Information Retrieval and Processing in Sensor Networks: Deterministic Scheduling vs. Random Access

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Abstract — **The effect of medium access control (MAC) for information retrieval on signal field reconstruction in large-scale sensor networks with finite density is analyzed. Two MAC schemes are compared: the deterministic scheduling and random access. For fixed sensor density, we show that there is a critical threshold of $e^{-\lambda(1+o(1))}$, where λ is the throughput of the random access protocol, on the sensor outage probability P_{out} beyond which the reconstruction performance of deterministic central scheduling is inferior to that of distributed random access.**

I. Summary

For many applications, a sensor network operates in three phases: sensing, information retrieval, and information processing. An appropriate network architecture for such applications is Sensor Networks with Mobile Access (SENMA) [1] which has two types of nodes: simple-functioning sensors randomly deployed in large number and a few powerful mobile access points that communicate with sensors. We focus on the latter two phases in SENMA. Specifically, for a signal field, we examine the effect of MAC for information retrieval on signal field reconstruction in a network with fixed sensor density.

We consider a 1-D field $\mathcal{A} = [0, D]$. The signal of interest $S(x)$ in $\mathcal{A}$ is assumed to be a homogeneous Ornstein-Uhlenbeck field with $S(x) \sim \mathcal{N}(0, \sigma_s^2)$. We assume that the randomly deployed sensors in $\mathcal{A}$ forms a 1-D homogeneous spatial Poisson field with local density ρ. At a prearranged time, all sensors take measurements. The measurement of a sensor at location x is $Y(x) = S(x) + N(x)$, where $N(x) \overset{i.i.d.}{\sim} \mathcal{N}(0, \sigma_N^2)$. Each sensor then stores its measurement along with the location information in a packet for collection.

Assuming slotted transmissions in a collision channel, we consider deterministic scheduling π_D and random access π_R for information retrieval within M slots of collection time. In π_D, when there exist sensors everywhere, schedule M equally-spaced sensors locations to transmit data is optimal [2]. For finite sensor density, to avoid scheduled locations void of sensors, the scheduler π_D enables a resolution interval of length ϵ centered at each desired location and collects one packet from each interval. If there are no sensors in a resolution interval, we say a sensor outage occurs. For the target probability of sensor outage P_{out}, the smallest interval length ϵ should satisfy

$$P_{\text{out}} = P[N(\epsilon) = 0] = e^{-\rho\epsilon}. \tag{1}$$

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In π_R, in contrast, sensors contend to access the channel with equal priority. The origins of received packets are random.

Assume M_o packets from distinct sensors are received within M slots of collection time. Let $\mathbf{p}_{M_o} = \{P_1, \cdots, P_{M_o}\}$ be the locations of the received packets. We estimate $S(x)$ at x using its two immediate neighbor samples by the MMSE smoothing. Let SNR $\triangleq \sigma_s^2/\sigma_N^2$. Given $\mathbf{p}_{M_o}$, we define the maximum field reconstruction distortion by

$$\mathcal{E}(\mathbf{p}_{M_o}, \text{SNR}) \triangleq \max_{x \in \mathcal{A}} E\{|\hat{S}(x) - S(x)|^2 \mid \mathbf{p}_{M_o}\} \tag{2}$$

where $\hat{S}(x)$ is the estimate of $S(x)$. The expected maximum distortion with a MAC is given by

$$\bar{\bar{\mathcal{E}}}(M, \text{SNR}) \triangleq E\{\mathcal{E}(\mathbf{p}_{M_o}, \text{SNR})\} \tag{3}$$

where the expectation is taken over locations $\mathbf{p}_{M_o}$ for $M_o = m$ and sample size M_o.

To compare the signal reconstruction distortion of the two MAC schemes, we define the ratio of excess distortion of π_R to that of π_D as

$$r \triangleq \frac{\bar{\bar{\mathcal{E}}}_R(M, \text{SNR}) - \bar{\bar{\mathcal{E}}}_R(\infty, \text{SNR})}{\bar{\bar{\mathcal{E}}}_D(M, \text{SNR}) - \bar{\bar{\mathcal{E}}}_D(\infty, \text{SNR})} \tag{4}$$

where $\bar{\bar{\mathcal{E}}}_R(\infty, \text{SNR})$ and $\bar{\bar{\mathcal{E}}}_D(\infty, \text{SNR})$ are the limiting distortions for a given SNR, defined by $\bar{\bar{\mathcal{E}}}(\infty, \text{SNR}) \triangleq \lim_{M\to\infty} \lim_{\rho\to\infty} \bar{\bar{\mathcal{E}}}(M, \text{SNR})$, which can be shown to be the same for π_D and π_R. The relative performance of π_R and π_D, therefore, depends on the value of r comparing with 1. The following theorem shows the expression of r and the condition for $r > 1$ (or < 1) in a network with large ρD.

Theorem 1 *Given $P_{out} > 0$, for all large M, there exist $\bar{N}_o(M) < \infty$, such that for all $\rho D > \bar{N}_o(M)$, the excess distortion ratio r is given by*

$$r = \ln P_{out}^{-\frac{1}{\lambda(1+o(1))}} \cdot \frac{1 + O(\frac{\ln\ln M}{\ln M})}{1 + O(\frac{\ln\ln M}{\ln M}) + \ln\frac{1}{P_{out}} O(\frac{1}{\ln M})} \tag{5}$$

where λ is the throughput of π_R. Furthermore, for large enough M, $r > 1$ for $P_{out} < e^{-\lambda(1+o(1))}$ and $r < 1$ for $P_{out} > e^{-\lambda(1+o(1))}$.

From (1), the threshold on P_{out} can be translated to the threshold of $\lambda(1 + o(1))$ on the expected number of sensors in each resolution interval, $\rho\epsilon$.

References

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