Analysis of Wired Short Cuts in Wireless Sensor Networks

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Abstract

In this paper we investigate the use of wired short cuts in sensor networks. This new paradigm augments a sensor network with a very limited wired infrastructure to improve its overall energy-efficiency. Energy-efficiency is obtained by reduction in average path length. We have developed an analytical model to analyze the gain in path length reduction by using short cuts. We have also conducted extensive simulations to validate our analysis. Our results show that there is an optimal wire length for which the path length reduction is at its maximum, beyond which it decreases. The optimal length is only a small fraction (37.8-50%) of the network diameter. In a network with 1000 nodes uniformly distributed on a disk the path length reduction saturates at 60-70% with 5-24 wires, depending on the location of the sink. Also, we find that restricting the knowledge about the wires to 2 hops does not degrade the performance from the case when we have global knowledge of all wires. These results show promise of the new paradigm.

1. Introduction

In this paper, we propose and study a new paradigm for sensor networks in which a partial wired infrastructure would augment the wireless sensor network, and in which wires may act as short cuts to create a small world [1]. The initial work on small worlds pointed out that for regular relative graphs (that are highly clustered) adding a few random short cuts decreases the degrees of separation (i.e., the average path length) drastically, resulting in a degree of separation similar to that of random graphs [2][3]. Our earlier work on small worlds in wireless networks showed that a similar relationship exists between spatial graphs (including wireless networks) and small worlds [4]. The short cuts need not be random but can be limited to only a fraction of the network diameter. In our previous work we treated the short cuts as logical contacts to which the path may traverse several hops [5] [6].

This work investigates the use of wires as physical short cuts to reduce the average hop count of the network. This in turn can increase the energy-efficiency of the sensor network as it reduces the number of transmissions in the network. In many applications like remote surveillance, it may not be possible to augment the network with wires. Also, for some networks, the duration of deployment makes the use of wires infeasible due to the cost. But for some applications like ecological monitoring in which the sensors monitor the environment for long durations, it can be economically feasible to do so. Such a network is being developed and deployed as a part of a project started by researchers at UCLA and partner universities. The Network Infomatical Systems (NIMS) [7] infrastructure consists of a collection of steel cables, each attached to any two points - buildings, trees, or other natural structure - that serve as suspension points. Nodes suspended on the cable collect data about the environment through a range of sensors which can be lowered or elevated, and also move, activate, and recover fixed nodes set along the cable pathway. They also have the ability to dock when necessary to recharge their energy source, removing energy constraints that have hobbled other sensor networks in the past. The cables can also be used for communication purposes.

In our network model, we focus on the class of sensor networks in which the data is routed towards a single sink. Traffic from the sensors is routed to the sink using greedy geographic routing. We assume that the nodes at the ends of the wires are simply more powerful sensors with much larger battery power, or have a mechanism by which they can replenish their power like in the case of the NIMS infrastructure. Also, we concentrate on networks in which the data generated by the nodes is low rate, which implies that

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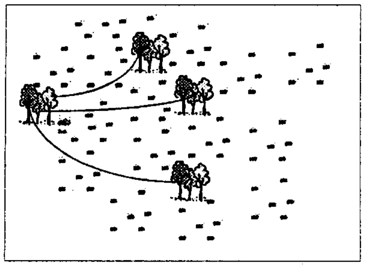

Figure 1. The new paradigm: Sensor network augmented by a few wires or cables to be used in communications as short cuts

we can safely assume that the wires are not bandwidth limited for the traffic they carry. Thus in our model, we have not considered the cost of the wired transmission. Using analytical modeling and simulations, we have focused on the following questions:

- How many wires are required to achieve maximum reduction in the average path length?
- What is the maximum attainable reduction?
- What is the minimum investment that leads to significant reduction in path length?
- How should the wires be placed?
- What happens if we restrict the information to some hops from the wire (instead of global knowledge of all wires)?

We have developed analytical model to obtain theoretical values for the average path length reduction. The analytical expression for the path length provides the reduction that can be obtained for any position of the sink. The expression shows that for our model, there is an optimal length of the wires for which the average path length is at its minimum. We further validate our analysis using extensive simulations. We compare the average path length obtained by using wires with the case having no wires. Our results show that the maximum reduction in average path length that can be obtained is 70% for the sink placed at the center and is over 60% when the sink placed at the edge of the network. The length of wire needed for the same reduction is higher when the sink placed at the edge. The maximum reduction is achieved with 24 wires when the sink is placed at the center. For a similar experiment, 5 wires give near saturation results for the sink placed at the edge. Thus results show that we need more number of wires when the sink is at the center than when at the edge, but the length of the wire required for is much larger for the sink positioned at the edge. Restricting the knowledge of the wire does not result in deterioration of performance for small wire lengths.

Overall, our results show the promise of this new paradigm of augmenting a sensor network with wires, in achieving a drastic reduction in path length (and hence significant improvement in energy-efficiency). A relatively small number of wires are needed, and the knowledge about locations of the wires need only be propagated a couple of hops away from the ends of the wires. To our knowledge no such work has been done studying the effect of adding wires to wireless sensor networks.

The rest of the paper is organized as follows. In section 2, we discuss related work to place our contributions in context. Section 3 discusses the problem formulation, evaluation metrics considered and the analytical model. In Section 4 we present our evaluation methodology. Simulation results and analysis are discussed in section 5. Section 6 discusses possible future extensions to this work. Concluding comments are presented in Section 7.

2. Related Work

Previous work has shown that wireless networks are spatial graphs that tend to be much more clustered than random networks and have much higher path length characteristics. It has been observed that by adding only few random links, path length of wireless networks can be reduced drastically [2], [3]. Our earlier work on small worlds in wireless networks showed that a similar relationship exists between spatial graphs (including wireless networks) and small worlds [4]. In our previous work, we had used this knowledge to use short cuts as logical contacts to develop efficient resource discovery techniques for large scale wireless networks [5], [6]. The work showed promising results for the use of short cuts as logical contacts. It further motivated research on the use of short cuts as physical contacts (either using wires or large range wireless). In this paper we focus on the use of short cuts as physical contacts for a subset of sensor networks which have a single sink.

Recently researchers at UCLA and partner universities have developed a new class of aerial, suspended robotic sensors able to monitor their own performance as they move themselves along a network of cables. The technology, known as Networked Infomechanical Systems (NIMS) [7] can be used to monitor a mountain stream ecosystem from the ground to the treetops for global change indicators, or observe coastal wetlands and urban rivers for biological pathogens. The NIMS infrastructure consists of a collection of steel cables. Each cable is attached to any two points – building, trees etc that can serve as suspension points. The cables can also be used to move robots that can monitor these sensors, and replenish resources like power. Such infrastructure

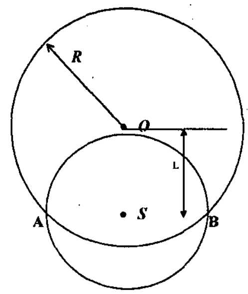

Figure 2. Figure showing how the wires are placed for a sink (S) placed at (0, -L)

support removes previous limitations of on site sensor networks, as nodes can be replaced, relocated and replenished. Our work can complement the efforts of the NIMS project as it gives us an insight into the use of wires for carrying data. By understanding the minimum investment required and the fundamental limitations we can gain insight into how the wires could be used as short cuts in sensor networks.

Various energy-aware routing protocols for sensor networks have been developed. Some of the protocols use data centric routing in which the nodes first exchange some metadata information before the actual data transmission [8, 9]. In [10], the authors propose LEACH, in which the nodes are organized into clusters and the lifetime of the network is increased by randomly choosing the cluster heads. These routing protocols explore one of the dimensions of increasing the energy efficiency of sensor networks. We have explored an orthogonal dimension in which energy efficiency is obtained by the use of wires. Our work is complementary where adding short cuts may work in conjunction with those schemes to even further improve the energy efficiency drastically. Base station repositioning has been suggested in [11] for increasing the network lifetime. Our work can be extended to develop schemes for wire placement when the sinks or the sensor nodes are mobile, which can complement the work in [11]. However, using mobility for energy efficiency may not work in some scenarios (like rugged terrains) where it may not be feasible (from a robotics perspective) to control the mobility of the base station and overcome natural obstacles. In such cases, it may be more feasible to install wires.

3. Problem Formulation and Models

3.1 Network Model

We consider a disk-shaped network topology. Sensors are distributed on the disk in a uniform random manner. Every node knows about its neighbors. The network is location-aware; that is, sensor nodes have some mechanism by which they can find out their location and their neighbors' locations (e.g., Hello messages). The network consists of only one sink. So the traffic from all the nodes in the network is routed towards the sink. The location of the sink can be anywhere in the network. The sensors and the sink are not assumed to be mobile.

3.2 Wire Model

The two ends of a wire are equipped with transceivers that enable only the ends of a wire to communicate with the wireless sensor network and with the other end of that wire. The ends of the wires have information about their locations and they share that information with nodes in the wireless sensor network up to h hops away. More will be said about this in the routing model.

The wires are placed with one end away one hop from the sink. The other end of the wires lie on a circle which has its center at the sink and the radius of the circle is the length of the wire. The nodes on the circle are equidistant from each other. One end of each wire is one hop from the sink, and the other end lies on a circle of radius ℓ, where ℓ is the length of the wire. When the sink is placed at an arbitrary position, the circle with radius ℓ may not lie completely inside the topology. In that case, the wired nodes are placed equally spaced out on the arc of radius ℓ lying within the topology. Figure 2 illustrates the placement of wires for an arbitrary position of the sink. If we consider wires of length ℓ, then a circle of radius ℓ centered at the sink intersects the topology at points A and B. One end of each wire is still one hop from the sink while the other end of the wires is placed equidistant on the arc A-B.

We assume that the bandwidth of the wires is large enough so that there are no bandwidth constraints on the wire. Also, we ignore MAC issues as well as the cost of sending packets on the wire. Another assumption we have made in our simulations and analytical models is that the communication between any two nodes A, B is symmetric, i.e. if A is in radio range of B, then B is in radio range of A.

3.3 Routing Model

The routing policy used is greedy geographic routing [12]. Thus when a node A has packets for a node B, it is assumed that it has the location of node B. Node A then transmits the packet to their neighbor who is geographically closest to B. Every node does the same until the packet reaches node B. If a node X receives a packet for node B, and it finds that none of its neighbors are closer to the destination than itself, then

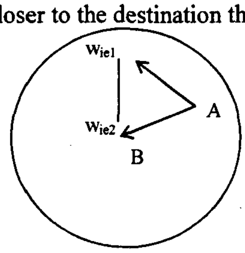

Figure 3.Routing policy when all nodes have the knowledge of all wires. The decision is shown for an arbitrary node A, where $w_{ie1} - w_{ie2}$ is the wire and B is the sink

the packet is dropped. Modified geographic routing like the one discussed in [13] deal with such cases, but we have not used such techniques for simplicity.

When there are no wires in the network, then the packets are routed to the sink using greedy geographic routing. When wires are introduced in the network, the packets may either be routed to the wire, or directly to the sink depending on the wire knowledge model. For our study we consider two cases about the knowledge of the wires locations. In one, we assume that all nodes in the network have full knowledge of the wires. The second assumes that knowledge about wire locations is propagated only h hops away from the wire end. So only nodes h hops from the end points of each wire know about the wire. Depending on the value of h, some nodes may have the location of more than one wire, whereas some nodes may not have the location of any wire. Also note that in our model, we assume that the sinks (S) must be either the source or the destination for all communications (i.e., the traffic flows from the sink to the sensors (in terms of queries for example) or from the sensors to the sink (in terms of reports)).

Let us first consider the routing decision for the case when all nodes in the network know about all the wires. Let the source and destination be A and B, respectively. Let there be n wires, denoted by w_i, $1 \le i \le n$. Let the two ends of the wire be denoted by w_{ie1} and w_{ie2}, with w_{ie2} representing the end closer to the destination. Let $d(x,y)$ represent the distance between any two points x and y. For each packet, the source computes:

1. $d_{wi} = d(A,w_{ie1}) + d(B,w_{ie2})$ for each wire w_i, i = 1 to n.
2. $d(A,B)$

The source then computes the minimum of the above $n + 1$ distance. If the minimum is $d(A,B)$, then the packet is sent towards the destination directly over the wireless links without using the wired short cut. If d_{wi} is minimum for some i, then the packet is sent from A

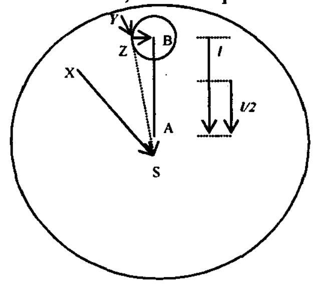

Figure 4.Routing policy when wire information is restricted to k hops from the wire. In the above figure, S is the sink; A-B is the wire of length ℓ. We have two nodes, X and Y wanting to send packets to S, both of which are outside the coverage of the wire A-B.

towards w_{ie1}. It then travels over the wired short cut to w_{ie2} and then finally reaches B from w_{ie2} over one hop wireless. This routing policy is illustrated in Figure 3.

When we have partial information about a wire, we assume that the knowledge about the locations of the two edges of a wire is propagated to only h hops from the wire. In that case, nodes take the routing decision in the following manner:

1. The source computes:
   1. $d_{wi} = d(A,w_{ie1}) + d(B,w_{ie2})$ for each wire w_i, i = 1 to k.
   2. $d(A,B)$

It may be possible that k is zero for some nodes. In that case, the nodes send the packet towards the sink (B) by sending it to the neighbor geographically closest to B. If k is greater than 0, then the nodes compute $(d_{wi})_{minimum}$ and compare it to $d(A,B)$. If $(d_{wi})_{minimum} < d(A,B)$ then the packet is sent towards w_{ie1} (to use the wire) else it is sent toward B.

2. An intermediate node checks to see if the destination of the packet is the sink. This is possible as we assume every node knows the location of the sink, and that the network has a single sink. If it is, then the node does the same computation as the source and may re-direct the packet to go through a wired short cut if the policy favors that route. This is illustrated in Figure 4.

3.4 The Energy-efficiency Metric

We define the energy-efficiency metric in terms of the average energy consumed in the network to get 1 bit delivered to its destination. If we consider the energy consumed by the network to be the sum of radio energy spent in transmitting and forwarding the packets, then the energy will be directly proportional to the number of hops traversed by the traffic. Alternatively this is represented in our work by the

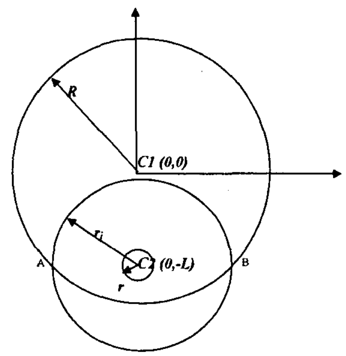

Figure 5.Figure showing the intersection area of the topology with a disk with centre at the sink and radius r_i. The intersection points are A and B.

average path length (or degrees of separation in the small world terminology). Hence reducing the average path length, reduces the energy consumed by the network, and subsequently increases the energy-efficiency of the overall sensor network. Let us call average path length to go to/from the sink to any other node in the network in the pure wireless case as '*l(0)*'. Also, let us call the average path length in case of using wires of length *i* meters as '*l(i)*'. We define the path length ratio $PLR(i)=l(i)/l(0)$. Hence, the reduction in path length due to wires of length *i* is $1-PLR(i)$.

Another aspect of energy efficiency is load balancing. In pure wireless sensor networks, nodes near the sink are used more often than other nodes and are susceptible to early energy depletion, sometimes disconnecting the network. By using distributed wires in the sensor network the traffic concentration on the nodes near the sink is alleviated. Hence we expect the lifetime (or useful time) of the network to be also extended in our paradigm. We shall study this aspect in our future work.

3.5 Analytical Model

In this section, we develop the analytical model for the average path length by adding short cuts. Through this model we shall reason about the maximum attainable gain (as reduction in the average path length) and the optimal wire length for the short cuts. Let the center of the topology be the point (0, 0). Let the sink be placed at location (0,-*L*). Let the radius of the topology be *R* and the range of the nodes be *r*.

We can draw concentric rings in the topology of varying radii with center at the sink. Let the radii of these concentric rings be r_i. Let us choose r_i as follows

$$r_i = i.r \quad , i = 1 \text{ to } \frac{R+L}{r} \tag{1}$$

Let $Area_i$ be the area of the circle of radius r_i that lies inside the topology (Figure 5). As the rings are multiples of the range of the nodes, the regions between these rings represent the area in which all nodes have the same hop count to the sink using purely wireless communication. Let us denote such regions by *RCH* (Region of Constant Hop Count). Further, nodes in RCH_i are *i* hops from the sink. The expression for the area of RCH_i ($ARCH_i$) is given by

$$ARCH_i = Area_i - Area_{(i-1)} \quad , \quad i = 2 \text{ to } \frac{R+L}{r} \tag{2}$$

$$ARCH_1 = Area_1 \tag{3}$$

As nodes are distributed uniformly in the network, the number of nodes in a *RCH* is proportional to the area of the *RCH*.

The average hop count for the pure wireless case is given by:

$$AHC = \frac{\sum_{i=1}^{i=\frac{R+L}{r}} i.RCH_i}{\pi R^2} \tag{4}$$

Now, let us introduce wires in the topology. Let us assume that the wires are of length *k*, and we have infinite number of wires connecting the sink to nodes *k* meters away. This means that there are infinite nodes on the other end of the wires. All these nodes are placed equidistant from one another on a ring of radius *k*.

Let us divide the topology into 3 regions centered at the sink– R1, RII and RIII. R1 represents the region of the topology within radius *k/2* from the sink. RII represents the region of the topology lying within arcs of radius *k/2* and *k*. RIII represents the region of the topology outside the arc of radius *k*. Now, since we are using greedy geographic routing, the nodes in region RI will *not* use the wire as the sink is closer to the nodes than the other end of the wire. Thus packets from all nodes in this region will be routed to the sink using wireless transmissions. The nodes in region RII and RIII will use the wire to reach the sink. Thus these nodes will send their packets using the wireless medium to the end of the wire *away* from the sink. The packets will then travel over the wire and be transmitted to the sink from the other end. In the presence of wires, we no longer have the fact that nodes in RCH_i are i hops from the sink. This is because now some nodes send the packets to one end of the wire rather that the sink. The expressions for the hop count of nodes in regions RI, RII and RIII are given by:

$$\text{RI:} \quad H1 = \frac{\sum_{i=1}^{i=\frac{k}{2r}} i ARCH_i}{\pi R^2} \tag{5}$$

$$\text{RII:} \quad H2 = \frac{\sum_{i=\frac{k}{2r}+1}^{\frac{k}{r}} (\frac{k}{r}+1-i).ARCH_i}{\pi R^2} \tag{6}$$

$$\text{RIII:} \quad H3 = \frac{\sum_{i=\frac{k}{r}+1}^{\frac{R+L}{r}} (i-\frac{k}{r}).ARCH_i}{\pi R^2} \tag{7}$$

Note that the expression for H1 is similar to equation (4). This is because in region RI nodes do not use the wire. The expression for RII and RIII are different as the average hop count is now the average hops taken by packets from nodes in RII and RIII to the *wire* and not the sink. The expression for the average hop count in the presence of wires is simply the sum of equations (5), (6) and (7):

$$AHC = \frac{\sum_{i=1}^{i=\frac{k}{2r}} i.ARCH_i + \sum_{i=\frac{k}{2r}+1}^{\frac{k}{r}} (\frac{k}{r}+1-i).ARCH_i + \sum_{i=\frac{k}{r}+1}^{i=\frac{R+L}{r}} (i-\frac{k}{r}).ARCH_i}{\pi R^2} \tag{8}$$

The expression for the AHC depends purely on $ARCH_i$. That in turn, depends on computing the values of $Area_i$. For an arbitrary position of the sink, $Area_i$ does not yield a closed form solution. This is because the arcs centered at the sink and having a radius r_i intersect the topology for some values of r_i, while may lie completely inside the topology for other values of r_i. The detailed derivation of $Area_i$ for an arbitrary position of a sink is provided in [14]. Once we have that, we can compute the average hop count with and without wires for different lengths of the wire.

We have plotted the path length ratio for varying wire length and three different sink locations in Figure 6. In the next section, we will compare the results obtained through simulation with the values obtained by using this model. The graphs show that the path length ratio decreases rapidly with increase in the wire length, after which the path length *increases*. We see this happening for each of the three positions of the sink. The rapid decrease is shown by the fact that path length ratio reaches 0.5 for wire length of 400m. For the sink placed at the edge, the path length ratio is at its minimum for wire length equal to $0.5D$, while it reaches the minimum at $0.375D$ for the sink placed at the center, D being the diameter of the topology. This result is quite significant, as it puts an upper limit on the recommended length of the wire to be placed in the network.

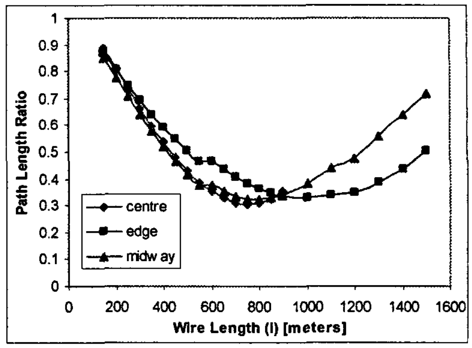

Figure 6.Path length ratio obtained for the reduction with the analytical model

There is one case which yields an analytical expression for the length of the wire required for minimum average path length. This is the case when the sink is placed at the center. The minimum path length for this case is found at the wire length of $\frac{2R}{\sqrt{7}} = 0.756R$, where R is the radius of the topology. This means that we get maximum reduction at wire length of 37.8 % of the diameter. In the following discussion, we provide the derivation of the above result.

For the sink placed at the centre, the disk centered at the sink having radius r_i and the topology do not intersect as they have a common center. Thus, the value of $Area_i$ is simply

$$Area_i = \pi r_i^2 \text{ , } i = 1 \text{ to } \frac{R}{r} \tag{9}$$

Thus the value of the area of RCH_i can be written as:

$$ARCH_i = \pi r^2 (2i-1) \text{ , } i=1 \text{ to } \frac{R}{r} \tag{10}$$

Substituting the value of $ARCH_i$ in equations (5), (6) and (7) and simplifying we obtain the values of H1, H2 and H3 as:

$$H1 = \left(\frac{x^3}{12} + \frac{x^2}{8} - \frac{x}{12}\right)\frac{r^2}{R^2} \tag{11}$$

$$H2 = \left(\frac{\frac{x}{2}(\frac{x}{2}+1)(4x+1)}{6}\right)\frac{r^2}{R^2} \tag{12}$$

$$H3 = \left(\frac{(z-x)(z-x+1)(x+2z-0.5)}{3}\right)\frac{r^2}{R^2} \quad (13)$$

Where $z = \frac{R}{r}$ and $x = \frac{k}{r}$. By summing up (11), (12), (13) and obtaining the first derivative with respect to x

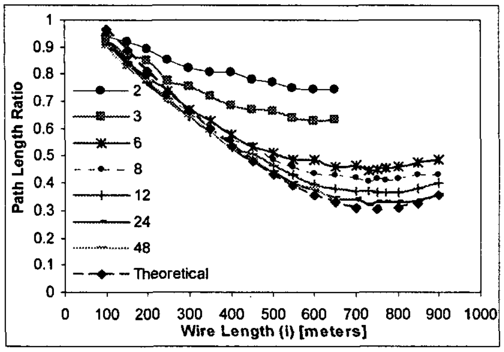

Figure 7.Path length ratio for sink placed at center. Graphs have been plotted for number of wires from 2-48.

and equating it to 0, we get $x = \frac{2}{\sqrt{7}}\sqrt{(z^2 - \frac{1}{6})}$. For most practical values of z, we can approximate $x \approx \frac{2z}{\sqrt{7}}$ without any significant error. In terms of length, this is equivalent to saying $k \approx \frac{2R}{\sqrt{7}}$.

Next, we discuss our simulation environment and our simulation results, and compare the simulation results with the theoretical values generated by the model in this section.

4. Evaluation Method

4.1 Simulation Setup

We use a disk topology similar to the analytical model. To provide uniform random distribution of nodes, the disk is divided into cells, with the density in each cell being constant. Within the cell, the nodes are placed randomly. The cells are used only for placing nodes in the network such that the nodes cover the entire network. We have made no assumption of the nodes knowing other nodes in their cell. While computing the average path length in the presence of wires, we assume that the cost of sending and receiving packets on the wire is negligible.

The simulation was written in *C*. Since we measure the path length reduction, we do not consider MAC layer issues. The parameters of the simulation were as follows. The range of all nodes was assumed to be the same, and was taken as r=55m. The radius of the topology was R=1000m. The number of nodes is 1000 nodes uniformly randomly distributed as described above. The network is divided into 100m x 100m cells, with the node density in each cell taken as 10. The traffic was generated randomly by the sensors and sent to the sink. Each experiment generated 200000 data packets. Geographic routing is used as described in Section 3[1].

4.2 Experimental description

We have conducted various experiments to investigate the different dimensions of the problem. Simulations have been conducted for the following cases: (1) varying the number of short cuts by varying the inter-wire angle, (2) varying the length of the wires, (3) varying the position of the sink, (4) limiting the information about wires locations to nodes k hops from the wire. In this case, a node forwards a packet towards the sink if it does not have any wire information. Once a packet reaches an intermediate node having the location of the wire, it makes a local decision if the packet needs to be forwarded to the sink, or to the short cut.

5. Analysis and Results

5.1 Sink placed at center

Figure 7 shows the average path length ratio for the sink placed at the center. The nodes in the topology are assumed to have full knowledge of all the wires. The curve we get from the analytical model has also been plotted. As we can see from the curves, the curve for the number of wires as 24 is very close to the theoretical result. This means that going beyond 24 radial wires (or inter-wire angle lesser than 15°) does not help in reducing path length further. Thus we can say that the number of wires saturates at 24. A mathematical analysis explaining why saturation occurs with 24 wires is given in [14]. The difference between the theoretical curve and the actual results can be attributed to the node placement. We have

[1] In greedy geographic routing a node forwards the packet to the neighbor closest to the destination. This technique may fail with local maxima [12][13] in which the forwarder itself is the closest node to the destination. Also, network partitions may be created due to random node placement. We reduce the effect of both of the above problems by using the uniform node placement technique. In our simulations, greedy routing failed to deliver less than 5% of the traffic for which we accounted by slightly increasing the traffic sent (from 200k packets to 210k packets). Thus, we ensure that our simulation results are not affected by local maxima or partition problems.

placed nodes in cells in a grid like manner, while the theoretical curve assumes uniform density across concentric rings.

The reduction with increasing length shown in Figure 7 indicates that the reduction we get increases rapidly with increasing length of the wire, but starts to saturate after some point. The maximum reduction is found at 75 % of the radius if the topology, close to the value obtained using the analytical model. The

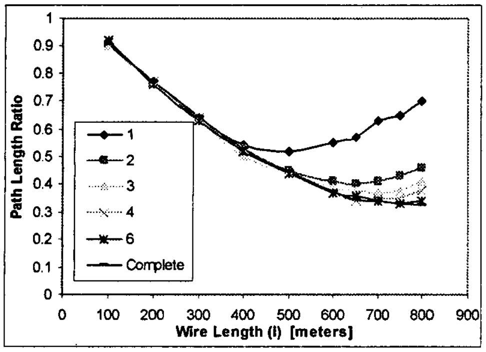

Figure 8.Path length ratio obtained by limiting the wire information to k hops. K is varied from 1 to 6.

maximum path length reduction we can get is around 68 % (path length ratio of 32 %). The curve obtained mathematically shows the maximum reduction that can be achieved at 70 %. Thus the simulation results obtained are very close to the analytical result.

However, as the reduction improves rapidly with increase in wire length, we do not need to add a large length of wire to get significant reduction. For example, if we have 3 wires, we can get reduction of 25 % by having the lengths of the three wires as 300m or 30 % of the Radius. Thus given a restriction on the total length of wire, we can use these curves in Figure 7 and 8 to determine if we need short cuts of smaller lengths, but more of them in number, or do we need smaller number of short cuts, but each of those shortcuts will be of large lengths. Obviously this decision is also affected by other factors like the capacity of the wires, traffic concentration around the wires in addition to applicability of wire installation according to the terrain of the sensor network. We do not claim that this decision can be made solely on these curves, just that they can be one of the factors in making the decision. We plan to investigate these other factors in the future.

Figure 8 shows the effect of limiting the wire information to k hops from the wires. The value of k is varied from 1 – 8. For the experiment, the number of wires was taken as 24, the saturation value obtained from the previous experiment. For this case, we see that performance is the same for small lengths of the wire. Beyond 300 meters, restricting the knowledge for 1 hop degrades the performance. The curve for 2-hop knowledge starts deviating from the curve for complete knowledge after about 600 m. For all lengths, 3 hops give the same performance as the complete knowledge case. Note that this is a function of the number of wires we use, because the smaller the number of wires, the more will be the degradation by restricting the information of the wires.

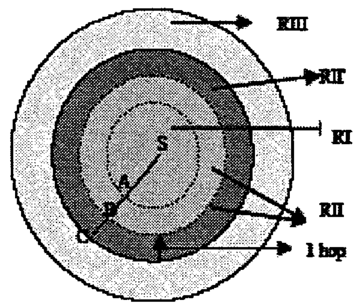

Figure 9.The sink is placed at the center. We have shown 1 wire of length ℓ in the topology (S-C). When they have complete knowledge of the wires, we have regions *R1*, *RII* and *RIII*. *RII* reduces to *RII'* when knowledge of the wires is restricted to 1 hop. In the figure, $SC = \ell$, $SA = \ell/2$, $SB = \ell - r$, with r being the radio range of the nodes.

There are two reasons for the gain to degrade beyond a certain length when we restrict the knowledge of wires:

1. For small lengths, the coverage of the wired nodes in the azimuthal angle overlaps. As the length increases, the coverage no longer overlaps and there are regions perpendicular to the radial direction in which nodes do not have information of any wired nodes.
2. In the radial direction, we can divide the topology into three regions – R1, RII and RIII. When we had complete knowledge, nodes in regions II and III used the wire. Now by restricting the knowledge, region II, has reduced from RII to RII' (Figure 9). For nodes in region III, the direction of the sink is same as the direction of the wired nodes. So the packets are forwarded hop by hop towards the sink, until it reaches a node which has the information about the wired nodes, and the packet is then *redirected* towards the appropriate wired node. If we have enough wires

for azimuthal coverage, this should happen for almost every packet originating in region III. Thus the overhead of restricting the knowledge in this case is the extra distance the packet travels due to the redirection, and this overhead is small when the number of wires is large. The real overhead comes because of region II transforming to region II'. Let's take the case when we restrict to 1 hop. Packets 2 hops from the wired nodes and x hops from the sink ($x > 2$) which earlier used to take 2 hops, now take x hops. This overhead becomes significant for larger lengths, as the difference between RII and RII' becomes larger. Even with the degradation for larger lengths, for large number of wires and lengths up to 30 % of the radius of the topology, restricting the knowledge to k hop

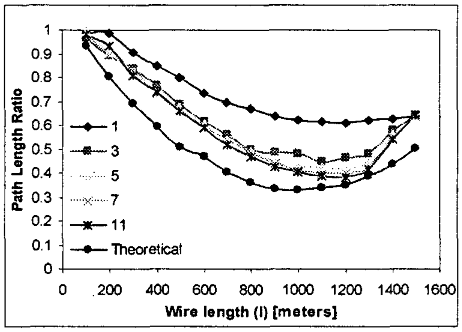

Figure 10.Path length ratio obtained by for the sink placed at the edge.

does not have any effect on performance. This is very significant as now we have a case for keeping a large number of wires, with each wires being of small length. This way we conserve energy by not propagating the knowledge of the wire more than k hop from the wire.

5.2 Sink placed at edge

Figure 10 shows the average path length reduction for varying number of wires when the destination is placed at the edge. The average path length reduction saturates at around 60 % (path length ratio of 40 %). This saturation occurs at a large value of wire length – around 50 – 60 % of the diameter of the topology. The saturation value is about 10% higher than the case when the sink is placed at the center. We see that the curves for the average path length ratio are almost identical for number of wires 5or greater. This value is much lesser than that for the sink placed at the center (~ 24). This can be attributed to the fact that the wires in this case need not cover the entire 360 *degrees*, but only the arc of radius ℓ that lies within the topology. This can be achieved with fewer wires. Even for this scenario, the gain we achieve increases rapidly as the length increases initially, after which we get diminishing returns. Another point of observation is the difference between the simulation results and the analytical result. This is because we place nodes in the network in a grid like manner. The analytical model though, assumes that the nodes within the concentric rings are proportional to the area of the region, which is not exact.

Figure 11 shows the effect of restricting the information of each wire to k hops from the wire. The value of k is varied from 1-6. The graph shows that for small lengths restricting the wire information does not affect the gain we can achieve. As the length increases, the different curves start to branch out. This can again be understood by dividing the entire

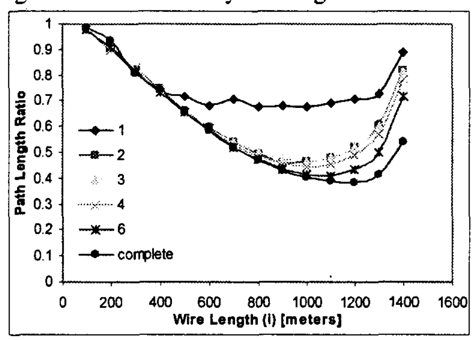

Figure 11.Effect of restricting wire information to k hops for sink placed at edge. K is varied from 1-6.

topology into regions RI, RII and RIII (Figure 9), centered at the sink. Restricting the knowledge to k hops means that the RII changes to RII'. This shifts the division between RI and RII from being at $\ell/2$ from the sink to $\ell - k$ from the sink, ℓ being the length of the wire. For large length, the difference between RII and RII' is much larger than that for the sink placed at the center. Consequently, we do not see the curves for k=6 and k=complete knowledge match for very large lengths ($\ell > R$). To illustrate this point, for a length of 500m, restricting to 2 hops is as good as complete knowledge. On the other hand, for a length of 1200, even 6 hops are not sufficient to give the same path length reduction as the complete knowledge case. As networks will typically have wire lengths to be a small percentage of the diameter of the network, we can restrict knowledge of wires to a minimum of 2 hops without performance degradation.

6. Future Work

The focus of this paper has been on path length reduction. A lot of work needs to be done to understand the application of short cuts to solving other problems.

Possible extensions to this work include:

• *Energy balancing* and *data extraction*: In sensor networks, the data gathered is transmitted via wireless transmission towards the sink. This means that the nodes close to the sink are heavily involved in packet forwarding and thus they can lose energy very rapidly. This can finally lead to the sink being partitioned from the rest of the network when all the nodes close to the sink have died, thus rendering the network useless. One solution of the problem has been suggested in [11]. A variant of the above problem is the data extraction problem [15]. In this, the sensors do not transmit their data continuously, but gather all their data and send it in one short 'en masse'. In such a case, the problem becomes of maximizing the data extracted from the network. For both of the above cases, short cuts can be used to distribute the forwarding done by the wireless nodes between nodes far away and close to the sink. This can lead to energy balancing between nodes close to the sink and far way from it. We plan to study the use of short cuts for such applications in the future.

• *Mobile sinks and sensors on wire*: Mobility has not been considered in this work yet. This is because most sensor networks, once deployed, are non-mobile. The NIMS project has introduced the concept of limited mobility in sensor networks by having mobile robots on cables. We plan to extend our work to address mobility in the future. We plan to consider both scenarios – limited mobility of the sensors and mobile sinks.

7. Conclusions

In this paper we have investigated a new paradigm for sensor networks. The paradigm uses wires in location aware sensor networks with a sink for achieving path length reduction. We have developed analytical models to analyze the average path length reduction for arbitrary position of the sink for differing lengths of the wire. The analytical results show that for any position of the sink, there is an optimal wire length for which the path length ratio is at its minimum, beyond which it *increases*. Further, for the sink placed at the center, this occurs for a wire length which is a small fraction of the network diameter (37.8 %). Simulations results show that the maximum reduction in average path length that can be obtained is 70 % for the sink placed at the center and is around 60 % for the sink placed at the edge of the network. The length of wire for significant reduction is higher when the sink placed at the edge. The maximum reduction is achieved with 24 wires when the sink is placed at the center. For the same experiment, 5 wires give near saturation results for the sink placed at the edge. Thus results show that we need more number of wires for the center than the edge, but the length of the wire required for significant reduction is much larger for the sink positioned at the edge. We have also investigated the effect of restricting the knowledge of the wires. Restricting the knowledge of the wire to 2 hops does not result in deterioration of performance for small wire lengths (less than 40 % of the radius). At wire lengths close to the radius of the topology, restricting the knowledge does show a decrease in performance. The model developed in this paper can be applied to investigating other issues in sensor networks like the data extraction problem. To our knowledge no previous work has addressed these issues of using wires in sensor networks.

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