Crucial Edge Detection in Sensor Systems under Energy Constraints

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Abstract. Although the wireless sensor nodes available today may be equipped with rechargeable batteries, the minimal energy capacity and low recharge rates hinder the sensor's lifetime and achievable performance. Sensor loses energy predominantly because of the redundant transmissions of sensed data. To avoid this, a sensor is modeled to transmit only the changes sensed in the event occurrence process, referred to as Transitions or Crucial Edges. For the proposed sensor model, we have developed a near-optimal decision-making policy. The policy, designed for a single rechargeable sensor, addresses the question “how long should the sensor sleep, and how long to stay active?”

1. Introduction

Wireless sensor networks have varied and important applications, such as military surveillance and habitat monitoring. Generally, these devices are small, low-cost and operate in remote conditions with seldom human intervention. Hence, these devices are expected to have long lifetime, and perform efficiently and reliably. However, due to the low energy capacity of the sensor this is seemingly not possible. The usage of rechargeable sensors does help but the lower recharge rates, due to the vulnerable environmental conditions, is a constraint. Hence, the sensor must operate judiciously in order to efficiently utilize the available energy. Also, sensors are generally known to make redundant transmissions of sensed data which consumes substantial amount of energy. By avoiding these redundant transmissions we can ensure energy conservation, and usage when required.

Consider rainfall occurrence as the monitored event process, Figure 1. It is raining when the event process is ON, and there is no rain if event process is OFF. For instance, we may observe rain between \( t_1=8 \) and \( t_2=12 \), and no rain between \( t_2=12 \) and \( t_3=15 \). For a monitoring station, the information required is the time at which rain starts and stops, which may be used to study the rainfall phenomenon in the area. The sensor model, considered in past and related work [1], would generally transmit the state of the event process every time slot between \( t_1=8 \) and \( t_2=12 \) and lose significant energy. We suggest that the sensor should only transmit the information at \( t_1=8 \) and \( t_2=12 \), since this information is enough to know the duration of rainfall. This information sensed and transmitted by the sensor is referred to as transition or crucial edge in the event occurrence process, marked by the change in state of event process.

The sensor must deactivate itself when appropriate, since an active sensor loses energy continuously. With reference to the above example, the sensor must be ideally active at time instants \( t_1=8 \) and \( t_2=12 \) and sleep between the two instants. But this is not simple as the above time instants are random. In order to perform efficiently and detect maximum number of transitions, the sensor must choose an appropriate sleep interval. Also, sensor must choose an optimum active interval, since longer activity means better chance of detecting transitions but at the cost of the available energy. The choice of sleep interval should be optimum since an inactive sensor is not capable of sensing, and may miss transitions. Practically, the sensor may miss one or more transitions but intelligently the sensor should realize and transmit the missed transition. Although this information is transmitted late, we believe a late transmission is better than no transmission.

The logic behind realizing a missed transition may be clear with the following analogy. Assume you decide to sleep while it is raining and rain has stopped before waking up. If the question asked is “how many times did rain stop/start while you were asleep”, the obvious answer is at least once the rain stopped but not sure if the cycle repeated. From this example and Figure 2 the logic is very much clear.
The sensor will realize and transmit the last missed transition if an odd number of transitions occur while inactive.

2. Experiment, Results, Discussion, and Significance

The sensor is modeled as a queuing system, with recharge quanta of energy as arriving entity following Bernoulli process, and an event driven energy discharge process. An active sensor loses energy continuously and additional energy is lost for any sensing performed during ON period. No additional energy is spent for sensing during OFF period. In addition to this, each transmission made by the sensor consumes the highest amount of energy. If an active sensor detects and transmits a transition, it fetches a maximum reward of 1. If the sensor is late in realizing and transmitting a missed transition, then a reduced reward is fetched. The reward function is an exponentially decreasing function and depends on the time taken by the sensor to transmit the last transition, in $t+6$ (Fig. 2), from the time of occurrence. For example, the reward fetched after transmitting the third transition, Fig. 2, is $e^{-2}$ ($<1$). If the sensor was active in time slot $t+6$, then reward is 1 ($e^0$).

The design of a decision-making policy, which is completely intuitive and the key to this research, is as follows:

- Sensor decides to activate and remains active for AI time slots, if sufficient energy is available.
- If the sensor is active and transition occurs, the sensor decides to sleep for SI time slots, since the next transition is expected to occur after some time and meanwhile the sensor may get recharged. However, an active sensor may also decide to sleep if sufficient energy is not available.
- If sufficient energy is not available, to activate, the sensor eventually dies. To activate, sensor must possess energy greater than the threshold level.
- As soon as the sensor is activated it first checks for any missed transition by comparing the observation made before deactivating and the current observation.

Any decision-making policy should decide the required Active Interval (AI) and Sleep Interval (SI), and is an event process based decision. Hence, during ON (OFF) period $AI=AI_{ON}(AI_{OFF})$, and $SI=SI_{ON}(SI_{OFF})$.

The best decision-making policy is a Four-Timer policy, and possesses a unique property called Toggle for ON and Vary for OFF (TOVO). The optimal values of AI/SI are $AI_{ON}=SI_{ON}=1$, $AI_{OFF}=AI^*(\geq1)$, and $SI_{OFF}=SI^*(\geq1)$. Since $AI_{ON}$ and $SI_{ON}$ are equal to 1, we consider them to toggle between each other. $AI^*$ and $SI^*$ are the optimal values of $AI_{OFF}$ and $SI_{OFF}$, respectively. This property is observed to hold for various system parameters. The performance of this policy can be characterized using a loose upper bound, and a tight lower bound, Figure. 3. By operating at optimal values, the sensor is able to have an energy balance in the given interval and the energy recharged will be energy discharged, Figure 4.

3. Conclusions

We have developed a novel, intuitive and simple decision-making policy for a single rechargeable sensor that achieves high performance under energy constraints.

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