Efficient Delivery of Information in Sensor Networks Using Smart Antennas

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Abstract. In this work we present a new routing protocol for sensor networks that utilizes smart antennas to propagate information about a sensed event towards a receiving center. Our protocol is suited for those cases where unexpected changes to the environment must be propagated quickly back to the base station without the use of complicated protocols that may deplete the network from its resources. The novelty of our approach lies in the fact that our protocol uses only local information and total absence of coordination between sensors; during a simple initialization phase each node uses the beam that lies towards the direction of the base station to transmit data and the beam lying on the opposite side of the plane to receive data. We provide detailed experimental analysis that demonstrates the feasibility of this approach, the necessity of using smart antennas in sensor networks and the advantages that are presented to communications due to their use. In particular, we demonstrate that sensed data are propagated by activating only the sensors that lie very close to the optimal path between the source of the event and the destination, resulting in low activation of the network's sensors. Furthermore, our protocol is very easy to implement and more importantly it is scalable as it remains independent of network size.

1 Introduction

Sensor networks [1, 2] have attracted much scientific interest during the past few years. Networks of thousands of sensors may represent an economical solution to some challenging problems: real-time traffic monitoring, building safety monitoring, wildlife monitoring, fire sensing, movement tracking, etc. These networks differ from wireless ad hoc networks in that their nodes are more energy constrained; nodes employed in sensor networks are characterized by limited resources such as storage, computational and communication capabilities. The power of sensor networks, however, lies exactly in the fact that their nodes are so small and cheap to build that a large number of them can be used to cover an extended geographical area, gather information in-site and process it in parallel enabling an accurate and reliable monitoring process. And is exactly this data delivery aspect that is the most common characteristic of sensor networks. Data, dynamically acquired from the environment, travel through the network towards some base station, offering low-latency real-time information that was previously hard or infeasible to get.

There are basically three types of schemes [3] concerning data delivery: continuous, event driven and observer-initiated. According to the first one, sensor nodes send their measurement to the base station at a specified rate, while in the event-driven model nodes send the measured data to the base station whenever they detect some type of activity that is worth reporting. In the observer-initiated scheme, the base station itself issues queries to any node in the network or to all nodes within a specific area, resulting in sensors collecting data and sending them back to the base station. Due to the limited resources available to nodes however, expensive routing protocols, costly flooding mechanisms, or complex algorithms that don't scale to large number of nodes cannot be used. Furthermore, random distribution of nodes in the physical environment, node failure probability during their deployment and dynamic change of nodes' power supply make the design of communication protocols a very challenging task.

Here we focus on the efficient propagation of a sensed event towards some receiving center, assuming an event-driven data delivery model. The need for communication between a regular sensor (the *source*) and some base station (called the *destination* or the *sink*) can arise at any time, possibly triggered by unexpected changes in the environment. It is exactly this change in the environment (a fire, a person entering a restricted area, etc.) that we feel it is important to reach the base station as quickly as possible without of course depleting the network from its resources through the use of complicated protocols. So, our focus is the design of localized algorithms where nodes collaborating with their neighbors achieve a *global objective*, that of delivering measured data to the base station.

In this paper we consider the use of smart antenna systems in order to achieve reliable and efficient data delivery in wireless sensor networks. Smart antennas in general have been for long considered unsuitable for integration in wireless sensor nodes. They consist of more than one antenna element and therefore require a larger amount of space than traditional antennas. In addition to that, processing of more than one signal requires more computational power and electronics that translate radio frequency signals to baseband signals suitable for processing. In this paper, however, we show that the use of smart antennas in sensor networks is in some cases obligatory and in other cases achievable, with minimal additional cost.

The rest of the paper is organized as follows. In Section 2 we examine the ability of sensor nodes to integrate smart antenna systems and the benefits of using such schemes in wireless ad-hoc communications. Is Section 3 we present the proposed routing algorithm that utilizes smart antenna systems, and in Section 4 we present the benefits of using this algorithm in the network layer of the sensor network. Finally we conclude our work and present directions for future research in Section 5.

2 Applying Smart Antennas in Sensor Networks

The aim for the future is to create sensor nodes (a.k.a. smart dust) that measure no more than 1 cubic millimeter in volume [4]. Sensor node architectures are currently advancing towards meeting these requirements [5]. In order to achieve efficient wireless communication in smart dust dimensions, one of two wireless mediums must be used: optics or radio frequency (RF).

Optical wireless is a promising technology for wireless communications. The dimensions of light emitting diodes (LEDs) and laser-diodes have reached sub-millimeter levels, and micro electromechanical systems (MEMS) technology has enabled these devices to be implemented with very low cost. Optical wireless is considered an optimal solution for certain sensor network environments. In in-flight sensor nodes, for example, communication is achieved using LEDs or laser beams that have large directivity even when diffused infrared (DI) methods are used. Using on-off-keyed signals to achieve omni-directional (OD) coverage, multiple infrared sensors and actuators are deployed inside sensor nodes. Steering and switching among directed beams is performed to find the best beam possible. In essence, these optical wireless transceivers are switched beam smart antennas that ensure OD coverage. Unfortunately, the main drawback of these optical wireless technologies is that optical communications are greatly affected by the environment. Oftentimes ambient lighting conditions produce interference and connections are cut abruptly when line of sight (LOS) signals are disrupted.

Furthermore, the use of narrow fixed beams in nodes that are randomly distributed in a certain geographical area does not provide the necessary connectivity to achieve data propagation through the network [6]. For example, after extensive simulations we have seen that using a simple flooding mechanism and directional beams with 60 degrees width the packet delivery ratio (PDR) does not surpass 40%, while the use of omni-directional antennas achieves 100% probability of delivery.

Radio frequencies are widely used for wireless communications in current sensor networks. RF presents several advantages with respect to other transmission techniques in terms of range, coverage, and power efficiency. Current implementations of sensor nodes use a single OD antenna to achieve coverage. It can be argued that smart antennas are not suitable for sensor nodes since they consist of more than one element and are therefore larger. However, when we refer to sensor nodes, we refer to three-dimensional structures. If a single- or two-dimensional half or quarter of a wavelength antenna can fit in a sensor node then more than one of these antennas should be able to fit into a three-dimensional node. In addition, inter-element spacing of a half or quarter wavelength between antennas should be possible (details omitted here). Since more than one antenna can fit in the same three-dimensional space, provision for patterns with larger directivity is possible.

The use of smart antennas in sensor nodes is not only feasible, but also highly desirable. As sensor node dimensions shrink, RF communication will be forced to utilize higher frequencies. Fundamental theory states, however, that transmission using higher frequencies results in lower effective communication ranges. To compensate for distance loss, higher gains have to be achieved. Increased gains, which can be attained using smart antennas, are necessary to preserve connectivity in networks and efficiently use a sensor node's energy source. The advantages of using smart antennas in ad-hoc communications has been demonstrated using small-scale and large-scale fading models in [7] where improvements of 20dB in received signal to noise ratio (SNR) can be realized and the bit error rate can be reduced by more than 60%. Moreover, the use of smart antennas can significantly decrease the nodes' power consumption, and therefore increase their lifecycle. Consider for example the log-distance large-scale model for the channel path loss,

$$P_r = P_t G_r G_t \left(\frac{\lambda}{4\pi} \right)^2 \frac{1}{d^n}, \tag{1}$$

where where G_r and G_t are the antenna gains of the receiver and the transmitter respectively, P_r and P_t are the corresponding signal powers, λ is the wavelength of the electromagnetic signal, d is the distance between receiver and transmitter and n (typically between 1.7 and 6) is the power loss exponent of the channel.

Using smart antennas with higher gain than omni-directional antennas, the range of each node increases by

$$R_{dir} = R_{omni} \sqrt[n]{\left(\frac{G_{dir}}{G_{omni}} \right)^2}, \tag{2}$$

where R_{omni} and R_{dir} are the ranges achieved by omni-directional and smart antennas respectively, and G_{omni} and G_{dir} are the corresponding gains. Assuming switched beam antennas with perfect sectorization, then $G_{dir}/G_{omni} \approx 360/BW$. Additionally, if we want to cover the same range using smart antennas, the transmission power of each node will be reduced to,

$$P_{t_{dir}} = P_{t_{omni}} \left(\frac{G_{omni}}{G_{dir}} \right)^2, \tag{3}$$

regardless of the channel model's power ratio. For example, if both the transmitter and the receiver of a communication link use appropriately oriented antennas with 180 degrees beamwidth (BW), then the total transmit power needed for communication is equal to a quarter of the power that omni-directional antennas would need.

In the following sections we show the improvements in the performance of the network and how routing in sensor networks can be accomplished with minimal computations and power consumption when the proposed use of smart antennas is imposed.

3 Overview of Routing Protocols and our Proposal

The problem of how to route data has been the subject of intense study in wireless sensor networks. Since these networks resemble mobile ad-hoc networks so closely, several MANET protocols have already been proposed for deployment. Popular routing solutions in such networks are DSDV [8], DSR [9], AODV [10] and TORA [11]. These protocols, however, are designed for networks with ID-based node addressing and are not considered efficient for sensor networks. A nice alternative constitutes attribute-based routing, where the final destination is identified by attributes such as location or sensor measurements. Sensor Protocols for Information via Negotiation (SPIN) [12] and Directed Diffusion [13] are two examples of attribute-based routing. In contrast with flat networks, hierarchical networks use clustering approaches to organize nodes into various levels of responsibilities. Then cluster-heads are selected to play the role of the coordinator of the other nodes in their clusters. LEACH (Low-Energy Adaptive Clustering Hierarchy) [14] and TTDD (Tow-Tier Data Dissemination) [15] are two such examples.

This abundance of routing protocols (of course the above list is by no means complete) suggests that efficient routing attempts to optimize a variety of different measures including efficiency, robustness, number of activated particles, etc. In our setting, however, where sensed data need to be sent to a receiving center, these approaches seem to overload the sensors' processors with unnecessary computations, as we only need to send a single message or packet back to the base station. Taking into account the small communication throughput and the limited memory and computational capabilities of sensor networks a simple flooding approach seems to be the best alternative.

Flooding is the most computationally efficient protocol due to its computational simplicity as every node broadcasts every new incoming packet. Therefore, data are bound to reach their destination, assuring correctness, and the protocol is immune to node failures, assuring robustness. Although this protocol can be integrated even in the most simplistic implementations of sensor nodes, it is extremely energy consuming as all nodes must receive and transmit the message at least once. Gossiping or wandering approaches [16] seem to alleviate this problem, at the cost, however, of increasing path lengths or failing to reach destination.

In this work we propose a new family of protocols that try maximizing efficiency and minimizing energy consumption by favoring certain paths of local data transmission towards the sink by using switched beam antennas at the nodes. Just like flooding, the protocol is very easy to be implemented as it only requires nodes to forward every new incoming packet. Unlike flooding however, it avoids depleting the network from its resources by restricting the nodes that receive and hence retransmit the message with the use of switched beam antennas.

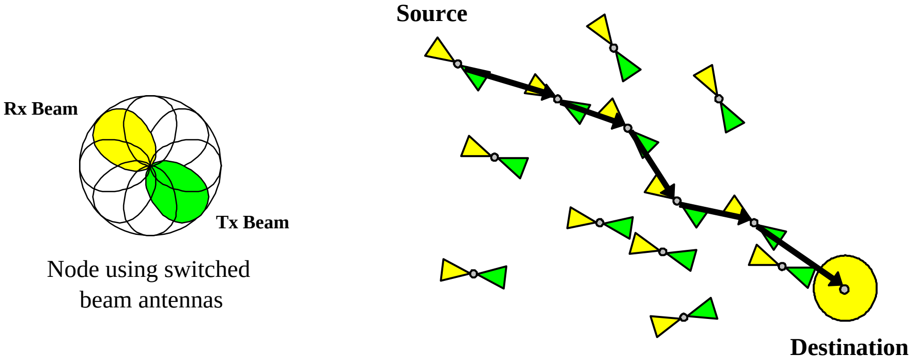


Fig. 1: Conceptual representation of the proposed protocol. All nodes have their transmit beams oriented towards the direction of the destination

Our proposal

The mechanism that controls this propagation of information is the following; during the initialization phase of the network, the base station transmits a beacon frame with adequate power to be able to reach all the network's nodes. A conceptual representation of the proposed protocol is shown in Figure 1. Each node switches among its diverse beams and finds the one that delivers the best signal. After the initialization phase, the nodes will use this beam only for transmitting data, and they will use the beam lying on the opposite side of the plane only for receiving data. During normal operation, nodes retransmit every new incoming packet that has not received before. As it might be expected the protocol is highly dependent on the antenna beam-width (BW). By carefully selecting the appropriate beam-width one obtains a tradeoff between robustness (the fraction of times the message reaches the destination) and load incurred in the network (measured in terms of overall power consumption in the network). This is demonstrated in the following section.

4 Experimental Validation

In order to analyze the performance of the algorithm described above, we performed a set of large scale experiments whose goal was to test the protocol's effectiveness under the following measures:

1. *Success of delivery*: Messages should be delivered to the destination with high probability.
2. *Low activation of sensors*: A small number (compared to the total number) of nodes must be activated for each data transmission towards the sink.

3. *Power efficiency*: The overall network power consumption should be as small as possible. Although the number of activated nodes is a good measure it is not sufficient for our implementation since in the case of smart antennas the energy spent for receiving a packet is larger than that of transmitting one.
4. *Robustness under node failures*: The protocol should be able to deliver data to the destination, even when a large number of nodes is not responding. Here we analyze the protocol by incurring a failure or death probability on every sensor before the execution of the protocol.
5. *Scalability*: The performance of the routing algorithm should be independent of network size.
6. *Simplicity*: Any routing algorithm that is deployed in sensor networks must be able to run in an 8-bit microprocessor, with minimal data memory (i.e. 4Kbytes).

4.1 A probabilistic variant of the protocol

The protocol described in the previous section is deterministic. This means that transmissions from the same source activate exactly the same set of nodes resulting in depletion of their energy. A way to reduce the utilization of the same sensors is to make the protocol probabilistic. A simple probabilistic variant is one where a sensor will retransmit a packet with probability depending on the power of the received signal. The closer this node is to a transmitting node, the greater the power of the received signal will be and hence the smaller the probability of retransmission. The intuition here is that nodes that are far from the sensor that is currently transmitting will retransmit with higher probability and hence information will reach the base station by using fewer nodes, and fewer hops. Hence the number of activated nodes will be reduced as well.

It should be noted that this new protocol uses *no distance* information (however, as we will show below the probability of retransmission is ultimately related to the distance of the receiver). At the receiver, the received signal strength varies from a maximum value $P_{r_{max}}$ to a minimum value $P_{r_{min}}$. These values depend on the sensitivity and the dynamic range of the receiver. According to the proposed protocol, the probability of retransmitting a received packet depends on the received signal strength. Therefore, when the received signal strength is close to $P_{r_{max}}$ then the probability of retransmitting the packet, $\Pr[Retransmit]$, will be close to zero. On the other hand, when the received signal strength is close to $\Pr_{r_{min}}$, $\Pr[Retransmit]$ will be close to 1. In general, the probability of retransmitting the packet will vary linearly between these limits, depending on the received signal strength according to the equation

$$\Pr[Retransmit] = 1 - \frac{P_r - P_{r_{min}}}{P_{r_{max}} - P_{r_{min}}}, \tag{4}$$

where P_r is the received power measured at the receiver, and all values are measured in dB.

It turns out that the proposed probabilistic protocol is highly depended on the distance between the transmitter and the receiver of a single packet, and on the path loss power exponent. According to Equation (1) and assuming that $P_{r_{min}}$ is received at the maximum range R of a sensor node, then

$$P_{r_{min}} = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{R^n}. \tag{5}$$

From Equations (1), (4) and (5) it is evident that the probability of retransmitting a packet is equal to

$$\Pr[Retransmit] \propto \left(\frac{d}{R}\right)^n. \tag{6}$$

Thus the probability depends on the distance d between the transmitting and receiving station and on the path loss power exponent n. According to [17], n depends on the specific environment that the sensor network is deployed in, and it takes values between 1.9 and 5.4. For our simulations, we have chosen a characteristic value of $n = 3.3$, which is common for outdoor environments.

In the rest of the paper we will study the behavior of this probabilistic protocol under the metrics that were mentioned in the beginning of this section.

4.2 Invariance under network size

It is obvious that the proposed protocol is extremely simple. Furthermore as it is demonstrated in Figure 2 it is scalable as its performance does not depend on network size but only on the average number of neighbors of each node. In this figure the activation and success ratios are shown as a function of the beamwidth for different network sizes ($N = 2500$, 5000 and 10000 nodes) provided the density (average number of neighbors μ) of each sensor remains the same, in this case $\mu = 10$, 25 and 50. As it can be clearly seen there is a very close match that essentially makes the behavior of the algorithm independent of network size.

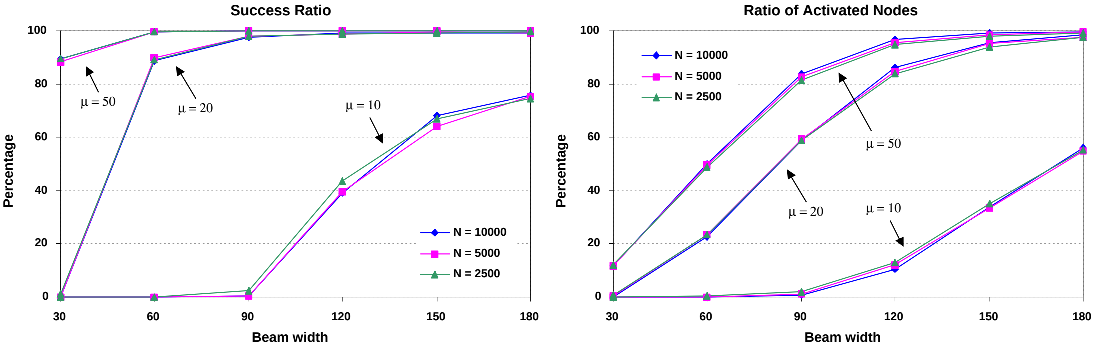


Fig. 2: Invariance under network size

Therefore, we will concentrate on proving the proposed protocol's power efficiency and effectiveness to reach destination. The effectiveness of the protocol is measured by the ratio of times the propagated event reached the sink while its efficiency is computed with respect to the number of activated nodes and the overall network power consumption. This last information is computed taking into account that a sensor's energy consumption depends on its communication range, its beamwidth, and the total number of packets it receives. Finally, as a case study, we compare the energy efficiency of our protocol against flooding and we show that the use of smart antennas can result in great savings. In order to evaluate our results, we used the sensor node model described in [18], which for completeness we present in Table 1.

Transmitter range:	1 to 10 m
Energy used	for reception: 30 nJ/bit
	for transmission: 20 nJ/bit + 1 pJ/bit/m^3
Packet sizes:	256 bits

Table 1: Node energy consumption model

Since we will also compare the proposed algorithm to the flooding mechanism that uses omni-directional antennas, the large-scale power model of Equations (1-3) can be used. According to Equation (3), the total power savings with respect to using omni-directional antennas at the nodes does not depend on the center frequency of the carrier signal or the path loss exponent of the channel. Therefore, the results of our simulations can be applied in all sensor network scenarios and for all wireless sensor node implementations that utilize a carrier frequency inside the RF or optical frequency spectrum.

We used the following setup for our experiments: $N = 10000$ sensors were spread uniformly at random in a square field of $10000m^2$, where all sensors have the same communication range R and switched beam antenna beam-width BW. We assume perfect sectorization of the beams and the same beam-width for transmit and receive beams. For each simulation run we choose the sensor with the smallest $x - y$ coordinates to be the source and the sensor with the largest $x - y$ coordinates to be the sink. In order to obtain valid statistical results all experiments were repeated a 1000 times. A typical run for $R = 3.5m$ and $BW = 30$ is shown in Figure 3.

4.3 Effectiveness

Figure 4 shows the success delivery ratio and activation percentage, when different ranges and different beam-widths are used. To have a reference measure, we include the correspondence between transmission range and average number of neighbors per node in the table that follows:

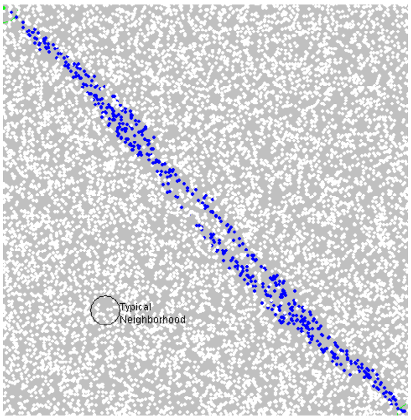
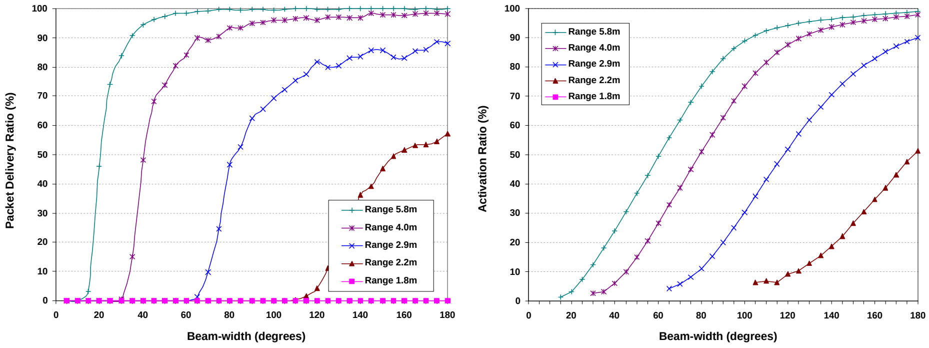


Fig. 3: Routing example for $N = 10000$, $R = 3.5m$ and $BW = 30$. Darker dots (blue) correspond to activated nodes (less than 5% in this case).

Range (in meters)	**Average Density μ**
1.8	10
2.2	15
2.9	25
4.0	50
5.8	100

In Figure 4(a) we see that the success ratio obeys a *threshold behavior*. So, for example, when $R = 5.8$ and $BW = 30$ the success probability is about 85% but when the beam-width BW is 15, the success probability drops to zero. And the same behavior may be observed for all values of R. It is also obvious from this figure that the larger the communication range (or average number of neighbors) is the better the success probability becomes for any given beam width. Hence if we want to achieve a success ratio of 90%, we can either choose a BW of about 180 degrees when $R = 2.9$, a BW of 70 when $R = 4.0$, or a BW of 35 when $R = 5.8$. So, one may ask: are all these settings equivalent? The answer of course depends on the number of activated sensors which is shown on Figure 4(b).

It can be seen in Figure 4(b) that given a specific range, the smaller the beam width is the lower the activation of sensors becomes. For example, to achieve a success ratio of 90% we see that we need about 90% of the sensors to be activated when R=2.9, while at R=5.8 less than 20% is activated to achieve the same result. However, one must be careful not to conclude from this figure that only antennas with small beam width and large transmission range should be used. For this conclusion to be valid, one must also take into account the power needed in order to transmit to a higher distance using a focused beam. This is something we do in a subsequent section.



(a) (b)

Fig. 4: (a) Success delivery ratio of proposed protocol. (b) Percentage of activated nodes

4.4 Robustness under Failures

We also investigated the fault-tolerance nature of our protocol when sensors die with various probabilities. The invariance of our algorithm under changes in the network size suggests the following approach: when we know that sensors may die with certain probability we can either plant more nodes or increase the communication range slightly to counteract the effect of dead nodes. In any case, using the results of Figure 4, we can optimize the algorithm's performance and obtain the required robustness.

4.5 Power Efficiency

To compute the power consumption of the network, we apply Equations (1-3) to the node model of Table 1 and show the results on Figure 5. In general, we observe that for narrow beam-widths and large transmission ranges, the total power that is consumed by the network in order to deliver a single packet is very small compared to using small transmission ranges and wide beam-widths. However, when we are allowed to work with antennas of fixed beam width then it is better to have a smaller transmission range. So for example when we restrict the beam-width to 80 degrees then in order to achieve packet delivery ratio (PDR)$>$ 90% it makes sense to use a system that transmits at a range of $4.0m$ and not further.

Finally, Figure 6 shows that the power consumed by the network when the proposed algorithm is used is much smaller than that of flooding. The main reason for the evident power efficiency of the proposed algorithm is caused by the small number of nodes that are activated in the network compared to the total number of nodes that are transmitting when flooding is used. Moreover, due to the use of highly directional antennas, the total number of received messages is reduced, and therefore the total number of activated receivers is highly reduced

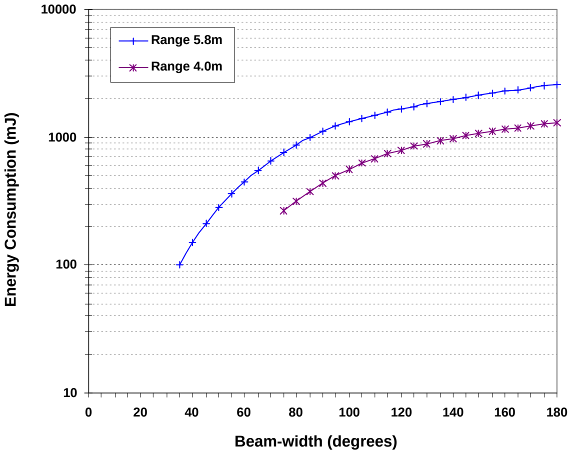


Fig. 5: Total network power consumption (mJ) in order to achieve PDR>90%

as shown in Figure 7. Since, according to Table 1, the energy cost of transmitting a packet is comparable to that of receiving, the total energy consumed by the network using the proposed algorithm can be up to two orders of magnitude less than that of omni-directional flooding.

5 Conclusions and Future Research

In this work we have presented a routing algorithm for sensor networks that utilizes smart antenna systems, where sensed data is sent to a receiving center using only local information and total absence of coordination between sensors. Due to the novelty of our proposal we pointed out the feasibility and necessity of using smart antennas in sensor networks, as well as the advantages that are presented to communication links due to their use. Our protocol is suited for those cases where unexpected changes to the environment (i.e. a fire, a person entering a restricted area, etc.) must be propagated quickly back to the base station without the use of complicated protocols that may deplete the network from its resources. Our protocol is very easy to implement as nodes do not have to decide whether or not to forward the message. The protocol ensures packet delivery and low energy consumption solely with the use of smart antenna systems on sensor nodes.

We plan to continue this line of research by also considering “random” paths (not necessarily optimal) so that data is propagated to the destination. “Randomness” could be applied in the choice of the node beam direction, the transmission power, or the node antenna’s beam-width (i.e with the use of variable gain switched beam antennas, like in [7]). Finally, mobility of sensors should be

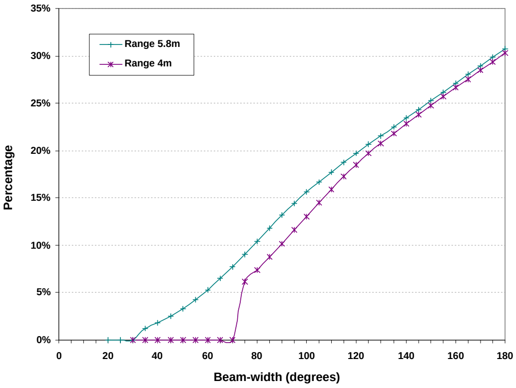


Fig. 6: Total network power consumption (%) with respect to flooding for PDR>90%

considered, so that networks using robotic sensors could be accounted for in the future. Of course, for this to be of any value, the protocol must again use only local information and no coordination between sensors.

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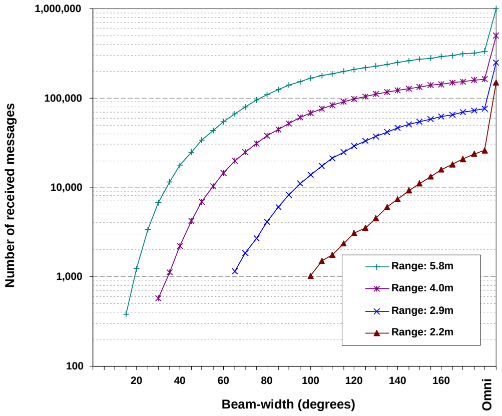

Fig. 7: Number of total received messages for the proposed algorithm and for flooding (Omni)

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