A General Cost Function to Reflect Sensor Support for Application QoS

Ou Yang, Chris Merlin, Wendi Heinzelman
Department of Electrical and Computer Engineering
University of Rochester
Rochester, New York 14623
Email:{oyang, merlin, wheinzel}@ece.rochester.edu

I. Introduction

As wireless sensor networks gain increasing prominence for a variety of practical applications, design challenges arise due to the sensors' limited energy supplies and due to the application-specific quality of service (QoS) requirements. Since sensors are usually battery-operated, and may not be rechargeable, protocol designers must look for energy-conserving mechanisms to prolong the network lifetime. Moreover, the sensor nodes are used for a variety of purposes, including data gathering (sensing), event tracking (processing), and communication/routing. Since different applications have different measures of QoS, much past work has looked at designing application-specific protocols to meet the specific QoS requirements of different applications. However, these protocols do not easily generalize, making it difficult to implement new applications for wireless sensor networks. We therefore propose a general cost function, called Sensor Replacement Index (SRI), to differentiate individual sensor's support to the application functionality. SRI can be computed for various applications and can be applied to a variety of protocols to help prolong the network lifetime while maintaining desirable QoS support. Simulation results show that combining SRI with minimum energy cost in the selection of active sensors enables the network to meet the application QoS requirements for much longer than using the minimum energy cost strategy alone.

II. Related Work

In [1] Shah et al. suggested randomly selecting a path to a destination among a pool of path candidates to avoid network partitions. The multiple paths to a destination are built using an energy metric while high-cost paths are discarded. Paths with a smaller cost are assigned a higher probability of being chosen. The metric is calculated per link as the sum of receive, send, and residual energies. In [2], we proposed managing a cross-layer protocol using the MiLAN middleware. Several tunable "knobs" were presented such as complex queries issued by the base station. We also introduced a new application cost for a protocol that jointly manages node activation and routing. This cost helps quantify the importance of a node to the network QoS in order to maximize the time for which the network will meet or exceed the application requirements. The work designed in this paper generalizes this cost function for a variety of applications. Sadler et al. [3] propose a shared platform among all layers of a protocol stack for cross-layer optimizations. The authors recommend using a table of interchangeable nodes (capable of handling the same application request) that lists equivalent nodes to be used by the routing protocol when a link breaks. Our SRI provides a similar means of determining which sensors are interchangeable and which are much more important to the application and should be used more conservatively.

III. General Cost Function

To differentiate an individual sensor's contribution to the application functionality, we propose a general cost function, called Sensor Replacement Index (SRI), which helps determine which sensors to activate and the corresponding routing path in order to maintain the requested application QoS while extending

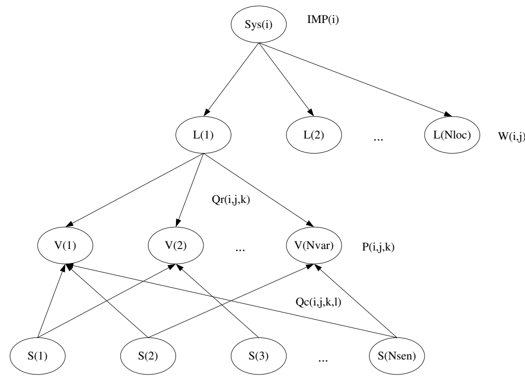


Fig. 1. Application requirements and sensors' capabilities.

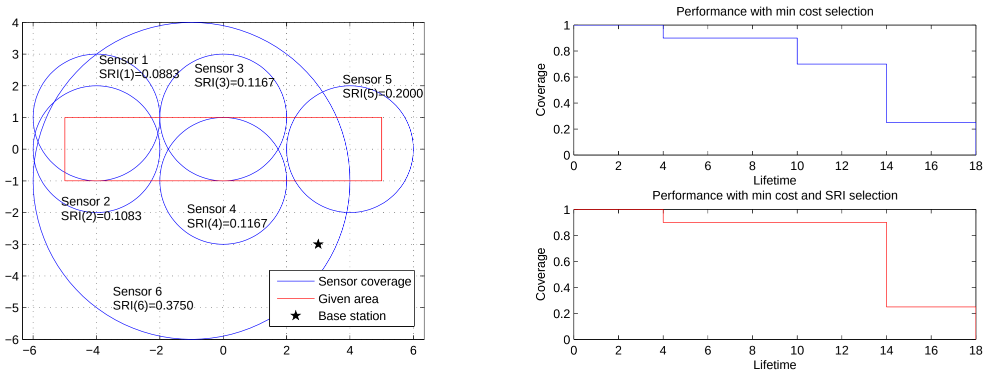
network lifetime. For a given application, a four-level graph, as shown in Fig. 1, is employed to describe the application requirements and the sensors' capabilities. The highest level is the system state level. An application can run in different system states, such as normal and alarm states, while the QoS requirements change accordingly. Each system state i is given a normalized measure of its importance $IMP(i)$ to the application. The second level defines every location of interest j under a particular system state i, with a normalized importance $W(i,j)$. For example, a monitoring application may supervise three locations: door, window and goods. In the normal state, monitoring doors and windows is more important, but in the alarm state, monitoring goods is more important. The third level consists of all variables of interest k, like sound and motion for the previous monitoring application, with their importance $P(i,j,k)$ under different locations j and system states i. The last level is the sensors themselves. Each sensor l has different QoS capability $Q_c(i,j,k,l)$ to meet the QoS requirement $Q_r(i,j,k)$ from variable k under location j and system state i. Based on the graph, the SRI of a sensor is defined as the summation of its importance-weighted QoS contribution to each combination of different variables, locations and system states.

$$SRI(l) = \sum_{i=1}^{N_{sys}} IMP(i) \cdot [\sum_{j=1}^{N_{loc}} W(i,j) \cdot (\sum_{k=1}^{N_{var}} P(i,j,k) \cdot \frac{Q_c(i,j,k,l) > Q_r(i,j,k)}{\sum_{o=1}^{N_{Sen}} Q_c(i,j,k,o) > Q_r(i,j,k)})] \tag{1}$$

SRI models the fact that the death of a sensor with high SRI may severely impair the application functionality. Since there may be more than one set of sensor nodes that can support the application requirements, all the sets with total SRI greater than 1.01 times the average total SRI should be removed from the pool of candidates to avoid using the sensor sets with higher importance to the application. Based on the knowledge of SRI, the sensor selection algorithm may choose one of the sensor sets from the candidate pool, and the routing algorithm may select the routing paths accordingly.

IV. Examples and Results

In this section, three applications are used to assess the improvement in application performance and network lifetime by considering the sensors' importance to the application (SRI). Specifically, we examine three different classes of applications and show how SRI can be defined for each of these applications and the benefit SRI provides in extending network lifetime. The three application classes are: coverage, which is an application with only one system state and one variable of interest; a fire alarm application, which has only one location of interest; and a monitoring application, which is an example with multiple system states, locations and variables. We assume all the nodes in the network can reach the base station in one hop, consequently routing is not considered here. Comparisons are made between two methods of sensor set selection. The first selects the sensor set with minimum energy cost from the source sensors to the base station, while the second method excludes all sets with high total SRI from consideration, and then uses the minimum energy cost criterion to select the sensor set from among those remaining.



(a) Sensor distribution in the coverage application.

(b) Coverage vs. lifetime.

Fig. 2. Coverage application.

A. *Coverage Application*

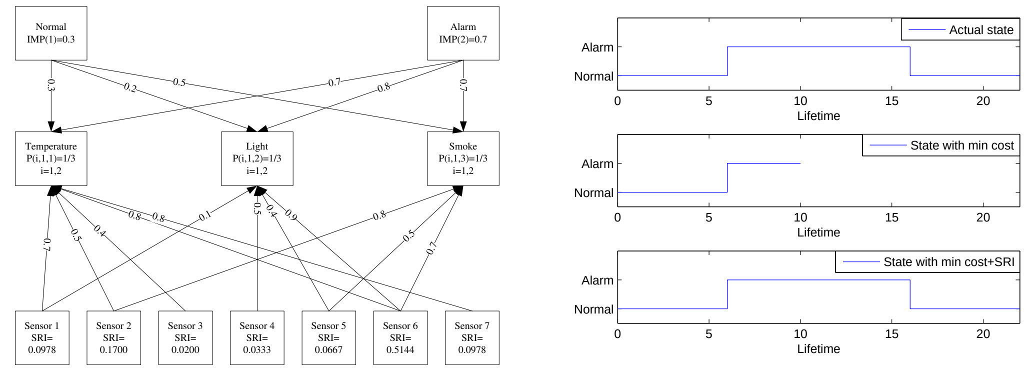
In coverage applications, the end user requires as much sensor coverage in a given area as possible. This application has only one system state. Every node has a fixed circular coverage, which overlaps with that of the other nodes and divides the given area into a number of locations. Only one variable, coverage, is considered. As shown in Fig. 2(a), 6 sensors are available to cover a rectangular area. The energy cost of each sensor is proportional to its distance to the base station. Fig. 2(b) shows that the overall coverage decreases more slowly when SRI is employed. Since sensors whose death significantly impair the overall coverage avoid being selected as source nodes until no other choice is available, the application maintains the largest achievable coverage as long as possible. In this example, if 70% coverage is required by the end user, then SRI helps prolong the application functionality from 10 time units to 14 time units.

B. *Fire Alarm Application*

A fire alarm system measures temperature, light and smoke in a given location, and it shifts between the normal state and the alarm state according to the sensor measurements. Since the application has only one location of interest, the four-level graph is reduced to three levels: system states, variables and sensors, as shown in Fig. 3(a). The numbers on each edge indicate the QoS requirements and the sensors' capabilities. Specifically, sensor 6 plays an important role in supporting all three variables under the alarm state, and thus has a high SRI. Simulation results show that compared to the minimum cost scheme, the combination scheme of minimum cost and SRI prolongs the network lifetime from 10 time units to 22 time units, and consequently provides the user with valuable information for longer. Since the most important sensor (sensor 6) should not be used in the normal state if possible, without the help of SRI, the network stops providing QoS support due to this sensor's early death. On the contrary, when SRI is considered, this sensor's energy is preserved until the alarm state occurs.

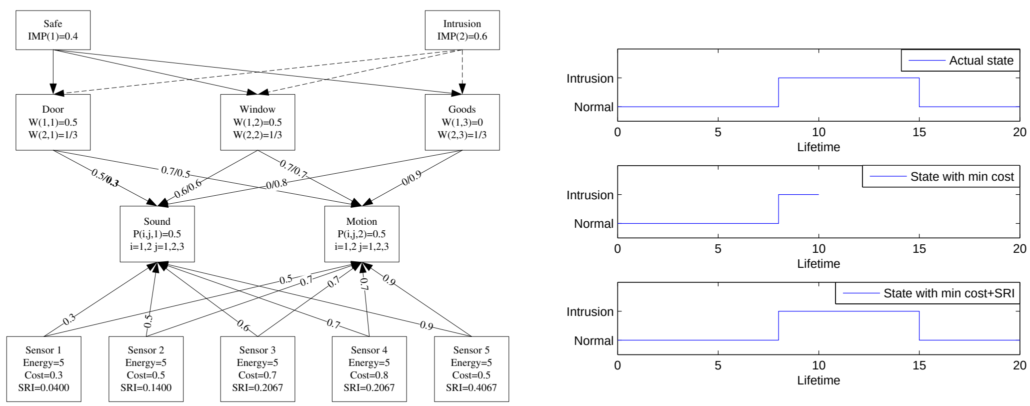
C. *Monitoring Application*

A monitoring application may be used to supervise safety in a warehouse. Fig. 4(a) shows its application requirements and the sensors' capabilities. Under the normal state, only two locations, door and window, need to be monitored. However, if the network reports an intrusion, it is also necessary to monitor the goods. All 5 sensors provide different support for two variables, sound and motion, but only sensor 5 can support the QoS requirements under the intrusion state, hence it has a very high SRI. In Fig. 4(a), the dashed lines and the numbers after a slash on each edge indicate the application requirements from the intrusion state. Fig. 4(b) shows the real state of the warehouse and the system state of the application. Compared to the minimum cost scheme, the combination of minimum cost and SRI doubles the network lifetime, and thus provides information about the state of the warehouse for longer. Specifically, for the



(a) Application requirements and sensors' capabilities. (b) System state vs. time.

Fig. 3. Fire alarm application.



(a) Application requirements and sensors' capabilities. (b) System state vs. time.

Fig. 4. Monitoring application.

normal state, sensors 3, 4 or 5 can support the QoS requirements, with their energy cost being 0.7, 0.8 and 0.5, respectively. However, their SRIs are 0.2067, 0.2067 and 0.4067. Thus, the minimum cost scheme would choose sensor 5 as the source node, and hence, it would die before the intrusion state ends. On the other hand, the combination scheme of minimum cost and SRI excludes sensor 5 because of its high SRI relative to the other sensors, and it chooses sensor 3 or sensor 4 as the source node in the normal state. The energy of sensor 5 is therefore saved to prolong the support for the intrusion state.

V. Summary and Future Work

As shown in the previous section, the proposed general cost function SRI can be easily applied to different applications in wireless sensor networks. SRI differentiates the individual sensor's support to the application requirements, and it enables the differences in sensor importance to the application to be taken into consideration in the selection of active sensors in different system states. So far, the effectiveness of SRI has only been assessed under the situation of one-hop centralized networks. The QoS performance and network lifetime in multi-hop networks will be examined in the future.

References

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