A Bandwidth-Efficient Soft-Decision Scheme for Distributed Binary Detection in Sensor Networks

Victor W. Cheng
Dept. of Comp. Sci. and Information Eng.
National Chi Nan University
Taiwan
Email: vicwk@csie.ncnu.edu.tw

Tsang-Yi Wang
Inst. of Communications Eng.
National Sun Yat-sen University
Taiwan
Email: tcwang@mail.nsysu.edu.tw

Hao Wang
Inst. of Communications Eng.
National Sun Yat-sen University
Taiwan
Email: u0222130@gmail.com

***Abstract*—The soft-decision fusion scheme on sensor detection in wireless sensor networks is able to improve the detection performance on the final decision made at the Fusion Center (FC). In this paper, a bandwidth-efficient transmission scheme using the soft-decision fusion scheme is proposed for distributed binary detection. In the scheme, the source coding is through the quantization process, but the output of the quantizer is analogously transmitted to the FC. In the FC, the Maximum-a-Posteriori (MAP) fusion rule is adopted to make the final decision. The problem of huge channel bandwidth demand can be avoided by using the considered data transmission scheme. The proposed scheme is illustrated with numerical examples highlighting its significant improvement in error performance at the FC as compared with the hard-decision scheme.**

Keywords–Distributed detection; bandwidth efficiency; fusion rule; wireless sensor networks.

I. Introduction

Distributed detection fusion using multiple sensors has a lot of applications in Wireless Sensor Networks (WSNs) [1] [2]. Conventionally, in the distributed parallel fusion network, a phenomenon in a specified environment is first observed by a sensor, and a decision based on the observation is made without exchanging the information with other local sensors. Then, each sensor transmits a signal to the Fusion Center (FC), where the final decision is made.

In contrast to the binary local decision case [3], many works have also studied the case of soft-decision fusion, in which the sensor observation is divided into M regions, where M is an arbitrary integer with $M > 2$ [4]–[11]. However, all the works mentioned above assume that the information of soft local decision is digitally transmitted to the FC, in which the information of each quantization level is mapped to several digital bits and the local quantizer output corresponding to the received quantization level is then utilized by the FC to make its final decision. As opposed to the existing works mentioned above, this study considers bandwidth-efficient transmission between the local sensors and FC in designing the soft-decision fusion scheme on the sensor observation. Specifically, the output of the quantizer is analogously transmitted to the FC. In the FC, the Maximum-a-Posteriori (MAP) fusion rule is adopted to make the final decision. Hence, by the proposed scheme, the problem of huge channel bandwidth demand can be avoided.

In the proposed scheme, the detection on the phenomenon is divided into M regions, where M is an arbitrary integer with $M \geq 2$. When the detection falls within a specific region, a conditional mean is adopted as a representation of the observation in the region. The goal of the proposed scheme is to minimize the decision errors at the FC with the MAP fusion rule via optimizing the region allocation.

The rest of this paper is organized as follows. Section II first depicts the proposed M-ary scheme for binary distributed detection problem. Section III shows the error performance of the M-ary scheme and its comparison with that of the conventional hard-decision scheme. Section IV concludes this work and discusses possible directions in the future.

II. Design of Soft-decision Fusion Scheme

In a binary detection environment under binary hypothesis H_0 and H_1 shown in Figure 1, assume a phenomenon A either $H_0 : A = \gamma$ or $H_1 : A = -\gamma$, where $\gamma > 0$, occurs symmetrically with equal prior probability $P[H_0] = P[H_1] = 0.5$. L sensors observe the measurements generated from H_0 or H_1 and the observation value by the l-th sensor is denoted by W_l, where $l = 1, \ldots, L$. W_l is independent and identically distributed (i.i.d.) from sensor to sensor. Also, assume $H_0 : W_l = \gamma + \eta_l$; $H_1 : W_l = -\gamma + \eta_l$, where η_l is a standard normal random variable. The probability density function (PDF) of W_l conditioned on H_0 or H_1 is $f_{W_l|H_0}(w) = e^{-(w-\gamma)^2/2}/\sqrt{2\pi}$ or $f_{W_l|H_1}(w) = e^{-(w+\gamma)^2/2}/\sqrt{2\pi}$. In the considered parallel fusion networks, the l-th sensor makes its own decision X, independent of all other nodes.

In this study, an M-ary source coding algorithm is applied on the observation at each sensor, where W_l at the l-th sensor is divided into M equally spaced regions, as shown in Figure 1. When M is even ($M = 2N$), the $2N$ regions are $I_{-N}, I_{-(N-1)}, \ldots, I_{-1}, I_1, \ldots, I_N$, and the $(2N-1)$ boundaries are $-(N-1)\Delta, -(N-2)\Delta, \ldots, -\Delta, 0, \Delta, \ldots, (N-1)\Delta$. Δ is the width of each region except for the two end regions I_{-N} and I_N. Similarly, when M is odd ($M = (2N+1)$), the $2N+1$ regions are $I_{-N}, I_{-(N-1)}, \ldots, I_{-1}, I_0, I_1, \ldots, I_N$, and the $2N$ boundaries are $-(N-\frac{1}{2})\Delta, -(N-\frac{3}{2})\Delta, \ldots, -\frac{1}{2}\Delta, \frac{1}{2}\Delta, \ldots, (N-\frac{1}{2})\Delta$. We define $p_n = P[W_l \in I_n|H_0] = Q(d_{low} - \gamma) - Q(d_{up} - \gamma)$, where $n = -N, -(N-1), ..., N$, d_{low} and d_{up} denote the lower and upper bounds of I_n, i.e., $I_n = \{W_l|d_{low} < W_l < d_{up}\}$, Q denotes the Q-function, and P denotes the probability function. p_n is the probability that W_l falls within region I_n when H_0 occurs. $(d_{up} - d_{low})$ is Δ except for I_{-N} and I_N,

 ISBN: 978-1-61208-744-3

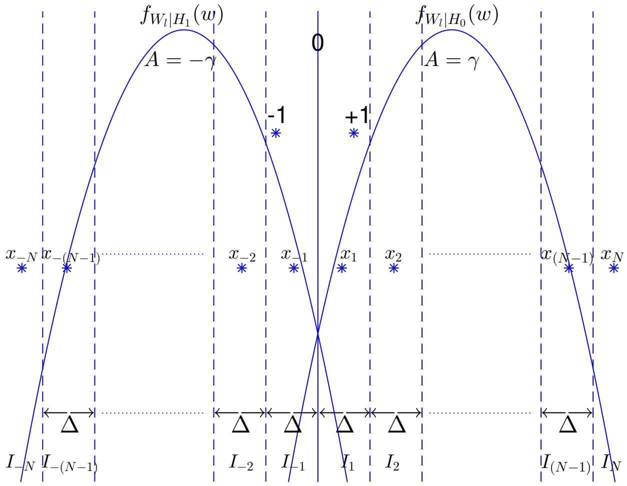

Figure 1. WSN with M-ary source coding on sensor detection

where $d_{low} = -\infty$ for I_{-N} and $d_{up} = \infty$ for I_N. From symmetry, $P[W_l \in I_n|H_1] = P[W_l \in I_{-n}|H_0] = p_{-n}$.

M-level quantization X is applied on the observation and $X = x_n$ is the representation value of the n-th region I_n. At the l-th sensor, x_n is defined as the conditional mean when W_l falls in I_n, i.e., $x_n = E[W_l|W_l \in I_n] = P[H_0]E[W_l|H_0, W_l \in I_n] + P[H_1]E[W_l|H_1, W_l \in I_n]$. From symmetry, $x_{-n} = -x_n$ and $x_0 = 0$.

The signal s_l transmitted to the FC by the l-th sensor is $x_n\sqrt{E}$, according to the decision on $W_l \in I_n$. Given γ and E/N_0, the goal of the proposed algorithm is to minimize the error rate P_e of the final decision at the FC via varying Δ to obtain the optimal region allocation. The average consumed energy $\bar{E}$ of the transmitted signal is $\bar{E} = \sum_{n=-N}^{N} p_n x_n^2 E$.

III. Results

The received signal from the l-th sensor at the FC is $R_l = s_l + n_l$, and the PDF of R_l is

$$\begin{aligned} f_{R_l|H_0}(r_l) &= \sum_{n=-N}^{N} \frac{p_n e^{-(r_l - x_n\sqrt{E})^2/N_0}}{\sqrt{\pi N_0}} \\ f_{R_l|H_1}(r_l) &= \sum_{n=-N}^{N} \frac{p_{-n} e^{-(r_l - x_n\sqrt{E})^2/N_0}}{\sqrt{\pi N_0}} \\ &= \sum_{n=-N}^{N} \frac{p_n e^{-(r_l + x_n\sqrt{E})^2/N_0}}{\sqrt{\pi N_0}} = f_{R_l|H_0}(-r_l) \end{aligned}$$

After all the received signals $R_1, R_2, , R_L$ have been collected at the FC from each of the sensors, the optimal Maximum-a-Posteriori (MAP) rule is applied to obtain the final decision $\hat{A} = \pm\gamma$, i.e., H_0 or H_1.

$$f_{R_l,R_2,\ldots,R_L|H_0}(r_l, r_2, \ldots, r_L) \underset{\hat{A}=-\gamma}{\overset{\hat{A}=\gamma}{\gtrless}} f_{R_l,R_2,\ldots,R_L|H_1}(r_l, r_2, \ldots, r_L).$$

Since $R_1, R_2, \ldots, R_L$ are assumed i.i.d., the MAP fusion rule at the FC is the combination of the log-likelihood.

$$\sum_{l=1}^{L} \log(f_{R_l|H_0}(r_l)) \underset{\hat{A}=-\gamma}{\overset{\hat{A}=\gamma}{\gtrless}} \sum_{l=1}^{L} \log(f_{R_l|H_1}(r_l)). \quad (1)$$

Without loss of generality, assume H_0 occurs, i.e., $A = \gamma$, and thus the error probability P_e of the final decision is

$$P_e = P\left[\sum_{l=1}^{L} \log(\frac{f_{R_l|H_0}(r_l)}{f_{R_l|H_1}(r_l)}) < 0\right]. \quad (2)$$

No closed form of P_e is obtained. Nevertheless, given γ, N, L, Δ, and E/N_0, P_e is derived via numerical analysis, and is optimized, i.e., minimized, by revising Δ iteratively.

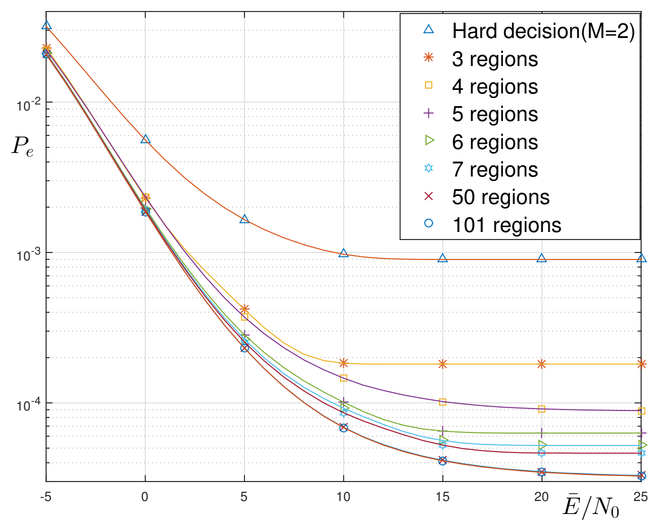

Figure 2. Fusion performance of the proposed soft-decision fusion scheme

We conduct the performance comparison of the proposed soft-decision scheme and the hard-decision scheme. Figure 2 illustrates P_e of the WSN under the proposed soft-decision fusion scheme with $\gamma = 1$. As it can be seen, P_e is lower than that of the hard-decision fusion system and is improved as M increases. No significant difference exists between $M = 50$ and $M = 101$. Furthermore, the flooring of the curves is observed at high signal-to-noise ratio (SNR), which is due to the fact that the erroneous behavior of the transmitted signal to the FC vanishes as SNR increases and hence the error performance is from the decision made by each sensor only.

IV. Conclusion

In this paper, a new M-ary scheme on the decentralized detection in WSN using analog transmission is proposed and examined. The problem of huge channel bandwidth demand is avoided by using the considered M-ary scheme. The goal of minimizing the decision errors at the FC via optimizing the region allocation is achieved. The error performance of the M-ary scheme is better than that of the hard-decision scheme. The behavior of the M-ary scheme when the transmitted signal to the FC is under a fading environment is open to further study.

 ISBN: 978-1-61208-744-3

Acknowledgment

This work is sponsored by the Ministry of Science and Technology of Taiwan (MOST) under grant MOST 106-2221-E-110-016-MY3.

References

[1] Q. Cheng, P. K. Varshney, J. H. Michels, and C. M. Belcastro, "Fault detection in dynamic systems via decision fusion," IEEE Transactions on Aerospace and Electronic Systems, vol. 44, no. 1, January 2008, pp. 227–242.

[2] Q. Ling, Z. Tian, and Y. Li, "Distributed decision-making in wireless sensor networks for online structural health monitoring," Journal of Communications and Networks, vol. 11, no. 4, August 2009, pp. 350–358.

[3] P. K. Varshney, Distributed Detection and Data Fusion. New York: Springer, 1997.

[4] S. C. A. Thomopoulos, R. Viswanathan, and D. C. Bougoulias, "Optimal decision fusion in multiple sensor systems," IEEE Transactions on Aerospace and Electronic Systems, vol. AES-23, no. 5, September 1987, pp. 644–653.

[5] S. Saha, A. Kumar, Priyanka, and R. Bhattacharya, "An LLR based cooperative spectrum sensing with hard-soft combining for cognitive radio networks," in 32nd International Union of Radio Science General Assembly Scientific Symposium (URSI GASS), Montreal, Canada, August 2017, pp. 1–4.

[6] M. Xiang and C. Han, "Global optimization for distributed and quantized bayesian detection system," in Proceedings of the Third International Conference on Information Fusion, Paris, France, July 2000, pp. ThC4 25–30.

[7] H. Varaee, G. Mirjalily, and A. Pouramini, "An analytical technique to determine the decision thresholds of multi-bit distributed detection in sensor networks," in 2009 Second International Conference on Computer and Electrical Engineering, Dubai, United Arab Emirates, December 2009, pp. 32–35.

[8] X. Fan, D. Duan, and L. Yang, "Multi-bit cooperative spectrum sensing strategy in closed form," in 2013 Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, November 2013, pp. 1473–1477.

[9] A. M. Aziz, "A soft-decision fusion approach for multiple-sensor distributed binary detection systems," IEEE Transactions on Aerospace and Electronic Systems, vol. 47, no. 3, July 2011, pp. 2208–2216.

[10] E. Nurellari, D. McLernon, and M. Ghogho, "Distributed two-step quantized fusion rules via consensus algorithm for distributed detection in wireless sensor networks," IEEE Transactions on Signal and Information Processing over Networks, vol. 2, no. 3, September 2016, pp. 321–335.

[11] H. Kasasbeh, L. Cao, and R. Viswanathan, "Soft-decision-based distributed detection with correlated sensing channels," IEEE Transactions on Aerospace and Electronic Systems, vol. 55, no. 3, June 2019, pp. 1435–1449.

 ISBN: 978-1-61208-744-3