POWER-AWARE DISTRIBUTED DETECTION IN IR-UWB SENSOR NETWORKS

Daniel Bielefeld, Gernot Fabeck, and Rudolf Mathar

Institute of Theoretical Information Technology, RWTH Aachen University
Aachen, Germany
{bielefeld,fabeck,mathar}@ti.rwth-aachen.de

ABSTRACT

The interplay between signal processing and wireless networking plays a crucial role in sensor networks deployed for detection and estimation applications. In this paper, an opportunistic power assignment strategy for IR-UWB sensor networks is presented which is designed to optimize detection performance in terms of the global probability of error. The opportunistic power assignment strategy utilizes both the detection error probabilities of individual sensors as well as network topology information, leading to significant performance gains compared to uniform power assignment.

1. INTRODUCTION

Distributed detection of phenomena of interest is one of the primary applications of wireless sensor networks [1, 2]. In the parallel fusion topology, the sensor nodes process their observations independently and make preliminary decisions about the state of the observed environment, e.g., absence or presence of a target. The sensors transmit the local decisions to a fusion center that combines the received decisions and computes the final detection result.

The transmission channels between the battery-operated wireless sensors and the fusion center are usually subject to noise and interference. In order to optimally design the distributed detection system, it becomes necessary to take wireless channel conditions into account [3]. On the other hand, modern transceiver technology allows the control of transmission quality in networks by sophisticated power assignment algorithms. In wireless sensor networks deployed for detection applications, the power assignment eventually should be designed to optimize signal processing metrics [4].

In this paper, we consider IR-UWB transceivers which are well suited for wireless sensor nodes due to low power consumption, resilience against multipath fading, and low system complexity. We present an opportunistic power assignment strategy in order to optimize signal processing performance in terms of the global probability of error.

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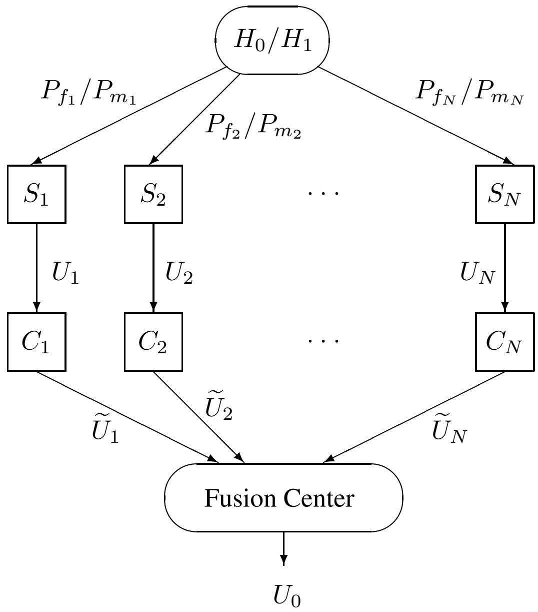

Fig. 1. Parallel fusion network with noisy channels.

The remainder of this paper is organized as follows. In Section 2, the problem of distributed detection in the parallel fusion network with noisy channels is stated. In Section 3, we discuss power assignment in IR-UWB networks. An opportunistic power assignment strategy based on a sensitivity analysis is introduced in Section 4. Finally, we present numerical results and conclusions in Section 5.

2. PARALLEL FUSION NETWORK WITH NOISY CHANNELS

The problem of distributed detection in the parallel fusion network with noisy channels can be stated as follows (see Fig. 1). We consider a binary hypothesis testing problem with hypotheses H_0 and H_1 indicating the state of the observed environment. The associated prior probabilities are $\pi_0 = P(H_0)$ and $\pi_1 = P(H_1)$. In order to detect the true

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state of nature, a network of N sensors $S_1, \ldots, S_N$ collects measurement data generated according to either H_0 or H_1, the two hypotheses under test. Each sensor processes its observation independently and makes a preliminary decision about the true hypothesis before sending it to the fusion center. In the case that every wireless sensor is allowed to transmit only one bit per observation, the sensor decisions are binary-valued random variables $U_j \in \{0, 1\}$, $j = 1, \ldots, N$. The resulting detection error probabilities for each sensor are given by the local probability of false alarm P_{f_j} and the local probability of miss P_{m_j} according to

$$P_{f_j} = P(U_j = 1|H_0), \quad P_{m_j} = P(U_j = 0|H_1) \tag{1}$$

for $j = 1, \ldots, N$. Upon local detection, the sensor nodes transmit the preliminary decisions $U_1, \ldots, U_N$ to the fusion center which is responsible for decision combining. The communication channels $C_1, \ldots, C_N$ between the wireless sensors and the fusion center are usually subject to noise and interference. We model the communication link C_j between sensor S_j and the fusion center by a binary symmetric channel with bit-error probability ε_j, i.e.

$$\varepsilon_j = P(\widetilde{U}_j = 1|U_j = 0) = P(\widetilde{U}_j = 0|U_j = 1) \tag{2}$$

for $j = 1, \ldots, N$. The potentially corrupted received local detection results $\widetilde{U}_1, \ldots, \widetilde{U}_N$ are combined to yield the final decision $U_0 \in \{0, 1\}$. The application-specific metric is chosen to be the sensor network detection performance in terms of the global probability of error

$$P_e = \pi_0 P_f + \pi_1 P_m \tag{3}$$

which can be written as a weighted sum of the global probability of false alarm $P_f = P(U_0 = 1|H_0)$ and the corresponding global probability of miss $P_m = P(U_0 = 0|H_1)$.

2.1. Optimal channel-aware fusion rule

Under the assumption of conditionally independent local detection results $U_1, \ldots, U_N$ and independent binary symmetric channels $C_1, \ldots, C_N$, the optimal channel-aware fusion rule can be implemented by a linear threshold rule [5]

$$\sum_{j=1}^{N} \widetilde{\lambda}_j \widetilde{U}_j \underset{U_0 = 0}{\overset{U_0 = 1}{\gtrless}} \vartheta \tag{4}$$

with effective sensor weights

$$\widetilde{\lambda}_j = \log\left(\frac{(1 - \widetilde{P}_{f_j})(1 - \widetilde{P}_{m_j})}{\widetilde{P}_{f_j} \widetilde{P}_{m_j}}\right) \tag{5}$$

for $j = 1, \ldots, N$, and a decision threshold

$$\vartheta = \log\left(\frac{\pi_0}{\pi_1} \prod_{j=1}^{N} \frac{1 - \widetilde{P}_{f_j}}{\widetilde{P}_{m_j}}\right). \tag{6}$$

The modified error probabilities $\widetilde{P}_{f_j} = P(\widetilde{U}_j = 1|H_0)$ and $\widetilde{P}_{m_j} = P(\widetilde{U}_j = 0|H_1)$ can be calculated as

$$\begin{aligned} \widetilde{P}_{f_j} &= P_{f_j} + \varepsilon_j(1 - 2P_{f_j}), \\ \widetilde{P}_{m_j} &= P_{m_j} + \varepsilon_j(1 - 2P_{m_j}). \end{aligned} \tag{7}$$

Note that for $P_{f_j}, P_{m_j} \in [0, \frac{1}{2}]$, and an arbitrary bit-error rate $\varepsilon_j \in [0, 1]$, the effective sensor weight $\widetilde{\lambda}_j$ is always less than or equal to the initial sensor weight λ_j which is given as

$$\lambda_j = \log\left(\frac{(1 - P_{f_j})(1 - P_{m_j})}{P_{f_j} P_{m_j}}\right). \tag{8}$$

2.2. Performance evaluation

In order to efficiently evaluate the sensor network detection performance in terms of (3), we employ an approach introduced in [6] which provides a tight upper bound on the probability of error P_e.

For the optimal channel-aware fusion rule (4), an upper bound on the overall probability of error P_e is given by

$$\begin{aligned} P_e \le\; & \pi_0 \varphi\Big(\frac{\vartheta_0}{\rho_0 \sqrt{N}}\Big) \exp\Big(-NH(\rho_0^2, b_0, \frac{\vartheta_0}{N})\Big) + \\ & + \pi_1 \varphi\Big(\frac{\vartheta_1}{\rho_1 \sqrt{N}}\Big) \exp\Big(-NH(\rho_1^2, b_1, \frac{\vartheta_1}{N})\Big), \end{aligned} \tag{9}$$

where $\varphi(x) = \exp(\frac{x^2}{2})(1 - \Phi(x))$, and Φ is the cumulative distribution function (cdf) of the standard normal distribution. The quantities involved are given by

$$\vartheta_0 = \vartheta - \sum_{j=1}^{N} \widetilde{\lambda}_j \widetilde{P}_{f_j}, \qquad \vartheta_1 = \sum_{j=1}^{N} \widetilde{\lambda}_j (1 - \widetilde{P}_{m_j}) - \vartheta,$$

$$\rho_0^2 = \frac{1}{N} \sum_{j=1}^{N} \widetilde{\lambda}_j^2 (\widetilde{P}_{f_j} - \widetilde{P}_{f_j}^2), \quad \rho_1^2 = \frac{1}{N} \sum_{j=1}^{N} \widetilde{\lambda}_j^2 (\widetilde{P}_{m_j} - \widetilde{P}_{m_j}^2),$$

$$b_0 = \max_j \; \widetilde{\lambda}_j (1 - \widetilde{P}_{f_j}), \qquad b_1 = \max_j \; \widetilde{\lambda}_j (1 - \widetilde{P}_{m_j}).$$

The function H is defined as

$$\begin{aligned} H(\rho^2, b, t) = & \left(1 + \frac{bt}{\rho^2}\right) \frac{\rho^2}{b^2 + \rho^2} \log\left(1 + \frac{bt}{\rho^2}\right) \\ & + \left(1 - \frac{t}{b}\right) \frac{b^2}{b^2 + \rho^2} \log\left(1 - \frac{t}{b}\right). \end{aligned}$$

Evaluation of expression (9) is straightforward and yields a computationally simple yet numerically tight upper bound on the probability of error P_e.

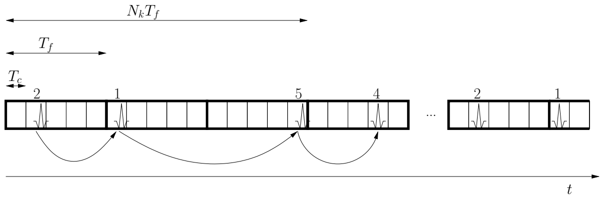

Fig. 2. Illustration of parameters used in the system model. In the example $c^{(k)} = (2, 1, 5, 4)$, $d_1^{(k)} = 1$, $d_2^{(k)} = 0$, and $N_k = 3$.

3. POWER ASSIGNMENT IN IR-UWB NETWORKS

As described in the previous section, the transmission of the preliminary detection results $U_1, \ldots, U_N$ from the sensor nodes to the fusion center is subject to noise. Physically, this noise is caused by thermal noise and in case of non-orthogonal channels additionally by interference from other sensor nodes. The channel quality can be controlled by an appropriate assignment of transmission power levels to the nodes. We consider IR-UWB transceivers which are well suited for wireless sensor nodes due to low power consumption, resilience against multipath fading combined with low system complexity. In particular, we consider IR-UWB with pulse position modulation with modulation index δ and pseudo random time hopping codes as multiple access scheme as described in [7]. The transmitted signal from sensor S_j to the fusion center can then be written as

$$s_j(t) = A_j \sum_{i=-\infty}^{\infty} w(t - iT_f - c_i^{(j)} T_c - \delta d^{(j)}_{\lfloor i/N_j \rfloor}), \quad (10)$$

where T_f denotes the length of a timeframe in which one impulse of form $w(t)$ is transmitted. Inside a timeframe, the impulse is delayed by an integer multiple of the chip length T_c according to the time hopping code $c_i^{(j)}$. Each data bit $d^{(j)}$ corresponding to the local decision U_j is transmitted by a number of N_j equally modulated pulses with amplitude A_j. Some exemplary parameters for one user are illustrated in Fig. 2.

According to [8], in a multi-user scenario the signal-to-interference-and-noise ratio (SINR) of the link between sensor S_j and the fusion center can be written as

$$\text{SINR}_j = N_j \frac{g_j p_j}{\sigma^2 \sum_{k \neq j} g_k p_k + \frac{1}{T_f}\eta}, \quad (11)$$

with p_j denoting the transmission power of sensor node S_j and σ^2 is a spreading gain parameter depending on the correlation properties of the employed pulse form. The path gain between sensor S_j and the fusion center is denoted by g_j. The energy of the additional noise is given by η. If each

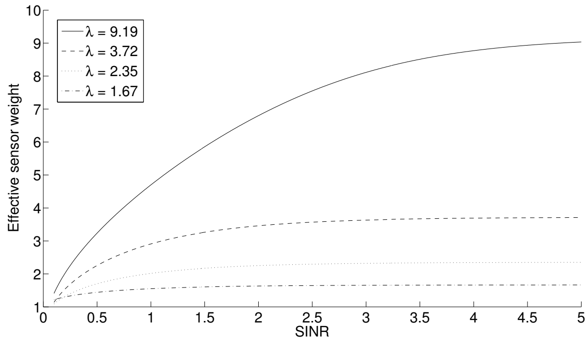

Fig. 3. Effective sensor quality $\widetilde{\lambda}$ as function of the SINR γ for different values of the initial sensor quality λ.

node has an individual quality of service (QoS) requirement in terms of the target SINR γ_j, the optimal transmission power, i.e., the minimal transmission power for each node to meet all QoS demands can be determined by the following system of linear equations [8]

$$\boldsymbol{p}^* = [\boldsymbol{I} - \boldsymbol{\Gamma}\boldsymbol{N}^{-1}\boldsymbol{B}]^{-1}\boldsymbol{\tau}. \quad (12)$$

Here $\boldsymbol{\Gamma}$ and $\boldsymbol{N}$ are diagonal matrices with the jth entry containing the target SINR γ_j and the number N_j of pulse repetitions for one data bit of the jth sensor, respectively. The vector $\boldsymbol{p}^*$ contains the optimal transmission power levels of the nodes. The entries b_{ij} of the matrix $\boldsymbol{B}$ are

$$b_{ij} = \begin{cases} \sigma^2 g_j / g_i, & i \neq j \\ 0, & i = j \end{cases} \quad (13)$$

and the jth element of vector $\boldsymbol{\tau}$ contains the entry

$$\tau_j = \frac{\eta \gamma_j}{T_f N_j g_j}. \quad (14)$$

A feasible power assignment to the given SINR requirements $\gamma_1, \ldots, \gamma_N$ is equivalent to a solution $\boldsymbol{p}^*$ with only positive entries which is the case if and only if the spectral radius of the matrix $\boldsymbol{\Gamma}\boldsymbol{N}^{-1}\boldsymbol{B}$ is less than one. If a feasible solution exists the SINR demands can be used to compute the corresponding bit-error rates. Using the standard Gaussian approximation as discussed in [9], the bit-error rate ε_j of node S_j can be stated as

$$\varepsilon_j = \frac{1}{2}\text{erfc}(\sqrt{\gamma_j}). \quad (15)$$

Note that ε_j is equivalent to the bit-error probability of the binary symmetric channel C_j as stated in (2).

4. POWER ASSIGNMENT STRATEGY BASED ON A SENSITIVITY ANALYSIS

In the following we propose an opportunistic power assignment strategy based on an application-specific choice of the

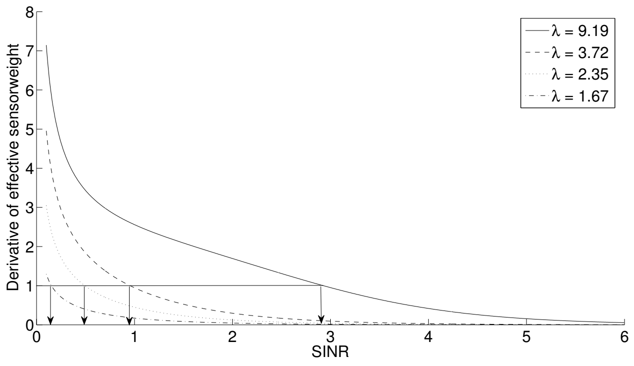

Fig. 4. Derivative $\partial\widetilde{\lambda}/\partial\gamma$ of the effective sensor quality $\widetilde{\lambda}$ with respect to the SINR γ. Here, the threshold ϱ is chosen to be equal to 1.

target SINRs γ_j. Our objective is to optimize the detection performance in terms of the global probability of error P_e.

Fig. 3 shows the effective sensor weight $\widetilde{\lambda}$ dependent on the target SINR γ for different initial sensor weights λ. It can be observed that for high values of γ the effective sensor quality approaches the initial sensor quality. In this case, increasing γ does not result in an improved effective sensor quality. The value of γ from which on the effective sensor quality $\widetilde{\lambda}$ is not further improved significantly, increases with the initial sensor quality λ. It is therefore advantageous to assign higher values of SINR to sensors with high initial quality than to ones with low initial quality. We employ a sensitivity analysis of the effective sensor weight and assign the SINR for which the slope of the effective sensor weight $\widetilde{\lambda}$ with respect to γ falls under a predetermined threshold ϱ. Fig. 4 illustrates this procedure.

The threshold value ϱ can be used as a trade-off parameter to balance total transmission power $p_{\text{tot}} = \sum_{j=1}^{N} p_j$ and global probability of error P_e.

To account for signal attenuation in the SINR assignment we also consider network topology information. In order to favor nodes near the fusion center with low pathloss, we use a weighting factor given by the inverse distance d_j of sensor S_j to the fusion center normalized by the maximal distance d_{max}. Eventually, we determine the designated target SINR γ_j of sensor S_j according to

$$\gamma_j = \left(\frac{d_j}{d_{\text{max}}}\right)^{-\beta} \cdot \left(\frac{\partial\widetilde{\lambda}_j}{\partial\gamma}\right)^{-1}(\varrho). \qquad (16)$$

The exponent β is chosen corresponding to a pathloss model. The opportunistic power assignment strategy is obtained by using the target SINRs (16) to compute the transmission power levels p_j of the individual sensor nodes as described in Section 3.

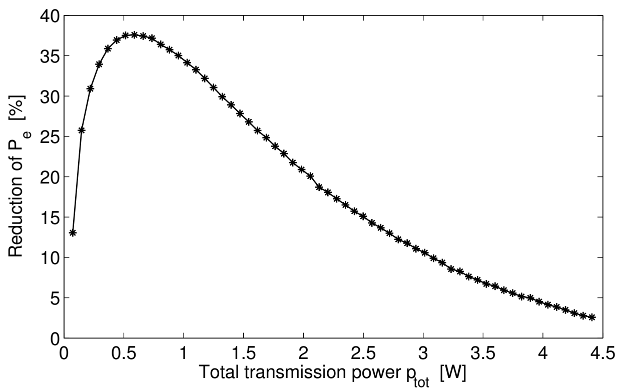

Fig. 5. Relative performance gain of the opportunistic strategy in terms of reduction of the global probability of error P_e compared to uniform power assignment.

5. NUMERICAL RESULTS AND CONCLUSIONS

In this section, we investigate the performance of the opportunistic strategy from Section 4 compared to uniform power assignment by simulation. The scenario is generated by randomly deploying the sensor nodes uniformly in a rectangular area. The fusion center is supposed to be located in the middle of the scenario. The local error probabilities P_{f_j} and P_{m_j} of the sensor nodes are assumed to be independent and uniformly distributed random variables in the range $[0, \frac{1}{2}]$. The involved parameters of the scenario and of the employed IR-UWB transceivers are summarized in Table 1.

Table 1. Parameters used in the simulation

parameter	value
Number of sensors	50
Area	100 m $\times$ 100 m
β	2
σ^2	$1.9966 \cdot 10^{-3}$
N_j	10
T_c	2 ns
T_f	100 ns
η	10^{-11} J
ϱ	0.8

Fig. 5 depicts the simulation results. The suggested strategy reduces the global probability of error P_e up to about 40 % compared to uniform power assignment for a fixed total transmission power. For high values of the total transmission power p_{tot}, the performance gain decreases due to quasi error-free transmission.

As a final remark, we point out that the proposed power assignment strategy might also be used to minimize total transmission power given a fixed upper bound on the global probability of error P_e.

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