On the Local Sensor Signaling for Inference Centered Wireless Sensor Networks

Biao Chen†

Extended Summary

Emerging wireless sensor network (WSN) technology has attracted steady interest among researchers from various fields. The fundamental task, ubiquitous to most WSN applications, is to convey useful information collected at distributed sensors to a decision maker. As such, much of the current work in WSN employs a data-centric approach – the objective there is to recover the original sensor observations under a fidelity measure. While appropriate for applications where the sensor observations are of primary interest (e.g., 2-D and 3-D measurement of temperature, CO_2 density, etc.), this data-centric approach may waste significant resources for inference-centered WSN where the primary goal is successful assessment of certain situation (e.g., detection of a target or a hazardous event).

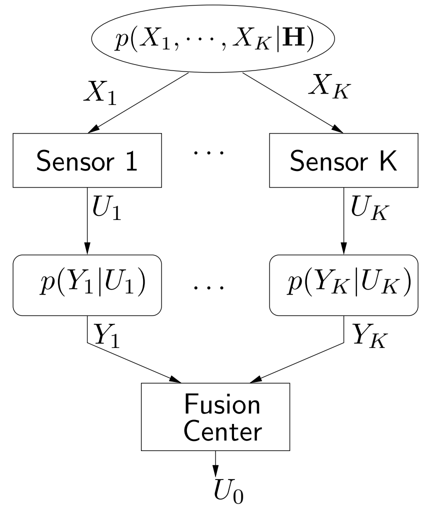
In this work, we consider a distributed detection problem and examine the local sensor signaling schemes to achieve optimal detection performance. Taking into account the omnipresent transmission channels for any wireless systems, a central theme is the integration of processing and transmission: the design of local processing should be channel informed. The present work indeed can be considered a dual problem to that studied in [1, 2] where channel-aware decision fusion algorithms at the fusion center were developed. Two cases are presented below. Assuming perfect channel knowledge (in terms of conditional probability function), we first establish optimality condition for local sensor decision rules under a Bayesian criterion. In the absence of channel knowledge, robust sensing through integrated processing/transmission design is investigated to combat potential link failure.

Optimal local signaling with channel knowledge

Denote by $\mathbf{H}_0$ and $\mathbf{H}_1$ the two hypotheses under test. We establish in this part the form of optimum local sensor decision rule in the presence of non-ideal transmission channels. We show that under certain conditions that are easily satisfied in practice, the optimum local decision rules turn out to be the likelihood ratio test (LRT). The optimality of LRT for local decision have been established for binary hypothesis testing under the conditional independence assumption [3–6]. These results, while obtained under various system setting and different criteria, all require that local decisions be accessible at the fusion center. The design of local decision rules in the presence of possible channel errors has been addressed under the NP criterion [7, 8]. There, optimality (in the person-by-person optimaization, or PBPO, sense) of LRT was established by assuming a simple binary symmetric channel (BSC) model between each sensor and the fusion center. Our approach is to adopt the Bayesian criterion to minimize

†The author is with Syracuse University, Department of EECS, 121 Link Hall, Syracuse, NY 13244. Phone/Fax: (315)443-3332/2583. Email : bichen@ecs.syr.edu.

the error probability at the fusion center. Further, we do not restrict ourselves to any specific channel types except that it is a parallel vector channel (cf. the figure below and equation (1)). The main result is summarized in the following theorem [9].



Theorem 1 *Assume that the local observations, X_k's, are conditionally independent and that the channels between sensors and the fusion center are characterized by*

$$p(Y_1, \cdots, Y_K|U_1, \cdots, U_K) = \prod_{k=1}^{K} p(Y_k|U_k) \tag{1}$$

If the fusion rule and the k^{th} local decision satisfy

$$P(U_0 = 1|\mathbf{y}^k, U_k = 1) - P(U_0 = 1|\mathbf{y}^k, U_k = 0) \geq 0 \tag{2}$$

$$P(U_0 = 0|\mathbf{y}^k, U_k = 0) - P(U_0 = 1|\mathbf{y}^k, U_k = 1) \geq 0 \tag{3}$$

where $\mathbf{y}^k = [y_1, \cdots, y_{k-1}, y_{k+1}, \cdots, y_K]$, with y_k being the observation of the channel output corresponding to the k^{th} sensor, then the optimum local decision rule for the k^{th} sensor amounts to the following LRT

$$U_k = \gamma_k(X_k) = \begin{cases} 1 & \text{if } \frac{p(x_k|H_1)}{p(x_k|H_0)} > \frac{\pi_0 \int_{\mathbf{y}^k} [P(U_0=1|\mathbf{y}^k, U_k=1) - P(U_0=1|\mathbf{y}^k, U_k=0)] p(\mathbf{y}^k|H_0) d\mathbf{y}^k}{\pi_1 \int_{\mathbf{y}^k} [P(U_0=0|\mathbf{y}^k, U_k=0) - P(U_0=0|\mathbf{y}^k, U_k=1)] p(\mathbf{y}^k|H_1) d\mathbf{y}^k} \\ 0 & \text{if } \frac{p(x_k|H_1)}{p(x_k|H_0)} < \frac{\pi_0 \int_{\mathbf{y}^k} [P(U_0=1|\mathbf{y}^k, U_k=1) - P(U_0=1|\mathbf{y}^k, U_k=0)] p(\mathbf{y}^k|H_0) d\mathbf{y}^k}{\pi_1 \int_{\mathbf{y}^k} [P(U_0=0|\mathbf{y}^k, U_k=0) - P(U_0=0|\mathbf{y}^k, U_k=1)] p(\mathbf{y}^k|H_1) d\mathbf{y}^k} \end{cases} \tag{4}$$

where $\pi_0 = P(\mathbf{H}_0)$ and $\pi_1 = P(\mathbf{H}_1) = 1 - \pi_0$ are the prior probabilities.

Remarks

- Conditions (2) and (3) amount to requiring that the fusion center employ a "monotone" fusion rule, hence are easily satisified by any sensible design.
- The PBPO approach implies that the obtained result is a necessary, not sufficient, condition for optimality. Multiple initializations may be needed to obtain global optimum.
- The test described in (4) for the k^{th} sensor is clearly coupled with the fusion rule as well as all the other sensors' local decision rules. Thus, applying Theorem 1 requires iteration among all the local sensor decision rules and the fusion rule.
- A close inspection of $\gamma_k(\cdot)$ in (4) also shows that the threshold for the LRT is directly affected by the transmission channels (embedded in the terms $P(U_0|\mathbf{y}^k, U_k)$ and $p(\mathbf{y}^k|H_i)$), indicating that the optimal sensor processing needs to be channel informed.

When the distributions under test have a monotone likelihood ratio [10], the test in (4) can often be translated as a simple thresholding of the observation itself hence is in essence a binary quantizer. The fact that this binary quantizer is channel informed suggests that the obtained local sensor decision rules can be considered as a distributed channel optimized source code. Notice the difference between this and conventional joint source-channel code: this binary quantizer is inference-driven (i.e., to minimize error probability) rather than data-centric (e.g., to minimize mean square error as used in [11, 12]). A design example will be presented to illustrate how to apply Theorem 1 in finding optimum local decision rules and how the channel characteristics affect the local decision rules.

Robust sensing using distributed multiple description signaling

For sensor networks operating in interference-rich and multipath-induced fading channels, it is inevitable that some transmissions may be lost. Furthermore, sensor failures happen more frequently to low-cost sensors in harsh environment. Thus, there is a great need to develop distributed signal processing algorithms that are robust to transmission/sensor failures. While sensor deployment and signal processing algorithms for fault tolerant sensor networks have been investigated (see, for example, [13]), addressing this issue from an integrated signal transmission and processing point of view has not been reported before.

This work is motivated by the multiple description code (MDC) that has been widely studied to combat transmission loss, mostly in the context of speech and image transmission [14]. As illustrated in Fig. 1(a) with two encoders and three decoders, the encoders are so designed that in the case of loss of one of the two channels, the decoder output is guaranteed with certain acceptable performance; while in the case of successful transmission of both sources, the decoder output (corresponding to Decoder 2) will have enhanced performance. While this principle may be carried over to WSN applications, the distributed nature makes it drastically different than the conventional MDC. In conventional MDC, the two encoders encode a common source, while in the context of WSN, each encoder encodes its own observations without access to the other's input source. This distributed MDC is illustrated in Fig. 1(b) and is termed **distributed multiple description signaling** (DMDS).

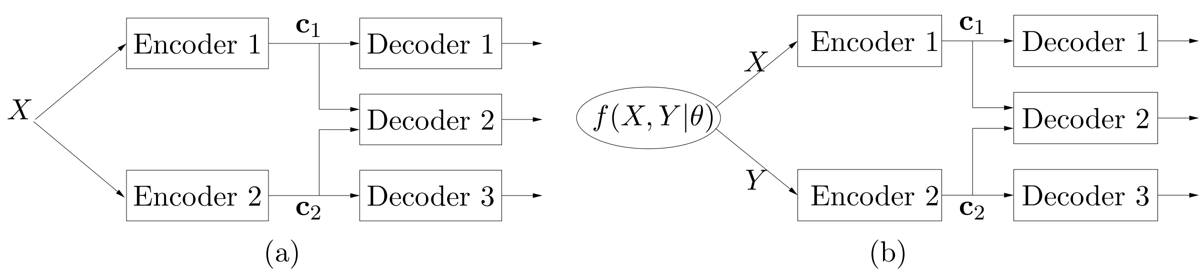


Figure 1: (a) Conventional MDC; (b) Distributed multiple description signaling.

The key to employing DMDS in WSN is to exploit the correlation among sensor observations. Notice this is true even under the usual and convenient assumption of conditional independence – the observations are still marginally correlated in the Bayesian framework when the underlying unknown parameter is considered random. Consider, for example, a binary detection problem using two sensors. In reference to Fig. 1(b), if only one of the two transmissions is successful, the best achievable performance is for each sensor to employ a maximum *a posteriori* (MAP) detector. Hence the question: if each sensor is designed to be the optimal detector with its own observation, will it attain the best possible performance when both transmissions are successful? We show that, using a simple two-sensor example with i.i.d. sensor observations under any given hypothesis, the MAP detectors employed at the local sensors do not yield optimal detection performance for Decoder 2. In short, performance at local sensors and at the fusion center are two conflicting requirements, much in the same way as the achievable minimum distortion in conventional MDC [15]. Simple geometric interpretation will be given to illustrate the rationale behind this performance conflict, as well as attempts to obtain achievable performance region for DMDS (using, for example, minimum achievable error probability), similar to that of the rate distortion region for conventional MDC [15].

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