IMPROVED CONNECTIVITY USING HYBRID UNI/OMNI-DIRECTIONAL ANTENNAS IN SENSOR NETWORKS

A Senior Honors Thesis

by

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ABSTRACT

Improved Connectivity using Hybrid Uni/Omni-Directional Antennas in Sensor Networks (April 2008)

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Connectivity in sensor networks is an important metric that describes the capability of networks to be able to report sensed information. The ability of member nodes to communicate with each other and collectively report data largely depends on connectivity. Density of node deployment, the transmission radius of the antenna and the communication paradigm employed has a significant effect on connectivity. A network deployment is said to be connected when every node within the network is capable of communicating, either via multi-hops or direct links to every other node in the network. This is a very strict connectivity requirement called 100% connectivity. This work deals with analyzing connectivity in various randomly deployed sensor network deployments and comparing metrics between omni and hybrid uni/omni-directional sensor networks. Specific results will be presented with varying node deployment densities and transmission radii and the levels of connectivity they guarantee. These results have significant impact on secure routing protocol design for wireless sensor networks and planning network deployments. I also present results on k-connectivity, which is a metric that represents network availability, along with the dependence on transmission radii, node densities and uni-directional antenna beam width.

ACKNOWLEDGEMENTS

First, I would like to thank the Office of Honors Programs to provide this great program and funding support for my research.

Second, I would also like to thank my advisor, Dr. Deepa Kundur, and my graduate student mentor, Sonu Shankar, for their time and effort in guiding me throughout the year to complete this research.

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CHAPTER I

INTRODUCTION[1]

Wireless sensor networks (WSNs) consist of small, low-cost, low-power, multifunctional sensor nodes which can communication in short distances. Each sensor nodes consists of sensing, data processing, and communication components. A large number of these sensor nodes collaboratively form wireless sensor networks. Sensor nodes are seldom densely deployed, they are open to failures and power consumption is limited. When densely deployed, neighbor sensor nodes are close to each other and it enables multi-hop communication to consume less power in transmission than the single hop communication. The multi-hop communication can also help reduce signal propagation effects which can occur in long distance wireless communication. The sensor nodes have self-organizing capabilities which means that the position of sensor nodes does not have to be pre-determined. This permits random deployment in terrains that are dangerous and inaccessible. Installed with an on-board processor, instead of sending raw data to the other nodes, a sensor node can process the raw data and transmit

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[1] This thesis follows the style and format of *IEEE Transactions, Journals, and Letters.*

only the required information. They can also be equipped with power scavenging component such as solar cells so that it can be left in the operation without recharging batteries for a long period of time [1].

Architecture

The main components of a sensor node are a sensing unit, a processing unit, a transceiver unit and a power unit. The sensing unit collects the data (analog signal) and its analog to digital converter (ADC) converts the data to digital then sends it to the processing unit. The processing unit manages the task list and procedures to collaborate with other sensor nodes. The transceiver unit sends and receives the data to neighboring sensors. The power unit manages and sometimes generates the power using solar cells if available. A general architecture is shown in Figure 1 [1].

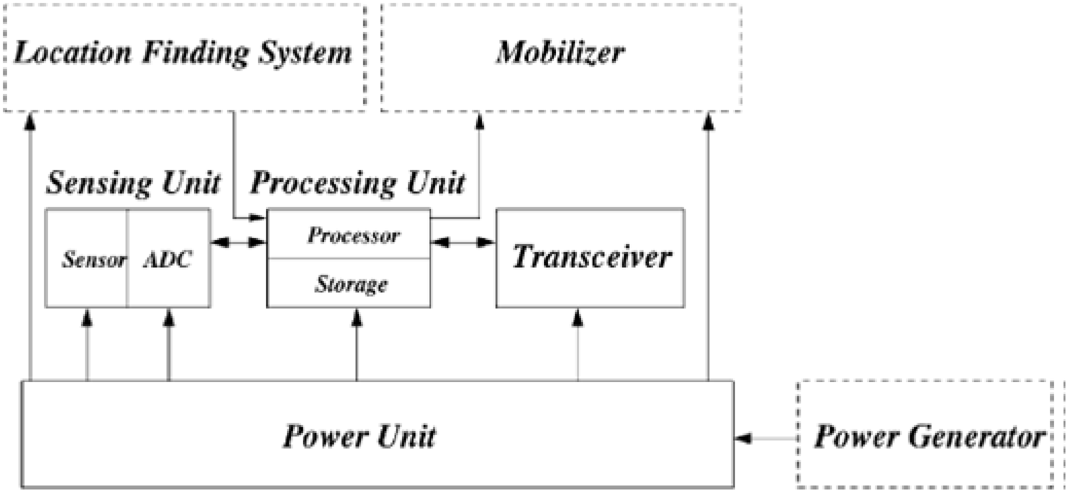


Figure 1 The sensor node architecture

Applications

The sensor networks with the features above are applicable in a wide range of applications such as health, military and environmental. A doctor can monitor patients' condition remotely for the convenience of the patients and understanding their condition remotely. It can be used to identify air and water contamination, and detect forest fires. In the military, it can be used for battlefield surveillance, tracking friendly forces' equipment, and assisting in the detection of nuclear, biological and chemical attacks [1].

CHAPTER II

BACKGROUND AND MOTIVATION

In wireless sensor networks, connectivity is crucial to maintain communication among nodes. Connectivity is a metric of the robustness and survivability of network deployments [8]. It is important to have the sensors 100% connected. A wireless network is 100% connected only if every member node is able to communication with every member node. A random deployment of nodes connected to a sink performing rare event detection is depicted in Figure 2. As seen, if the node 3 is not connected to the rest of the network, the activity detected by the node 3 will not be reported to the sink.

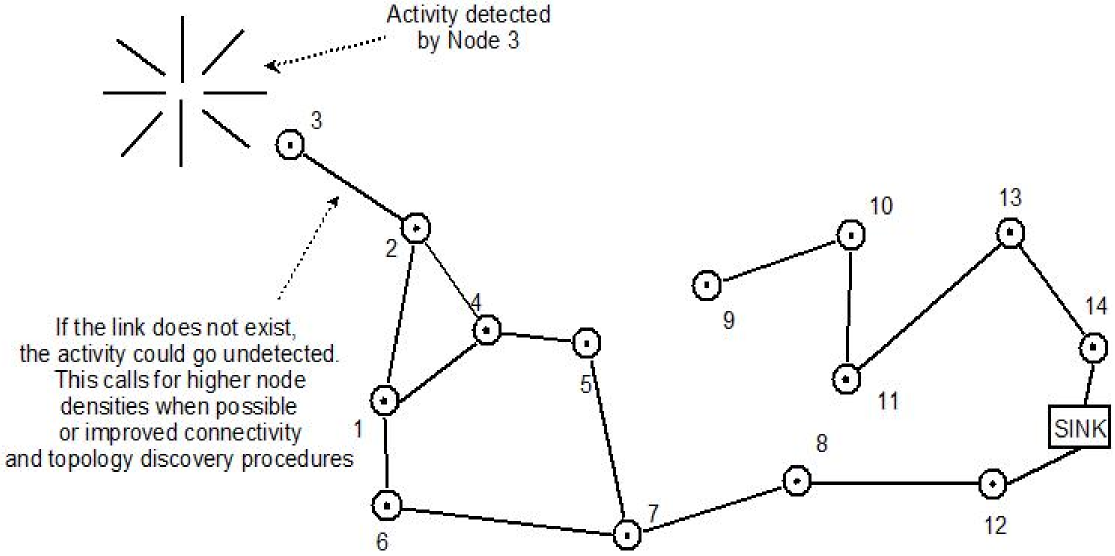


Figure 2 Example emphasizing on the importance of connectivity in WSNs

There are two existing paradigms for antennas in wireless sensor networks: omni-directional and uni-directional. An omni-directional antenna can transmit signal over a 360 degree angle and a uni-directional antenna has a preferred direction of transmission which focuses more energy in one direction than the other, usually propagating the signal over a sector with a beam width that is a fraction of 360 degrees [9]. Figure 3 illustrates the radiation patterns of the two antenna paradigms.

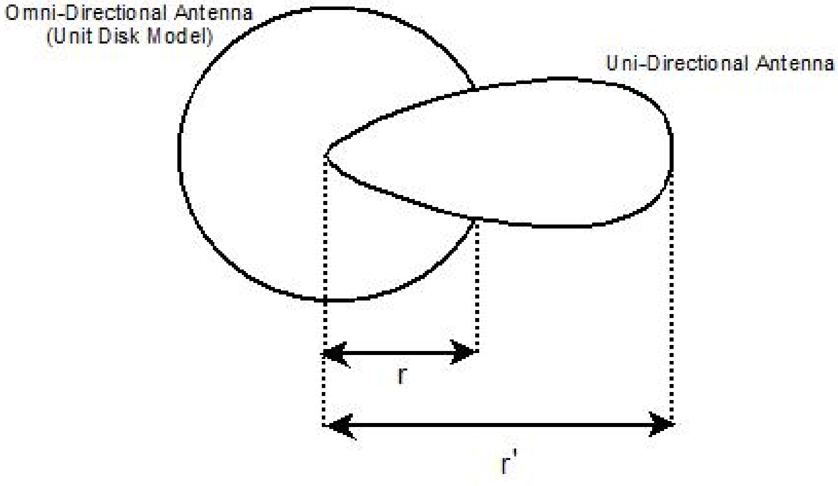


Figure 3 Uni-directional vs omni-directional: radiation patterns

As shown in Figure 4, omni-directional wireless sensor networks are modeled such that a bidirectional link is established between neighboring sensor nodes if they are within communication radius *r*. Therefore the connectivity is a function of *r* and density *ρ* [3]. On the other hand, for uni-directional sensor networks as shown in Figure 5, a direct link is established from node 1 to node 2 only if node 2 falls within the communication range *r* and the communication sector angle *α* of node 1. From the Figure 5, it is clear that the existence of path from node 2 to node 3 does not guarantee that the path from node 3 to node 2 exists. Therefore, the connectivity of uni-directional sensor networks is a function of *r*, *ρ* and *α*.

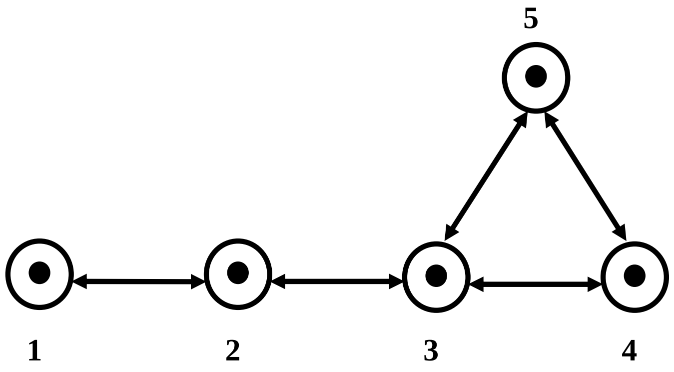
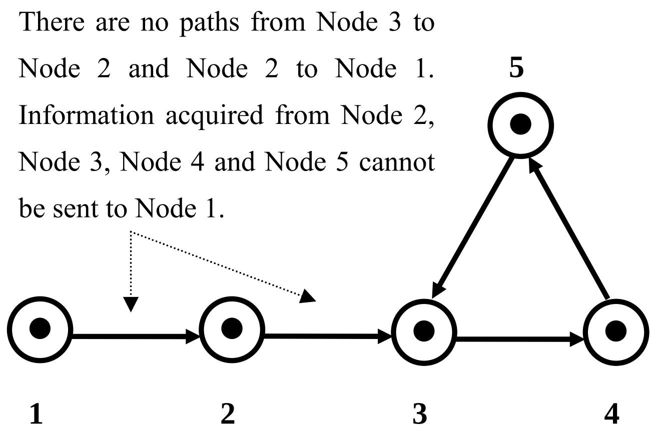


Figure 4 Omni-directional networks model



There are no paths from Node 3 to Node 2 and Node 2 to Node 1. Information acquired from Node 2, Node 3, Node 4 and Node 5 cannot be sent to Node 1.

Figure 5 Uni-directional networks model

Uni-directional wireless sensor networks have some advantages over omni-directional wireless sensor networks [11], [12]. Because it focuses the transmitting signal in one direction, it reduces interference between signals of other sensor nodes, increases signal strength and provides longer communication range. Even though uni-directional sensors might provide numbers of advantages over omni-directional wireless sensor networks, guaranteeing high levels of connectivity is a great challenge especially in random deployments scenario. This is due to the random orientation of sensor nodes deployed [4]. Thus, although uni-directional sensor networks have a very fundamental advantage in terms of longer communication reach, to be able to exploit it a new communication paradigm needs to be developed.

Another metric for measuring connectivity in sensor networks is that of "k-connectivity". This metric deals with improving the "availability" in networks. Availability basically stands for the capability of the network to continue performing functions and tasks in the event of the loss of links owing to environmental reasons or owing to network attacks. Improved availability is often achieved by rerouting the traffic along alternative paths. Accordingly, k-connectivity is a key property of highly available networks.

A network graph is said to be k–connected (k = 1, 2, 3, . . .) if for each node pair there exist at least k disjoint paths connecting them. Equivalently, a graph is k–connected if and only if no set of (k − 1) nodes exists whose removal would disconnect the graph. In other words, if (k − 1) nodes fail, the graph is guaranteed to be still connected. Similarly, a graph is called k–edge–connected if and only if there are at least k edge–disjoint paths between every pair of nodes. If a graph is k–connected, then it is also k– edge–connected, but the reverse implication is not necessarily true. The edge connectivity λ(G) is defined analogously to the (node) connectivity κ(G) [13].

CHAPTER III

RELATED WORK

Most of the work related to connectivity in wireless sensor networks has traditionally been focused on the existence of omni-directional antennas and topology control or neighborhood management procedures to ensure required levels of connectivity. Our work is focused on a rather hybrid approach that involves the use of both omni and uni-directional antennas. In this section, I list some of the works that are related to our paper.

The Multi-path Location Aided Routing (MLAR) [6] protocol is extended in [2] to include capability of directional antennas. This work mainly intends to reduce the protocol overhead and improve performance on metrics such as packet delivery ratio and end-to-end latency. The authors particularly look at reducing the number of rebroadcasts and routing hops by using the fact that directional antennas have a longer radio transmission range over a sector.

Omni-directional and Uni-directional deployments of sensor networks are compared in terms of connectivity in [5]. Specifically, the authors describe a sufficient condition on the beam width of the uni-directional antenna so that the directional sensors consume less than or the same energy to achieve the same connectivity of the resulting deployment in comparison with a deployment that uses omni-directional antennas.

In [10] the authors analyze the connectivity of sensor networks with uni-directional links. More specifically, the authors look at directional links that exist owing to the assymetric nature of real-world deployments and links between nodes. The authors report that connectivity has a heavy-tail distribution and that using only bi-directional links could cause partitions in the network.

The more recent area of security in directional wireless sensor networks is dealt with in [7]. As mentioned earlier, networks that entirely assume uni-directional links can create the added essence of security as many attack models that were previously easy to launch on networks owing to the very nature of the omni-directionality of the links cannot be launched with the same ease anymore. The authors in the paper propose a secure routing model that assumes uni-directional links and motes with such antennas. They look at the special case of free Space Optical (FSO) sensor networks.

The work related to bridging network partitions in [11] is very relevant to our paper. The authors in the paper propose a new routing scheme that considers the use of uni-directional links to bridge partitions. In networks without partitions, uni-directional antennas are used to repair damaged or temporarily broken links.

CHAPTER IV

HYBRID APPROACH

The hybrid approach involves using sensor nodes that are capable of both uni-directional and omni-directional communication. The nodes will be able to transmit omni-directionally and also uni-directionally in sectors of set beam width. I now describe and justify the extended reach possible in each sector. The energy required by a sensor node to transmit signal is proportional to the area covered. Therefore, an omni-directional antenna with radius r will consume power proportional to πr^2. A uni-directional antenna with communication sector angle α will consume power proportional to $\frac{\alpha}{2} r'^2$ with the assumption that power consumed by side lobes is negligible [5]. Both in omni and uni-directional case, if the total power consumption is kept the same, then $\pi r^2 = \frac{\alpha}{2} r'^2$. From this equation, one can derive $r' = r\sqrt{\frac{2\pi}{\alpha}}$. This is graphically presented in Figure 6.

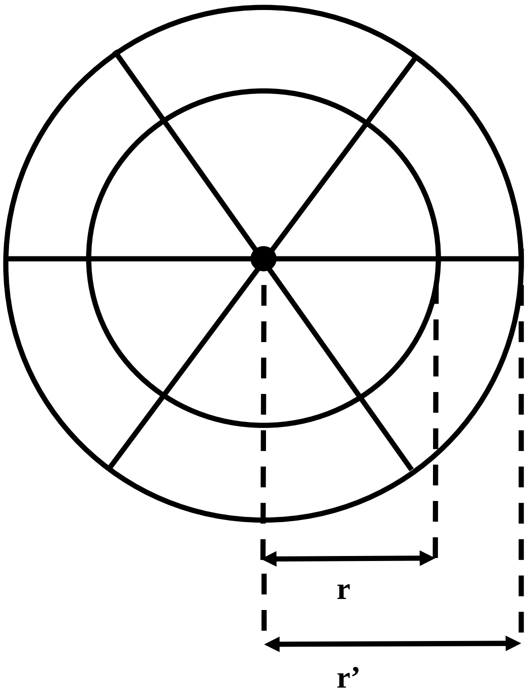


Figure 6 Hybrid uni/omni-directional antenna

Each node scans its neighborhood for other member nodes on all sectors and updates a locally maintained neighborhood table. This procedure is used during the initial neighborhood discovery stage when the nodes are deployed on the field. The nodes will switch sectors during transmission according to the destinations of packets in queue.

Figure 7 and Figure 8 below explain using the context of a linear network how the hybrid approach helps improve connectivity in random sensor network deployments.

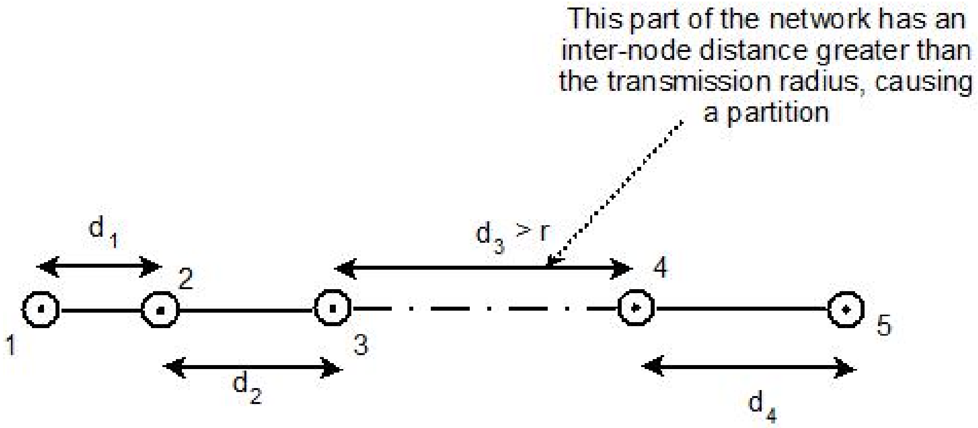


Figure 7 Partitioned network with omni-directional antenna

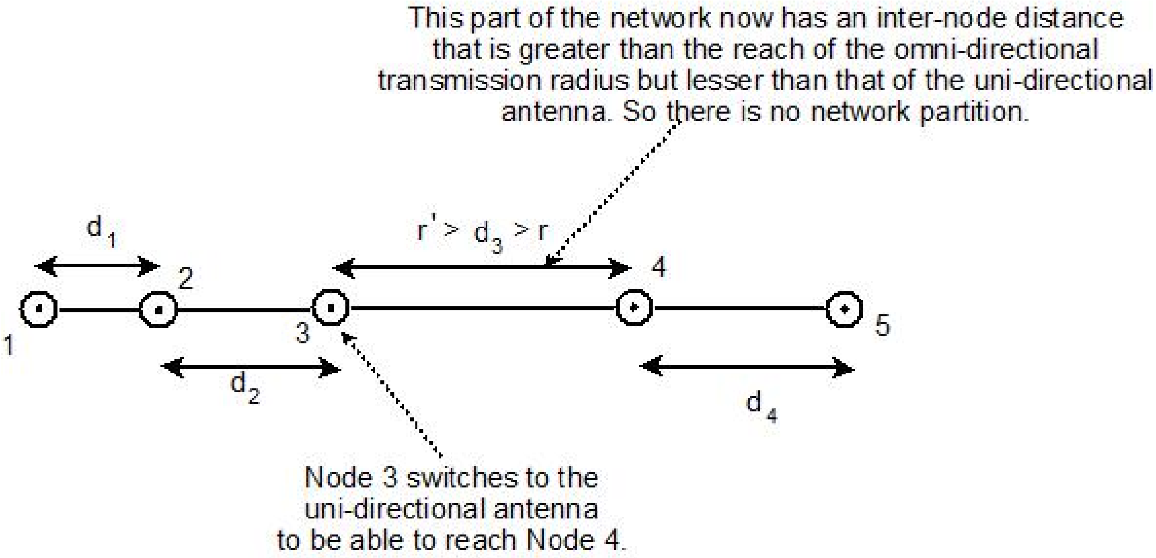


Figure 8 100% connected network with hybrid antenna

CHAPTER V

SIMULATION AND RESULTS

The 2-D model for the results shown below is a randomly distributed network of nodes in a unit square. I am interested in computing the probability of 100% network connectivity, which guarantees that every pair of nodes can communicate with each other. I generated 1000 random topologies to be able to compute the probability. To understand the relationship with node density and transmission radius empirically, I varied the normalized *r* between 0 and 0.5 and *n*, the node density, between 10 and 100. I also demonstrate the effects of varying the beam width from $\frac{\pi}{6}$ to $\frac{\pi}{3}$ for increasing transmission radius.

Figure 9 shows the probability of 100% connectivity for varying *r* (normalized) for omni-directional antenna and $\frac{\pi}{6}$, $\frac{\pi}{4}$, and $\frac{\pi}{3}$ hybrid antennas when the node density, *n*, is set to 10.

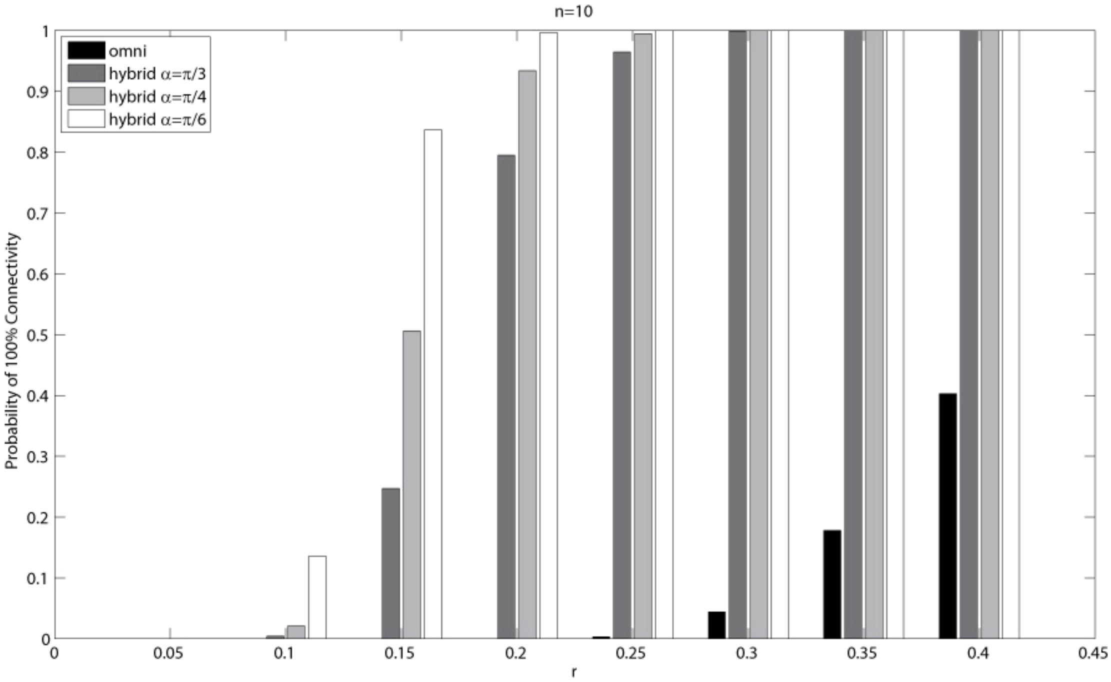


Figure 9 Probability of 100% connectivity when varying *r* for *n*=10

The probability of 100% connectivity remains zero for the omni-directional case until *r* reaches 0.25. However, the probability of 100% connectivity is non-zero for all hybrid cases starting from *r* = 0.1. For $\alpha = \frac{\pi}{3}$, the probability would reach near 1 (0.965) at *r* = 0.25. For $\alpha = \frac{\pi}{4}$ and $\alpha = \frac{\pi}{6}$ the probability would reach near 1 (0.934 and 0.997 respectively) at *r* = 0.02. On the other hand the omni-directional case would stay under 0.5 in all *r* values (0.403 the highest).

Figure 10 shows the probability of 100% connectivity for varying node density, n, for omni-directional antenna and $\frac{\pi}{6}$, $\frac{\pi}{4}$, and $\frac{\pi}{3}$ hybrid antennas when the transmission radius, *r*, is set to 0.2.

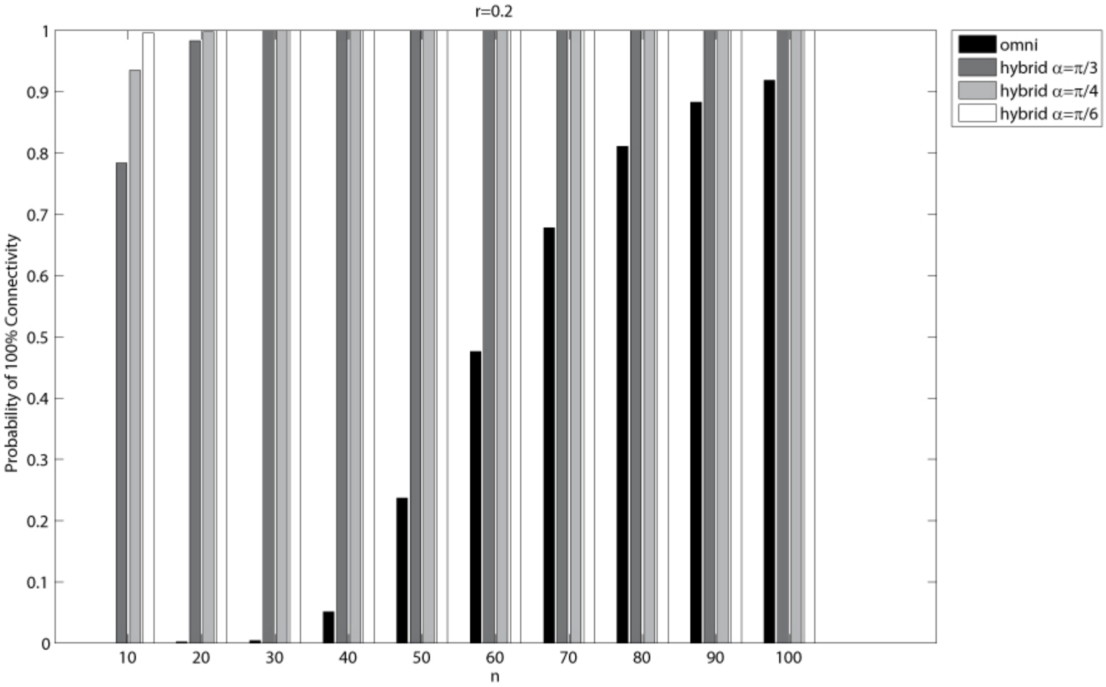


Figure 10 Probability of 100% connectivity when varying *n* for *r*=0.2

The probability of 100% connectivity is non-zero for all the hybrid cases. Indeed, all the hybrid cases reach near the probability of 1 when *n* = 20 (0.983, 0.998 and 1 for $\alpha = \frac{\pi}{3}$, α

$= \frac{\pi}{4}$ and $\alpha = \frac{\pi}{6}$ respectively). On the other hand, the omni-directional case would never reach the probability of 1 even when the node density is 100 (0.919).

Although at very high node densities (*n*) and transmission radii (*r*), difference in probability of connectivity is smaller, at lower values, the difference is phenomenal. As seen from the plots, with increasing transmission radii, the hybrid approach is phenomenally faster to reach a probability of 1. I notice that the hybrid approach reaches the probability of 1 at a transmission radius of 0.2, when the antenna beam width $\alpha = \frac{\pi}{6}$. In contrast, I find that the omni-directional case could not reach a probability of 1 for the transmission radii considered. Interestingly, with increasing node densities and a constant transmission radius of 0.2, I found that the hybrid approach guarantees a probability of 1 even at very low node densities. This was not so with the omni-directional case as is clearly visible from the plots.

I now present results of the probability of 2-connectivity for a randomly deployed network of nodes. The set up for the following set of simulations is the same as that used for generating results for 100% connectivity probability. I am only interested in analyzing the cases when each node in the deployment has at least two disjoint and independent paths towards the centrally located sink.

Figure 11 shows the probability of existence of two disjoint paths for varying *r* (normalized) for omni-directional antenna and $\frac{\pi}{6}, \frac{\pi}{4}, \frac{\pi}{3}$ hybrid antennas when the node density, *n*, is set to 10.

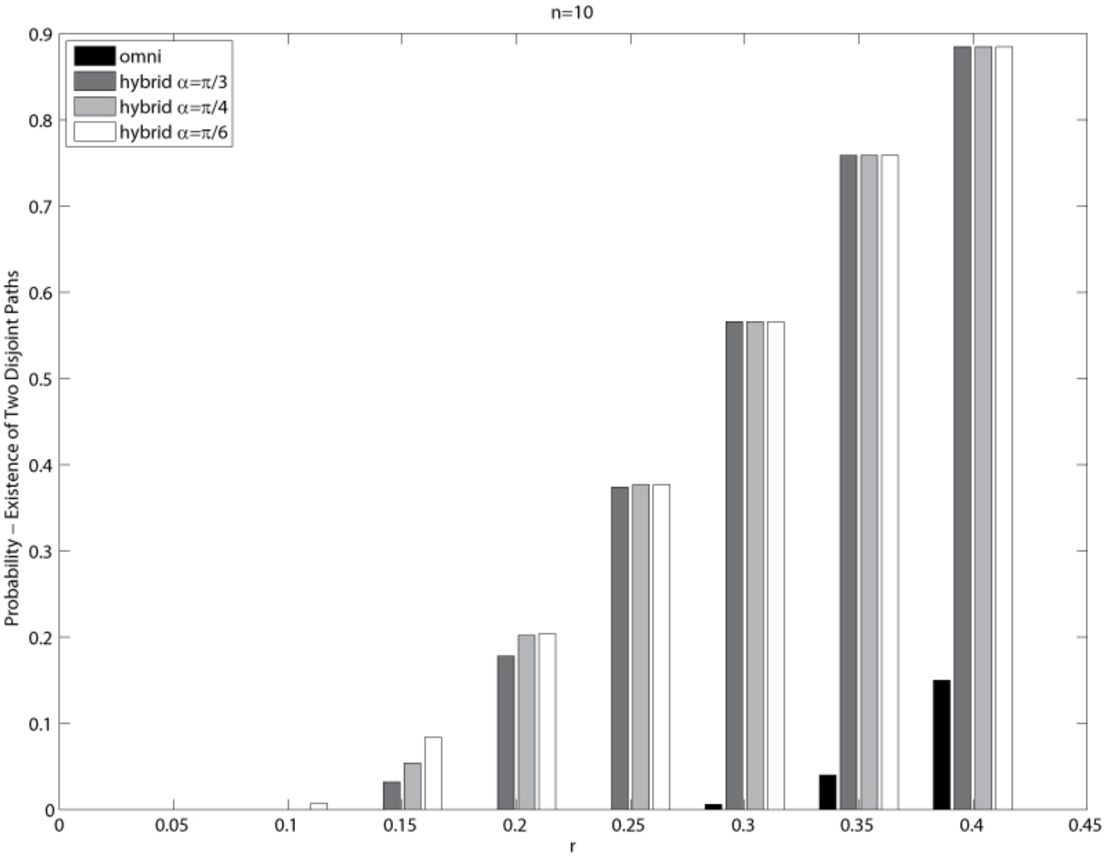


Figure 11 Probability of existence of two disjoint paths when varying *r* for *n*=10

The probability of existence of two disjoint paths for omni-directional antenna remains zero until *r* = 0.25. Even at *r* = 0.25, the probability for the omni-directional antenna is very low (0.006). However, for all hybrid cases, the probability is over 0.5 (0.566). The onmi-directional case would only reach up to the probability of 0.15. Nevertheless, the hybrid cases would reach near 0.9 (0.885) when *r* = 0.4.

Figure 12 shows the probability of existence of two disjoint paths for varying node density for omni-directional antenna and $\frac{\pi}{6}$, $\frac{\pi}{4}$, and $\frac{\pi}{3}$ hybrid antennas when the transmission radius, *r*, is set to 0.2.

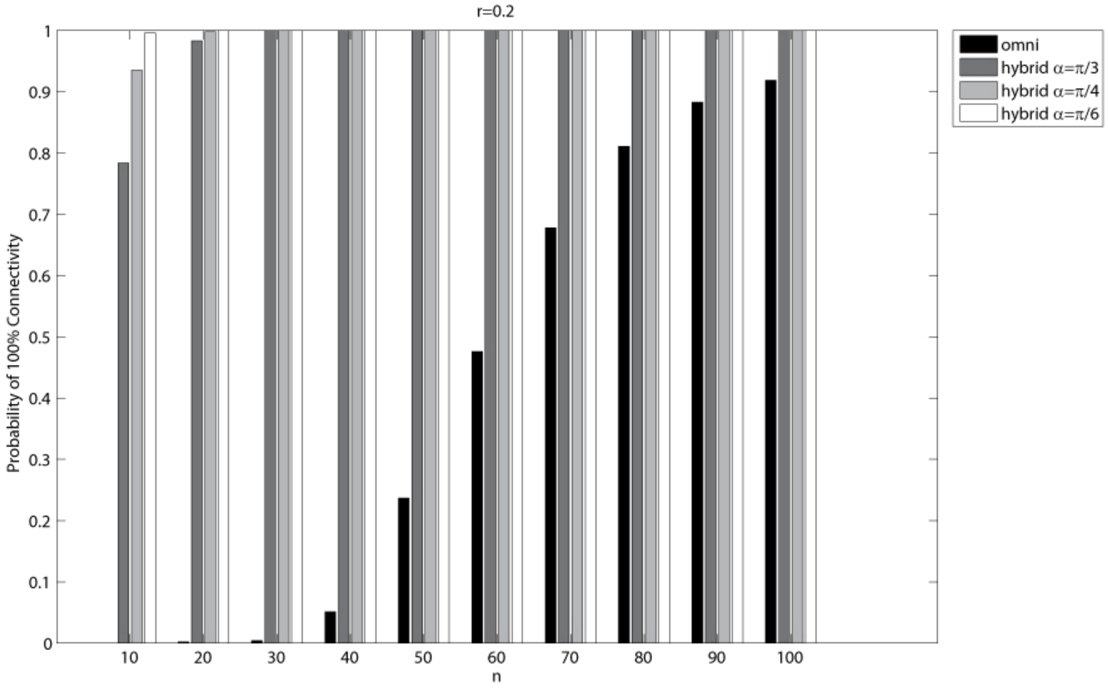


Figure 12 Probability of existence of two disjoint paths when varying *n* for *r* = 0.2

When the node density, *n*, is 20, the probability of existence of two disjoint paths for the hybrid cases are near 1 (0.983, 0.998 and 1 for $\alpha = \frac{\pi}{3}$, $\alpha = \frac{\pi}{4}$ and $\alpha = \frac{\pi}{6}$ respectively). On the other hand, the probability for the omni-directional case is 0.002 when *n* = 20.

CHAPTER VI

CONCLUSION AND COMMENTS

The results presented in the previous section describe the phenomenal benefits of using a hybrid approach in sensor networks. The most motivating observation is the performance of a hybrid enabled sensor network deployment at low transmission radii and node densities. The ability to provide higher levels of connectivity at low transmission radii and scanty node densities could prove to be crucial to many applications especially when the areas monitored by the sensor network deployments are less accessible. Although 100% connectivity can be a stringent requirement out of a sensor network, the results presented provide some insight into the advantages of a hybrid scheme and would have great utility when considering disaster recovery and security monitoring applications. The results on disjoint paths motivate the use of the hybrid paradigm in environments where the network deployment will be prone to recurrent link losses caused by interference and also in hostile areas where an imminent threat exists in the form of possible network attacks.

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EDUCATION

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Undergraduate Research Fellows Program, TAMU 08/2007-05/2008

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- Studying to analyze connectivity in various sensor network deployments and comparing metrics between omni-directional and hybrid uni/omni-directional wireless sensor networks
- Two-semester research culminating in a senior honors thesis

Undergraduate Summer Research Grants, TAMU 05/2007-08/2007

Project Title: *Temperature dependence of* $YBa_2Cu_3O_{7-\delta}$ *superconducting properties*

- Participated in research to improve critical current density of $YBa_2Cu_3O_{7-\delta}$ through variation of deposition temperature
- Conducted transmission electron microscopy images and data analysis

Project Title: *Characteristics of multiferroic* $BiFeO_3$ *under different percentage composition*

- Participated in research to develop thin nanocomposite $BiFeO_3$ multiferroic films and discover the nanocomposite formation under various percentage compositions
- Prepared targets, masks, and transmission electron microscopy samples
- Conducted pulsed laser deposition

Tutor for Foundation of Electrical and Computer Engineering 2006-2007

Volunteered to tutor for midterm and final exams in ENGR 111 class as part of the program to increase the freshman retention rate in the College of Engineering

PUBLICATIONS & PRESENTATIONS

Ji Heon Kwon, Poster presentation on “Improved Connectivity using Hybrid Uni/Omni-Directional Antennas in Sensor Networks,” Texas A&M SRW poster session, March 25, 2008, College Station, TX

Jie Wang, **Ji Heon Kwon** et al., "Flux pinning in YBCO thin film samples linked to stacking fault density," APPLIED PHYSICS LETTERS 92, 082507, (2008)

Jiheon Kwon, Poster presentation on “Deposition temperature dependence of YBCO transport properties,” Texas A&M USRG poster session, August 3, 2007, College Station, TX

HONORS & AWARDS

Academic Excellence Award Scholarship, Texas A&M University	2007-2008
Robert Kennedy Scholarship, Department of ECE	2007-2008
USRG Grants, Dwight Look College of Engineering	2007
Industrial Affiliates Scholarship, Department of Computer Science	2006-2007
Rickel Scholarship, Department of Computer Science	2005-2006
Dean’s list, Dwight Look College of Engineering	2004-2008

SKILLS

Hardware description language: Verilog
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High-level languages: C++, Java
Algorithm development environments: MATLAB, Maple
Design automation tools: SIMULINK, PSpice, MAX+PLUS II

LEADERSHIP & ACTIVITIES

Student Engineers’ Council	2007-2008
Undergraduate Curriculum Committee, Dept. of Computer Science	2006
Computing Service Advisory Committee, Dept. of Computer Science	2005
Computing Society, Representative to Student Engineers’ Council	2005
Honors Student Council	2005
Asian American Association, Treasurer	2004-2006