Cross-Layer Design of IR-UWB Sensor Networks for Distributed Detection Applications

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***Abstract*—Cross-layer design for wireless networks aims at optimizing system-wide performance measures by exploiting dependencies between different network layers. In this paper, an opportunistic power assignment algorithms for IR-UWB sensor networks is presented that is especially designed for distributed signal detection under resource constraints. Specifically, the objective is to minimize the global probability of error of distributed detection systems, given a fixed level of total transmission power. The cross-layer approach for the allocation of transmission power is based on individual sensor detection quality as well as location information. It leads to significant performance gains compared to uniform power assignment for both the parallel and the serial sensor network topology.**

I. Introduction

Distributed detection of signal sources in a region of interest is one of the primary applications of wireless sensor networks [1]. In distributed detection, the sensor nodes process their observations locally and make preliminary decisions about the state of the monitored environment, e.g., absence or presence of a target [2]. The local decisions are transmitted over noisy channels and combined to obtain a final detection result with high reliability. The main objective in the design of sensor networks for distributed detection applications in either the parallel or serial topology is the minimization of the global probability of error. In the parallel topology, the sensor nodes transmit their local decisions to a fusion center that combines the received decisions and computes the final detection result. In the serial topology, the sensors successively form decisions that depend on the received decision of a preceeding sensor as well as the own local observation until a final result is reached.

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

As enabling technology for wireless sensor networks, we consider impulse radio ultra-wideband (IR-UWB) transceivers which are well suited for wireless sensor nodes due to low power consumption, resilience against multipath fading, and low system complexity. IR-UWB offers the attractive possibility to achieve high data rates with low transmission power and low complexity transceiver hardware [5]. Multiple channel access is usually realized by pseudo random time hopping, resulting in multiple access interference. The amount of interference in IR-UWB networks can be controlled by an appropriate assignment of transmission power levels to the nodes in the network.

In this paper, we present opportunistic power assignment algorithms for IR-UWB sensor networks that are designed to optimize the signal processing performance of distributed detection systems in terms of the global probability of error given a total amount of transmission power. The capability of the approach is demonstrated for both the parallel and the serial sensor network topology.

The remainder of the paper is organized as follows. In Section II, the problem of distributed detection in the parallel and the serial topology is stated. The considered IR-UWB system model is described in Section III. An opportunistic power assignment strategy based on a sensitivity analysis is introduced in Section IV. Finally, we present numerical results and conclusions in Section V.

II. Distributed Detection

The problem of distributed detection can be stated as follows. We consider a binary hypothesis testing problem with hypotheses H_0, H_1 indicating the state of the observed environment and associated prior probabilities $\pi_0 = P(H_0)$, $\pi_1 = P(H_1)$. In order to detect the true state of nature, a network of N sensors collects random observations $X_1, \dots, X_N$, which are distributed according to the underlying hypothesis. Each sensor makes a preliminary decision about the true hypothesis before sending it to either the fusion center in the parallel topology or a neighboring sensor in the serial topology.

In the case that every wireless sensor is allowed to transmit only one bit per observation, the sensor decisions are binary-valued random variables $U_j \in \{0, 1\}$, $j = 1, \dots, N$. The

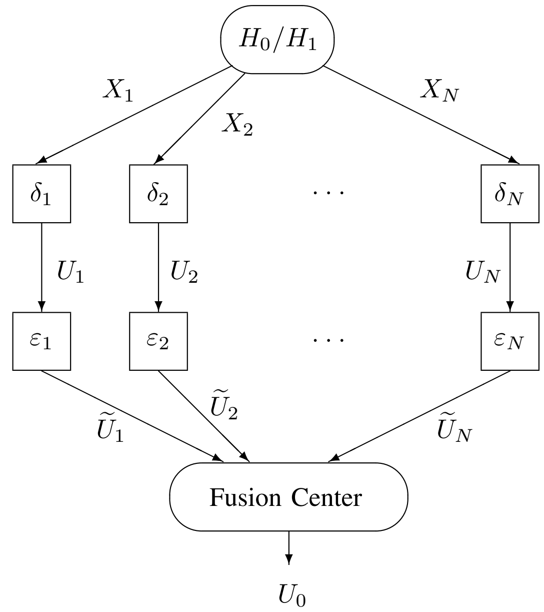

Fig. 1. Parallel fusion network with noisy channels.

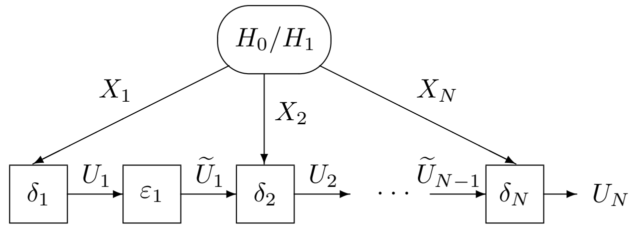

Fig. 2. Serial network with noisy channels.

local detection error probabilities for each sensor are given by the local probability of false alarm $P_{f_j} = P(U_j = 1|H_0)$ and the local probability of miss $P_{m_j} = P(U_j = 0|H_1)$. Upon local detection, the sensor nodes transmit the preliminary decisions $U_1, \ldots, U_N$ to either the fusion center in the parallel topology or a neighboring sensor in the serial topology in order to perform decision combining. Due to noisy channels, the received decisions $\widetilde{U}_1, \ldots, \widetilde{U}_N$ are potentially corrupted. We follow an approach suggested by Ferrari and Pagliari [6] and model the communication link of the jth sensor by a binary symmetric channel with bit-error probability ε_j, i.e.

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

for $j = 1, \ldots, N$. 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

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

Based on the modified error probabilities (2), we define the effective sensor weights

$$\widetilde{\lambda}_j = \log\left(\frac{(1 - \widetilde{P}_{f_j})(1 - \widetilde{P}_{m_j})}{\widetilde{P}_{f_j}\widetilde{P}_{m_j}}\right) \tag{3}$$

for $j = 1, \ldots, N$. 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

$$\lambda_j = \log\left(\frac{(1 - P_{f_j})(1 - P_{m_j})}{P_{f_j}P_{m_j}}\right). \tag{4}$$

A. Parallel fusion network

In the parallel fusion network, the sensors process their observations independently by forming local decisions

$$U_j = \delta_j(X_j), \quad j = 1, \ldots, N, \tag{5}$$

before transmitting them to a distinguished fusion center (see Fig. 1). The received and potentially corrupted local detection results $\widetilde{U}_1, \ldots, \widetilde{U}_N$ are combined to yield the final detection result $U_0 \in \{0, 1\}$. The performance metric for the parallel fusion network is the probability of error at the fusion center according to

$$P_e = \pi_0 P_f + \pi_1 P_m \tag{6}$$

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 $P_m = P(U_0 = 0|H_1)$. Under the assumption of conditionally independent sensor observations $X_1, \ldots, X_N$ and independent binary symmetric channels, the optimal channel-aware fusion rule can be implemented by a linear threshold test

$$\sum_{j=1}^{N} \widetilde{\lambda}_j \widetilde{U}_j \underset{U_0 = 0}{\overset{U_0 = 1}{\gtrless}} \vartheta \tag{7}$$

with decision threshold ϑ. The probability of error P_e of the fusion rule (7) can be evaluated efficiently using a large deviation technique presented in [7].

B. Serial network

In the serial topology, the first sensor makes a decision $U_1 = \delta_1(X_1)$ which only depends on its own observation and subsequently transmits it to its neighbor (see Fig. 2). The succeeding sensors form decisions

$$U_j = \delta_j(\widetilde{U}_{j-1}, X_j), \quad j = 2, \ldots, N, \tag{8}$$

which depend on the received and potentially corrupted decision $\widetilde{U}_{j-1}$ of the preceeding sensor as well as the own observation X_j. The performance metric for the serial network is the probability of error P_e of the Nth sensor according to

$$P_e = \pi_0 P_{f_N} + \pi_1 P_{m_N}. \tag{9}$$

Applying locally optimal detection at each sensor, the probability of error P_e of the last node can be calculated iteratively. For a low number of sensors (e.g., $N \leq 5$) the serial network usually outperforms the parallel one [8].

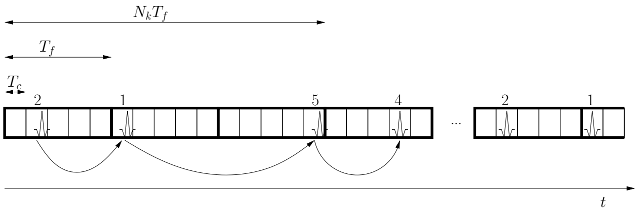

Fig. 3. Illustration of parameters used in the system model. In the example $c^{(k)} = (2, 1, 5, 4)$, $d_1^{(k)} = 1$, $d_2^{(k)} = 0$, and $N_k = 3$.

III. Power Assignment in IR-UWB Networks

Due to low power consumption and low transceiver complexity, IR-UWB is a promising candidate as an air interface for wireless sensor nodes. Therefore, we assume each sensor node to be equipped with an IR-UWB transceiver unit. In particular, we consider IR-UWB with pulse position modulation with modulation index α and pseudo random time hopping codes as multiple access scheme as described in [9]. The transmitted signal from the jth sensor can then be written as

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

where T_f denotes the length of a time frame in which one impulse of form $w(t)$ is transmitted. In the frame, 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 of the jth sensor is transmitted by a number of N_j equally modulated pulses with amplitude A_j. Some exemplary parameters for one sensor node are illustrated in Fig. 3.

According to [10], in a multi-user scenario the signal-to-interference-and-noise ratio (SINR) can be written as

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

with p_j denoting the transmission power of the jth sensor node. The parameter σ^2 depends on the correlation properties of the employed pulse form $w(t)$. The path gain between the jth sensor and the corresponding receiver is denoted by g_j. In case of the serial network topology where the detection results are subsequently transmitted from sensor to sensor, orthogonal channels are attained and the interference term $\sigma^2 \sum_{k \neq j} g_k p_k$ in (11) disappears. In both topologies the transmitted signal is subject to additive white Gaussian noise with energy η. If each node has an individual quality of service (QoS) requirement in terms of a 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 [10]

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

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 matrix $\boldsymbol{B}$ are

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

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

$$\tau_j = \frac{\eta \gamma_j}{T_f N_j g_j}.$$

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. Using a special case of the dimensionality reduction procedure presented in [10], the power of the jth node in the parallel fusion network can be computed very efficiently by

$$p_j = \frac{\frac{\eta}{T_f \sigma^2}}{g_j \left(\frac{N_j}{\sigma^2 \gamma_j} + 1 \right) \left(1 - \sum_{k=1}^{N} \frac{1}{\frac{N_k}{\sigma^2 \gamma_k} + 1} \right)}. \quad (13)$$

For the serial network the determination of the transmission power is further reduced to

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

If a feasible solution of (12) exists, the SINR requirements $\gamma_1, \ldots, \gamma_N$ can be used to compute the corresponding bit-error rates. Using the standard Gaussian approximation for multiple access interference as discussed in [11], the bit-error rate ε_j of the jth sensor node can be expressed as

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

Note that ε_j is equivalent to the bit-error probability of the binary symmetric channel as described in (1).

IV. 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 target SINRs γ_j. Our objective is to optimize the sensor network detection performance in terms of the global probability of error (6) or (9), respectively.

Fig. 4 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

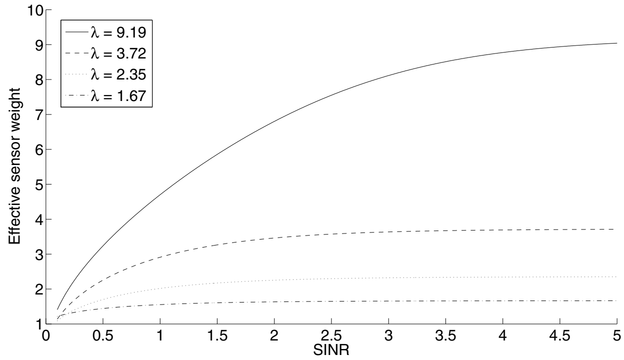

Fig. 4. Effective sensor quality $\widetilde{\lambda}$ as a function of the SINR γ for different values of the initial sensor quality λ.

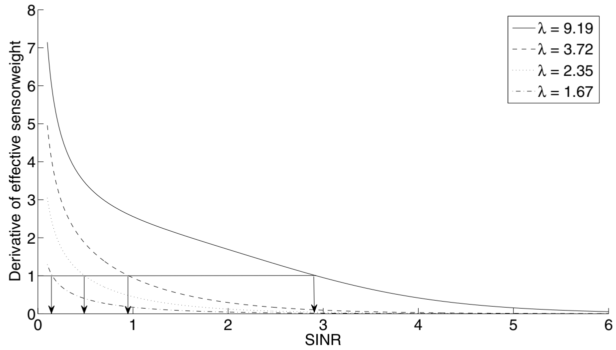

Fig. 5. Derivative $\partial\widetilde{\lambda}/\partial\gamma$ of the effective sensor quality $\widetilde{\lambda}$ with respect to the SINR γ. The threshold ϱ is chosen to be equal to 1.

falls under a predetermined threshold ϱ. Fig. 5 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 location information. Wireless sensors near to the fusion center or near to the corresponding neighboring node, respectively, are favored because in the case of low pathloss a high SINR can be realized by comparatively low transmission power. We use a weighting factor given by the inverse distance d_j of the jth sensor to its receiver normalized by the maximal distance d_{max}. Eventually, we determine the designated target SINR γ_j of the jth sensor according to

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

The exponent β is chosen corresponding to a pathloss model.

The opportunistic power assignment strategy is obtained by using the target SINRs (16) in order to compute the transmission power levels p_j of the sensor nodes according to (13) or (14), respectively.

V. Numerical Results and Conclusions

In this section, we investigate the performance of the opportunistic strategy from Section IV compared to uniform power assignment by simulations for both the parallel and the serial network topology. For the parallel fusion network, the scenario is generated by randomly deploying sensor nodes uniformly in a rectangular area A. The fusion center is supposed to be located in the middle of the scenario. For the serial network, we use uniformly distributed distances in the range $[0, d_{\text{max}}]$ between neighboring nodes. The local detection error probabilities P_{f_j} and P_{m_j} of the individual sensor nodes are assumed to be independent random variables in the range $[0, \frac{1}{2}]$. The involved parameters for both scenarios and for the employed IR-UWB transceivers are summarized in Table I.

Fig. 6 depicts the simulation results for the parallel fusion network. The suggested strategy reduces the global probability of error P_e up to over 35 % compared to uniform power

TABLE I
PARAMETERS USED IN THE SIMULATION

parameter	value
N_{par}	50
N_{ser}	5
A	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

assignment given a fixed total transmission power. The performance gain for the serial network is up to 20 % as illustrated in Fig. 7. For high values of the total transmission power p_{tot}, the performance gain decreases for both network topologies due to quasi error-free transmission.

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.

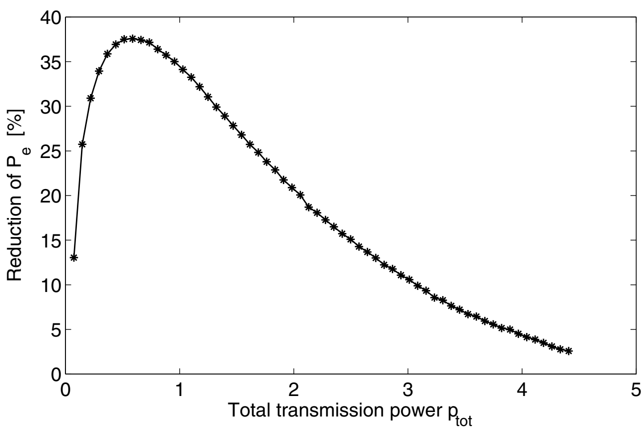

Fig. 6. Relative performance gain of the opportunistic strategy in terms of reduction of the global probability of error P_e compared to uniform power assignment for the parallel fusion network.

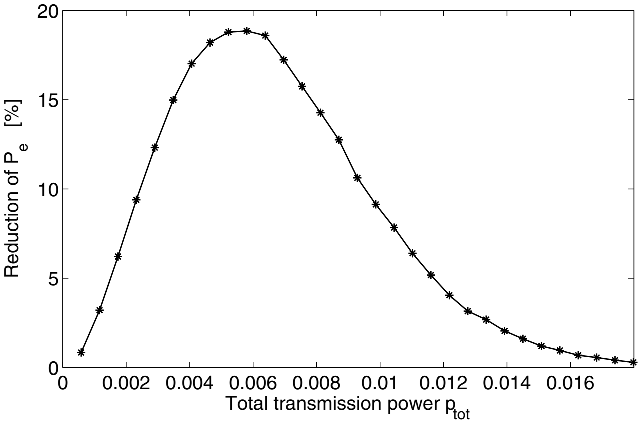

Fig. 7. Relative performance gain of the opportunistic strategy in terms of reduction of the global probability of error P_e compared to uniform power assignment for the serial network.

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