Experimental Insights into Quality of Information

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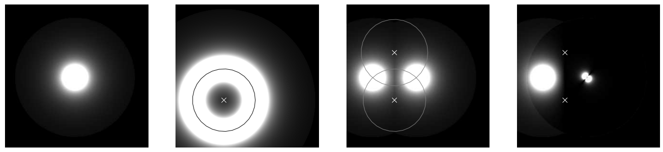
***Abstract*—In this paper we examine the Quality of Information (QoI) at the output of a wireless sensor network by considering the difference between the monitored environment and the interpreted data produced by the network. Using practical examples in an experimental setting, we hope to shed light on the concept of QoI and on the manner of estimating and evaluating it. We use a real wireless network of thirty-four Motes, in combination with simulated events, to help us formulate and understand the concept of QoI and its associated technical questions. Using algorithms such as trilateration and clustering to interpret the outputs of the sensor network, we explore several definitions of QoI, incorporating peak signal to noise ratio and the proportion of correctly detected events. Furthermore we investigate the impact that different packet transmission approaches have on the QoI and network power use. We show that QoI is time-varying, and that in-network processing allows QoI levels to be maintained while reducing network load.**

Sensor systems are an integral part of military command and control systems and the Quality of Information (QoI) delivered by a sensor network (SN) is a very important area of concern. The QoI of a SN can be viewed informally as the difference between the data that the output of the SN produces concerning some "environment" that is being monitored, and the actual events in that environment which one wishes to observe or track. Although various definitions of QoI have been proposed [1], [2], it is fair to say that there is no agreed overall definition that is as well accepted as, say, the definitions of Quality of Service (QoS) in communication networks, or Quality of Images in computer vision.

We consider simple practical examples in an experimental setting, in the hope of shedding light on the concept of QoI and on the manner of estimating and evaluating it. The setting that is being considered includes a number of wireless sensing Motes, each of which contains a light detector. The radio of the Motes allows each Mote to send packets to its neighbours, and over multiple hops all the way to a single output "sink" Mote which collects all the packets that it receives. We switch small lights of fixed brightness on and off in the area of the SN. The intensity of each light follows an inverse square law over the distance from their location. When a light is on, the Motes which are close enough to the light can sense that it is on, and approximately measure the intensity of the light, but cannot sense the direction from which the light is coming. Provided that only one light turns on at a time, the sink Mote can deduce the range of a particular light to the Mote that is reporting it. Therefore a single reading will be interpreted at the receiver as a **circle** with the Mote at its centre. With readings from two Motes, the information at the output of the SN is in the form of the **intersection** of two approximately defined circles. It is easy to imagine how the information at the sink becomes difficult to interpret if there are many Motes, and many light sources which may be on simultaneously. Note that in this paper we use "lights" as a surrogate source of radiation instead of more sophisticated means such as other wireless radio signals.



(a) Location of the light in reality (b) Sensed interpretation using a single Mote (c) Sensed interpretation using a two Motes (d) Difference between (a) and (c)

Fig. 1. Example interpretation at the sensor network output of one or two readings. The location of the Motes reporting measurements is shown by small crosses.

Consider an observer with a bird's-eye view of the environment that captures a video sequence G_t of the events on the ground. We therefore record the state of all the light points on the usually dark ground at time t. Suppose that at the sink there is an algorithm which tries to recreate the image that is reported by the camera. Due to errors introduced by network delays and losses, the video sequence V_t the output of the SN produces will be an approximation of G_t. Now consider the two frames G_t and V_t at the same time instant t; we can think of G_t as the signal, while V_t is the "signal plus noise". Thus we define the **mean square error** or noise M_t, and the **peak signal to noise ratio** (PSNR) Q_t, at time t as:

$$M_t = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}[G_t(i,j) - V_t(i,j)]^2}{I \times J} \quad (1)$$

$$Q_t = \frac{max\{G_t(i,j) : 1 \leq i \leq I, 1 \leq j \leq J\}}{M_t} \quad (2)$$

where $G_t(i,j)$ and $V_t(i,j)$ are the pixel values of G_t and V_t respectively, and $I \times J$ is the size of the frame. We may use either Q_t or M_t as the QoI produced by the SN at time t. One may however wish to be more sophisticated, and consider both accuracy in detection and false alarms. Clearly this discussion has not exhausted, by far, the question of how QoI can be defined but it hopefully provides some insight into the factors

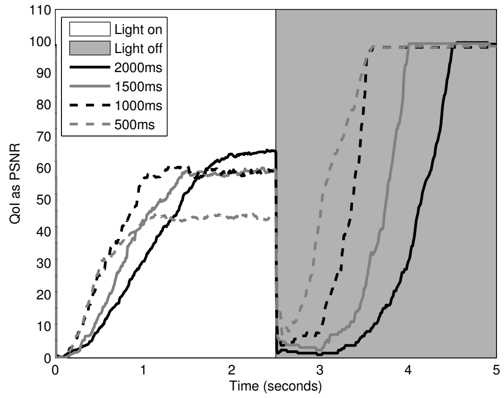


Fig. 2. An ensemble average of the QoI over the light's on and off cycles.

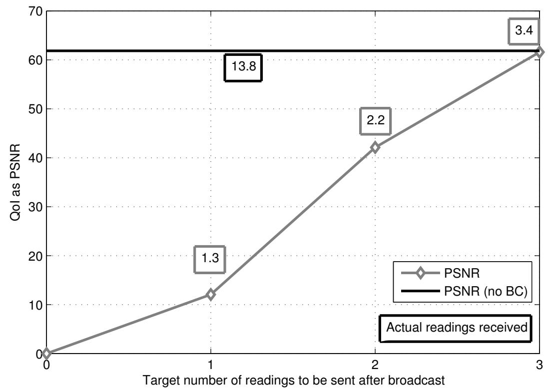


Fig. 3. QoI resulting from only the top n readings, possible due to broadcasts. The mean number of readings used for each value of n is shown above the PSNR values.

we may consider, and some of the quantitative approaches that can be pursued.

In the approach that we have suggested we see that QoI will be a time varying quantity, which will also depend on network delays, computational delays, network losses, and on the algorithms that are used to obtain the view V_t at the SN output. In our first experiment, the setting uses 20 wireless sensing Motes, placed at regular intervals of $1m$, in a $4m \times 5m$ rectangular grid, and an additional 14 routing Motes including the sink. A single light turns on and off *every two and a half seconds* in a random location within the area of the SN. The light has a brightness which can be sensed by a Mote up to a distance of $125cm$, but not beyond. The Motes themselves take measurements at some predefined sampling rate and transmit their readings over multiple hops to the sink, where they are used to create the view V_t. Figure 2 shows an ensemble average of the time varying PSNR for one "on" and "off" period resulting from this approach. When the light is off, we treat the absence of light as our signal by inverting the frame in G_t. As packets arrive at the sink with readings of zero, or as the validity of existing readings expires, we can recreate this frame perfectly so the PSNR rises to 100 (the limit we have arbitrarily applied). We can see that the *latency* between the light turning on or off and the arrival of measurements at the SN output results in a gradual increase in the PSNR or QoI, with faster sampling rates resulting in lower latencies. However, for a sampling interval of $500ms$, this benefit is not evident, and additionally the QoI achieved is lower than in the other cases. The extra load this sampling rate places on the network results in a significantly higher packet loss rate of 0.48, compared to 0.07 with a $2000ms$ sample interval.

We have run experiments using a different approach to packet transmission, where our aim is to reduce the overall network traffic. When a Mote senses the presence of light it broadcasts its reading so that other Motes in the area, which may have also sensed the same light, receive it. This allows the Motes to intelligently determine whether to transmit their readings to the SN output. For example, only the Mote with the strongest reading (logically the Mote closest to the origin of the light) may transmit its reading. This approaches should reduce the number of packets travelling on the multi-hop route to the SN output as well as the power consumption. In Figure 3 we show results from experiments where the Motes with the top n readings send their readings. The PSNR values shown are the mean of those achieved by the time just before the light turns off. The results from an equivalent experiment where all Motes are sending their readings are shown for reference. We see that, when using broadcasts, there is an approximately linear relationship between n and the QoI. The number of readings received at the sink is slightly higher than n, as some Motes may not receive all broadcasts, and therefore transmit their readings despite not having one of the n strongest readings.

A full version of this paper will appear in the proceedings of MASS 2008 [3]. There we observe how, in this context, QoI is influenced by sampling rate, network properties, and the nature and complexity of the scenario and monitored environment. By treating the environment as a series of video frames and fusing the outputs to reconstruct these frames, the PSNR can be meaningfully applied to the problems as a QoI metric.

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