Fusion of Censored Decisions in Wireless Sensor Networks

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***Abstract*—Sensor censoring has been introduced for reduced communication rate in a decentralized detection system where decisions made at peripheral nodes need to be communicated to a fusion center. In this letter, the fusion of decisions from censoring sensors transmitted over wireless fading channels is investigated. The knowledge of fading channels, either in the form of instantaneous channel envelopes or the fading statistics, is integrated in the optimum and suboptimum fusion rule design. The sensor censoring and the ensuing fusion rule design have two major advantages compared with the previous work. 1) Communication overhead is dramatically reduced. 2) It allows incoherent detection, hence, the phase information of transmission channels is no longer required. As such, it is particularly suitable for wireless sensor network applications with severe resource constraints.**

***Index Terms*—Censoring sensor, decision fusion, fading channels, wireless sensor networks.**

I. Introduction

IN A WIRELESS sensor network (WSN) tasked with a distributed detection problem [1], geographically dispersed sensor nodes are used to make peripheral decisions based on their own observations. These decisions are transmitted through wireless channels to a fusion center where a final decision regarding the state of an event is made. In many WSN applications involving *in situ* unattended sensors operating on irreplaceable power source, severe resource constraints as well as the time-sensitive nature of many detection problems require prudent use of power/bandwidth and other resources. The sensor censoring idea, first proposed by Rago *et al.* in 1996 [2] for reduced communication rate, is a very suitable candidate for local sensor signaling.

With censoring sensors, only those sensors with informative observation, measured by their local likelihood ratio (LR) values, send the LR to the fusion center. Using the canonical parallel fusion structure with binary hypothesis and conditionally independent sensor observations, it was shown in [2] that the optimal "no-send" region for any given sensor, defined on the LR domain, amounts to a single interval for both the Bayesian and Neyman–Pearson (NP) criteria. This is illustrated in Fig. 1(a), where $[t_1, t_2]$ corresponds to the "no-send" region; i.e., if the LR falls in-between t_1 and t_2, the sensor does not transmit its LR to the fusion center. Furthermore, in the case of sufficiently small prior probability of the target-present hypothesis and severe communication constraint, the optimal (in the sense of minimum error probability) lower threshold of the "no-send" region was shown to be 0, i.e., $t_1 = 0$ [see Fig. 1(b)]. Similar result was also established later in [3] using the NP criterion. An intuitive explanation is that when a target is less likely to be present, the extreme communication constraint prohibits sending low LR values that happen much more often.

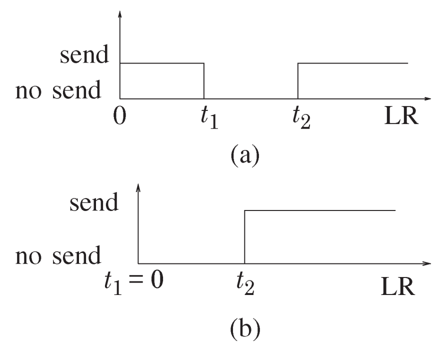

Fig. 1. (a) Sensor censoring region. (b) Special case when $t_1 = 0$.

For the case with $t_1 = 0$, the censoring scheme is effectively an LR test (LRT)-based transmission scheme: Whenever the local LR exceeds t_2, the sensor transmits the LR; otherwise, the sensor remains silent. In this paper, we take the above sensor censoring to its extreme case—if the local LR exceeds t_2, the sensor sends only a single bit,[1] indicating that the LR falls into the "send" region, instead of the LR value in its entirety. Such an extreme censoring scheme has also been considered in [3] in the context of studying locally optimum distributed detection.

Closely related to the present work is the development of channel-aware decision fusion rules for WSN where a binary local sensor signaling is assumed [4]–[6]. Compared with our previous work, the sensor censoring scheme enjoys significant energy efficiency—instead of sending a binary signal at every time slot, each sensor will stay quiet if its LR falls below t_2. Another important advantage is that the sensor censoring scheme allows the fusion center to employ fusion rules based on incoherent detection. Acquiring phase information of transmission channels can be costly as it typically requires training overhead. This overhead may be substantial for time-selective fading channels when mobile sensors are involved or the fusion center is constantly moving [consider, for example, the reach back channel with the receiver mounted on a unmanned aerial vehicle (UAV) or a moving vehicle]. Thus, we concentrate on incoherent-detection-based decision fusion rules in the present work. Notice that if channel phase information is available, the fusion rules developed in [4]–[6] can be applied directly—the

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[1]As usual, this single bit corresponds to a particular waveform that is sent from the sensor to the fusion center. As is typical in digital communication, this waveform is represented by a constellation point with appropriately chosen basis function(s). We assume further that a "1" is sent, indicating that the basis function is chosen to coincide with the actual waveform.

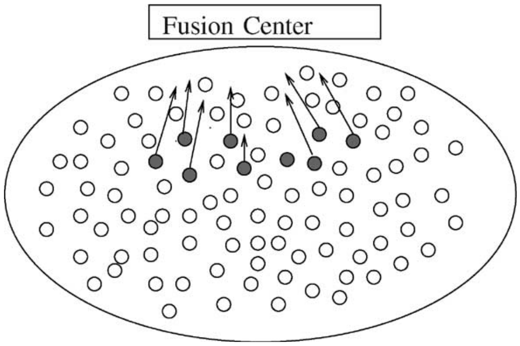

Fig. 2. Illustration of the ON/OFF signaling for local sensors. Only those sensors (shaded) whose LR exceeds a certain threshold are alarmed and send signals to the fusion center.

censoring scheme is equivalent to a binary scheme with one constellation point coinciding with the origin.

Specifically, resorting to incoherent detection schemes, we develop optimum fusion rules for the following two scenarios: 1) when the fading channel envelopes are available at the fusion center and 2) when only the fading statistics are available. Under the low signal-to-noise ratio (SNR) regime, we further reduce the optimal fusion rule into simple test statistics that are both easy to implement and not subject to prior knowledge requirement. These test statistics also provide insights into some simple intuitive test statistics. For example, the censoring scheme amounts effectively to an ON/OFF signaling at local sensors where only alarmed sensors send signals to the fusion center, as illustrated in Fig. 2. An intuitive detection scheme is to employ an energy detector (ED); i.e., the fusion center simply sums up all the signal powers from all the sensors. Indeed, under certain channel fading models, we show that this simple scheme is the optimal detector in the low-SNR regime.

We remark here that our emphasis in this work is the development of fusion algorithms with ON/OFF signaling for a fading environment. Another important issue is the local sensor decision rule, i.e., how to determine the censoring threshold t_2. This is not addressed in this paper. We assume, instead, that local sensors employ a sensor censoring scheme with known t_2. Therefore, the local sensor performance indices (probabilities of false alarm and detection) can be readily calculated. We note that censoring threshold design has been addressed in [7] where detector efficacy is optimized by assuming a simplified ALOHA protocol for the sensor communications.

The organization of the paper is as follows. In the next section, we introduce the system model and derive the optimum LR-based fusion rule with the knowledge of fading channel envelope. Two suboptimum fusion statistics are also provided. In Section III, we derive, under Rayleigh, Ricean, and Nakagami fading channel models, the optimum fusion rules, assuming only the knowledge of the fading channel statistics. Numerical examples are provided in Section IV, followed by conclusions in Section V.

II. Optimal Fusion Rule With the Knowledge of Channel Envelope

The sensor fusion system employing ON/OFF signaling with a canonical parallel fusion structure is depicted in Fig. 3. The K sensors collect observations and calculate their respective LR values. For each sensor, if its LR value exceeds a precalculated threshold t_2, it transmits a binary signal (say, $u_k = 1$) to a fusion center. Otherwise, if the LR falls below the threshold, $u_k = 0$, i.e., the sensor remains silent during this transmission period. We assume that the observations are independent across sensors conditioned on any given hypothesis. The probabilities of false alarm and detection of the kth local sensor node are denoted by P_{fk} and P_{dk}, respectively. They can be computed easily using the knowledge of the hypotheses under test and the LR threshold t_2. The local sensor outputs, u_k, $k = 1, \ldots, K$, are transmitted over parallel channels that are assumed to undergo independent flat fading. We denote by h_k and ϕ_k the fading envelope and phase of the kth channel, respectively. We further assume a slow fading channel, whereby the channel remains constant during the transmission of one decision.

The above model yields the channel output for the kth sensor, given as

$$y_k = \begin{cases} n_k, & \text{the } k\text{th sensor decides } H_0 \\ h_k e^{j\phi_k} + n_k, & \text{the } k\text{th sensor decides } H_1 \end{cases} \tag{1}$$

where n_k is a zero-mean complex Gaussian noise whose real and imaginary parts are independent of each other and have equal variance σ^2, hence, $E[|n_k|^2] = 2\sigma^2$.

If both h_k and ϕ_k are known, the optimum LR-based decision fusion rule can be easily derived [4], [6]. Notice that with censoring, we are replacing $\{+1, -1\}$ with $\{1, 0\}$, hence, with phase information, the equivalence between the two schemes (save some scaling factors) is reminiscent to the rotation and shift invariance principle in digital communications. Thus, we concentrate now on the incoherent case, i.e., we develop fusion statistics based on the output envelope, or equivalently, the output power.

Denote by z_k the signal power for the kth channel output, i.e., $z_k = |y_k|^2$, hence, given h_k, it is easy to get

$$p(z_k|u_k = 0, h_k) = \frac{1}{2\sigma^2} e^{-\frac{z_k}{2\sigma^2}}$$
$$p(z_k|u_k = 1, h_k) = \frac{1}{2\sigma^2} I_0\left(\frac{h_k}{\sigma^2}\sqrt{z_k}\right) e^{-\frac{h_k^2 + z_k}{2\sigma^2}}$$

where $I_0(.)$ is the zeroth-order modified Bessel function of the first kind.

Using z_k instead of y_k in the fusion rule design and assuming knowledge of the fading channel envelope and the local sensor performance indices, the logarithmic LR (LLR) can be derived in a straightforward manner as

$$\Lambda = \log \frac{p(z_1, \ldots, z_k|H_1)}{p(z_1, \ldots, z_k|H_0)}$$
$$= \sum_k \log \frac{P_{dk} p(z_k|u_k = 1) + (1 - P_{dk}) p(z_k|u_k = 0)}{P_{fk} p(z_k|u_k = 1) + (1 - P_{fk}) p(z_k|u_k = 0)} \tag{2}$$
$$= \sum_k \log \frac{P_{dk} I_0\left(\frac{h_k}{\sigma^2}\sqrt{z_k}\right) e^{-\frac{h_k^2}{2\sigma^2}} + (1 - P_{dk})}{P_{fk} I_0\left(\frac{h_k}{\sigma^2}\sqrt{z_k}\right) e^{-\frac{h_k^2}{2\sigma^2}} + (1 - P_{fk})}. \tag{3}$$

We consider next the low-SNR approximation for Λ.

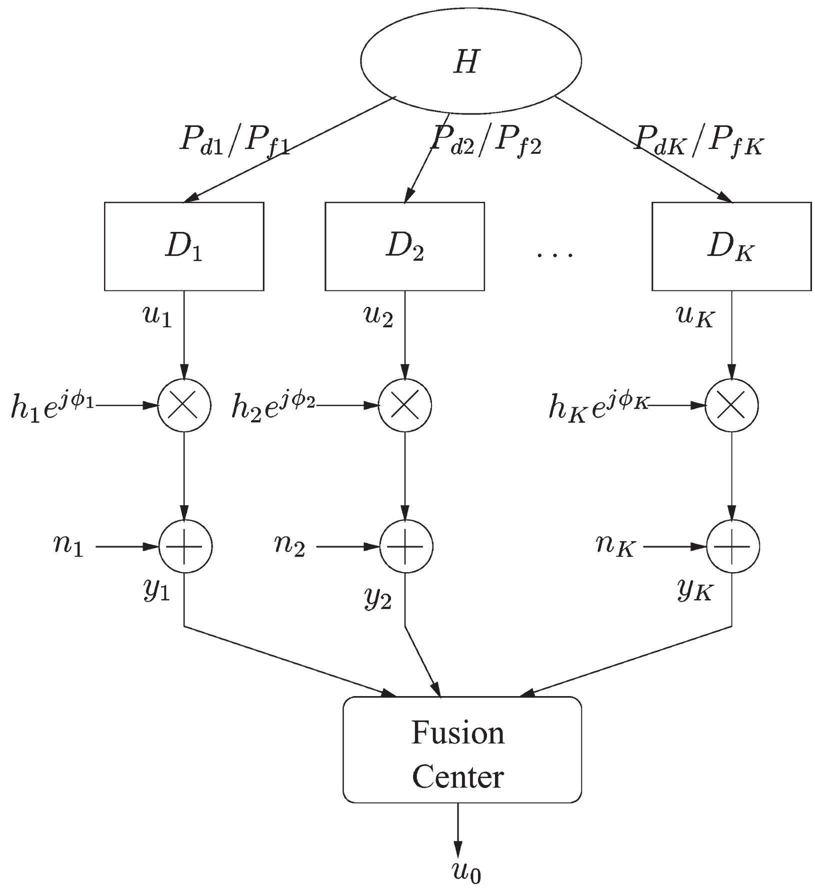

Fig. 3. Parallel fusion model in the presence of fading and noisy channel between the local sensors and the fusion center.

Proposition 1: As the channel noise variance $\sigma^2 \to \infty$, i.e., SNR $\to 0$, and assuming identical local sensor performance, Λ in (3) reduces to

$$\Lambda_{\text{WED}} = \sum_k h_k^2 z_k. \tag{4}$$

To verify this, notice from [8] that

$$I_0(x) = \sum_{i=0}^{\infty} \frac{\left(\frac{1}{4}x^2\right)^i}{(i!)^2}. \tag{5}$$

Applying (5) to $I_0((h_k\sigma^2)\sqrt{z_k})$ and keeping only the first two terms for large σ^2, we get

$$I_o\left(\frac{h_k}{\sigma^2}\sqrt{z_k}\right) \approx 1 + \frac{\left(\frac{h_k}{\sigma^2}\sqrt{z_k}\right)^2}{4}. \tag{6}$$

Plugging this into (3) and using, for small x, $e^{-x} \approx 1 - x$, we can show that (3) reduces to

$$\Lambda \approx \sum_k \log\left[1 + \frac{(P_{dk} - P_{fk})\left(\frac{h_k^2}{2\sigma^4}z_k - \frac{h_k^2}{2\sigma^2}\right)}{1 + P_{fk}\left(\frac{h_k^2}{2\sigma^4}z_k - \frac{h_k^2}{2\sigma^2}\right)}\right]$$

where we only keep the terms up to the order of $1/\sigma^4$. Using the fact that $\log(1+x) \approx x$ for small x, this can be further reduced to

$$\Lambda \approx \sum_k (P_{dk} - P_{fk})\left(\frac{h_k^2}{2\sigma^4}z_k - \frac{h_k^2}{2\sigma^2}\right).$$

Given that the envelopes h_ks are known, this test statistic is equivalent to $\sum_k (P_{dk} - P_{fk})h_k^2 z_k$ as the term independent of z_k can be discarded. Furthermore, if local sensors have identical performance indices, this statistic is equivalent to (4) in Proposition 1. This is a weighted sum of the received signal power from all sensors, hereafter termed as the weighted energy detector (WED).

III. Channel-Statistics-Based Fusion Rules

The LR-based fusion rule developed in the previous section requires knowledge of the channel fading envelope. Due to the limited resources, this information may not be available at the fusion center. Without the knowledge of fading channel envelope, we derive in this section the channel statistics-based LRT using the channel output power z_k. Notice that obtaining channel fading statistics typically is much less costly than acquiring instantaneous envelopes. Three popular fading channel models, namely, the Rayleigh, Ricean, and Nakagami, are considered in this section.

A. Rayleigh Fading Channel

In a purely diffuse scattering environment without a dominant path, the channel is typically modeled as Rayleigh fading channel. Without loss of generality, we assume that the Rayleigh fading channel has unit power, i.e., $E[h_k^2] = 1$. Thus

$$p(h_k) = 2h_k e^{-h_k^2}.$$

Given $p(h_k)$, we then calculate the conditional probability density function (PDF) $p(z_k|u_k)$

$$p(z_k|u_k) = \int_0^\infty p(z_k|h_k, u_k)p(h_k)dh_k.$$

Straightforward computations yield

$$p(z_k|u_k = 0) = \frac{1}{2\sigma^2} e^{-\frac{z_k}{2\sigma^2}}$$
$$p(z_k|u_k = 1) = \frac{1}{1+2\sigma^2} e^{-\frac{z_k}{1+2\sigma^2}}.$$

Notice that both of them are exponentially distributed with respective mean values equal to $2\sigma^2$ and $1 + 2\sigma^2$. With these conditional PDF, one can easily construct the LLR as

$$\Lambda = \sum_k \log \frac{P_{dk} \frac{1}{1+2\sigma^2} e^{-\frac{z_k}{1+2\sigma^2}} + (1 - P_{dk}) \frac{1}{2\sigma^2} e^{-\frac{z_k}{2\sigma^2}}}{P_{fk} \frac{1}{1+2\sigma^2} e^{-\frac{z_k}{1+2\sigma^2}} + (1 - P_{fk}) \frac{1}{2\sigma^2} e^{-\frac{z_k}{2\sigma^2}}}. \quad (7)$$

Next, we consider low-SNR approximations. We have the following proposition.

Proposition 2: As $\sigma^2 \to \infty$, the LLR in (7) reduces to a form equivalent to

$$\sum_k (P_{dk} - P_{fk}) \frac{z_k}{2\sigma^2(1 + 2\sigma^2)}. \quad (8)$$

The proof is straightforward by applying first-order Taylor series expansion for e^{-x} and $\log(1 + x) \approx x$ for small x.

With identical local sensors, the above low-SNR approximation of LLR is equivalent to

$$\Lambda_{\text{ED}} = \sum_k z_k \quad (9)$$

which is termed ED for obvious reasons. This ED comes as an intuitive detection statistic: From Fig. 2, the more alarmed sensors, the larger the total received signal power at the fusion center is.

B. Ricean Fading Channel

If there is a line of sight (LOS) between a local sensor and the fusion center, the channel is typically modeled as a Ricean fading channel. The channel gain can be written as

$$A_k e^{j\theta_k} + w_k$$

where $A_k e^{j\theta_k}$ denotes the "LOS component" and w_k denotes the "diffuse component," assumed to be zero-mean complex Gaussian with variance σ_w^2.

Assuming $u_k = 1$ when H_1 is decided, the observation at the fusion center is

$$y_k = \begin{cases} n_k, & \text{the } k\text{th sensor decides } H_0 \\ A_k e^{j\theta_k} + v_k, & \text{the } k\text{th sensor decides } H_1 \end{cases} \quad (10)$$

where $v_k = w_k + n_k$ is complex Gaussian with zero mean and variance $\sigma_w^2 + 2\sigma^2$.

Recognizing that (10) is essentially in the same form as (1) with h_k, ϕ_k, and n_k replaced with A_k, θ_k, and v_k respectively, it is straightforward to write out the corresponding LLR in a similar form as (3). Furthermore, one can show, in the same spirit that (4) was derived, that the low-SNR approximation, assuming identical local sensors, is

$$\Lambda_{\text{WED2}} = \sum_k A_k^2 z_k.$$

This is similar to the WED statistic in (4) except A_k is the envelope of LOS, not of the overall channel. Since the LOS component is typically stationary, A_k can be easily acquired through temporal accumulation.

C. Nakagami Fading Channel

Another commonly used flat fading model is the Nakagami fading channel, which is more general than Rayleigh and Ricean fading. With unit power assumption, the Nakagami fading channel has an envelope distribution of the form

$$P(h_k) = \frac{2(m)^m h_k^{2m-1}}{\Gamma(m)} e^{-mh_k^2}$$

where $m \geq 1/2$. Therefore

$$p(z_k|u_k = 0) = \frac{1}{2\sigma^2} e^{-\frac{z_k}{2\sigma^2}}$$
$$\begin{aligned} P(z_k|u_k = 1) &= \int_0^\infty p(z_k|h_k, u_k)p(h_k)dh_k \\ &= \int_0^\infty \frac{1}{2\sigma^2} I_0\left(\frac{h_k}{\sigma^2}\sqrt{z_k}\right) \\ &\qquad \times e^{-\frac{h_k^2+z_k}{2\sigma^2}} 2(m)^m \frac{h_k^{2m-1}}{\Gamma(m)} e^{-mh_k^2} dh_k \\ &= \frac{m^m}{\Gamma(m)} \frac{e^{-\frac{z_k}{2\sigma^2}}}{2\sigma^2} \\ &\qquad \times \sum_{i=0}^\infty \frac{z_k^i (i + m - 1)!(2\sigma^2)^{m-i}}{(i!)^2(1 + 2\sigma^2 m)^{i+m}} \end{aligned}$$

where we used (5) in the integration.

In the same spirit as in (2), the LLR under the Nakagami fading can be constructed given the above conditional probabilities. Unlike the case with the Rayleigh and Ricean fading

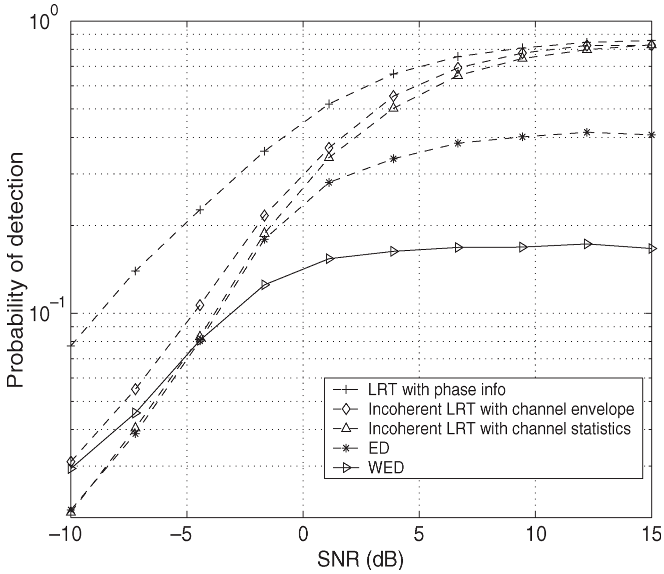

Fig. 4. Probability of detection as a function of channel SNR for Rayleigh fading channels.

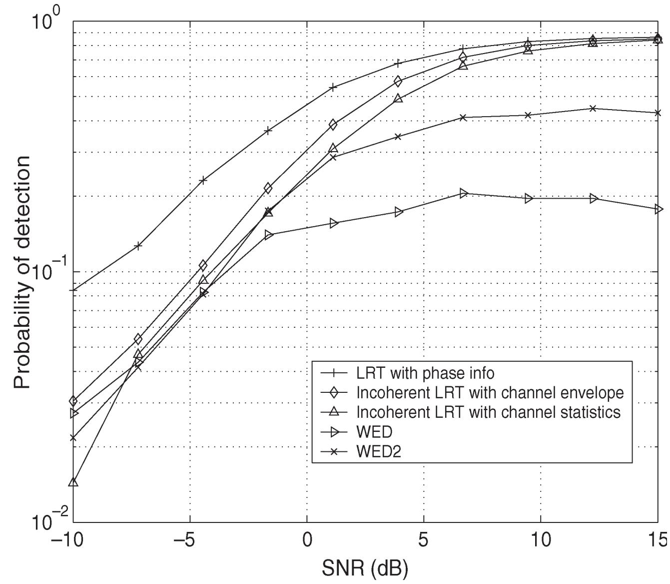

Fig. 5. Probability of detection as a function of channel SNR for Ricean fading channels.

channels, the LRT for the Nakagami case involves series with infinite terms, hence, do not have a closed-form expression. We show next, however, that at low-channel SNR, i.e., $\sigma^2 \to \infty$, and with identical local sensors, the LLR again reduces to an ED.

As $\sigma^2 \to \infty$, the resulting LLR can be derived as

$$\begin{aligned}
\Lambda &= \sum_k \log \frac{P_{dk}P(z_k|u_k=1)+(1-P_{dk})P(z_k|u_k=0)}{P_{fk}P(z_k|u_k=1)+(1-P_{fk})P(z_k|u_k=0)} \\
&= \sum_k \log \Bigg[1+(P_{dk}-P_{fk})\frac{m^m}{\Gamma(m)} \\
&\qquad \times \sum_{i=1}^{\infty} \frac{z_k^i (i+m-1)!(2\sigma^2)^{m-i}}{(i!)^2(1+2\sigma^2 m)^{m+i}}\Bigg] \\
&\overset{(a)}{\approx} \sum_k (P_{dk}-P_{fk})\frac{m^m}{\Gamma(m)} \sum_{i=1}^{\infty} \frac{z_k^i (i+m-1)!(2\sigma^2)^{m-i}}{(i!)^2(1+2\sigma^2 m)^{m+i}} \\
&\overset{(b)}{\approx} \sum_k (P_{dk}-P_{fk})\frac{m^m}{(m-1)!}\frac{z_k m!(2\sigma^2)^{m-1}}{(1+2\sigma^2 m)^{m+1}} \\
&\overset{(c)}{\approx} \sum_k \frac{P_{dk}-P_{fk}}{4\sigma^4} z_k
\end{aligned}$$

where all approximations stem from the fact that $\sigma^2 \to \infty$. Specifically, we used $\log(1+x) \approx x$ for small x in (a), kept only the first term in the inner sum in (b), and used $(1+2\sigma^2 m)^{m+1} \approx (2\sigma^2 m)^{m+1}$ in (c). Again, with identical sensors, the test statistic reduces to the intuitive ED in (9). An interesting fact is that this low-SNR approximation is not a function of the Nakagami shape parameter m. Furthermore, this result is the same as that of the Rayleigh fading channel, which is not surprising, considering that Rayleigh fading is a special case of Nakagami with $m = 1$.

IV. Performance Evaluation

Figs. 4–6 show the simulation results of the detection probability as a function of channel SNR for various fusion statistics under the Rayleigh, Ricean, and Nakagami fading channels, respectively. We also include the coherent LRT assuming the knowledge of the channel phase information [4]. This coherent LRT provides uniform performance bound among all detection statistics. The system false alarm rate at the fusion center is fixed at $P_{f0} = 0.01$. In all examples, the total number of sensor is 8 with sensor level $P_{fk} = 0.05$ and $P_{dk} = 0.5$. Some remarks are in order.

1) In the Ricean fading case, the LOS envelope A_k is generated randomly from a uniform distribution $U(A-\Delta, A+\Delta)$, with A satisfying $A^2/\sigma_w^2 = 1$; i.e., the average Ricean factor is chosen to be 1. Specifically, we choose $A = 1$, $\sigma_w^2 = 1$, and $\Delta = 0.2$. The variation in A_k models the discrepancy of LOS strength for different sensors due to dispersive geographical locations.
2) In the Nakagami fading case, we choose $m = 2$.
3) From the NP lemma, it is clear that the LR-based fusion rule provides the best detection performance. Among the three LRTs, the performance degrades as the prior information utilized in each LRT decreases. Thus, coherent LRT performs better than incoherent LRT using channel fading envelope, which, in turn, is better than incoherent LRT using only the fading statistics.
4) As SNR decreases, the two incoherent LRTs approach their respective low-SNR approximations in all cases.[2]
5) In all cases, ED and WED suffer performance loss at high SNR. This is not surprising, given that these alternatives are only low-SNR approximations of the optimal LR-based fusion statistics.

[2]We do not include the LRT using fading statistics for the Nakagami fading in Fig. 6 as it involves infinite sum. While one can truncate the infinite sum, we notice that the low-SNR approximation itself is already a trundated version.

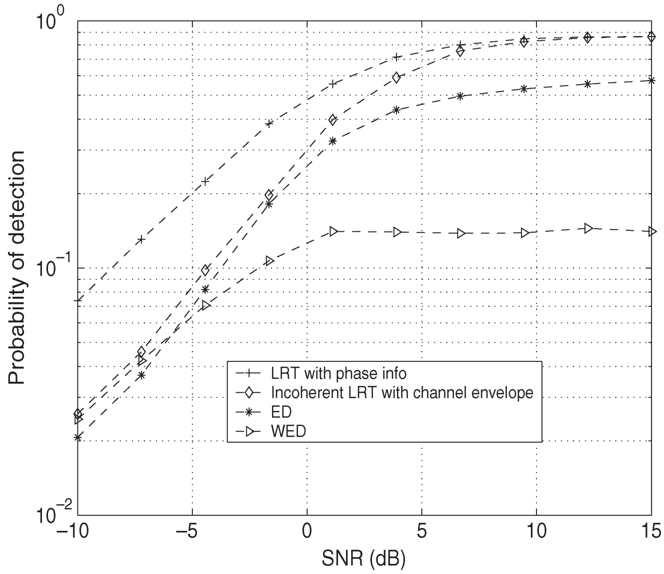

Fig. 6. Probability of detection as a function of channel SNR for Nakagami fading channels with $m = 2$.

V. Conclusion

Fusion of censored decisions transmitted over fading channels in WSN is studied in this paper. The ON/OFF signaling, in addition to lower communication overhead, allows the development of fusion statistics without knowledge of channel phase information. Both cases, one assuming the knowledge of channel fading envelope and the other the fading statistics, are treated and the optimum LRT is derived under each scenario. For the case of known fading statistics, we consider Rayleigh, Ricean, and Nakagami fading channels. Suboptimum detection statistics, derived as low–SNR approximations of the optimal LRT, are obtained and provide some theoretical justification to some intuitive test statistics, such as the ED.

The work reported here focuses on the low-SNR regime. As such, the proposed suboptimal statistics suffer performance loss at moderate to high SNR compared with the optimal LR-based fusion statistics. This motivates some of our ongoing research to look for fusion statistics that exhibit robust detection performance in wider SNR ranges.

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