Towards Improved Connectivity with Hybrid Uni/Omni-Directional Antennas in Wireless Sensor Networks

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***Abstract*— Connectivity is a crucial requirement for wireless sensor network deployments. Without being able to guarantee a reasonable level of connectivity, many critical network operations may not be possible. Traditionally, omni-directional antennas have been used for communication in wireless sensor networks. In this paper, we analyze the effects on connectivity when a hybrid approach towards antennas is employed, by using both omni and sectorized uni-directional antennas. We present results that help understand the relationship between node density, transmission radius, uni-directional antenna beam width and network connectivity. We demonstrate that, under a broad class of conditions, a hybrid sectorized approach drastically improves connectivity and reaches higher probabilities of 100% connecitivity at much smaller node densities and transmission radii. We also suggest neighborhood management procedures for a hybrid approach and comment on the costs involved in practically implementing our paradigm.**

I. INTRODUCTION

A common characteristic of many envisioned applications of sensor networks is the main motivation behind promoting such technology, viz., the collection, organization and report of information, which requires well-connected nodes. The study of directional communications for sensor networks has been a topic of growing recent interest [1,2]. Furthermore, there is emerging activity in the area of hybrid omnidrectional/directional sensor network systems. Directed communications has advantages that include lower power consumption, extended communication radius and higher bandwidths. Directional links also have the benefit of physical-layer and network-level security; most known attacks on sensor networks assume bi-directional links and cannot be launched otherwise.

In this paper, we investigate improvements in connectivity using a hybrid approach, where-in a directional antenna is selectively employed at times when omnidirectional communication is insufficient owing to the topology or intermittent interference. We exploit the property that directional communications (e.g., directional RF antennas) have longer communication reach than their omni-directional counterparts. Further, we comment on the cost of practically implementing such an approach and suggest modifications to common neighborhood management protocols.

Most of the related work in the area of sensor network connectivity and routing improvement has traditionally been focussed on using omni-directional antennas and few have been motivated with generating a paradigm favorable to uni-directional antennas. Kranakis *et al.* [1] describe a sufficient condition on the beam width of the uni-directional antenna so that the directional sensors consume the same energy to achieve the same connectivity of the resulting deployment in comparison with one using omni-directional antennas. This motivates the use of uni-directional antennas but assumes a paradigm different from our work. Okorafor *et al.* [2] deal with the more recent area of security in directional wireless sensor networks. The authors look at the special case of free space optical (FSO) sensor networks and motivate the use of uni-directional antennas to improve attack resilience. Saha and Johnson [3] work on bridging network partitions which is relevant to our work as it proposes a new routing scheme that considers the use of uni-directional antennas to fix broken links and bridge partitions. To the best of our knowledge, there is no work that specifically reports on improvements on 100% connectivity using uni-directional antennas demonstrating the advantages of a hybrid paradigm in which omni-directional and sectorized uni-directional antennas are employed. 100% connectivity is, in part, a measure of robustness and utility of networks often used in mission critical settings. Here, the isolation of even a small set of nodes can be problematic when network availability is needed.

From [1], the energy required by an antenna to reach all nodes within its radius is proportional to the area covered and is given in Eqs. (1) and (2) where r is the omni-directional antenna transmission radius, r' is the uni-directional range in the direction of peak gain, α is the antenna beam width, P is the transmission power consumed at each antenna and C and C' are appropriate constants. It is assumed that the signal is transmitted over the primary lobe making other lobes negligible.

$$P = C.\pi r^2 \tag{1}$$

$$P = C'.\frac{\alpha r'^2}{2} \tag{2}$$

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We consider the case where power consumption is the same for each type of antenna and assume $C = C'$. Then, the ratio $k = r'/r$ quantifies the additional reach possible by a uni-directional antenna over its omni-directional counterpart and this improvement depends on the uni-directional antenna beam width.

$$k = r'/r = \sqrt{\frac{2\pi}{\alpha}} \geq 1 \tag{3}$$

Eq. (3) tells us that for a directional antenna with a smaller beam width, we will see larger gains in terms of the distance the signal can reach.

II. IMPROVEMENTS WITH THE HYBRID APPROACH

In this paper we assume that nodes are static, with uniform random distribution and capable of both omni-directional and directional communications. Directional communications is modeled via sectorized uni-directional antennas, dividing the entire omni-directional region of 2π radians into a number of sectors according to the antenna beam width. Practical implementations of these nodes would employ smart antenna technology capable of digital beamforming as will be described later. We assume that each sector can be activated, one at a time so that at any instant the node may appear to be equivalent to a uni-directional antenna and that reception is omni-directional. In the omni-directional mode, each node is capable of transmitting at a radius r. When switched to the uni-directional mode, each node is capable of transmitting at a radius r' related to r by Eq. (3), in each sector.

Our simulation set up is intended to provide better insights into the relationship between connectivity, beam width, node density and transmission radius. The 2-D model for the results shown below is a randomly distributed network of nodes in a unit square. We are interested in computing the probability of 100% network connectivity, which guarantees that every pair of nodes can communicate with each other. We generated 1000 random topologies to be able to compute the probability. To understand the relationship with node density and transmission radius empirically, we varied the normalized r between 0 and 0.5 and n, the node density, between 10 and 100. We also demonstrate the effects of varying the beam width from $\pi/6$ to $\pi/3$ for increasing transmission radius. The plots are shown in Fig. 1. - Fig. 2.

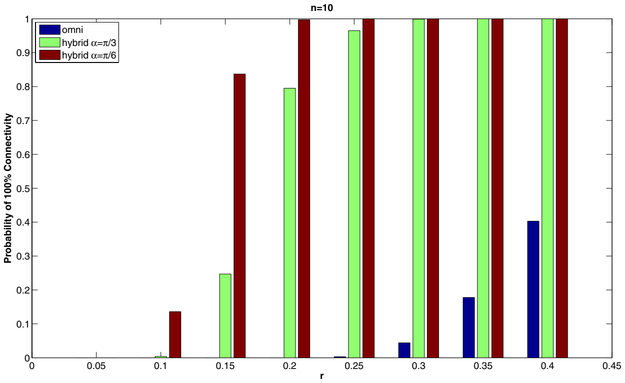

Fig. 1. $\alpha = \pi/6$ and $\pi/3$, r ranges from 0.05 to 0.45, n is constant at 10

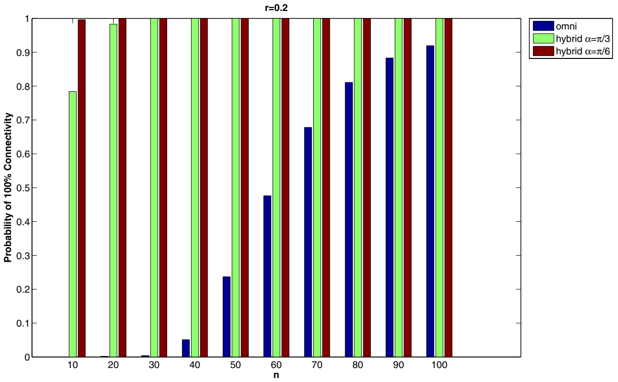

Fig. 2. $\alpha = \pi/6$ and $\pi/3$, n ranges from 10 to 100, r is constant at 0.2

As seen from the plots, with increasing transmission radii, the hybrid approach is drastically faster to reach a probability of 1. We notice that the hybrid approach reaches the probability of 1 at a transmission radius of 0.2, when the antenna beam width $\alpha = \pi/6$. In contrast, for the transmission radius range considered until 0.45, we find that the omni-directional case could not reach a probability of 1. Interestingly, with increasing node densities and a constant transmission radius of 0.2, we found that the hybrid approach guarantees a probablity of 1 even at lower node densities. The omni-directional case moves towards a probability of 1, but with a gradual increase and is only able to reach a probablity of 0.9 at our maximum of 100 nodes. To provide some insights on the effect of uni-directional antenna beam width, we also present results from the case when α is $\pi/3$. As is noticed from the plots, when the beam width is larger, the hybrid approach takes longer than it does otherwise to reach higher probabilities of connectivity. It has to be noted that it still grows remarkably faster than that of the omni case.

The results presented in this 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.

III. HYBRID OPERATION: PROCEDURES AND COST ANALYSIS

In the previous section, we demonstrated the improvements obtained from using a hybrid approach in the context of the probability of 100% connectivity. Now, we briefly describe a procedure that may be appended to any existing neighborhood

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management protocol. This would explain in detail how a protocol can be modified so that it can perform the function of switching between sectors and also switching from a sector to the omni-directional mode. This also explains when switching is necessary. We also describe in brief our estimates of the extra overheads incurred in terms of unit cost, operation power and delays when we replace a conventional omni-directional RF transceiver equipped mote with one that employs smart antennas capable of controlled directional transmission.

A. Neighborhood Management and Switching

The most common and simple neighborhood discovery algorithm that is employed in sensor networks involves each member node broadcasting a $HELLO$ message so that any neighboring node within its omni-directional reach will be able to hear its transmission. Upon receiving such a packet, a neighboring node will respond with a $HELLO\ RESPONSE$ packet and both nodes update their neighbor tables with the identities of each other, which is included in every transmission. A modified version of such a protocol for uni-directional sensor networks is seen in [4]. For our hybrid approach we present a procedure that may be incorporated in existing sensor network stack implementations as an interface detail between the network and link layers.

A very simple algorithm that may be used is described below:

Algorithm 1 Hybrid Approach - Neighborhood Management Extension

```
$Set$ Antenna Mode = $OMNI$
$Run$ Neighborhood Discovery Procedure
Populate Neighborhood Table
$Set$ Antenna Mode = $UNI$
for $SECTOR = 1$ to $SECTOR = 6$ do
    $Run$ Neighborhood Discovery Procedure
    Populate Neighborhood Table
end for
```

For each node in a network, the antenna mode is first set to omni-directional and the $HELLO$ message exchanges will be carried out followed by updating the neighborhood table. The same is repeated for each available sector; 6 sectors, each of beam width $\pi/3$ are used as an example in the algorithm described above. In addition to existing information, the sector and antenna mode will be stored at each node. In Fig. 3. we provide an example of a node updating its neighborhood table. As seen, we begin with the omni-directional case for Node 1 and Nodes 2, 3, 4, 9 and 8 are enlisted. The shaded region shows the area over which the message broadcast can be received by any listening node positioned accordingly. The procedure continues with scans in Sectors I through VI and for those sectors where neighbors are found, entires are correspondingly made. As reception is modeled as omni-directional, we assume the existence of a cheap compass at each node so that responses may be sent back to Node 1 in the right sector. Another low cost but sub-optimal approach is to send responses for node 1 in all available sectors until an acknowledgement is received for the same. Sending sectors may be appended to packets along with node identities for this reason. Fig. 3. also emphasizes on the fundamental advantage of using a hybrid approach for enhanced connectivity as seen in the shaded regions extending beyond the circle when each sector is activated.

Although the major traffic model employed for sensor networks is that of source-to-sink, where for a static network a node senses data and typically has the same next hop that would be used for the shortest path towards the sink, there are cases when data may have to be sent to other neighbors. Load balancing routing protocols and also applications that require collaboration between sensor nodes for data aggregation and other purposes are some examples where ad-hoc communication might be required. Thus, although switching sectors will not be required for a majority of the lifetime of a node, it is still a necessity for the operation of any sensor network deployment. The neighborhood management procedure described above will work in unison with an existing stack's routing protocol by switching sectors according to the destination of the packet in a node's transmit queue. Further optimization may be envisioned in terms of grouping packets in queue according to the sectors required for transmission based on the QoS requirements embedded into the packet.

B. Implementation Overheads

Now, we analyze the cost of using our approach in terms of hardware and implementation overhead. We envision our paradigm being implemented using smart antenna technology. Smart antennas have for many years been demonstrated to be able to support a variety of beamforming algorithms and have been used in cellular communication systems to improve capacity and range [5]. Beamforming is a technique that utilizes signal processing techniques to control the sensitivity and direction of antenna radiation patterns. An electronically steerable linear array of antenna elements may be employed to achieve the antenna characteristics that we desire in the RF module present on our hybrid sensor nodes. It has to be noted that a circular array would provide improvements in terms of form factor and size.

Smart antennas have very recently been considered specifically for sensor networks as seen in [6] which describes a smart antenna sensor mote platform. There is also significant work that uses components available off the shelf for applications in vehicular networks [7]. For our requirement we believe using an array of 4 antenna elements would suffice for generating 6 sectors of beam width $\pi/3$ each. This is justified via. the following relationship [8]:

$$n_e = \frac{\lambda}{d.sin(\alpha/2)} \tag{4}$$

n_e is the number of elements in the array, λ is the operating wavelength, d is the antenna spacing and α is the beam width.

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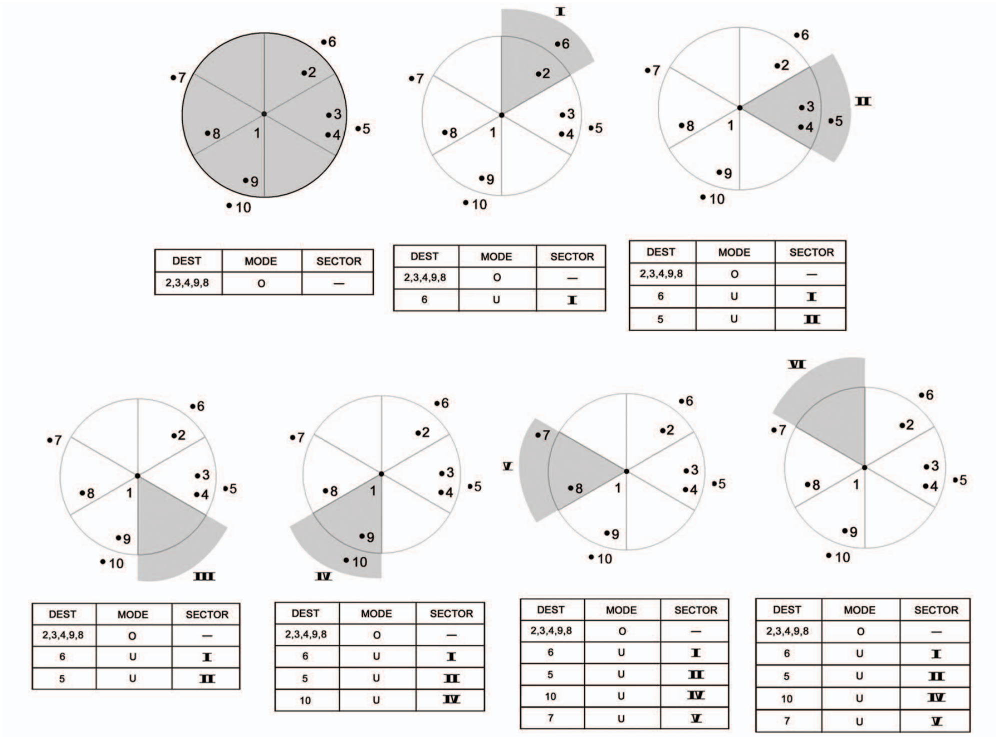

DEST	MODE	SECTOR
2,3,4,9,8	O	—

DEST	MODE	SECTOR
2,3,4,9,8	O	—
6	U	I

DEST	MODE	SECTOR
2,3,4,9,8	O	—
6	U	I
5	U	II

DEST	MODE	SECTOR
2,3,4,9,8	O	—
6	U	I
5	U	II

DEST	MODE	SECTOR
2,3,4,9,8	O	—
6	U	I
5	U	II
10	U	IV

DEST	MODE	SECTOR
2,3,4,9,8	O	—
6	U	I
5	U	II
10	U	IV
7	U	V

DEST	MODE	SECTOR
2,3,4,9,8	O	—
6	U	I
5	U	II
10	U	IV
7	U	V

Fig. 3. Neighborhood Management with Hybrid-equipped Nodes

As antenna elements are typically spaced $d = \lambda/2$ apart in an array, the number of elements can be generalized as

$$n_e = \frac{2}{sin(\alpha/2)} \tag{5}$$

Smart antennas are implemented today with digital beamformers [9] and so switching sectors does not incur any costs in terms of power or delay. Assuming such digital beamformers, costs may include a possible increase in the operating voltage and unit cost as components increase in terms of the number of antennas required for beamformimg. If we consider an omnidirectional node to have a single antenna then n_e will be the additional number of antennas required.

IV. CONCLUSION AND COMMENTS

In this work we have presented results on connectivity improvements using a hybrid approach towards antennas in sensor networks. Based on the results obtained here, routing and link layer protocols could be modified to make room for antenna modes and sector specifications. Our results are particularly interesting at lower node densities and transmission radii, motivating the use of a hybrid approach under these conditions for achieving better connectivity.

Although 100% connectivity can be a stringent requirement out of a sensor network, the results we present give us some insight into the advantages of a hybrid scheme and would have great utility when considering disaster recovery and security monitoring applications. We have largely looked at the directional RF case and plan to study optical links soon. We also intend to study the improvements in k-connectivity and network availability. Further, we believe that our hybrid approach can provide significant improvements to the security of a sensor network and its resilience to network attacks and intend investigating the same.

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