Frequency-Hopping/M-ary Frequency-Shift Keying Wireless Sensor Network Monitoring Multiple Source Events

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***Abstract*—In this contribution, a novel wireless sensor network (WSN) assisted by M-ary frequency-shift keying (MFSK) modulation and frequency-hopping (FH), referred to as the FH/MFSK WSN, is proposed to monitor multiple source events (SEs). In the FH/MFSK WSN, the multiple SEs of each with multiple states are observed by a common group of local sensors (LSNs), each of which observes simultaneously all the SEs. The LSNs convey their decisions through wireless channels to the fusion center (FC) with the aid of MFSK and FH. At the FC, the SEs' states are detected using noncoherent fusion rules. In this contribution, two noncoherent fusion rules are investigated. The first one is the equal gain combining (EGC) fusion rule, while the second one uses both the EGC and iterative interference cancellation (IIC), which is referred to as the EGC-IIC fusion rule. The detection performance of the FH/MFSK WSN employing the proposed EGC or EGC-IIC fusion rule is investigated, when assuming the wireless channels experience independent Rayleigh fading. Our studies show that the FH/MFSK WSN may constitute one of the promising WSN schemes for some special application scenarios. It is capable of monitoring simultaneously multiple SEs of each with multiple states, is low-complexity owing to using the noncoherent fusion rule and, furthermore, is capable of achieving promising detection performance, as it can make use of the diversity in both frequency and space domains.**

I. Introduction

In WSNs, many works have been done in order to achieve reliable signal detection at fusion center (FC), while depending on minimum communication traffic between local sensors (LSNs) and FC, and low-complexity fusion detection rules [1–5]. In literature, numerous detection algorithms have been proposed and studied in the context of binary source events (SEs). Specifically, the classic Bayes rule, which was first introduced to the distributed sensor networks by Tenney [6], has widely been considered for detection in WSNs [2]. The optimum likelihood ratio (LR) fusion rule considered in [4] is capable of achieving the optimum performance, but also demands the most a-priori information for detection. In order to reduce the a-priori information required by the LR fusion rule, approximate but sub-optimum fusion rules have been proposed, including, for example, the Chair-Varshney fusion rule [4] operated in the high SNR region, the maximum ratio combining (MRC) fusion rule [3, 4] that is efficient in the low-SNR region, etc. In addition to the above, there are also many other fusion rules considered for WSNs of binary states, including the Neyman-Pearson rule [2], maximum likelihood (ML) rule [2–4], equal gain combining (EGC) rule [3, 4], etc. In the context of the non-binary SEs, [7] has proposed a fusion rule by minimizing a mean loss function, [8] has considered an asymptotic optimal rule, while in [5], the fusion detection of an M-ary SE has been investigated by merging the fusion detection with channel decoding. In WSNs, coherent fusion rules are often preferred for the applications demanding high data rate. However, there are a range of applications, which weight the implementation complexity over the data rate. In these WSNs, noncoherent fusion rules are usually preferred, which achieve the fusion detection without relying on channel estimation.

In this contribution, we propose a parallel triple-layer WSN [4], which monitors simultaneously multiple M-ary SEs with the aid of noncoherent fusion rule. Specifically, in our proposed WSN, the multiple M-ary SEs are observed by a range of LSNs, each of which observes all the SEs. The LSNs convey their observations to the FC using M-ary frequency-shift keying (MFSK) modulation assisted by frequency-hopping (FH). Hence, for convenience, our WSN is referred to as the FH/MFSK WSN. In the FH/MFSK WSN, the FH is introduced not only for assisting the FC to distinguish the SEs, but also for reducing the correlation among the signals transmitted by the LSNs, so that the fusion detection can benefit from both the space diversity and the frequency diversity. Explicitly, the frequency diversity becomes more important, when the LSNs are closely distributed, making the signals transmitted by different LSNs correlated in space. In this contribution, two types of noncoherent fusion rules are proposed and studied associated with the FH/MFSK WSN, which are the EGC fusion rule and the fusion rule designed based on EGC and iterative interference cancellation [9], referred to as the EGC-IIC fusion rule. The detection performance of the FH/MFSK WSN is investigated, when assuming that the wireless channels between LSNs and FC experience Rayleigh fading. Our studies address the effects of various aspects on the achievable detection performance of the FH/MFSK WSN.

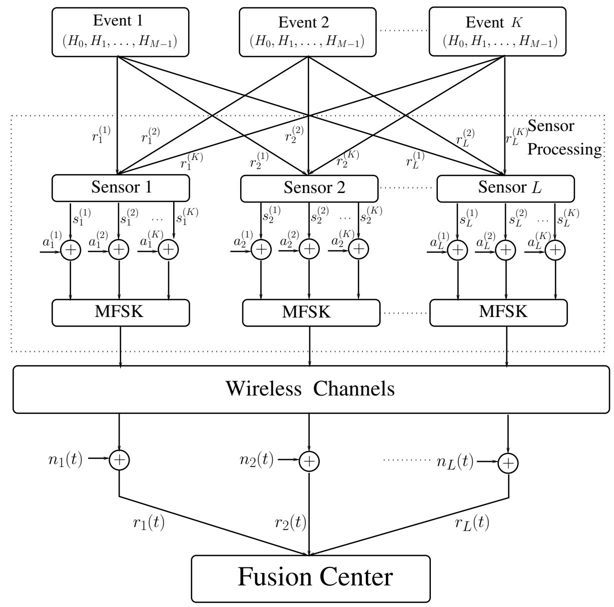

Fig. 1. Triple-layer system model for the FH/MFSK WSN monitoring multiple M-ary events.

II. System Description

The system model for our triple-layer FH/MFSK WSN monitoring multiple SEs is displayed in Fig. 1. In this FH/MFSK WSN, we assume that there are K SEs, each of which has M possible states (hypotheses). The K SEs are monitored simultaneously by L number of local sensors (LSNs). We assume that every LSN is capable of observing simultaneously the K SEs without observation interference. In fact, we can view that each LSN consists of K sub-sensors, each of which monitors one SE. These K sub-sensors share one common wireless transmitter to send their decisions to the FC. Explicitly, this system arrangement has the advantages including that: (a) the number of LSNs does not increase with the number of SEs monitored and, hence, the system may not need to use a big number of LSNs, even when there are many SEs; (b) owing to using a relatively low number of LSNs, synchronization among the local sensors can become relatively easy. As shown in Fig. 1, after a LSN obtains K observations

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for the K SEs, it first makes the local decisions about the states that the K SEs are at and, then, conveys its decisions to the FC through the wireless channel with the aid of MFSK and FH. Finally, the states of the SEs are detected at the FC after it collects all the related signals from the L LSNs. Below we provide more details about the operations carried out in the FH/MFSK WSN.

A. Source Events

In practice, the SEs are usually analogue signals. For convenience of processing, they are usually digitalized to finite states. In this contribution, we assume that each SE has M states represented by M hypotheses expressed as $H_0, H_1, \ldots, H_{M-1}$, as shown in Fig. 1. We assume that each of the M states of a SE has the same probability to present. Each of the K SEs is observed by L number of LSNs and every of the LSNs monitors simultaneously all the K SEs.

B. Signal Detection and Processing at Local Sensors

At a LSN, such as LSN l, the observation $r_l^{(k)}$ is obtained from the kth SE, as seen in Fig. 1. Based on $r_l^{(k)}$, the lth LSN makes a local decision about the state that the kth SE is currently at, and this state is expressed as $m_l^{(k)} \in \{0, 1, \ldots, M-1\}$, as shown in Fig. 1. The erroneous and correct detection probability of the LSNs are expressed as P_{se} and P_d, respectively, where $P_d = 1 - P_{se}$. We assume that, whenever an erroneous decision is made by a LSN, the erroneous state estimated by the LSN has the same probability to be any of the $(M-1)$ erroneous states.

Let us collect the K estimates of LSN l into the vector $\boldsymbol{s}_l = \left[s_l^{(1)}, s_l^{(2)}, \cdots, s_l^{(K)}\right]^T$. Furthermore, let

$$\boldsymbol{S} = [\boldsymbol{s}_1 \; \boldsymbol{s}_2 \; \cdots \; \boldsymbol{s}_L] \tag{1}$$

which is an $(K \times L)$ matrix. As shown in Fig. 1, following the detection of the SEs, the LSNs convey their decisions to the FC based on the FH/MFSK principles, which are operated as follows.

Let a symbol transmission time be T_s seconds, which is evenly divided into L time-slots with each LSN using one time-slot to transmit its K decisions. We assume that the WSN system has in total M orthogonal frequency bands, whose center frequencies form the set $\mathcal{F} = \{f_0, f_1, \ldots, f_{M-1}\}$. These M frequencies are used for both FH and MFSK modulation, which are implemented as follows. Let $\boldsymbol{a}^{(k)} = [a_1^{(k)}, a_2^{(k)}, \ldots, a_L^{(k)}]^T$ be a FH address (or pattern) assigned for transmission of the kth SE's state, where $a_l^{(k)}$ is an element of the Galois field $GF(M)$, i.e., $a_l^{(k)} \in GF(M)$. Based on $\boldsymbol{a}^{(k)},\ k = 1, 2, \ldots, K$, we form the matrix

$$\boldsymbol{A} = \left[\boldsymbol{a}^{(1)} \; \boldsymbol{a}^{(2)} \; \cdots \; \boldsymbol{a}^{(K)}\right]^T \tag{2}$$

Then, the FH operations can be represented as

$$\boldsymbol{M} = [\boldsymbol{m}_1 \; \boldsymbol{m}_2 \; \cdots \; \boldsymbol{m}_L] = \boldsymbol{S} \boxplus \boldsymbol{A} \tag{3}$$

where $\boldsymbol{m}_l = \left[m_l^{(1)} \; m_l^{(2)} \; \cdots \; m_l^{(K)}\right]^T$ for $l = 1, 2, \ldots, L$, and $\boldsymbol{S} \boxplus \boldsymbol{A}$ is defined as the element-wise addition operation in $GF(M)$, implying that $m_{ij} = S_{ij} \oplus A_{ij}$ with $\oplus$ representing the addition operation in $GF(M)$. Explicitly, we have $m_{ij} \in GF(M)$, which is suitable for MFSK modulation by mapping m_{ij} to the frequency $f_{m_{ij}}$. Let us express the corresponding frequencies as

$$\boldsymbol{F}(\boldsymbol{M}) = \begin{bmatrix} f_{m_1^{(1)}} & f_{m_2^{(1)}} & \cdots & f_{m_L^{(1)}} \\ f_{m_1^{(2)}} & f_{m_2^{(2)}} & \cdots & f_{m_L^{(2)}} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m_1^{(K)}} & f_{m_2^{(K)}} & \cdots & f_{m_L^{(K)}} \end{bmatrix} \tag{4}$$

where the lth column contains the frequencies to be transmitted by the lth LSN. Consequently, based on the principles of MFSK, the signal transmitted by the lth LSN during the ith symbol-duration $iT_s < t \leq (i+1)T_s$ can be expressed in complex form as

$$\begin{aligned} s_l(t) = & \sum_{k=1}^{K} \sqrt{P} \psi_{T_h}\left(t - iT_s - [l-1]T_h\right) \\ & \times \exp\left(j2\pi[f_c + f_{m_l^{(k)}}]t + \phi_l^{(k)}\right),\ l = 1, \ldots, L \end{aligned} \tag{5}$$

where P denotes the transmission power, which is assumed the same with respect to all the L sensors, f_c is the main carrier frequency and $\{\phi_l^{(k)}\}$ are the initial phases introduced by the carrier modulation. In (5), $\psi_{T_h}(t)$ is the pulse-shaped signaling waveform, which is defined over the interval $[0, T_h)$ and satisfies $T_h^{-1} \int_0^{T_h} \psi^2(t)dt = 1$.

We assume that the M frequencies used by the FH/MFSK WSN are sufficiently separated, resulting in that each of them experiences independent flat Rayleigh fading. Then, the signal received from the lth LSN by the FC during $iT_s < t \leq (i+1)T_s$ can be expressed as

$$\begin{aligned} r_l(t) = & \sum_{k=1}^{K} h_l^{(k)} s_l(t) + n_l(t) \\ = & \sum_{k=1}^{K} \sqrt{P} h_l^{(k)} \psi_{T_h}(t - iT_s - [l-1]T_h) \\ & \times \exp(j2\pi[f_c + f_{m_l^{(k)}}]t + \phi_l^{(k)}) + n_l(t), \\ & l = 1, \ldots, L,\ \ k = 1, \ldots, K, \end{aligned} \tag{6}$$

where $h_l^{(k)}$ denotes the channel gain in the context of the lth LSN and the MFSK frequency for SE k, and it obeys the complex Gaussian distribution with zero mean and a variance of 0.5 per dimension. Furthermore, in (6), $n_l(t)$ represents the Gaussian noise process presenting at the fusion center, which has zero mean and a single-sided power-spectral density (PSD) of N_0 per dimension.

III. Signal Detection at Fusion Center

In the FH/MFSK WSN monitoring multiple SEs, signals for different SEs may be transmitted on the same frequency at the same time, which generates the multi-event interference (MEI) [9]. The MEI may significantly degrade the achievable detection performance, if it is not treated properly. In this paper, two noncoherent fusion rules are studied, both of them have relatively low complexity. The first one is the conventional EGC fusion rule, while the second one is the proposed EGC-IIC fusion rule, which carries out iteratively the EGC and interference cancellation (IC), in order to mitigate the MEI.

The FC starts the detection by forming a time-frequency matrix $\boldsymbol{R}$ of $(M \times L)$-dimensional based on the observations extracted from the signals received from the L number of LSNs. Specifically, when the square-law noncoherent detection is considered, the elements of $\boldsymbol{R}$ have the values

$$\begin{aligned} R_{ml} = & \Bigg| \frac{1}{\sqrt{\Omega P} T_h} \int_{iT_s+(l-1)T_h}^{iT_s+lT_h} r_l(t) \psi_{T_h}^*(t - iT_s - [l-1]T_h) \\ & \times \exp(-j2\pi[f_c + f_m]t) dt \Bigg|^2, \end{aligned} \tag{7}$$

where $m = 0, 1, \ldots, M-1$ and $l = 1, 2, \ldots, L$, and $\Omega = E[|h_l^{(k)}|^2]$ denotes the average channel power. Since it has been assumed that the M number of frequency bands invoked are orthogonal to each other, hence there is no interference between any two frequency bands. Consequently, upon substituting (6) into (7) and absorbing the carrier phase $\phi_l^{(k)}$ into $h_l^{(k)}$, we obtain

$$\begin{aligned} R_{ml} = \left| \sum_{k=1}^{K} \frac{\mu_{mm_l^{(k)}} h_l^{(k)}}{\sqrt{\Omega}} + N_{ml} \right|^2,\ m = 0, 1, \ldots, M-1; \\ l = 1, 2, \ldots, L \end{aligned} \tag{8}$$

where, by definition, $\mu_{mm_l^{(k)}}=1$, if $m=m_l^{(k)}$ while $\mu_{mm_l^{(k)}}=0$, if $m\neq m_l^{(k)}$. In (8), N_{ml} represents a complex Gaussian noise sample in terms of the mth frequency band and the lth time-slot, which is given by

$$N_{ml}=\frac{1}{\sqrt{\Omega P T_h}}\int_{iT_s+(l-1)T_h}^{iT_s+lT_h} n_l(t)\psi^*_{T_h}(t-iT_s-[l-1]T_h)\times\exp(-j2\pi[f_c+f_m]t)dt \quad (9)$$

which can be shown that has mean zero and a variance of $LN_0/(\Omega E_s)=L/\bar{\gamma}_s$, where $E_s=PT_s$ represents the total energy for transmitting one M-ary symbol with each LSN's transmitted energy per symbol being $E_h=E_s/L$, while $\bar{\gamma}_s=\Omega E_s/N_0$ denotes the average SNR per symbol.

Note that, as mentioned previously, there exist the cases that a given LSN needs to activate the same MFSK frequency for two or more SEs. In this case, as shown in (5), there will be several terms having the same MFSK frequency and the same initial carrier phase. Consequently, for the R_{ml} in (8) corresponding to this frequency, there may be several $m_l^{(k)}$'s, which make $\mu_{mm_l^{(k)}}=1$ but correspond to the same value for their $h_l^{(k)}$'s.

Based on the time-frequency matrix $\boldsymbol{R}$, the FC carries out the final detection in the principles of EGC or EGC-IIC fusion rule as follows.

A. Equal-Gain Combining Fusion Rule

In the context of the EGC fusion rule, the FC detects the kth SE's state by first carrying out the frequency de-hopping, forming the detection matrix

$$\boldsymbol{D}^{(k)}=\boldsymbol{R}\boxminus(\boldsymbol{1}\otimes\boldsymbol{a}_k^T),\ k=1,2,\ldots,K \quad (10)$$

where $\boldsymbol{1}$ denotes an all-one M-length column vector, $\otimes$ denotes the Kronecker product between two matrices, while $\boldsymbol{A}\boxminus\boldsymbol{B}$ is defined as the element-shift operation in $GF(M)$, yielding $d^{(k)}_{(m\ominus a_l^{(k)})l}=R_{ml}$, where $\ominus$ is the minus operation in $GF(M)$. In other words, the (m,l)th element in $\boldsymbol{R}$ is mapped to the $(m\ominus a_l^{(k)},l)$th element in $\boldsymbol{D}^{(k)}$, after the frequency de-hopping operations of (10).

Based on (10), the EGC fusion rule then forms the M decision variables for detection of the kth SE's state, expressed as

$$d_m^{(k)}=\sum_{l=1}^{L}d_{ml}^{(k)},\ m=0,1,\ldots,M-1;\ k=1,2,\ldots,K \quad (11)$$

Finally, for each of $k=1,2,\ldots,K$, the largest of $\{d_0^{(k)},d_1^{(k)},\ldots,d_{M-1}^{(k)}\}$ is selected, the subscript index of which is a value in $\{0,1,\ldots,M-1\}$, which represents the estimate of the state that the kth SE is currently at.

The EGC fusion rule may experience serious MEI, which significantly degrades the reliability of the FH/MFSK WSN. Below we describe another fusion rule, namely the EGC-IIC fusion rule, which is capable of enhancing the reliability of the FH/MFSK WSN in comparison with the EGC fusion rule.

B. EGC-IIC Fusion Rule

When the EGC-IIC fusion rule is employed, the EGC and IC are iteratively operated by detecting the SEs in the order from the most reliable SE to the least reliable SE. In order to find the reliability of the detection, in this contribution, a low-complexity reliability measurement method is proposed, which measures the reliability of an EGC-based detection based on the formula

$$L^{(k)}=\frac{\max_2\left\{d_0^{(k)},d_1^{(k)},\ldots,d_{(M-1)}^{(k)}\right\}}{\max_1\left\{d_0^{(k)},d_1^{(k)},\ldots,d_{(M-1)}^{(k)}\right\}} \quad (12)$$

where $\max_1\{\cdot\}$ and $\max_2\{\cdot\}$ represent, respectively, the maximum and 'second' maximum of the decision variables of $\{d_0^{(k)},d_1^{(k)},\ldots,d_{M-1}^{(k)}\}$, which are given by the EGC of (11). In our EGC-IIC, an estimate to the state of a SE is rendered more reliable than the other estimates, if its $L^{(k)}$ value is lower than any of the other $L^{(k)}$ values.

Let us assume that the FC has the knowledge of the FH addresses in $\boldsymbol{A}$ assigned to the K SEs. Then, the EGC-IIC algorithm can be stated as follows.

1) **Initialization**: $\boldsymbol{R}^{(0)}=\boldsymbol{R}$.
2) **EGC-IIC detection**: for $i=1,2,\ldots,N\leq K-1$, the following steps are executed:
   a) **Frequency de-hopping**: for those $(K-i+1)$ SEs having not been detected, the detection matrices, $\boldsymbol{D}_i^{(1)},\boldsymbol{D}_i^{(2)},\ldots,\boldsymbol{D}_i^{(K-i+1)}$, are formed based on (10), with the aid of the FH addresses of these undetected SEs.
   b) **Forming decision variables**: For each of the $(K-i+1)$ SEs, the M decision variables are formed based on the EGC principles, as shown in (11).
   c) **Reliability Measurement**: The reliabilities with respect to all the $(K-i+1)$ SEs are measured based on (12), which are expressed as $L_i^{(1)},L_i^{(2)},\ldots,L_i^{(K-i+1)}$.
   d) **Finding and detecting the most reliable SE**: The most reliable SE is identified as
   $$k'\leftrightarrow L_i^{(k')}=\min\left\{L_i^{(1)},L_i^{(2)},\ldots,L_i^{(K-i+1)}\right\} \quad (13)$$
   and the state of the most reliable SE is detected as the subscript index of the largest in $\{d_0^{(k')},d_1^{(k')},\ldots,d_{M-1}^{(k')}\}$, as the EGC fusion rule considered in Section III-A. Let the estimated state be expressed as $\hat{m}^{k'}$.
   e) **Update $\boldsymbol{R}^{(i-1)}$ to $\boldsymbol{R}^{(i)}$**: $\boldsymbol{R}^{(i)}$ is updated from $\boldsymbol{R}^{(i-1)}$ by removing its elements at $(\hat{m}^{k'}\oplus a_l^{(k')},l)$ for $l=1,2,\ldots,L-1$.
3) For the rest $(K-N)$ SEs, they are just detected based on the EGC fusion rule, as stated in Section III-A.

From the above-stated EGC-IIC algorithm, we can see that the IC operations are only implemented with the first N reliable SEs, while the other $(K-N)$ SEs are simply detected based on the EGC fusion rule described in Section III-A. The reason behind this proposed EGC-IIC is that, in the FH/MFSK WSN, there are three factors affecting the fusion detection, which are the detection reliabilities of LSNs, wireless channel and the MEI. Due to the unreliable detection at the LSNs, even a SE measured based on (12) with the highest reliability might be detected in error. In this case, applying the IC will generate negative effect on the following detections. Furthermore, it can be shown that this negative effect becomes worse as the number of SEs invoked and/or the number of LSNs increase. Note that, for given values of K and L, there exists a value for N, which yields the best detection performance, as illustrated by our results in Section V.

IV. Analysis of Characteristics

Our proposed FH/MFSK WSN employs a range of characteristics, which can be summarized as follows. First, noncoherent detection is implemented at the FC, which does not require to consume extra energy for channel estimation. This energy-efficient and low-complexity detection strategy is beneficial to the life-time of battery-powered WSN. Second, in addition to supporting multiple SEs, the FH/MFSK techniques employed is capable of providing frequency diversity for the fusion detection. The frequency diversity becomes more important, when the LSNs are close to each other, which may generate correlated fading in the space-domain. On the other hand, owing to the frequency diversity obtained from the FH/MFSK, the LSNs may be distributed within a relatively small space but still convey the FC independently faded signals, so that the detection performance of the FC is not degraded by the correlated fading experienced in the space-domain. Third, the proposed FH/MFSK WSN can simultaneously monitor multiple SEs of each with multiple states. Each LSN serves all the SEs and, hence, a FH/MFSK WSN does not have to use a big number of LSNs. However, the side effect of using one LSN to transmit simultaneously multiple frequency modulation signals is the possible high peak-to-average power ratio (PAPR), which is not power-efficient, if not treated appropriately. Forth, in the FH/MFSK WSN, in addition to the EGC and EGC-IIC considered in this contribution, other advanced noncoherent detection schemes [9] may be implemented, which may enhance further the detection performance.

Finally, we note that the overall performance of the FH/MFSK WSN is jointly determined by the detection performance of the L LSNs, the wireless channels, and the MEI. If the detection performance of the L LSNs is poor, then, the overall performance will most probably be poor, even when the wireless channels from LSNs to FC are perfect and there is no MEI. Similarly, the overall performance of the FH/MFSK WSN will degrade, if the wireless channels becomes unreliable and the MEI is high. Hence, when considering the optimization in the FH/MFSK WSN, the detection schemes at the LSNs and FC need to be jointly considered. In general, in the FH/MFSK WSNs, the performance of LSNs may be improved by employing the advanced sensing techniques, the fading of wireless channels can be compensated by making use of the frequency and space diversity, while the MEI may be mitigated with the aid of various noncoherent signal processing techniques [9].

V. Performance Results

In this section, the BER performance of the FH/MFSK WSN employing either EGC or EGC-IIC fusion rule is investigated, when assuming that the wireless channels from the LSNs to the FC experience Rayleigh fading channels. The number of bits per symbol is $b = \log_2 M$, and natural mapping from binary symbol to M-ary symbol is assumed.

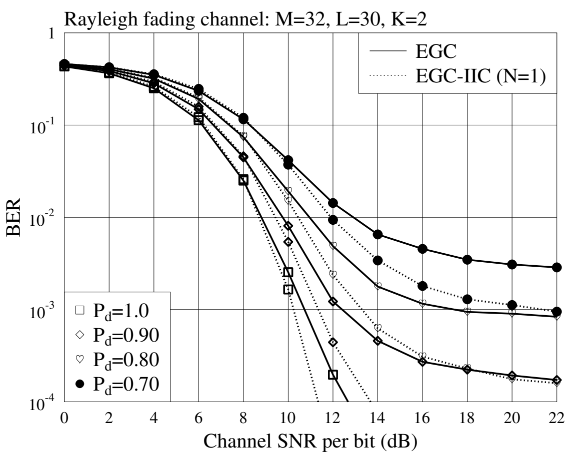

Fig. 2. BER versus channel SNR per bit performance of the FH/MFSK WSN supporting $K = 2$ SEs using $L = 30$ LSNs, when communicating over Rayleigh channels.

Fig. 2 shows the BER performance of the FH/MFSK WSN employing $L = 30$ LSNs monitoring $K = 2$ SEs of each with $M = 32$ states (hypotheses). From the results, we can explicitly observe that both the LSNs' reliability and the channel SNR have strong impact on the overall achievable detection performance of the FH/MFSK WSN. As shown in Fig. 2, the BER performance of the FH/MFSK WSN degrades, as the correct detection probability P_d decreases from $P_d = 1$ to $P_d = 0.7$. However, for both the EGC and EGC-IIC fusion rules, an BER of 0.01 can be achieved at a reasonable channel SNR, which is typically lower than 14 dB. Additionally, from Fig. 2, we can see that, for all the P_d values considered, the EGC-IIC fusion rule outperforms the EGC fusion rule, when the channel SNR is sufficiently high.

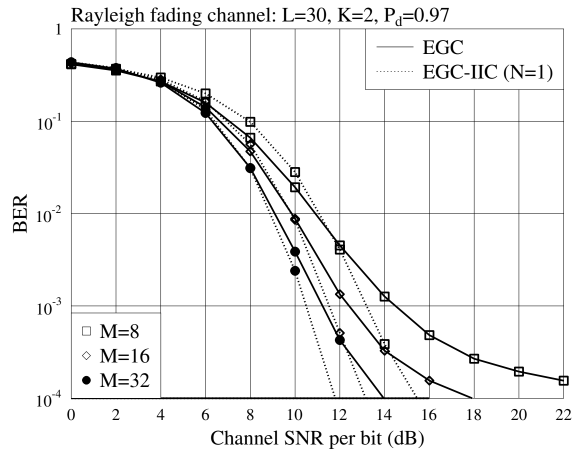

Fig. 3. BER versus channel SNR per bit performance of the FH/MFSK WSN supporting $K = 2$ SEs using $L = 30$ LSNs with $P_d = 0.97$, when communicating over Rayleigh channels.

In Fig. 3, we illustrate the effect of the value of M on the BER performance of the FH/MFSK WSN supporting $K = 2$ SEs using $L = 30$ LSNs with $P_d = 0.97$. We can observe that the EGC-IIC fusion rule outperforms the EGC fusion rule, provided that the channel SNR is sufficiently high. However, if the channel SNR is not sufficient, the EGC-IIC fusion rule may be outperformed by the EGC fusion rule. This observation becomes very explicit for the case of $M = 8$. Furthermore, the results of Fig. 3 show that the BER performance of the FH/MFSK WSN improves significantly, as the number of states of M increases.

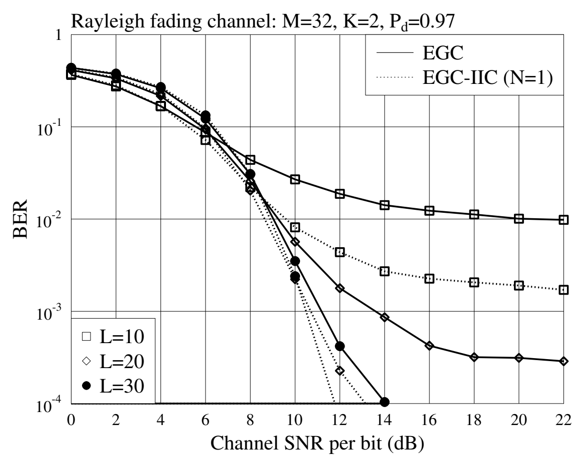

Fig. 4. BER versus channel SNR per bit performance of the FH/MFSK WSN supporting $K = 2$ SEs employing various number of LSNs with $P_d = 0.97$, when communicating over Rayleigh channels.

Fig. 4 illustrates the impact of the number of LSNs used on the BER performance of the FH/MFSK WSN supporting $K = 2$ SEs, when the LSNs have a correct detection probability of $P_d = 0.97$. As shown in Fig. 4, when the channel SNR is sufficiently high, the BER performance of the FH/MFSK WSN improves, as the WSN employs more LSNs for attaining the space diversity. However, when the channel SNR is not enough, using more LSNs may result in degraded BER performance, due to the errors occurred at the LSNs. From Fig. 4, again, we can find that the EGC-IIC fusion rule outperforms the EGC fusion rule, provided that the wireless channels are reasonably reliable.

Fig. 5 shows the BER versus channel SNR per bit performance of

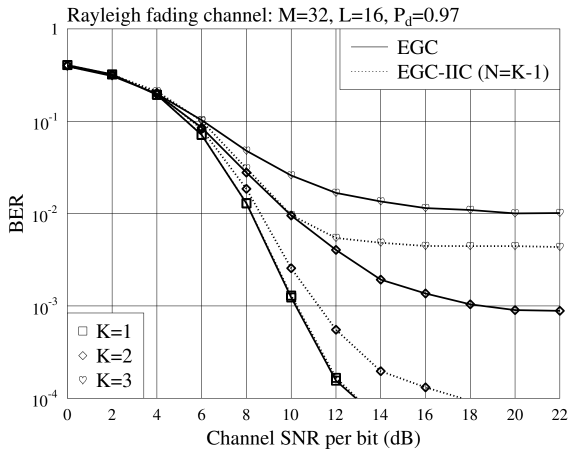

Fig. 5. BER versus channel SNR per bit performance of the FH/MFSK WSN employing $L = 16$ LSNs operated at a correct detection probability $P_d = 0.97$, when communicating over Rayleigh channels.

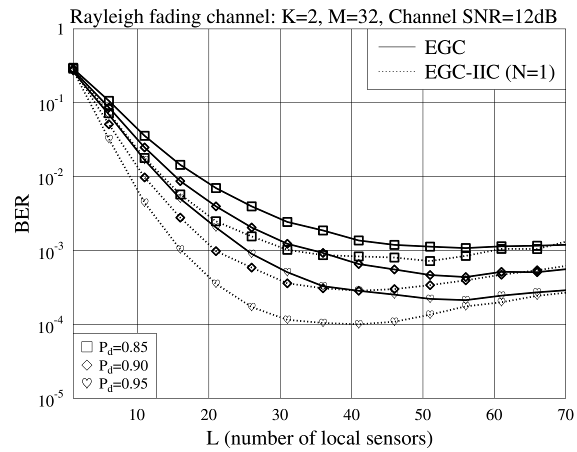

Fig. 7. BER versus number of local sensors for the FH/MFSK WSN supporting $K = 2$ SEs, when communicating over Rayleigh fading channels.

the FH/MFSK WSN supporting $K = 1,\ 2$ or 3 SEs, when the EGC or EGC-IIC fusion rule is used. Explicitly, for both the EGC and EGC-IIC fusion rules, the BER performance of the FH/MFSK WSN degrades as the SEs supported increases, although, for $K = 2,\ 3$, the EGC-IIC fusion rule yields better BER performance than the EGC fusion rule.

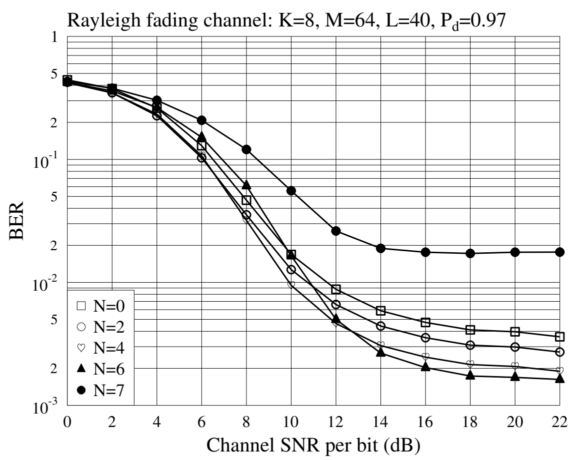

Fig. 6. BER versus channel SNR per bit performance of the FH/MFSK WSN supporting $K = 8$ SEs using $L = 40$ LSNs at $P_d = 0.97$, when various orders of IIC are applied.

In Fig. 6, we study the effect of the number of iterations, expressed by N, used in the EGC-IIC fusion rule on the BER performance of the FH/MFSK WSN. Note that, $N = 0$ corresponds to the pure EGC fusion rule, while $N = K - 1$ corresponds to the full EGC-IIC fusion rule, where full $(K - 1)$ IC stages are applied. From the curves in Fig. 6, we can observe that, at a given channel SNR, there exists a value for N, which yields the best BER performance for the FH/MFSK WSN having the parameters as shown in the figure. For example, at the channel SNR of 10 dB, the EGC-IIC using $N = 4$ stages of IIC attains the lowest BER. By contrast, at the channel SNR of 16 dB, the EGC-IIC using $N = 6$ stages of IIC achieves the lowest BER. Note that, using more stages of IC will result in more detection delay. Hence, for those delay sensitive WSNs, the trade-off between detection delay and achievable BER performance may also need to be taken into account.

Finally, in Fig.7, we illustrate the BER performance of the FH/MFSK WSN against the number of LSNs. As shown in Fig.7, when the total transmission energy for a SE's state is given, there exists an optimum number for the number of the LSNs employed, which results in the best overall detection performance of the FH/MFSK WSN. Furthermore, it seems that the optimum number reduces, as the reliability of the LSNs' detection becomes higher. Again, from the results of Fig.7, we can see that, when $K = 2$, the EGC-IIC fusion rule significantly outperforms the EGC fusion rule.

VI. Conclusions

Our studies show that the proposed FH/MFSK WSN with the low-complexity EGC or EGC-IIC fusion rule is capable of achieving promising detection performance for the practically reasonable values for the LSNs' reliability, channel SNR, etc. In general, provided that the channel SNR is sufficiently high, the EGC-IIC fusion rule outperforms the EGC fusion rule. However, the EGC-IIC fusion rule demands slightly higher complexity and also imposes extra detection delay than the EGC fusion rule. For both the EGC and EGC-IIC fusion rules, there exists a value for the number of LSNs used, which yields the best BER performance of the FH/MFSK WSN. Additionally, when the number of SEs is high, there exists an optimal number of IIC stages, which results in the lowest BER.

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