up together, the length of connections is important. It determines how fast for a message to arrive at a sink node. Illustrated in Figure 10, for Random graphs, a node takes an average of 3 hops to reach all other nodes at only 5% link density using both unidirectional and bi-directional links, while it takes 3.7 hops at 15% link density using only bi-directional links. With Euclidean graphs in Figure 11, a node with random transmission power takes an average of 3.2 hops to reach all other nodes at only 5% link density using both unidirectional and bi-directional links whereas it takes 4.3 hops at 15% link density using only bi-directional links. The average path length of a node with fixed transmission power, regardless of directionality, is in between. It takes an average of 4.7 hops at 5% link density.

4 CONCLUSION AND FUTURE WORK

By studying the impact on performance on using unidirectional links, in addition to bi-directional links, in ad-hoc networks, this paper offers a better understanding on the future routing protocol design for ad-hoc network. By using unidirectional links, in addition to bi-directional links, the routing performance will improve greatly. Both unidirectional and bi-directional links in the Random graph and Euclidean graph approaches are investigated.

In order to accurately evaluate the use of unidirectional links, the Random graph approach serves as a theoretical benchmark, while the Euclidean graph approach shows the ability of the network to transmit messages to most, if not all, of the nodes within a small number of hops on the provision of the minimal network connectivity. The simulation results show the presence of a significant proportion of unidirectional links, and the improvement of network performance by increasing network connectivity and reducing path length.

As the experiment in this paper covers only stationary wireless nodes with two power transmission modes, it is possible to extend the study to take node mobility and its effect on link reliability into account. In addition to unidirectionality, other aspects of link characteristics such as bandwidth and error rate can be explored. The study of unidirectionality in a large-scale network is also of interest.

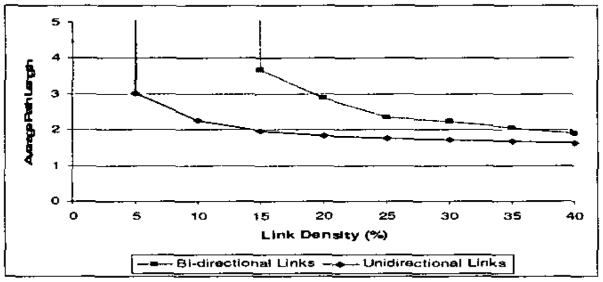


Figure 10: Average Path Length in Random Graph

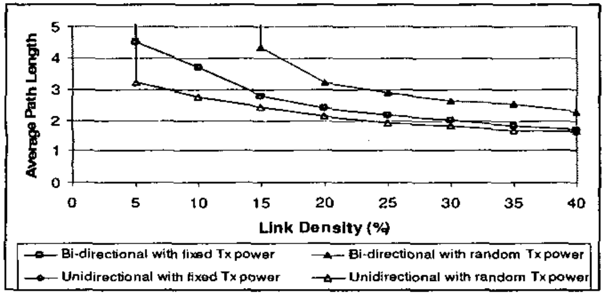


Figure 11: Average Path Length in Euclidean Graph

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