QoS-Based Geographic Routing for Event-Driven Image Sensor Networks

Laura Savidge, Huang Lee, Hamid Aghajan, Andrea Goldsmith
Wireless Sensor Networks Lab, Stanford University, Stanford, CA 94305
Email: {laura, huang, hamid}@wsnl.stanford.edu, andrea@systems.stanford.edu

***Abstract*— We investigate the use of distributed image sensing for network localization, dynamic routing, and load balancing in wireless sensor networks. In particular, the image sensors are first used to obtain angular bearing information between each network node and a set of other nodes, mobile agents, or targets. This data is used to construct the relative geographic topology of the network. The image sensors are then employed to make periodic measurements, which are reported to the destination via multihop routing. Nodes may also infrequently detect an event from which a set of image frames need to be reported. These high-bandwidth event reports may cause packet queues to develop at the routing nodes along paths to the destination. We propose a distributed routing scheme that employs a cost function based on location data, in-node queue sizes, and energy levels at neighboring nodes. Our scheme also implements a set of relative priority levels for the event-based and periodic data packets. Simulation results are presented and indicate improved network lifetime, lower end-to-end average and maximum delays, and significantly reduced buffer size requirements for the network nodes.**

I. Introduction

Visual data can often provide a wealth of information about a network's surroundings. In many applications of wireless sensor networks, only certain attributes of events are of interest to the observer. Detection of situations that may need the observer's attention or intervention [1], monitoring the rate at which moving objects flow through the observed environment [2], [3], or registering the types and quantities of certain objects or events [4] are among such applications. These applications may only require occasional transmission of images to the observer. For example, in an application to monitor the flow of vehicular traffic on a highway, the nodes of the network periodically transmit packets containing average speed information in each lane [5]. Occasionally, when a node detects a vehicle with a speed outside of a predefined range, it may buffer and transmit a few image frames [6], which can be used for various law enforcement or accident scene analysis purposes.

In many applications of wireless sensor networks, the knowledge of the location of an event is also desired. Hence, it is important that the location of the network nodes be known. As proposed in this work, image sensors provide information that can be used to perform automated network localization and topology construction. Such topology information can be employed to develop efficient geographic data routing schemes supporting the applications of interest.

In this work, visual observations between the network nodes or simultaneous observations of a moving object by several nodes are used to derive angular bearing information between the nodes in a neighborhood. A collection of such angle data yields a scaled solution to the network node localization problem. Using the position information obtained in the localization step, a location-based cost is then defined as part of a routing cost function. The cost function follows geographic routing models based on the distance to the destination node [7], [8], [9], [10], or based on the angular bearing towards the destination [11], [12], [13]. Geographic routing algorithms eliminate the need for in-node routing tables and avoid outdated state information.

We will focus on routing for event-driven applications of image sensor networks, in which low-bandwidth periodic as well as event-based data packets are routed through the network. The event-based data is considered to be of a high-bandwidth nature and its transmission over a network hop would generally require significantly more bandwidth than the periodic measurements. Handling large bursts of event packets can cause significant local delays along the best path chosen by existing geographic routing schemes.

The proposed distributed routing scheme associates a cost to each hop that depends on its existing queue. The remaining energy at the node is also considered as a cost parameter. Cost functions defined for queue size and energy are added to the position-based cost for greedy routing towards the destination.

Providing quality of service (QoS) support on an end-to-end basis is infeasible in wireless sensor networks designed to operate under distributed decision making mechanisms. Our work aims to improve end-to-end latency and provide best-effort QoS support in geographic routing by employing two mechanisms in its distributed routing scheme: a cost function based on the queue length at the routing candidates, and a set of relative priority levels for the different packet types. The effect of these priorities is incorporated into the queue length cost function of the receiving node and is used by the transmitting node to order the transmission of packets between the two type. As our routing scheme is based on using local information, the notion of an end-to-end QoS guarantee does not apply. However, as we explain later, such guarantees may not apply to event-driven routing in wireless sensor networks due to the multiplicity of participating source nodes reporting an event, and the reliance of most designs on the incorporation of fault tolerance and multi-path routing schemes in the design of these networks.

Performance of the proposed routing scheme is studied via

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simulation. The effect of different weighting factors for the three routing cost function components on the network performance is analyzed. In particular, using queue cost significantly lowers the average and maximum delays, and drastically reduces the node buffer size requirements. Furthermore, including energy cost significantly increases the network lifetime. More generally, we see that adding the queue size and energy costs to the cost function of greedy routing and incorporating a packet type prioritization scheme allows various tradeoffs to be made between the different performance factors of the network. While MAC layer prioritization schemes may also provide QoS support, they are not the focus of this paper. We assume a periodic MAC scheme in our simulations.

The remainder of the paper is organized as follows. In Section II the basic setup of the network is described. In Section III network localization methods using visual observations are presented. In Section IV prioritized geographic routing schemes based on distance-based or angle-based greedy algorithms and local information of queue length and energy are proposed and analyzed. Concluding remarks are included in Section V.

II. Distributed Imaging for Sensor Networks

We consider networks of image sensors that generate heterogeneous types of data, namely *periodic*, single packet measurement data as well as infrequent, *event-based* image data packets transmitted by nodes upon detection of an event of interest. The network nodes are assumed to be energy-constrained and deployed in a random and dense fashion, and multi-hop routing is used to route packets to a destination that is not power-constrained, which we call a base station. For example, in flow monitoring applications, an event of interest may be defined as an abnormality in the speed or direction of the flow of objects. In controlled area monitoring, an event may be defined as the movement of an object through the visual field of view of an image sensor. The network nodes periodically generate packets either to report a set of measurements or to annouce their operation status to the base station. Upon detection of an event, the observer may desire to access visual information about the event. It is assumed that event-based packets are decomposed into several packets of the same length as the periodic packets. We assume a periodic medium access scheme, so packets are assumed to be of equal size to ensure that the periodic nature of the medium access mechanism is maintained. Thus, to minimize delay, event-based packets originating from a source may be routed through different multi-hop paths for delivery to the base station.

A. System Model

The system is modeled in the two-dimensional plane, assigning both position and orientation parameters to each image sensor. All image planes are assumed to be perpendicular to the system plane. We use a pinhole camera model described by the equation

$$\varphi = \tan^{-1}\left(\frac{2d}{D}\tan\left(\frac{\psi}{2}\right)\right), \qquad (1)$$

where φ represents an observed object's angular displacement from the camera's orientation direction, d represents the distance from the center of the image plane in pixels, D represents the image plane dimension in pixels and ψ represents the field-of-view angle of the image sensor. This relationship can easily be derived from the pinhole model shown in Fig. 1(a).

During network localization and topology discovery steps, nodes utilize visual information to determine their own position with respect to the position of surrounding nodes and the base station. The propagation protocol relies on common fields of view between nodes to spread location information. Hence, localization of all nodes is unlikely in a network of field-of-view constrained image sensors with random topology. However, it can be assumed in dense network deployments that adequate observations are made by the nodes in either method for the localization task. Alternatively, the use of omni-directional image sensors can be initially assumed to establish localization and study the performance of the proposed routing protocol. We will examine the efficiency of our routing protocol under the assumption of complete localization as well as when a subset of nodes remain unlocalized due to the limited field-of-view angle of image sensors.

III. Vision-Enabled Topology Discovery

Topology discovery in a wireless sensor network is often needed for system-level functions such as routing as well as application specific activities requiring location information. The use of signal strength of the RF signal has been used for estimating distances between the nodes for localization. While the technique is attractive from a device cost perspective, experience has shown that such measurements yield poor distance estimates [14]. Much improved accuracies can be obtained by time-of-flight measurements when acoustic and RF signals are used together [15] at additional hardware cost.

Visual information obtained through the use of image sensors deployed for various applications enables novel approaches to the node localization process. Given a camera model, a node can map its longitudinal image information to angles in the two-dimensional system plane. In the two localization methods presented in this paper, nodes share information regarding common observation of either other nodes (Sec. III-A) or of a moving beacon (Sec. III-B) to solve for position and orientation information. While these localization techniques involve only small clusters of nodes, topology discovery propagates throughout the network using a protocol presented in Sec. III-C.

A. Localization using Observations Between Nodes

We consider the two-dimensional localization problem shown in Fig. 1(b). Choosing one node as origin of the relative coordinate system, a neighboring node is used to define the unit length. It is assumed that these two reference nodes can observe each other and by doing so they determine their orientations θ_0 and θ_1 with respect to the relative coordinate system. The rationale for making this assumption will be

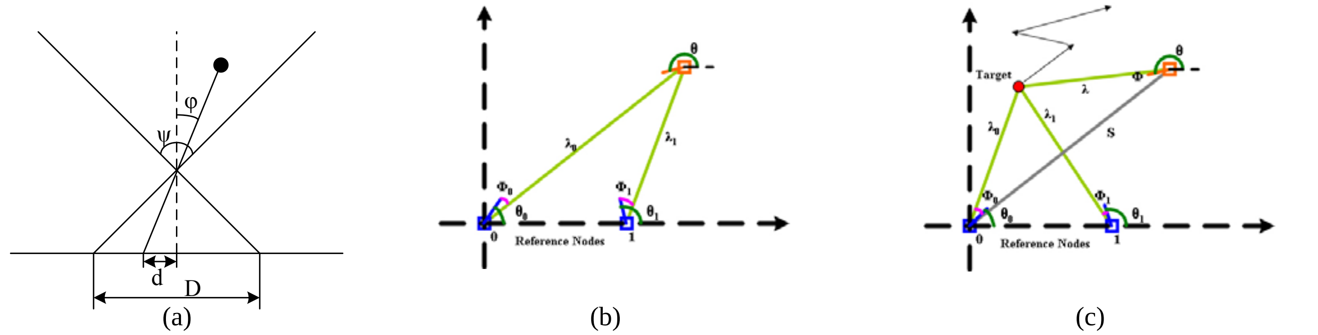


Fig. 1. (a) Pinhole camera model. (b) Localization using observations between nodes. (c) Localization using common observations of moving target.

discussed when we describe a protocol for propapagtion of the topology information in Sec. III-C. The two reference nodes then identify a third unlocalized node which is in visual range of both. Each reference node uses image processing techniques to identify the angular offset of the unlocalized node (e.g. via an RF and LED beaconing scheme), and the angles are labeled ϕ_0 and ϕ_1. The two observed angles are then related by

$$S_0 + \lambda_0 e^{j\theta_0} e^{j\phi_0} = S_1 + \lambda_1 e^{j\theta_1} e^{j\phi_1}, \tag{2}$$

where S_0 and S_1 represent the positions of the two reference nodes and λ_0 and λ_1 represent their respective distances from the unlocalized node.

By separately considering the real and imaginary parts, the equation can be rewritten as

$$\lambda_0 cos(\theta_0 + \phi_0) - \lambda_1 cos(\theta_1 + \phi_1) = Re\{S_1 - S_0\} \tag{3}$$

$$\lambda_0 sin(\theta_0 + \phi_0) - \lambda_1 sin(\theta_1 + \phi_1) = Im\{S_1 - S_0\} \tag{4}$$

Thus the problem can be written as a system of linear equations with two unknowns:

$$\begin{bmatrix} cos(\theta_0 + \phi_0) & -cos(\theta_1 + \phi_1) \\ sin(\theta_0 + \phi_0) & -sin(\theta_1 + \phi_1) \end{bmatrix} \begin{bmatrix} \lambda_0 \\ \lambda_1 \end{bmatrix} = \begin{bmatrix} Re\{S_1 - S_0\} \\ Im\{S_1 - S_0\} \end{bmatrix} \tag{5}$$

Using the solution for λ_0, the location of the third node, S, can be written as the sum of vector S_0 and the vector from S_0 to the node, and takes the form

$$S = S_0 + \lambda_0 e^{j\theta_0} e^{j\phi_0} \tag{6}$$

To complete the localization process, the unlocalized node must determine its orientation by observing one of the two reference nodes. As the position of both nodes are known, the orientation can be easily found using basic trigonometry.

B. Localization using Common Observations of a Target

This section proposes a similar localization algorithm for networks with limited common observations between nodes but which employ a moving target or beacon. We establish an identical coordinate system, designating one node as origin and the distance to a neighboring node as one unit length. A moving beacon traverses the network where it is observed by the two reference nodes at each stage as well as other unlocalized nodes. It is assumed that all nodes participating at each stage can observe the moving target simultaneously. This can be achieved by a synchronization signal broadcast, which can emanate from the base station or from the beaconing moving agent. This synchronization concept is similar to [16], and provides adequate accuracy if the moving beacon stops at the observation instance or moves slowly.

After constructing the relative coordinate system, we define the sensor orientations θ_0, θ_1 for the reference nodes and θ for a third, unlocalized node, as shown in Fig. 1(c). More than one unlocalized node can participate in the operation, each of which would be able to calculate its position by communicating only with the reference nodes. An observation of the target is made at the unlocalized node at the same time instance as the two reference nodes. We assume that the orientations of the two reference nodes, θ_0 and θ_1, are known. This is easily accomplished if the two nodes can observe each other. The observed angle of the nodes at the nth observation is denoted by ϕ_0^n, ϕ_1^n, and ϕ^n and the unknown distance between each sensor and the target is denoted by λ_0^n, λ_1^n, and λ^n. Two independent equations can be obtained from each observation by relating the positions of the unlocalized nodes, the target, and both reference nodes. Thus for N observations we have

$$S = \lambda_0^n e^{j\theta_0} e^{j\phi_0^n} - \lambda^n e^{j\theta} e^{j\phi^n},\ n = 0, \ldots, N-1 \tag{7}$$

$$S = \lambda_1^n e^{j\theta_1} e^{j\phi_1^n} - \lambda^n e^{j\theta} e^{j\phi^n} + 1,\ n = 0, \ldots, N-1 \tag{8}$$

where $S = le^{j\delta}$ is the position of the unlocalized node in polar coordinates. For N observations, there are a total of $3N+1+2$ (λ_0^n, λ_1^n, λ^n, θ, l, δ) unknown parameters and $4N$ equations which come from the real and imaginary parts of (7) and (8). Hence, we need at least $N \geq 3$ observations to solve for all unknown parameters. The Gauss-Newton method or a steepest descent iterative scheme can be used to solve for these nonlinear equations [17]. The solution includes both the unlocalized node's position and orientation information, making observation of a reference node for orientation purposes unnecessary. While this localization algorithm is more mathematically complex than the first method and requires observations of a moving target or beacon, observations between the nodes is unnecessary. The results of an experimental deployment employing this method are presented in Sec. III-E. In practical network deployments, a combination of both methods could be employed to promote improved localization coverage.

C. Propagation of Topology Information

The methods for propagating topology information for the two proposed localization algorithms are very similar. The localization process using observations between nodes (Sec. III-A) begins with nodes close to the base station and continues recursively to more distant nodes until all are localized. The base station initiates the process by requesting a response from all unlocalized neighboring nodes. The first to reply becomes the designated helper node. The distance between the base station and helper node defines the unit length in the system-wide coordinate system in which the base station's position is the designated origin. Thus, the helper node's $(1, 0)$ location is established and it proceeds to determine its orientation with respect to the base station. This can be achieved, for example, through the use of an LED mounted on the base station which is illuminated at the designated time.

After localization of the first node is complete, the base station and the helper attempt to localize other neighboring nodes. A variety of schemes can be used to order the nodes. The simplest method of identifying neighbors is to use the order of response to the base station's initial broadcast. The chosen unlocalized neighbor is asked to illuminate its LED and attempts are made to localize the node using the described method. The base station regulates radio communication during the entire process and assigns unique labels to each node.

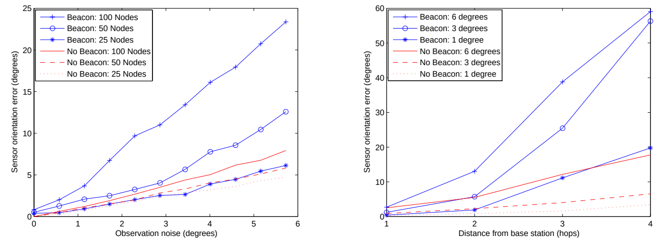
The first round of localization concludes when all base station neighbors have acted as helper nodes to attempt to localize common neighbors. The second round involves nodes which cannot see the base station but can be observed by two previously localized nodes. The base station first chooses a localized node, identified by its localization order. This node requests a helper and attempts to localize neighboring nodes in a similar fashion. Once a new node is localized in the local coordinate system, a simple coordinate transformation yields the desired global position information. The process continues recursively, each node determining the base station's angular positioning as mapped to its own image plane with the help of two previously-localized nodes. Notifications sent to the base station after the localization of each node allows the base station to regulate the entire process, ensuring that no more than one node illuminates its LED at any time.

Localization with a moving beacon (Sec. III-B) follows a similar protocol, but propagation direction is determined by the beacon's path instead of node response times, and only neighbors that observe the moving beacon respond to requests.

After localization, nodes may not know the positions of all of their neighbors. To share this information, nodes can broadcast their position information. Alternatively, if only angular information is required, nodes can individually illuminate their LED for observation by neighbors, determining their angular positions with respect to each other.

D. Simulation Results

Simulations are implemented to study the effect of observation noise propagation on both localization algorithms. To ensure unrestricted topology discovery propagation, we assume the cameras are capable of $360°$ viewing. Positions and orientations of the nodes as well as the beacon coordinates are set randomly. For the algorithm based on using a moving beacon, nodes make a minimum of three common beacon observations before calculating their positions.



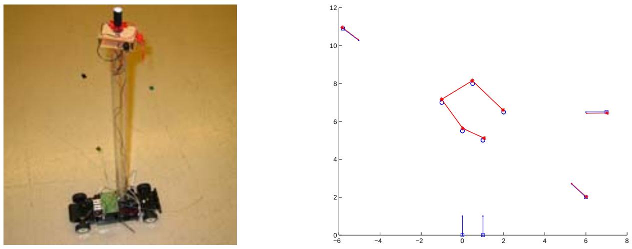
(a) (b)

Fig. 2. (a) Effect of observation noise on sensor orientation error. (b) Effect of number of hops to base station on sensor orientation error in presence of observation noise.

The effect of observation noise on both localization methods is shown in Fig. 2. Observation noise in degrees is modeled as a uniformly distributed variable and is added to the observation angle towards the beacon or another node. The input noise is added to observations made by all the participating nodes in each method. As Fig. 2(a) indicates, for localization using observations between the nodes, the resulting errors are comparable with the observation noise for all the simulated networks, while for the localization using common observation of a moving beacon the error is comparable to the observation noise only for networks of 25 or fewer nodes. The effect of error propagation per number of hops away from the base station is shown more directly in Fig. 2(b). One way to improve the performance in this case is to increase the number of beacon observations for each localization effort. However, for applications in which the location information is mainly used for geographic routing, large location errors in remote nodes from the base station may have less effect on the efficiency of the routing scheme than location errors for nodes closer to the base station. This is because the effect of such errors would be corrected as the packet is forwarded closer to the base station. In fact, the idea that nodes far away from the base station require less precise location information has been exploited in routing for mobile ad-hoc networks [18], [19] to adjust the frequency of location updates. Further discussion about the effects of missing location information on our routing scheme is included in Sec. IV.

E. Experimental Results

We implemented an experiment to demonstrate the applicability of the localization scheme based on common observations of a moving beacon with real image sensors. In the experiment a set of five Agilent Technologies ADCM 1670 image sensor modules are deployed in an indoor environment. The localization algorithm is programmed in MATLAB and runs on laptop computers. All nodes communicate with each other over wireless channels where IEEE 802.11b is adopted as the underlying protocol. The experiments use API libraries and MATLAB functions developed for controlling image sensors and performing packet transmission over wireless channels [20]. The image sensors have a field-of-view of approximately 45 degrees. We apply a background subtraction method to detect the moving target, which in this experiment is a remote-controlled car (Fig. 3 (a)).



(a) (b)

Fig. 3. (a) The moving target. (b) Experimental localization results using common observations of a moving target.

While the target travels in the network, a reference node periodically broadcasts synchronization signals. The sensor nodes then grab images of the target simultaneously. We assume the orientations of the two reference nodes are known from a prior localization step. The reference nodes then broadcast the positions of the target on their image planes. When enough observations are made, the localization algorithm is run at each unlocalized node. Experimental results are shown in Fig. 3(b), and indicate a set of estimates very close to the actual measured quantities.

IV. Event-Driven Geographic Routing in Image Sensor Networks

Large bursts of event packets from image sensors can cause long delays in delivery of both event and periodic data, reduce network throughput, and result in uneven energy distribution among nodes when existing routing schemes are employed. In event-driven applications, the priorities for periodic and event-based data packets may be different. To offer support for these different priorities, the routing node may hold two separate buffers to queue the periodic and event-based packets.

Often consigned to a MAC layer protocol, queue size considerations are especially critical for event-driven transmissions which could potentially clog the network with data, and hence warrant consideration within the routing scheme as well.

For providing QoS-based support in transmission of two packet types in a distributed routing protocol, three factors need to be considered in the MAC and routing layers. First, a medium access control scheme with QoS support is needed, which assigns transmission priority to a node with a high-priority packet. Second, the node can implement a two-queue mechanism and apply a queue selection scheme according to the relative priorities of the two packet types. Third, the node should select among its communication neighbors the one with the shortest expected delay in relaying the packet. In this paper the medium access scheme requirements are not considered, hence the proposed routing protocol is based on packet prioritization and neighbor selection and offers a best-effort approach to addressing QoS support for a routing scheme with two packet types.

In this section we propose geographic routing schemes for hybrid data types with adjustable priority ratios. Geographic routing requires only local information regarding neighbors' positions relative to the base station. The routing scheme aims to improve packet delay as well as balance the packet load among the nodes. This is done by considering the length of the queue at each node as well as remaining energy levels as factors in the routing decision. A weighted cost function including position, queue, and energy parameters allows flexibility in design tradeoffs such as between average packet delays and network lifetime. Our proposed scheme for implementing relative queuing priority is based on assigning a priority ratio between the event-based and periodic packets, and is described in detail below. Network lifetime, maximum required queue size, and average delay for each type of data packets are the performance factors considered in evaluating the different routing schemes proposed.

A. Routing Algorithm

We consider the problem of routing two types of data: i) periodic, low-bandwidth data and ii) event driven, high-bandwidth data. In order to allow transmission of event data to and from nodes with maximum allowable packet sizes, we assume that event data is broken up into smaller packets with the same length as that of the periodic data packets. Such events occur at random intervals throughout the lifetime of the network, and infrequently enough to justify the use of low-bandwidth nodes. By breaking up large event data packets into multiple packets, our proposed routing scheme also provides additional load balancing in energy consumption.

We propose a cost function in which three parameters of neighboring nodes are considered when making next-hop routing decisions: position relative to the base station, existing queue size, and remaining energy. A weighted cost function calculated at the transmitting node determines their relative importance. The cost function can be written as follows:

$$c(i) = c_p(i) + \alpha \cdot c_q(i) + \beta \cdot c_e(i), \quad (9)$$

where c_p, c_q, and c_e denote position cost, queuing cost, and remaining energy cost, respectively, and α and β determine the relative weights of the three node parameters. The variable i denotes members in the set of neighbors for which the cost function is evaluated. In networks of hybrid data, the queuing cost varies depending on packet type. For all networks, the lowest cost neighbor is chosen as the next-hop node. Thus, only local information is used to make routing decisions. The absence of a global routing scheme reduces the network's setup and updating costs, eliminates the need for storage of network-wide routing information at each node, and alleviates the possibility of incorrect information at the nodes as changes in system topology occur.

Nodes must broadcast an upkeep packet including a node's identification, current queue size(s), and remaining energy periodically throughout its lifetime. Time between broadcasts represents a tradeoff between overhead communications and outdated cost function parameters.

B. Position (Distance or Angle) Cost

Geographic routing protocols employ greedy progression schemes based either on distance to the base station [7], [8], [9], [10], or angular offset from the direction towards the base station [11], [12], [13]. In distance-based routing, neighboring nodes linearly positioned closest to the base station yet within radio range of the node are marked as favorable packet forwarding candidates. In angle-based routing, a neighbor's angular offset from the base station θ as seen by the transmitting node is used to identify favorable next-hop neighbors. A neighboring node with small angular offset from the base station is preferred to a node with large angular offset. In both schemes a path is dynamically constructed from the originating node to the destination using only local forwarding decisions.

Both distance-based and angle-based routing schemes can get into loops caused by the geometry of the network. For example, it can be shown that angle-based routing does not guarantee delivery to the destination in network graphs that have low connectivity or non-convex faces [13]. It has been shown [11] that certain graph architectures such as Delaunay triangulation can be used to guarantee packet delivery. However, techniques to convert the network's toplogy to conform to such architectures [21] result in large overhead and are prohibitively costly in randomly deployed, dense wireless networks. It is proved in [12] that randomizing angle-based routing by selecting between the two neighbors with the smallest separation from the angular bearing from the node to the destination can result is a scheme with guaranteed delivery in any graph with general convex subdivision.

For distance-based routing schemes, position cost $c_p(i)$ is equal to a node's normalized, linear distance from the base station in the system's defined unit lengths. All distances are normalized to the largest distance within the node's neighbors such that for the node farthest from the base station among the next-hop candidates, $c_p = 1$.

For angle-based routing schemes, we use several geometric properties to create an appropriate cost function. We first define the base station's direction as 0 degrees, making the range of θ from $-\pi$ to π. Thus the cost function is non-increasing from $-\pi$ to 0 and non-decreasing from 0 to π.

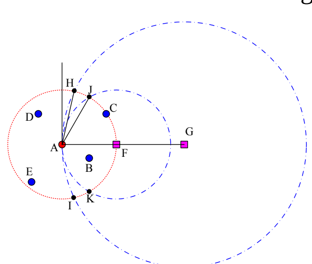


Fig. 4. Angle cost concept.

Fig. 4 illustrates node A's situation when transmitting a data packet. In the figure, nodes B, C, D, and E are next-hop candidates and node G is the base station. First, we observe that any neighbor in the large circle centered at G is closer to the base station than node A. The angle $\measuredangle HAG$ must be smaller than 90 degrees as H is located on this circle. We then consider the limit case such that the base station is located at position F. Any neighbor in the small circle centered at F is closer than node A. Thus, we can say that any node in the area AJFK is better than other potential next-hop nodes. Because the angle $\measuredangle JAF$ is 60 degrees, we can conclude that any node within 60 degrees is better than node A, and nodes offset more than 90 degrees are worse than node A. Based on this observation, we divide the cost function into three sections. We give a cost function with small slope to the area where θ is between 0 and 60 degrees, medium slope to the area where θ is between 60 and 90 degrees, and large slope to the remaining area. The function is normalized so that it ranges from 0 to 1. An example cost function is shown in Fig. 5(a).

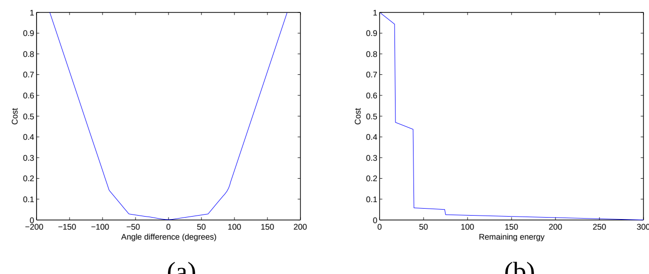


Fig. 5. Cost functions for (a) angular difference, (b) remaining energy.

C. Queue Cost with QoS-Based Considerations

End-to-end packet delays can be costly in real-time applications, and optimization mechanisms need to be employed based on the application requirements. Most approaches to addressing latency issues are derived from the notion of QoS in the context of wireless ad-hoc networks, and depend on rather complex protocols that are too costly for resource-constrained wireless sensor networks. Several delay-aware routing techniques have been proposed, including [22] which attempts to improve delays in congested networks through base station relocation. In [23] considerations about the number of neighbors a routing node is assigned to service are used to construct a path towards the destination. Additionally, the routing algorithm in [24] uses global knowledge of node queue sizes by the gateway to calculate end-to-end least-cost paths and generate routing tables. In the same work, a real-time and a non-real-time queue are proposed for allowing high priority data packets to take precedence over the regular packets. In [25] a QoS-aware routing protocol is proposed for handling regular traffic on a best-effort basis while providing support priority for real-time data from video sensors. The mentioned method finds a least-cost and energy-efficient path that meets a certain end-to-end delay requirement, but provides no method of QoS support for different levels of priority between the two data types. Sequential Assignment Routing (SAR) is a protocol proposed in [26], which bases the routing decision on the three factors of energy, QoS on each path, and the priority level of each packet in order to construct a tree-structured, end-to-end routing multi-path from the source to the destination.

Solutions based on the concept of end-to-end QoS may not be applicable in wireless sensor networks both due to their complexity as well as the overhead of maintaining the routing tables, and more fundamentally because most event-driven applications in wireless sensor networks are not of an end-to-end nature [27]. For example, although the event data are routed towards a single sink node, there are usually several sensor nodes within an area that are influenced by the event, which all attempt to route their event-driven data generally via the same or overlapping sets of paths. The notion of optimized end-to-end paths for each of the individual data streams may not be practical since event data contributed from multiple sources may cause a rapid change in the congestion pattern along the common parts of the paths. When a route becomes congested, such protocols either suffer a delay or need to initiate a new round of route discovery. In addition, in many applications, due to the large correlation in the data generated by the nodes from an event, packet losses or delays in data from a single sensor node may be tolerable to a certain extent, making an optimal end-to-end path for data from any single node unnecessary.

A method based on geographic routing and local delay values is proposed in [28]. The SPEED method uses a protocol based on distance-based greedy routing, in which the next hop node is selected among a subset of neighboring nodes within a node's forwarding set. First, the forwarding set is divided into two groups of nodes based on the relay speeds. The selection is made among the subset with the smaller delay. The protocol focuses on reducing the end-to-end delay of packets that need to travel across the network to or from the base station as compared to the delay of local, peer-to-peer packets. As such, the QoS support requirements for handling both periodic and event-based data cannot be directly implemented. Furthermore, the measure for delay at a neighboring node is based on the recent history of packet delays from the time of entering the node's queue till the time an ACK is received from the next routing node. This is a backward-looking measure and does not consider the current length of the queue to which the new packet is supposed to be added. The method also does not consider any energy metric in its routing protocol.

i. Periodic Data Packet Mode of Operation

We define queuing cost c_q as the expected number of rounds a new packet will have to wait at a neighboring node. As queue length directly determines the queuing delay at a node, the queuing cost function of a next-hop candidate is linear. We set the cost for queue size as the total number of packets awaiting transmission at the node including the potential new packet, i.e. $c_q = Q_{periodic} + 1$.

ii. Hybrid Data Packet Mode of Operation

When both data types are present in the network, nodes may apply FIFO ordering with one queue or may give priority to certain data as prescribed by the application. We consider a two-queue implementation in which nodes store packets of each data type in separate queues and decide which data type to transmit based on a probability derived from the ratio of data type priorities. A new packet is always placed at the end of its respective queue, and packets may only be sent from the front of the queue. This retains FIFO ordering within each data packet type. We define p as the probability that an event packet is chosen for transmission. As each node transmits a packet every round, this implies that periodic data is transmitted with probability $1 - p$ (Fig. 6).

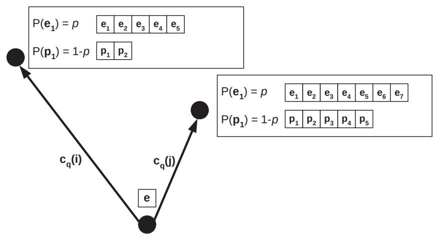


Fig. 6. Queues.

To determine queue cost for hybrid networks, we model the method of packet transmission as a negative binomial distribution and use the distribution's expected value to define c_q. For this distribution to apply, we assume that at least one packet exists in both queues at all nodes throughout the lifetime of the network. Let X be a random variable representing the number of rounds necessary for a total of r accumulated successes, where we define transmission of an event packet as a success, and in which event packets are sent with probability p. We see that this is equivalent to the queue cost c_q for an event packet at the end of a queue of length r, which will leave the node only after r event packets are sent. Since each round can be considered an independent trial, the expected number of required rounds is given by the expected value of the negative binomial random variable X with parameters r and p, which is given by $E[X] = r/p$.

We can now write two queuing cost functions based upon the expected amount of queuing delay a packet will encounter at a next-hop node:

$$\text{Event packets:} \quad c_q = \frac{Q_{event} + 1}{p} \tag{10}$$

$$\text{Periodic packets:} \quad c_q = \frac{Q_{periodic} + 1}{1 - p} \tag{11}$$

where Q_{event} and $Q_{periodic}$ are the existing lengths of the node's event and periodic queues, respectively, and p is the predefined probability that the node sends an event packet as opposed to a periodic packet on any given round. The queues are incremented by one in the function to account for the effect of the potential new packet's presence in the queue.

While we have assumed that for all nodes, neither queue ever empties completely, this is likely untrue. However, the chosen c_q is an upper bound on the expected queuing delay. To retain the validity of the cost function, a node could abstain from one transmission round if it contains no queued packet of the selected data type. Allowing nodes in this situation to transmit packets of the other data type would only decrease the actual delay cost for packets in the existing queue.

D. Energy Cost

We consider the remaining energy of neighboring nodes to prolong network lifetime by avoiding packet transmissions to nodes with little remaining energy. Let the maximum energy

Random	Random routing decisions
A/R	Angle-based, random selection between 2 best nodes
A	Angle-based, zero queue and energy cost ($\alpha = 0, \beta = 0$)
A/Q	Angle-based w/ queue cost ($\alpha = 10, \beta = 0$)
A/E	Angle-based w/ energy cost ($\alpha = 0, \beta = 100$)
A/Q/E	Angle-based w/ queue and energy costs ($\alpha = 10, \beta = 100$)
D/R	Distance-based, random selection between 2 best nodes
D	Distance-based, zero queue and energy cost ($\alpha = 0, \beta = 0$)
D/Q	Distance-based w/ queue cost ($\alpha = 10, \beta = 0$)
D/E	Distance-based w/ energy cost ($\alpha = 0, \beta = 100$)
D/Q/E	Distance-based w/ queue and energy costs ($\alpha = 10, \beta = 100$)

(A)

Payload size (periodic)	1 packet
Payload size (event)	10 packets
Packet generation frequency (periodic)	10 rounds
Packet generation frequency (event)	$\lambda = 100$ rounds
Terrain	(350m, 350m)
Node number	196
Node placement	uniform
Radio range	75m
Initial energy (periodic-only networks)	200 units
Initial energy (hybrid networks)	400 units

(B)

TABLE I

(A) DESCRIPTION OF ACRONYMS AND THE COST FUNCTION PARAMETERS USED FOR ROUTING SCHEMES, (B) SIMULATION SETTINGS.

in each node be $E_{\max}$. To prolong lifetime of individual nodes, c_e should be a non-increasing function from 0 to $E_{\max}$. We choose to assign low cost for the first 50% energy and assign high cost for rest. Fig. 5(b) shows an example of an energy cost function that follows this premise.

E. Missing Location Information

It is likely that under any localization method a percentage of the network nodes may remain unlocalized. For geographic routing it has been shown that only limited local topology knowledge is needed to make energy-efficient routing decisions [29]. In [30] the effects of limited or erroneous location information on the routing delay and throughput capacity of geographic routing are studied. It is shown, for example, that even with only rough estimates of angular bearing to the base station such as the quadrant information, the time to reach the destination is within a constant factor of straight-line greedy routing. In [23] a different approach to using angle information is employed by exploiting a node's knowledge about the general direction of the destination to make local routing decisions.

In practical deployments of image sensor networks, when cameras have a limited field-of-view, some nodes may not participate in adequate observations and remain unlocalized. An extension to the cost function can address the cases of unlocalized neighbors. For example, unlocalized nodes may be assumed to be at the farthest distance within the neighborhood or at the average distance that the localized neighbors have with the transmitting node. Such assumptions can be readily reflected in the cost function proposed earlier. This allows the unlocalized nodes to participate in routing and their queue buffers and battery power be utilized to help deliver the packets to the base station. A simulated example of such a case is included in the next section.

F. Simulations and Discussion

The simulation environment contains 196 network nodes deployed in an area of size 350x350 m. The communication range of each node is fixed at 75 m. We simulate routing with varying cost function parameters on periodic-only data as well as a hybrid of the two data types. For all simulations, periodic, single-packet data is generated at each node every 10 rounds, where starting rounds are randomly staggered between nodes. Event occurrences are modeled as a Poisson random process with $\lambda = 100$. Once an event occurs, a randomly chosen detecting node and all its neighbors each generate 10 packets of data all of which are added to their existing queues. In simulating periodic-only data operation, each node is initially supplied with 200 energy units, and in the hybrid data operation, each node begins with 400 energy units. Nodes consume one unit of energy for every packet transmitted. Table I(A) describes the various schemes simulated and the set of coefficients used in cost functions. Table I(B) summarizes the simulation parameters used.

i. Periodic Data Packet Mode of Operation

Figs. 7 (a), (b) show the number of alive nodes over time in periodic mode for angle-based and distance-based schemes, respectively. We observe that energy considerations ($\beta = 100$) extend the network's lifetime between 43% and 63%. Network lifetime is defined by the first node death. That the average network lifetime over many simulations for all schemes without energy cost is approximately equal to the initial node energy implies that in these methods, at least one node is transmitting a packet every round. A large β in the system cost function promotes a more even load distribution and increases network's lifetime.

	Network Lifetime (rounds)	Packets Deliv'd (pkts)	Delay (Ave.) (rounds)	Delay (std.) (rounds)	Delay (Max.) (rounds)	Max. Queue (pkts)
Random	202.4	2509	23.6	39.1	221.3	51.0
A/R	201.7	3670	3.4	2.3	12.3	76.7
A	200.2	3623	3.3	2.3	12.7	87.0
A/Q	200.3	3885	2.3	1.3	6.0	1.0
A/E	297.7	5001	4.7	3.5	18.3	60.0
A/Q/E	275.7	5238	2.9	1.9	9.0	5.0
D/R	201.0	3698	3.2	2.3	11.7	88.3
D	200.3	3525	4.0	3.8	19.7	122.3
D/Q	200.7	3893	2.0	1.0	4.3	1.0
D/E	334.7	5288	3.7	3.7	20.7	56.0
D/Q/E	305.0	5703	2.0	1.0	4.7	5.3

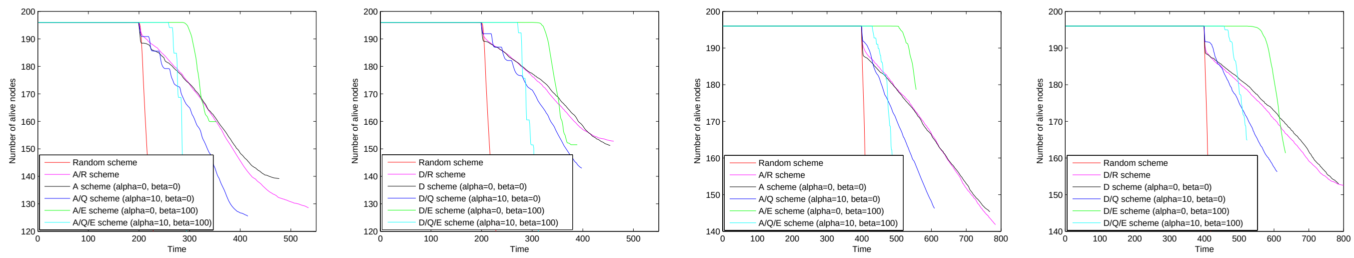
TABLE II

PERFORMANCE UNDER PERIODIC DATA GENERATION MODE.

Queue size comparison in Table II reveals a dramatic reduction in the maximum queue length for routing schemes with queue size consideration in the cost function. While maximum queue size does not directly affect a network's performance it dictates space requirements for the memory-limited nodes. The table also shows that the total number of packets delivered to the base station follows a similar trend to the network lifetime.

ii. Hybrid Data Packet Mode of Operation

Table III shows that in the presence of event data, differences in average delay for periodic packets with and without



(a) (b) (c) (d)

Fig. 7. Number of alive nodes over time in (a) periodic data mode for angle-based schemes, (b) periodic data mode for distance-based schemes, (c) hybrid data mode for angle-based schemes, (d) hybrid data mode for distance-based schemes.

queue and energy considerations are present, but small. It is likely that while periodic packets near the event experience long delays, the many packets from other parts of the network are unaffected. Observation of the maximum delay for periodic packets reveals the significant delay improvement when node queue sizes are considered for routing decisions. For some applications, large delays even for a small number of periodic packets could be unacceptable and in this scenario, a routing scheme with large α should be chosen.

The average delays of event packets in hybrid networks are significantly decreased in routing schemes with queue size considerations, and to a lesser extent in those with only energy consideration. Instead of counteracting queue size considerations as in networks with periodic-only data, A/E and D/E schemes helped distribute the large amount of simultaneous event data with energy cost consideration. This is partly due to the fact that accepting and transmitting several packets generated by an event by a node causes rapid energy depletion and increases the node's energy cost function value. This makes other nodes better choices for accepting additional event packets as would queue cost consideration.

Figs. 7(c), (d) show the number of alive nodes over time in hybrid mode for angle-based and distance-based schemes, respectively. With energy awareness ($\beta = 100$) network's lifetime is extended by 29% to 43%. As with periodic-only data, queue size considerations drastically improve the node storage requirements by decreasing the maximum queue size during the lifetime of the network. This is particularly important in hybrid networks where many event packets from several nodes in the same area can result in extremely lengthy queues. Fig. 8 shows delay histograms for event packets in distance-based schemes. The shape of distributions for schemes considering queue size as a cost indicates a much better delay performance.

The effects of changing the relative priorities of the event packets and periodic packets on the average and maximum delay numbers are shown in Fig. 9(a). While the average delay numbers behave rather steadily with a change in the priority parameter p, the effect of such ratio on the maximum delay each packet type encounters in the network is clearly pronounced as indicated in the figure.

Finally, as discussed earlier, it would be interesting to study the behavior of the proposed schemes in cases where some of the network nodes are not localized. We conclude the simulations by presenting an example in which 50% of the network nodes are unlocalized. The transmitting node assumes that its unlocalized neighbors are located at a distance to it equal to the average distance of all its localized neighbors. This is used to calculate the cost function for all the neighbors, and hence allows the unlocalized nodes with short queue lengths or high remaining energy to participate in packet routing. Results of simulating such a scenario for the A/Q/E and D/Q/E schemes are presented in Fig. 9(b), and indicate that both schemes show reasonable performance under this scenario.

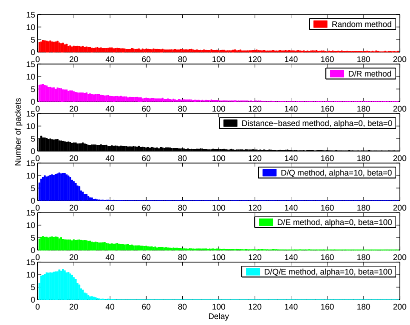
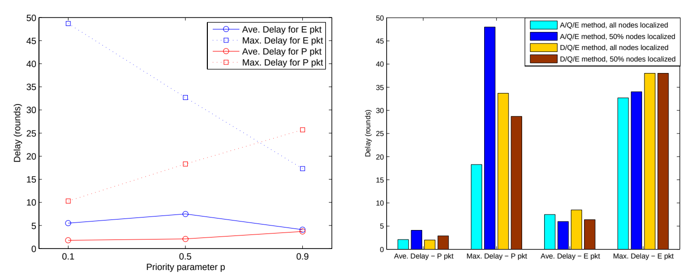


Fig. 8. Delay histograms for event data in distance-based schemes.



(a) (b)

Fig. 9. (a) Effect of relative priority level p in the A/Q/E method. (b) Effects of 50% unlocalized nodes on the Ave. and Max. delays of event and periodic packets in the A/Q/E and D/Q/E methods.

V. Conclusions

In this paper, we have motivated the use of image sensors in network localization for geographic routing with adjustable priority support for event-driven applications. We show that if a network of image sensors is deployed for event detection and reporting, observations made by the image sensors can be used to find a solution to the localization problem. The location or angular bearing information can then be employed in a geographic routing scheme, which also uses the queue

	Network Lifetime (rounds)	Average Throughput (packets/round)	Packets Deliv'd (pkts)	Periodic Packet Ave. Delay (rounds)	Periodic Packet Delay std. (rounds)	Periodic Packet Max. Delay (rounds)	Event Packet Ave. Delay (rounds)	Event Packet Delay std. (rounds)	Event Packet Max. Delay (rounds)	Max Queue (pkts)
Random	400.0	13.7	5480	14.5	44.4	398.7	86.7	126.4	499.2	114.8
A/R	400.3	20.0	8006	1.5	2.7	17.3	18.2	18.9	90.3	199.3
A	400.0	19.7	7880	2.4	3.9	30.7	23.3	33.0	151.3	199.0
A/Q	400.7	22.7	9095	1.9	3.0	22.7	7.6	8.3	45.7	15.0
A/E	528.3	20.0	10566	3.2	4.5	30.0	9.2	9.9	47.7	118.3
A/Q/E	517.3	21.1	10915	2.1	2.7	18.3	7.5	6.6	32.7	12.7
D/R	400.7	20.9	8374	1.9	3.7	32.0	25.8	29.1	137.3	213.3
D	400.0	18.5	7400	2.9	5.4	40.7	20.4	26.2	139.7	256.0
D/Q	400.3	22.9	9166	1.3	2.5	20.0	10.2	9.7	42.7	13.7
D/E	575.3	17.2	9895	5.6	9.1	53.3	13.0	20.5	101.3	113.7
D/Q/E	491.0	21.4	10507	2.0	3.5	33.7	8.5	7.7	38.0	18.0

TABLE III

NETWORK PERFORMANCE COMPARISON FOR DIFFERENT ROUTING SCHEMES UNDER HYBRID DATA GENERATION MODE. RELATIVE PRIORITY p=0.5.

size and energy level from one-hop neighbors to make the next-hop decision. This results in a load-balanced routing protocol, in which load balancing is achieved both in terms of energy consumption by the nodes and the delays incurred by the packets. The use of two relay queues at each node was proposed to handle the two periodic and event-based packet types. By allowing relative priority levels for the different packet types, the proposed routing scheme suggested an approach driven by QoS considerations that significantly improved the average and maximum end-to-end latency of prioritized packets. Simulation results indicated that the algorithm both improved packet delays and extended the network lifetime while lowering buffer size requirements and allowing flexibility in design tradeoffs.

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