BeamStar: A New Low-cost Data Routing Protocol for Wireless Sensor Networks

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Abstract— **Deployment of large-scale sensor networks calls for low-cost sensors and energy efficient routing schemes. The recent advances in light-weight Operating Systems, VLSI technologies, and wireless communications have greatly reduced the size and cost of wireless sensor devices. However, delivering sensed data to base stations, both reliably and energy-efficiently, is still a challenging problem. Scalable, energy-efficient, and error-resilient routing schemes are needed for such networks, with minimum requirements on sensor nodes. In this paper, we present a base station-assisted, location-aware routing protocol, which we call BeamStar, for wireless sensor networks. We make a major paradigm change by shifting computational intensive and energy consuming routing control overhead from sensor nodes to base stations. In BeamStar, each base station uses a *directional antenna* with *power control*. We show that these two capabilities are sufficient for each sensor node to determine its location, and the local location information is sufficient for power-efficient routing. Therefore, sensors are relieved of control and routing burdens, such as maintaining clusters and exchanging control information, yielding substantial energy savings. In addition, each data packet is forwarded in a constrained, loop-free mesh towards the base station, making data delivery robust to sensor failures and transmission errors. The proposed routing scheme is suitable for large-scale, dense sensor networks monitoring rare events.**

I. INTRODUCTION

Sensors are special devices used to monitor environmental parameters (such as humidity and temperature) or some special events (such as the motion of a target object) in a sensed field. Generally, sensors perform two types of operations: sensing and communicating observed phenomena home. Networked sensors are widely used in various scenarios, such as monitoring seismic structure response, marine microorganisms, contaminant transport, ecosystems, and battlefields.

Wireless sensor networks, in which each sensor is equipped with wireless transeivers, are especially useful when infrastructure is unavailable. The recent advances in light-weight Operating Systems, VLSI technologies, and wireless communications have greatly reduced the size and cost of wireless sensor devices. Therefore, it is possible to deploy large-scale, dense wireless sensor networks to provide spacially and timely dense environmental monitoring. On the other hand, delivering sensed data to base stations both reliably and energy-efficiently is still a challenging problem attracting tremendous research efforts [1]. The following characteristics are desirable for a routing protocol designed for such networks:

- Scalability: routing protocols should perform well as the network size grows.
- Low complexity: routing algorithms should be simple, i.e., with minimum processing and storage requirements, since sensors generally have very limited computational capabilities and memories.
- Energy-efficiency: sensors are usually powered by batteries, while recharging is not feasible. In order to extend the lifetime of the sensors (and thus the sensor network's lifetime), the routing protocol should be energy efficient.
- Error-resilience: wireless sensors are usually deployed in harsh environments (e.g., in the wildness), and are thus exposed to possible damages from, e.g., rain, snow, high or low temperature. In addition, wireless links in a wireless sensor network is fragile and error-prone. Therefore, an error-resilient routing protocol is desirable to ensure successful delivery of data packets.

In addition, the network topology changes when sensor nodes die or when new sensors are deployed. In this case, the network may need reconfiguration, requiring routing protocols be robust to such dynamic reconfigurations.

In this paper, we present a new low-cost routing protocol, called BeamStar, for wireless sensor networks. We take the above criteria as design goals. The proposed routing algorithm is based on the following observations. First, it would be desirable for a sensor to spend most of the energy on its two fundamental operations: sensing and data forwarding. In other words, the routing protocol should have minimum control overhead on the sensors for an extended network lifetime. Second, there is an asymmetry in the capability and available resources in sensor nodes and base stations. It would be desirable to shift the burden of network control and management to resource-abundant and more sophisticate base stations, while keeping sensor nodes as simple as possible. Consequently, we take a totally different design philosophy from previous work, by shifting control and management functionalities to base stations and relieving sensor nodes with such burden. In BeamStar, a base station scans the network using a power controlled directional antenna. The distance of a sensor to the base station can be uniquely determined by the power level used for a received control message, while the relative angle of the sensor to the base station is determined by the direction of the base station transmission. We show that such location information suffices efficient routing of sensor data. More specifically, the proposed protocol consists of the

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following two key components:

- Base station-assisted location discovery: in BeamStar, each sensor needs to find out its location. Rather than resorting to Global Positioning System (GPS) devices and exchanging location information distributedly as in many existing location-based protocols [2]–[6], location discovery is performed in a centralized manner in BeamStar, where *base stations performs power-controlled scan of the sensor network using a directional antenna, and sensors infer their locations from received control messages sent by the base station*. Therefore, the burden of location discovery is shifted from resource/capability constrained sensors to resource-abundant, more sophisticate base stations.
- Location-aware data forwarding: the location information suffices efficient routing of data packets. After receiving a data packet, each sensor simply examines the value of several header fields, then either drops or rebroadcasts the packet. *The forwarding decision is based on location information set by the base station*. Therefore, there is no need for maintaining a location table [2] or a routing table [7] in every sensor node. In BeamStar, packets are forwarded towards the base station via *multiple paths*. The redundancy in packet forwarding ensures reliable delivery of data packets.

The proposed protocol allows extremely simple sensor designs, such as microsensors or even nanosensors, since all the control functionalities are implemented on base stations. In BeamStar, there is no need to exchange location, control, and routing messages among sensors. During the configuration phase, a sensor only needs to receive one or more control messages from the base station. Therefore, almost all energy is spent on the two key essential functions: sensing and forwarding sensed data. Furthermore, data packets are relayed only by those sensor nodes within the same sector toward the base station and will not involve sensor nodes in other sectors. This will help conserve substantial energy in the network and thus prolong network lifetime. Therefore, BeamStar is a *power-efficient* routing protocol. In addition, the routing scheme is also *error-resilient*, since each data packet may be forwarded along multiple paths, yielding a better chance of successful delivery.

Due to the page limit, we present the BeamStar protocol in this paper, while the performance studies will be presented in a sequel paper. The rest of this paper is organized as follows. We present the proposed routing protocol in Section II. Practical considerations and extensions of BeamStar are discussed in Section III. We discuss related work in Section IV. Section V concludes the paper.

II. THE BEAMSTAR ROUTING PROTOCOL

Consider a large-scale, dense sensor network consisting of thousand or even millions of sensors over a wide region sensing, e.g., chemical and biological agents. Assume that each sensor node is equipped with an inexpensive omni-directional antenna with a short transmission range. Should there be an event, the sensor data must be quickly relayed to the base station along the sensor network cloud.

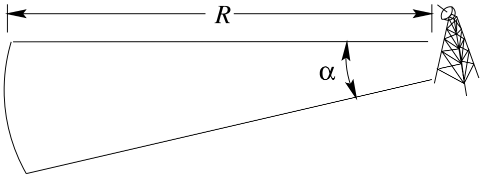

Fig. 1. A sector made by a power-controlled direction antenna transmission.

In the following, we present the two key components of the proposed routing protocol designed for large-scale, dense sensor networks.

A. Base Station-Assisted Location Discovery

For such large scale sensor networks, a fully-distributed routing algorithm, although technically correct, may result in substantial power consumption to perform control functions (e.g., message exchanges to build up and maintain routing tables), or high requirements on the sensor node design (e.g., CPU, memory, energy, or GPS devices), which may not be optimal in terms of energy efficiency, cost, and scalability. Although hierarchical or cluster-based routing schemes are efficient in achieving scalability, the non-trivial overhead in maintaining the hierarchy in traditional clustering schemes should be minimized in order to apply such schemes in large scale, dense sensor networks.

Our approach in this paper is to explore potential infrastructure support by the base station to perform intelligent location discovery. This is a major departure from existing location-based routing approaches, which may require considerable communication overhead or GPS devices. In particular, we assume that the base station is not energy constrained and is equipped with a *directional antenna* with *power control* capability. With this scheme, the covered area of each base station transmission is a sector, as illustrated in Fig. 1. The radius of the sector, R, is determined by the transmission power, while the span of the sector, α, is determined by the beamwidth of the directional antenna. To determine the relative position of a node (or group of nodes) to the base station, the base station scans the entire sensed region using different power levels. In other words, the base station sends control messages containing the current directionality information (indicating the relative direction toward the base station) and the transmission power level (indicating the relative distance toward the base station) to each direction multiple times, each with a different power level. A node's location is thus determined by the directionality of the last base station transmission (called *Sector Number* (SN)), as well as the lowest power level information that it can receive from the base station (called *Ring Number* (RN)). We therefore define the ID of a sensor to be the combination of its RN and SN, i.e., $\{SN, RN\}$.

Control messages broadcasted by the base station can have a format as that shown in Fig. 2. The *BaseID* field carries

BaseID	SN	RN	InitSeqNumber	Other control information

Fig. 2. The packet format of a control message from the base station.

the identifier of the base station, which will be useful when multiple base stations are used (see Section III). The *SN* field carries the index associated with the direction of the current transmission, while *RN* is the index associated with the current transmission power. The following field $InitSeqNumber$ provides the flexibility to set different initial sequence numbers for sensors in different locations. Additional control information can also be carried in the packet. When a sensor k receives multiple control messages (see Fig. 3), it chooses its Sector Number (SN_k) and Ring Number (RN_k) according to:

$$\begin{cases} SN_k = \max_{i\in\{\text{rcvd ctrl msgs}\}}\{SN_i\} \\ RN_k = \min_{i\in\{\text{rcvd ctrl msgs}\}}\{RN_i\} \end{cases} \tag{1}$$

Such a base station assisted location discovery process is illustrated in Fig. 3. As shown in Fig. 3(a), we have one base station serving as the sink node for the entire network. By employing power control and tuning the phase angle of the directional antenna at the base station, we can imagine that the network is logically partitioned into regions. To identify the location of a region in the network, in Fig. 3(b), the base station transmit to the first region (shaded area), by adjusting its phase angle, beamwidth, and transmission power. During this transmission, the directional antenna broadcasts a message with $\{SN, RN\} = \{1, 1\}$, to all nodes within this region. Subsequently, in Fig. 3(c), the base station adjusts the power level of its directional antenna to the next higher level and broadcasts a message with location information $\{SN, RN\} = \{1, 2\}$. Those sensor nodes that have acquired ID $\{1, 1\}$ from the earlier scan will not change their ID, since through simple comparison, they can determine that a smaller ring number received earlier represents its geographical location (see Eq. (1)). All other nodes covered by the transmission but without location information will store this ID, i.e., $\{SN, RN\} = \{1, 2\}$, to represent their geographical locations. Figure 3(d) shows the case for a subsequent antenna transmission with a higher power level and location information $\{SN, RN\} = \{1, 3\}$. Again, nodes with a smaller ring number obtained during earlier transmissions will not change their IDs, according to (1). Only those nodes without any location information will record this ID $\{1, 3\}$. Figures 3(e) and (f) show a similar process for the case with $SN = 2$ and RN changing from 1 to 2. By repeating power control (RN) and phase change (SN), all sensor nodes can derive their IDs (i.e., location information). Note that during this process, there is no need for each sensor node to exchange any information with its neighbors. The complexity on the control plane has been effectively shifted from each sensor node to the base station.

Note that BeamStar requires the entire sensor network be within the maximum transmission range of the base station, such that the sensors can be configured by the base station as shown by the example in Fig. 3. For sensor networks that expand vast areas, multiple base stations may be necessary to provide, possible overlapped, coverage for the sensor nodes (see Section III-D).

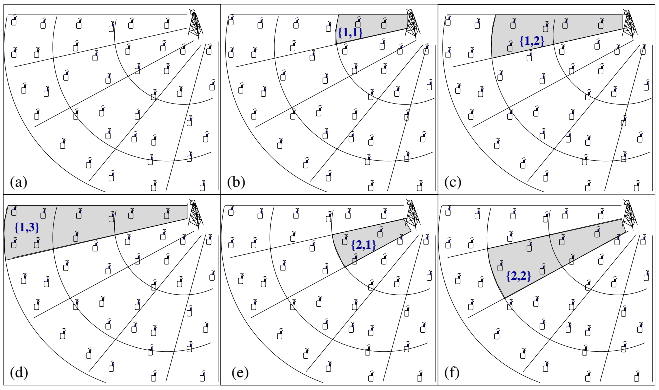

Fig. 3. An illustration of the base station-assisted location discovery process: (a) Logically partitioned regions; (b) The first transmission with $\{SN$=1, RN=1$\}$; (c) The second transmission with $\{SN$=1, RN=2$\}$; (d) The third transmission with $\{SN$=1, RN=3$\}$; (e) The fourth transmission with $\{SN$=2, RN=1$\}$; (f) The fifth transmission with $\{SN$=2, RN=2$\}$.

B. Location-Aware Data Forwarding

After the initialization phase, we now show that routing of sensor data packets can be implemented with minimum complexity. Since generally low-cost, short-range radio is used in the sensor nodes, it is necessary to use multi-hop routing for data packets. The format of a sensor data packet is shown in Fig. 4. The header fields are:

- $BaseID$: the identifier of the destination base station. This field is useful when multiple base stations are deployed, with possible overlapped coverage for certain regions in the network.
- $SourceLocID$: the location identifier, i.e., $\{RN, SN\}$, of the source sensor node.
- $LastRelayLocID$: the location identifier of the last sensor node that forwarded this data packet.
- $PacketSeqNumber$: the sequence number of the packet. It is set by the source sensor node when the packet is generated.

In order to avoid forwarding the same packet multiple times, each sensor maintains a *sequence number*. The initial sequence number is set by the base station during the initialization phase. The sequence number is set to each packet originated from this node and is increased by one for each data packet originated from the same region. Furthermore, each node also maintains a *sequence number table*, which stores the largest sequence number received from other regions. When a new data packet is received, the sensor examines the packet's $SourceLocID$ and compares the packet's $PacketSeqNumber$ with that in the sequence number table. If the packet has a $PacketSeqNumber$ larger than that in the table, the corresponding table entry is updated with the received $PacketSeqNumber$ and the packet will be forwarded. Otherwise, the packet is dropped.

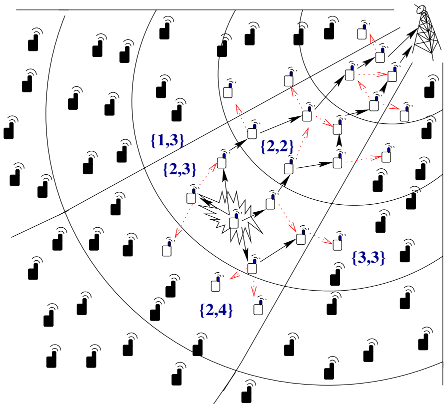

Fig. 5. An illustration of the location-aware data forwarding upon detection of an sensor event. Involved sensor nodes are in white.

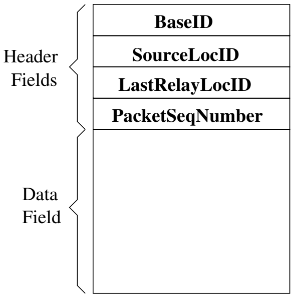

Fig. 4. The packet format of a sensor data packet.

We use the example in Fig. 5 to illustrate the packet routing process. Suppose that an event is detected by a sensor node in a region with ID $\{2, 3\}$. This sensor node will generate a data packet, set the sequence number field in the packet header, and then broadcast the data packet to its neighbors. Upon receiving this packet, the neighboring sensor nodes (with the same ID) will also increases their local sequence number and further broadcast the packet to their neighbors, until eventually, all nodes within this region receive this packet. Note that the use of sequence number ensures that each sensor node will broadcast this packet only once.

At the four boundaries of this region, only sensor nodes in the region with ID $\{2, 2\}$ will further relay this packet; packets received by the nodes in other three neighboring regions, i.e., regions with IDs $\{2, 4\}$, $\{1, 3\}$, and $\{3, 3\}$, will be dropped. This is due to the fact that relaying in these regions will not bring the packet closer to the base station. The forwarding decision is made with a simple comparison of the IDs of the current node and the last relay node (i.e., $LastRelayLocID$ in the received packet). Only sensor nodes in region $\{2, 2\}$ have an identical SN and a smaller RN, and will thus relay this packet toward the base station. By following this process of broadcast, reception, and drop or rebroadcast among the sensor nodes, the packet (or duplicate copies of the same packet) will be eventually delivered to the base station.

There are many advantages of using this routing scheme. First, the intermediate sensor nodes do not need to store a routing table or maintain flow-state related information. There is even no need for the sensors to discover their one-hop neighbor nodes. Each node operates in a purely stateless manner, using only local location information (i.e., its ID and sequence number table, which come from received packets for free). The operations and thus the requirement on the sensor node design are minimal, allowing low-end and low-cost sensors to be used. Second, the storage requirement is also minimal. With BeamStar, each node only needs to store its ID, sequence number, and a sequence number table, which suffice for efficient routing. Moreover, the size of the sequence number table is quite small, since the number of rows is upper-bounded by the total number of rings in the sector to which it belongs (or the number of power levels of the base station). Third, The routes to the base station are loop-free due to the use of sequence numbers and sensor IDs. Fourth, since every data packet is essentially forwarded by multiple nodes through different routes, multiple copies of the same data packet will be delivered to the base station. Such redundancy is necessary in wireless sensor networks where links are fragile and sensor nodes are vulnerable [8].

III. PRACTICAL IMPLICATIONS

In this section, we discuss practical considerations in implementing the proposed protocol. We also present possible extensions of BeamStar for a better performance.

A. *Wake Up On-Demand*

To further conserve energy, we can put the sensor nodes to a “sleep” state after the initialization phase, since in the idle mode, sensors may be as power hungry as in the receiving or even the transmitting mode [9] [10]. When there is need to receive or transmit data, the dual radio design in [9] can be used to awake a sleeping sensor. In order to return to the sleep mode when transmissions are over, each sensor starts a keep-alive timer when it wakes up, and refreshes the timer each time when a new data packet is received or transmitted. When the timer expires (i.e., no data packets received or transmitted during the last time window), the sensor goes to sleep again. The timer value can be set by base station during the initialization or a reconfiguration phase. This *wake up on-demand* scheme is especially useful for sensor networks that monitor rare events, where we can trade off latency for energy savings.

B. *Query for Events*

In many applications, it is necessary to allow the base station query the sensor network for certain events. This function can be easily supported by BeamStar. To query a specific region, the base station can adjust its direction according to the target SN_t, set its transmission power level according to the target RN_t, and then transmit a query message with the target ID $\{SN_t, RN_t\}$. By a simple comparison of the IDs, sensors in other regions will ignore this query, while sensors in the target region will generate responses and route them to the base station through multi-hop relays. In the case that the sensors are put to sleep for energy savings, the base station can wake up the sensors in the intermediate regions simultaneously before sending the query message, thus the response latency can be greatly reduced.

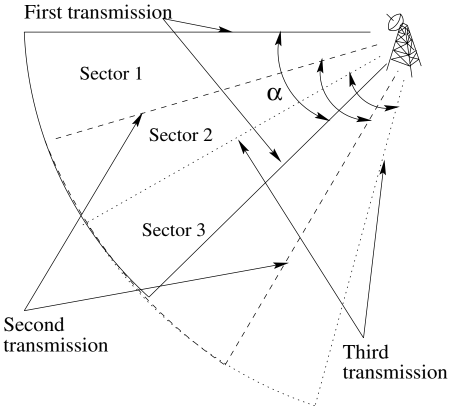

Fig. 6. An illustration of creating smaller sectors than the minimum angle of the directional antenna. With three overlapped transmissions, sectors with a $\alpha/3$ span are created, where α is the beamwidth of the directional antenna.

C. Creating Finer Regions

With the location discovery scheme described in Subsection II-A, regions get larger as ring number increases. Although larger regions make sensing data less precise, such imprecision is allowed by most of the sensor applications. Furthermore, this is justified by the so called *distance effect*: the farther an event is, the less important it is, and thus the less accurate sensing is allowed.

When higher sensing accuracy is necessary, the size of the regions can be reduced by choosing finer power levels and setting narrower beamwidths for the directional antenna of the base station. In addition, the overlapped scanning scheme shown in Fig. 6 allows creating sectors narrower than the minimum beamwidth of the directional antenna, in case that the minimum antenna beamwidth is still too coarse. Let the antenna beamwidth be α. In the example shown in Fig. 6, the base station makes three *overlapped* transmissions sequentially, by shifting its directional angle by $\alpha/3$ each time. Each sensor node, after receiving multiple control messages, uses Eq. (1) in selecting its SN. Then after the transmissions, three sectors each with a span of $\alpha/3$ will be created.

D. Deploying Multiple Base Stations

BeamStar can be easily extended to support multiple base stations in even larger sensor networks. The basic operation of the sensor nodes are the same as discussed before, with only a slightly increased storage requirement.

An example of a sensor network with two base stations is presented in Fig. 7. In this application scenario, the base stations perform their scans in turn. After the scans, two sets of overlapped regions are formed, as shown in Fig. 7(a) and 7(b), respectively. Every sensor node then is assigned with two IDs, each associated with one of the base stations. When a sensor detects an important event, it can simply choose the closer base station (by comparing the RNs of its two IDs) to forward the packet to. An intermediate sensor node, after receiving a data packet, will first check the $BaseID$ of the packet (set by the source node). Then, the node makes comparison and drop/forward decision using the ID and sequence number table associated with the chosen base station.

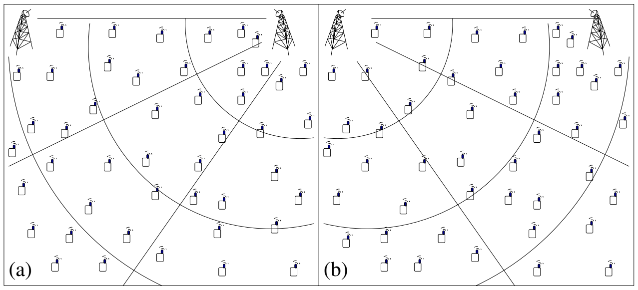

Fig. 7. Deploying two base stations, where the base stations take turns scanning the sensed field. (a) Regions formed by the base station in the upper right corner. (b) Regions formed by the base station in the upper left corner.

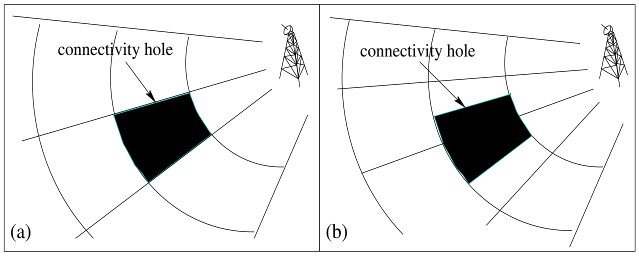

Fig. 8. Rescan the sensor network to bypass connectivity holes: (a) Region $\{2,2\}$ lost connectivity; (b) The new regions formed by a power-controlled direction antenna rescan, where connectivity is restored.

A refined scheme can also be applied in the multiple base station case, in order to balance the traffic load and energy consumption of the sensors. Suppose there are N base stations. With this scheme, the source sensor randomly chooses a base station i as destination with probability p_i defined as:

$$p_i = \frac{\frac{1}{RN_i}}{\sum_{k=1}^{N} \frac{1}{RN_k}}. \tag{2}$$

With (2), traffic generated by the source node is distributed among all the base stations in a fashion such that a closer base station is chosen with a higher probability.

E. Reallocation and Reorganization

When the sensor network is reorganized (e.g., old sensors are damaged or run out of energy) or reallocated (e.g., new sensors are deployed), or when the base station moves to a new location, the regions can be quickly reestablished by a new scanning process. On the other hand, the base station can scan the network and refresh the location information in the sensor nodes periodically. In particular, the base station can periodically query the region with the highest ring number in each sector in order to test connectivity within the sectors. When a sector loses connectivity, as indicated by a timeout, the base station can simply rescan the network to form new regions to restore connectivity. For example, in the example shown in Fig. 8(a), there is a connectivity hole in the sensor network (marked in black). After rescanning the sensor network with new directions, a set of new regions are formed, as shown in Fig. 8(b), and the connectivity hole is circumvented.

Such reconfiguration has a very low cost, since there is no need to distribute routing, configuration, or location information among the sensors. Rather, each sensor node just needs to receive one or more configuration messages from the base station, and then the reconfiguration is accomplished.

IV. RELATED WORK

Routing in ad hoc or sensor networks has been an active area for years [1], [11]. Many protocols exploit location information to simplify routing operations [2]–[6]. For an excellent survey, see [12]. Although these protocols have less computational complexity in routing, they have extra hardware requirements and control overhead on acquiring and distributing location information (e.g., using GPS devices or querying a location database). With BeamStar, location discovery is performed only at the initialization phase by power controlled directional antenna scans. The only overhead on the sensors in BeamStar is the reception of one or more control messages from the base station. There is no need for GPS devices, thus allowing low-end and low-cost sensor design. No traffic is generated, and thus no energy is spent, on distributing location information. Consequently, BeamStar is energy efficient in the sense that most of the energy is spent on sensing and data forwarding.

Several sensor routing protocols, such as Lowe-Energy Adaptive Clustering Hierarchy (LEACH) [13] and GRAdient Broadcast [8], are designed for large-scale sensor networks. LEACH provides a distributed cluster formation technique, in which sensors elect and rotate cluster heads and form clusters without the involvement of base stations. Therefore, considerable amount of energy may be spent on maintaining the clusters. Although the centralized cluster scheme, LEACH-C, uses base station for cluster formation, it requires each sensor know its location (e.g., via a GPS device) and transmit its location to the base station [13]. The routing scheme in LEACH requires intelligent sensors with power control capability. Furthermore, the cluster heads communicate directly to the base stations, which is more energy consuming than multi-hop routing. In BeamStar, sensing regions are formed by power-controlled directional antenna scans, with minimum requirement and cost on sensor nodes. Moreover, data packets are forwarded through multi-hop relays to the base station, which has been shown to be more power efficient.

In GRAB [8], a data sink sets up a cost field in the network by broadcasting an advertisement packet to the entire network. Each node, upon receiving the advertisement packet, calculates the minimum cost from itself to the data sink. Then, data packets can be forwarded from higher cost nodes to lower cost nodes, through a mesh with a controllable width lying between the source and the data sink. BeamStar has the similar error-resilient advantage as GRAB, since in BeamStar, data packets are also forwarded through multiple paths. However, our scheme has less control overhead than GRAB since there is no need for the sensors to exchange control messages in BeamStar, resulting in energy savings.

V. CONCLUSIONS

In this paper, we presented BeamStar, a scalable, energy-efficient, and error-resilient routing scheme for wireless sensor networks. The proposed scheme is motivated by two observations: (1) It is desirable for sensor nodes to spent most energy on the two fundamental functions: sensing and data forwarding. (2) Since management and control are indispensable, especially in large-scale networks, we can shift the control burden to relatively resource-abundant and more sophisticate base stations. In the proposed BeamStar protocol, the network is partitioned to regions by power controlled base station scans using a directional antenna. Then, routing can be performed using only local location information at each node with minimum processing and control overhead, thus allowing simple, low-cost sensor designs. With BeamStar, each data packet is relayed in an interleaved, loop-free mesh constrained in a sector towards the base station, making data delivery robust to sensor failures and transmission errors. This proposed protocol is suitable for large-scale, dense sensor networks monitoring rare events.

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