Decision Fusion under a Dynamic Wireless Sensor Network over Noncoherent Multi-Access Channels

Xiao-Guang Yuan, Wei-Tao Zhang, Dong-Zhu Feng, and Feng Han

***Abstract*—In order to solve the decision fusion issue under a dynamic wireless sensor network (WSN) based on noncoherent multi-access channels, a decision fusion rule based on the quadrature components of the information received by fusion center is proposed. It is assumed that the distribution of fading channels submits a Rayleigh distribution and the number of sensors follows a Poisson distribution in the WSN. The analysis and simulation on detection performance of the decision fusion rule are made under different system parameters. Compared with the optimal likelihood ratio decision fusion rule, the proposed decision fusion rule can provide very close detection performance with smaller computation and less information.**

***Index Terms*—Dynamic wireless sensor network, noncoherent multi-access channels, decision fusion, Rayleigh fading, poisson distribution.**

I. Introduction

Recently, due to their high flexibility, robustness, mobility, and cost effectiveness, wireless sensor networks (WSNs) have attracted much attention, and the issues of decision fusion based on WSNs have become a very active research area. Usually, a typical WSN consists of a large number of low-cost and low-power sensors. When the decision fusion is processing, each sensor makes a local decision based on its observation, and transmits its decision to the fusion center via a wireless channel, finally, the fusion center gives a global decision based on the local decisions. Considering the influences of nonideal channels on the decision fusion, fusion rules with the statistical information of channels have been proposed in [1] and [2]. Aiming to improve the performance of decision fusion, in [3] and [4], decision fusion issues in large-scale WSNs has been studied. The above-mentioned researches are based on the parallel access scheme. Under this scheme, an independent wireless channel is required between each sensor and fusion center for information transmission, which requires large communication bandwidth. In order to reduce the requirement of communication bandwidth, some researchers investigated decision fusion issues over multi-access channels [5], [6]. The present researches are based on the static WSNs in which the number of sensors is constant. However, the number of sensors involved in decision making may change dynamically in practice, influenced by the reliability of sensors. Some research on decision fusion in dynamic wireless sensor network is also given in [7]. However, it is assumed that the decisions made by sensors are transmitted to fusion center through a large number of typical parallel channels which is difficult to implement in practical application. For this reason, we will give some results on decision fusion issues in a dynamic WSN over more compact noncoherent multiaccess channels in this paper.

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II. System Model

Fig. 1 shows the system model of a dynamic WSN decision fusion system which consists of local sensors, multi-access channel and fusion center (H_1 means that an event occurs, and H_0 means that an event does not occur). These components are described as below.

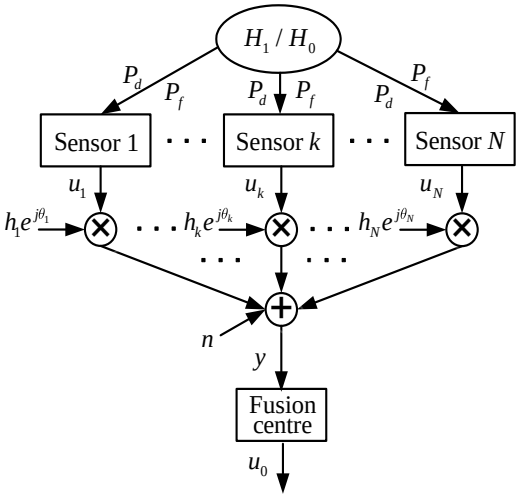


Fig. 1. System model of a dynamic WSN decision fusion system.

A. Local Sensors

Local sensor k (k = 1, 2, …, N) in the system makes the decision u_k according to the observation x_k, and it is assumed that the observations received by sensors are conditioned independent of each other. Moreover, without loss of generality, It is assumed that the number of local sensors involved in decision (denoted by N) submits Poisson distribution:

$$f(N) = \frac{\lambda^N e^{-\lambda}}{N!}, \quad N = 0, ..., \infty. \tag{1}$$

where, λ is the average number of sensors involved in decision.

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When arbitrary sensor k involves in decision, according to its observation x_k, local sensor k makes a binary decision u_k (k=1, …, N): If the H_1 is detected, then u_k = 1 will be made; and if the H_0 is decided, then u_k = 0 will be made. Based on the censoring transmission strategy, the local sensor k only transmits u_k = 1 to the fusion center via the wireless channel. The detection probability and false alarm probability of sensor k are denoted by P_{dk} and P_{fk} , respectively:

$$P_{dk} = P(u_k = 1 | H_1). \quad (2)$$

$$P_{fk} = P(u_k = 1 | H_0). \quad (3)$$

In order to simplify the derivation of decision fusion rule, it is assumed that all the sensors are identical, meaning P_{dk}=P_d and P_{fk}=P_f for all k.

B. Multi-Access Channel

The local decisions of sensors are transmitted via multi-access channel, the information received by fusion center (denoted by y) is:

$$y = \sum_{k=1}^{N} h_k u_k e^{j\theta_k} + n, \quad u_k = 0,1. \quad (4)$$

where h_k is envelope fading of the local decision u_k, which submits Rayleigh distribution with unit power ($E(h_k^2)$=1), and its probability density function (pdf) is:

$$f(h_k) = 2h_k e^{-h_k^2}, \quad h_k \geq 0. \quad (5)$$

And θ_k is phase distortion of the local decision u_k, which submits uniform distribution [0, 2π). n is a zero-mean complex Gaussian noise whose real and imaginary parts have equal variance σ_n^2. Here, we define ρ (Unit: dB) as a measure of noise level of multi-access channel:

$$\rho = 10\log_{10}(1/2\sigma_n^2). \quad (6)$$

C. Fusion Center

Finally, according to received information y, the fusion center makes the global decision u_0, and the system detection and false alarm probabilities are denoted by P_{d0} and P_{f0}, respectively.

$$P_{d0} = P(u_0 = 1 | H_1). \quad (7)$$

$$P_{f0} = P(u_0 = 1 | H_0). \quad (8)$$

III. Decision Fusion Rule

Under the noncoherent channels, the information y received by fusion center can be decomposed into quadrature components, which are denoted by y_I and y_Q, respectively:

$$\begin{bmatrix} y_I \\ y_Q \end{bmatrix} = \sum_{k=1}^{N} \begin{bmatrix} x_{Ik} \\ x_{Qk} \end{bmatrix} u_k + \begin{bmatrix} n_I \\ n_Q \end{bmatrix}. \quad (9)$$

where, x_{Ik}=h_k cosθ_k and x_{Qk}=h_k sinθ_k are i.i.d. Gaussian random variables with mean zero and variance 0.5; n_I and n_Q are i.i.d. Gaussian random variables with mean zero and variance n_I 、n_Q. Using the above y_I and y_Q a decision fusion rule is obtained:

$$\Lambda = y_I^2 + y_Q^2 \underset{H_0}{\overset{H_1}{\gtrless}} \tau. \quad (10)$$

where, τ is the threshold of decision fusion rule, meaning if $\Lambda \geq \tau$, fusion center makes global decision u_0=1; otherwise, fusion center makes global decision u_0=0.

In order to obtain the expressions of the system detection probability P_{d0} and false alarm probability P_{f0}, we derive the conditional pdf of Λ under the hypothesis H_1 and H_0 at first:

$$f(\Lambda = z | H_1) = \sum_{N=0}^{\infty} f(N) f(\Lambda = z | N, H_1)$$

$$= \sum_{N=0}^{\infty} \frac{\lambda^N e^{-\lambda}}{N!} \sum_{k=0}^{N} \binom{N}{k} \frac{(P_d)^k (1-P_d)^{N-k}}{2(k+\sigma_n^2)} e^{-\frac{z}{2(k+\sigma_n^2)}}. \quad (11)$$

$$f(\Lambda = z | H_0) = \sum_{N=0}^{\infty} f(N) f(\Lambda = z | N, H_0)$$

$$= \sum_{N=0}^{\infty} \frac{\lambda^N e^{-\lambda}}{N!} \sum_{k=0}^{N} \binom{N}{k} \frac{(P_f)^k (1-P_f)^{N-k}}{2(k+\sigma_n^2)} e^{-\frac{z}{2(k+\sigma_n^2)}}. \quad (12)$$

Obviously, it is difficult to calculate P_{d0} and P_{f0} using (11) and (12). So, it is necessary to find approximations of (11) and (12). It is noted that when the value of λ in the Poisson distribution is very large, the Poisson distribution approaches a Gaussian distribution. We can get:

$$\sum_{N=N_1}^{N_2} \frac{\lambda^N e^{-\lambda}}{N!} \approx 1. \quad (13)$$

where, N_1= [$\lambda - 6\sqrt{\lambda}$], N_2= [$\lambda + 6\sqrt{\lambda}$], and [ ] is the rounding operation. According to this conclusion and the approximation of $f(\Lambda=z|N,H_1)$ and $f(\Lambda=z|N,H_0)$ in [6], we can get:

$$f(\Lambda = z | H_1) \approx \sum_{N=N_1}^{N_2} \frac{\lambda^N e^{-\lambda}}{N!} \cdot \frac{1}{2(NP_d + \sigma_n^2)} e^{-\frac{z}{2(NP_d + \sigma_n^2)}}. \quad (14)$$

$$f(\Lambda = z | H_0) \approx \sum_{N=N_1}^{N_2} \frac{\lambda^N e^{-\lambda}}{N!} \cdot \frac{1}{2(NP_f + \sigma_n^2)} e^{-\frac{z}{2(NP_f + \sigma_n^2)}}. \quad (15)$$

With (14) and (15), the P_{d0} and P_{f0} can be approximated to:

$$P_{d0}=\int_{\tau}^{\infty} f\left(\Lambda=z\mid H_1\right)dz=\sum_{N=N_1}^{N_2}\frac{\lambda^N e^{-\lambda}}{N!}e^{-\frac{\tau}{2\left(NP_d+\sigma_n^2\right)}}. \quad (16)$$

$$P_{f0}=\int_{\tau}^{\infty} f\left(\Lambda=z\mid H_0\right)dz=\sum_{N=N_1}^{N_2}\frac{\lambda^N e^{-\lambda}}{N!}e^{-\frac{\tau}{2\left(NP_f+\sigma_n^2\right)}}. \quad (17)$$

IV. Performance Analysis and Simulation

In Fig. 2, the ROC curves obtained by using approximations (16) and (17) and those by simulations are plotted under three different values of ρ. The simulation results in Fig. 2 are based on 10^5 Monte Carlo runs. From the figure, it is clear that the results obtained by approximations are very close to simulation results. And the system detection performance is improved with the increasing value of ρ.

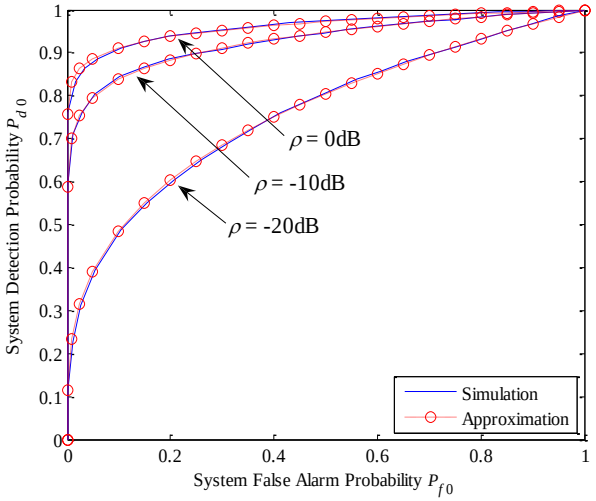


Fig. 2. ROC curves of simulation and approximation. λ=500, P_d=0.5, P_f=0.02.

With the (14) and (15), we can get the likelihood ratio decision fusion rule of Λ (denoted by $L(\Lambda)$) :

$$L(\Lambda)=\frac{f\left(\Lambda\mid H_1\right)}{f\left(\Lambda\mid H_0\right)}$$

$$\approx\frac{\sum_{N=N_1}^{N_2}\frac{\lambda^N}{N!\left(NP_d+\sigma_n^2\right)}e^{-\frac{\Lambda}{2\left(NP_d+\sigma_n^2\right)}}}{\sum_{N=N_1}^{N_2}\frac{\lambda^N}{N!\left(NP_f+\sigma_n^2\right)}e^{-\frac{\Lambda}{2\left(NP_f+\sigma_n^2\right)}}}\underset{H_0}{\overset{H_1}{\gtrless}}\tau_L. \quad (18)$$

where, τ_L is the decision threshold of $L(\Lambda)$, meaning if $L(\Lambda)\geq\tau_L$, u_0=1; otherwise, u_0=0.

It can be regarded that $L(\Lambda)$ is a nonlinear transformation of Λ. Fig. 3 shows that the relation between $L(\Lambda)$ and Λ under three different values of ρ. The results show that the $L(\Lambda)$ is a monotonically increasing transformation of Λ. Therefore, a conclusion similar to [3] is obtained: Λ and $L(\Lambda)$ are equivalent in terms of detection performance.

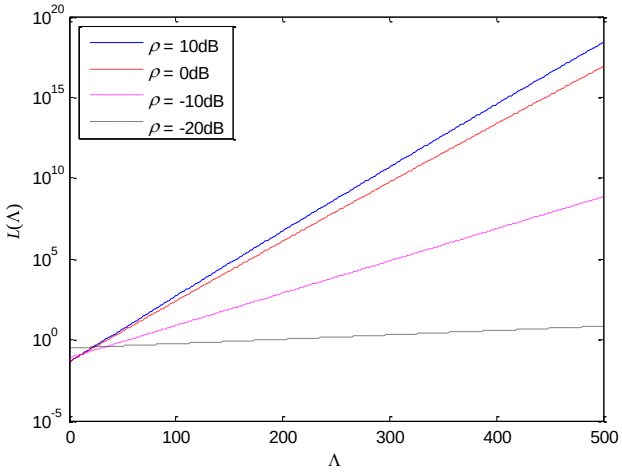


Fig. 3. The relation between $L(\Lambda)$ and Λ under different value of ρ. λ=500, P_d=0.5, P_f=0.02.

In order to prove the above conclusion, the ROC curves of $L(\Lambda)$ and Λ under three different values of ρ obtained by simulation are given in Fig. 4. The simulation results in Fig. 4 are based on 10^5 Monte Carlo runs. Similar to the conclusion of analysis, the simulation results show that the performance of Λ is very close to that of $L(\Lambda)$.

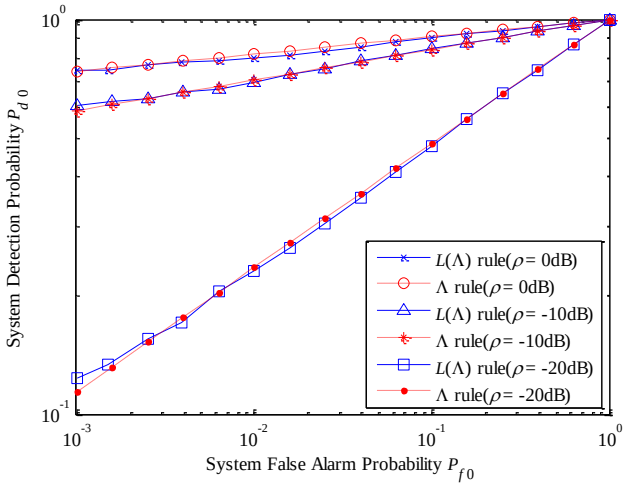


Fig. 4. ROC curves of $L(\Lambda)$ and Λunder different value of ρ. λ=500, P_d=0.5, P_f=0.02.

V. Conclusion

In this paper, a new decision fusion rule is proposed for dynamic WSN over noncoherent multi-access channels. The analysis and simulation show that the performance of the proposed decision fusion rule is very close to that of the optimal likelihood ratio decision fusion rule, besides, the proposed decision fusion rule requires smaller computation and less information compared with the optimal likelihood ratio decision fusion rule.

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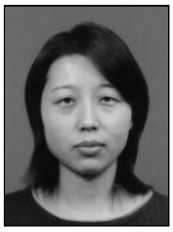
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