# Distributed Detection with Transmit-Only Sensors and a Successive Interference Cancellation Receiver

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***Abstract*—A low-cost deployment of wireless sensor networks heavily depends on the availability of low-complexity sensor nodes. In this paper, a sensor network with simple transmit-only IR-UWB sensor nodes is analyzed, that is deployed for distributed detection of signals in a region of interest. The nodes transmit their local decisions with a fixed transmission power over non-orthogonal channels to a fusion center, where the received local decisions are combined to a final decision with high reliability. The fusion center is assumed to be equipped with a successive interference cancellation receiver. For this receiver, a novel detection ordering scheme tailored for distributed detection is proposed. Numerical results illustrate that it leads to a significant performance gain in terms of the application-specific performance metric compared to a conventional non application-specific detection order.**

## I. Introduction

Detection of phenomena of interest is one of the primary applications of wireless sensor networks and often the initial task of an overall sensing process. In distributed detection with a parallel fusion architecture, 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 which combines the received decisions and computes the final detection result with high reliability.

The transmission channels between the battery-operated sensor nodes 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 [1]. The reliability of the transmission can, e.g., be controlled by appropriate assignment of transmission power levels to the sensor nodes. In [2], we proposed an opportunistic cross-layer approach for power assignment, that jointly considers sensor detection qualities and wireless channel conditions with the goal to minimize the global probability of detection error for a given budget of total transmission power. In that strategy the fusion center employs a bank of independent receivers. Each receiver processes the power controlled signal of one sensor and treats the interference of other nodes as noise. The cross-layer power assignment leads to significant performance gains compared to uniform power assignment to all nodes. However, the strategy requires that the sensor nodes are capable of adjusting their transmission power, which increases the node complexity. Moreover, to exchange the necessary control information in the network, each node needs a receiver unit. To circumvent the first problem, in [3] a sensor selection scheme is proposed in which the power control of a sensor reduces to the decision to either transmit with full power or to not transmit at all. For very low levels of transmission power, this strategy performs well, but still a receiver unit on each node for the exchange of control information is required.

In this paper, we consider transmit-only wireless sensor nodes, which can significantly reduce the deployment cost of wireless sensor networks [4], [5]. A very efficient transmitter design is possible if impulse radio ultra-wideband (IR-UWB) is used as transmission scheme. Transmitters for IR-UWB can be realized by a single specially designed diode [6]. Further advantages of IR-UWB as transmission technology for wireless sensor networks are a good energy efficiency, a high resilience against multi-path fading and the provision of a high system capacity. To control the network performance we consider a more complex multi-user receiver at the fusion center. Compared to the bank of independent receivers in [2], in this paper we assume additional successive interference cancellation (SIC). In SIC receivers, the detected signals of users are iteratively subtracted from the received sum signal of all users, resulting in decreased interference for the detection of the following signals. SIC-based receivers have been widely analyzed especially for CDMA based cellular networks, e.g, [7], [8]. In [9], [10], [11] it is demonstrated that SIC receivers can also be employed for IR-UWB systems. A crucial issue in the design of SIC receivers is the ordering of the detection process. In the literature, the detection ordering is usually designed to minimize the mean bit-error rate (BER) of all sensors. The optimal ordering strategy for this goal is a descending order of the received signal to noise and interference (SINR) values [12], [13]. In this paper, we consider the global probability of detection error as application-specific performance metric. For this metric, we propose a novel application-specific ordering scheme, which is based on the analysis in [2] and includes individual sensor detection qualities in the determination of the detection order. Numerical results illustrate, that although the mean BER is increased compared to conventional ordering, the global probability of detection error can be significantly decreased by employing the proposed strategy.

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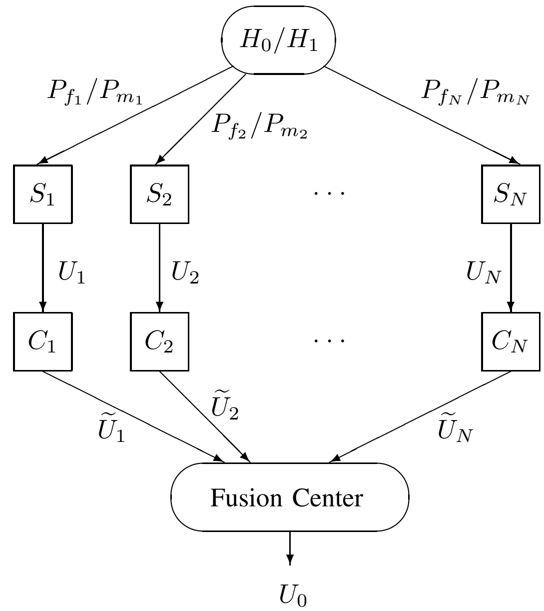


Fig. 1. Parallel fusion network with noisy channels.

The remainder of the paper is organized as follows. In Section II, distributed detection with noisy communication channels and in Section III the considered IR-UWB transmission scheme is described. Section IV introduces the novel detection ordering scheme. Numerical results of the system performance are presented in Section V and conclusions are drawn in Section VI.

## II. Distributed Detection

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 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

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

for $j = 1, \ldots, N$. Upon local detection, the sensor nodes transmit the preliminary decisions $U_1, \ldots, U_N$ to the fusion center in order to perform 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 $\varepsilon_j$, i.e.

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

for $j = 1, \ldots, N$. The potentially corrupted received 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

$$P_e = \pi_0 P_f + \pi_1 P_m \qquad (3)$$

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 $P_m = P(U_0 = 0|H_1)$.

### A. 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

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

with effective sensor weights

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

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

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

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

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

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

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

## III. Transmission model

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

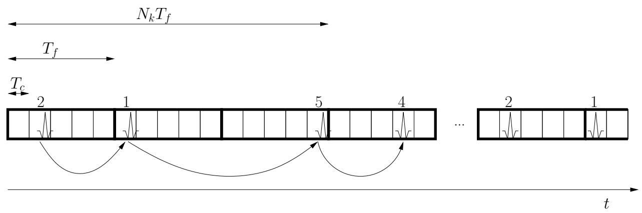


Fig. 2. Illustration of parameters used in the system model. In the example $c^{(k)} = (2, 1, 5, 4)$, $d_1^{(k)} = 1$, $d_2^{(k)} = 0$, and $N_k = 3$.

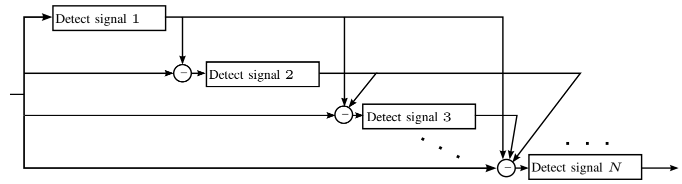


Fig. 3. Illustration of the considered SIC scheme at the receiver of the fusion center. The detected signals are iteratively subtracted from the received sum signal.

suited for wireless sensor nodes due to low power consumption, resilience against multi-path fading combined with low system complexity. In particular, we consider IR-UWB with pulse position modulation with modulation index $\delta$ and pseudo random time hopping codes as multiple access scheme as described in [14]. The transmitted signal from sensor $S_j$ to the fusion center can then be written as

$$s_j(t) = A_j \sum_{i=-\infty}^{\infty} w(t - iT_f - c_i^{(j)} T_c - \delta d^{(j)}_{\lfloor i/N_j \rfloor}), \quad (9)$$

where $T_f$ denotes the length of a time frame in which one impulse of form $w(t)$ is transmitted. 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.

If the transmitted signal of other nodes $S_{k \neq j}$ is treated as noise, the signal-to-interference and noise ratio (SINR) $\gamma_j$ of the link between sensor $S_j$ and the fusion center reads as

$$\gamma_j = N_j \frac{g_j p_j}{\varsigma^2 \sum_{k \neq j} g_k p_k + \frac{1}{T_f} \eta}, \quad (10)$$

with $p_j$ denoting the transmission power of sensor node $S_j$ and $\varsigma^2$ 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 $\eta$. In this paper, we assume a constant and uniform transmission power for all nodes, which cannot be adjusted. This assumption allows for a very low complexity implementation of the nodes' radio unit. At the fusion center, we consider a SIC-receiver (see Fig. 3). The fusion center receives the sum of all sensor signals and detects the first signal by treating the signals of all other nodes as noise. The detected signal is then subtracted from the sum-signal in order to decrease the amount of interference for the next detection steps. From the resulting signal after subtraction the next signal is detected. In this iterative procedure, for the detection of the signal of $S_j$ the detected signals of all previous sensors $S_1, \ldots, S_{j-1}$ are subtracted from the sum signal. The procedure ends when the last signal is detected. The SINR $\gamma_j$ of the $j$th detected signal in the detection process is given by

$$\gamma_j = N_j \frac{g_j p_j}{\varsigma^2 \sum_{k=j+1}^{N} g_k p_k + \varsigma^2 \sum_{l=1}^{j-1} \kappa_l g_l p_l + \frac{1}{T_f} \eta}, \quad (11)$$

where the term $\varsigma^2 \sum_{l=1}^{j-1} \kappa_l g_l p_l$ is the remaining interference of already cancelled signals. The remaining fraction $\kappa$ of a signal results, e.g, from errors in channel estimation.

## IV. Application-Specific Detection Ordering

The overall performance of a SIC-receiver heavily depends on the order in which the signal detection is performed.

In this section, we propose an application-specific detection ordering scheme for the receiver described in the previous section. It aims to minimize the global probability of detection error $P_e$ at the fusion center. As given by (5), the effective sensor weight $\widetilde{\lambda}_j$ of $S_j$, which is a measure for the sensor detection quality depends on the bit-error probability $\varepsilon_j$ of the channel between node $S_j$ and the fusion center. Using the Gaussian approximation, the bit-error rate (BER) $\varepsilon_j$ depends on the SINR $\gamma_j$ according to

$$\varepsilon_j = \frac{1}{2} \text{erfc}(\sqrt{\gamma_j}). \quad (12)$$

Fig. 4 illustrates the influence of the SINR $\gamma_j$ of the link between $S_j$ and the fusion center on the effective sensor quality $\widetilde{\lambda}_j$. Of course, $\widetilde{\lambda}_j$ increases with an increasing SINR. But it can also be observed, that for a given SINR value the slope of the curve increases with the original sensor quality $\lambda$. This implies that increasing the SINR at this point for sensors with high $\lambda$ results in a higher benefit in terms of an increased $\widetilde{\lambda}$ than increasing the SINR for sensors with low $\lambda$. In [2], this observation is used to derive an opportunistic determination of SINR values for all sensors. The SINR is then realized by appropriate assignment of transmission power levels, such that

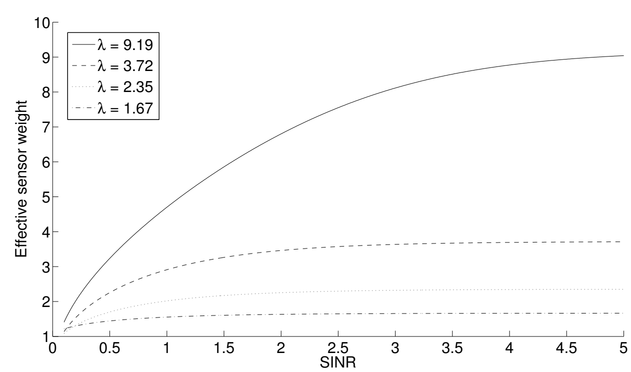


Fig. 4. Effective sensor quality $\widetilde{\lambda}$ as function of the SINR $\gamma$ for different values of the initial sensor quality $\lambda$.

all SINR requirements are fulfilled. In this paper, we consider transmit-only sensors which are not capable of controlling their transmission power and do not have a feedback channel to exchange control information. However, in case of a SIC receiver at the fusion center, the SINR of the sensors can to some extent be controlled by the detection ordering of the receiving process. The later the signal of a node is detected in the receiving process, the more signals have already been subtracted from the sum-signal, the lower is the amount of interference, and finally the higher is the resulting SINR of this node. From this perspective it would be advantageous to sort the detection of signals with ascending sensor quality $\lambda$, such that the SINR of the node with the highest $\lambda$ is maximally increased. In conventional systems however, the ordering is done in descending order of the received signal power. This strategy is optimal in terms of a minimal mean channel bit-error rate of the nodes [12]. The intuitive reasoning behind the approach is, that the strongest signals should be detected first, such that the strongest interfering signals are subtracted for as many following signals as possible. This fact of course applies also for our considered application. Therefore, we suggest to combine these two approaches by defining a novel ordering metric $m$, which is tailored for distributed detection. This ordering metric $m_j$ of $S_j$ is finally given by

$$m_j = \lambda_j g_j, \tag{13}$$

where $\lambda_j$ is the original sensor detection quality, which can be estimated by the fusion center and $g_j$ is the path gain between $S_j$ and the fusion center.

## V. Numerical Results

In this section we present simulation results that illustrate the performance of the described strategy. The scenario is generated by randomly deploying $N$ sensor nodes uniformly in a rectangular area $A$. The fusion center is located in the middle of the scenario. As path loss model we assume signal attenuation according to $d^{-\beta}$. The involved parameters for the scenario and the IR-UWB transceivers are summarized in Table I. As an example for distributed detection, we consider the problem of detecting the presence or absence of a known signal in Gaussian noise, i.e., we assume that the observations $X_1, \ldots, X_N$ at the local sensors are conditionally independent distributed according to

$$\begin{aligned} H_0\colon X_j &\sim \mathcal{N}(0, \sigma_j^2), \\ H_1\colon X_j &\sim \mathcal{N}(\mu_j, \sigma_j^2), \end{aligned} \tag{14}$$

$j = 1, \ldots, N$. The variance $\sigma_j^2$ describes Gaussian background noise and the mean $\mu_j$ indicates the deterministic signal component under hypothesis $H_1$ at sensor $S_j$. At sensor $S_j$, the local observation signal-to-noise ratio (SNR) is given by

$$\mathrm{SNR}_j = 10 \log_{10}\left(\frac{\mu_j^2}{\sigma_j^2}\right) \quad [\mathrm{dB}]. \tag{15}$$

The log-likelihood ratio $L_j$ of the observation $X_j$ is

$$\begin{aligned} H_0\colon L_j &\sim \mathcal{N}\Big(-\frac{\mu_j^2}{2\sigma_j^2}, \frac{\mu_j^2}{\sigma_j^2}\Big), \\ H_1\colon L_j &\sim \mathcal{N}\Big(\frac{\mu_j^2}{2\sigma_j^2}, \frac{\mu_j^2}{\sigma_j^2}\Big). \end{aligned} \tag{16}$$

In the simulation, we assume the local observation signal-to-noise ratios $\mathrm{SNR}_1, \ldots, \mathrm{SNR}_N$ to be independent and identically uniformly distributed between 0 and 10 dB. Fig. 5 illustrates the absolute probability of detection error $P_e$ depending on the transmission power $p$ of the nodes for both the conventional ordering by received power and the proposed application-specific ordering scheme. It can be observed that the proposed strategy leads to a lower probability of detection error $P_e$ over the entire range of analyzed transmission power levels $p$. The absolute gap is slightly increasing with an increasing transmission power. Fig. 6 shows the relative performance gain. For a wide range of transmission power levels this gain is almost constant at about $16\,\%$. Note that to achieve this gain no increased hardware complexity is necessary, since only the ordering of the detection process is changed. The considered reference strategy leads to the minimum mean BER. Fig. 7 shows for different numbers of sensor nodes how much this performance measure is degraded by using the proposed strategy. Especially for low numbers of sensors this degradation is very high, up to almost $30\,\%$ for 10 nodes. For higher numbers of nodes the degradation decreases. Fig. 8 shows the dependency of the relative performance gain of our considered performance measure on the number of nodes. For all considered levels of transmission power the gain increases monotonically with the number of nodes. The slope of the gain curve decreases with $N$. For medium and high transmission power the relative performance gain is almost the same. For moderate numbers of sensors (up to about 15) the highest performance gain is observed for a low transmission power. Up to this point, we focused on the performance improvement of the proposed application-specific detection ordering scheme given a fixed transmission power $p$. However, in practice the inverse question might also be relevant, i.e., how much transmission power can be saved by employing the proposed strategy to maintain a prespecified probability of detection error $P_e$. Fig. 9 and Fig. 10 show corresponding numerical results for 50 sensor nodes for the proposed strategy

TABLE I
Parameters used in the simulation.

| parameter | value |
|---|---|
| $N$ | $1, \ldots, 50$ |
| $A$ | $100$ m $\times$ $100$ m |
| $\beta$ | 2 |
| $\sigma^2$ | $1.9966 \cdot 10^{-3}$ |
| $N_j$ | 10 |
| $T_c$ | 2 ns |
| $T_f$ | 100 ns |
| $\eta$ | $10^{-11}$ J |
| $\kappa$ | 0.3 |

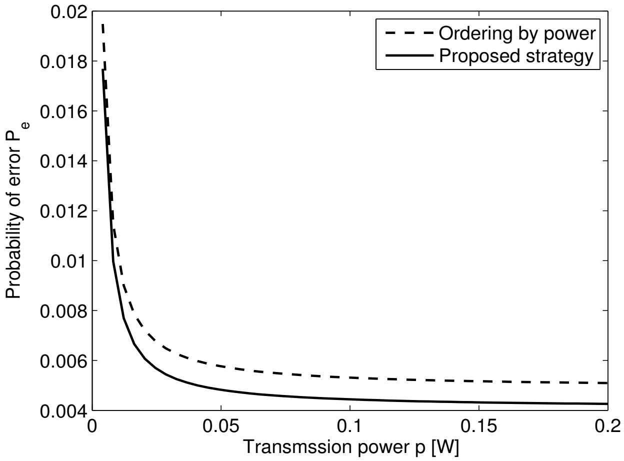


Fig. 5. Global probability of detection error $P_e$ depending on the transmission power $p$ for ordering by power and the proposed strategy.

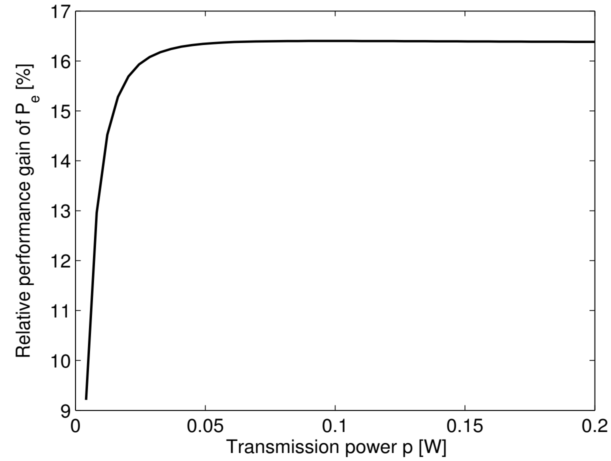


Fig. 6. Relative performance gain in percent of the proposed strategy compared to ordering by power depending on the transmission power $p$.

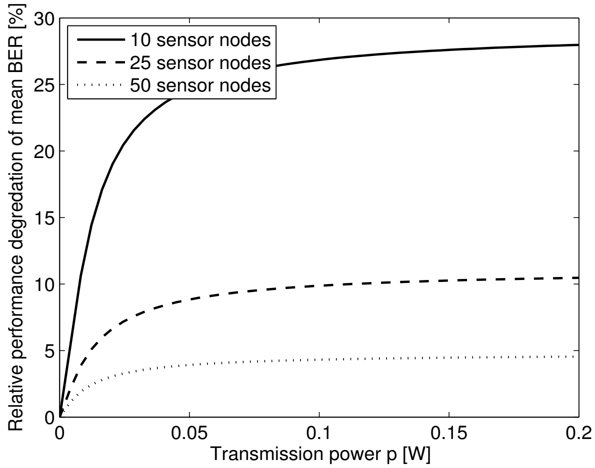


Fig. 7. Relative performance degradation in percent of the mean BER of the proposed strategy compared to ordering by power for different numbers of sensor nodes.

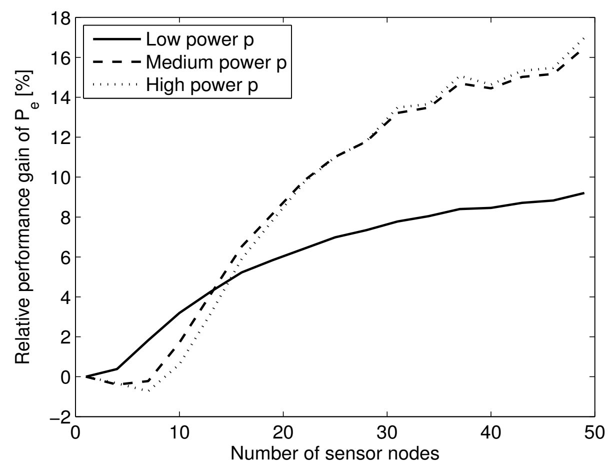


Fig. 8. Relative performance gain in percent of the proposed strategy compared to ordering by power for low, medium and high transmission power $p$.

and conventional ordering by power. In Fig. 9 the transmission power of the nodes is given depending on the intended global probability of detection error $P_e$. It can be observed that for both curves there is a point from which on the slope of the curves significantly increases with decreasing $P_e$. Of course, we cannot achieve arbitrarily small values of $P_e$, since the performance is limited by the detection performance of a system without any channel errors. However, it can be seen, that the proposed ordering scheme has two advantages. First, the necessary transmission power is always lower compared to ordering by power and second, very low levels of the global probability of detection error $P_e$, that cannot be realized by conventional ordering can be achieved by the novel scheme. Note, that this is also in accordance with the results from Fig. 5. Finally, Fig. 10 illustrates the relative percentaged power savings for the relevant range of probabilities of detection error $P_e$. As expected from Fig. 9, the relative power savings increase with a decreasing probability of detection error $P_e$. Yet, even if higher levels of $P_e$ can be tolerated for the detection application, power savings of about $20\,\%$ are still considerable.

## VI. Conclusions and Outlook

In this paper, we proposed an implementation of distributed signal detection by a low-cost deployment with IR-UWB transmit-only sensor nodes and a successive interference cancellation receiver at the fusion center. The SINR of the channels between nodes and the fusion center are controlled by an application-specific detection ordering at the receiver instead of power control at the transmitters. The proposed strategy leads to significant performance gains compared to conventional detection ordering schemes, that aim to minimize the mean BER of all nodes at the receiver. Moreover, the scheme also allows to considerably reduce the transmission

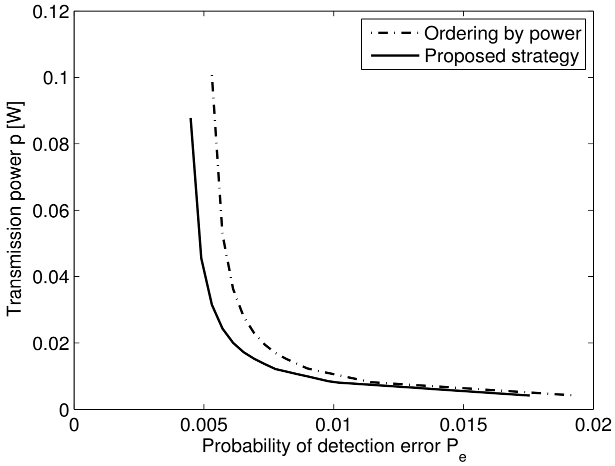


Fig. 9. Transmission power $p$ required to maintain a prespecified global probability of detection error $P_e$ for ordering by power and the proposed strategy for $N = 50$ sensor nodes.

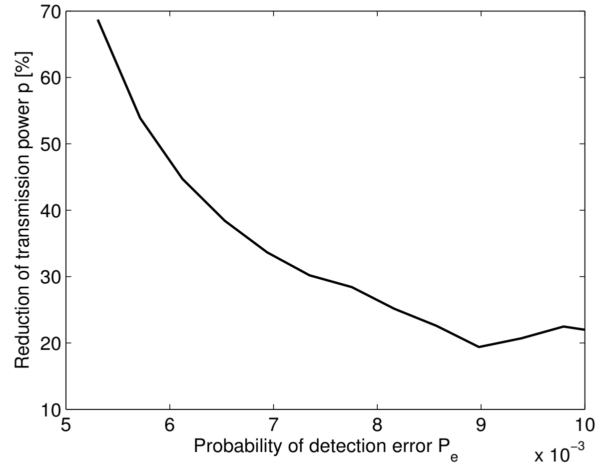


Fig. 10. Relative power savings in percent of the proposed strategy compared to ordering by power depending on the intended global probability of detection error $P_e$ for $N = 50$ sensor nodes.

power of the nodes necessary to maintain a given global probability of detection error. In our future work, we plan to conduct a direct comparison of the power control approach and the approach suggested in this paper. It would be furthermore interesting to optimize and evaluate the performance of a combination of these two approaches with power controllable transmitters and a SIC-based receiver with an application-specific detection ordering.

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## REFERENCES

[1] J.-F. Chamberland and V. Veeravalli, "Wireless sensors in distributed detection applications," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 16–25, May 2007.

[2] D. Bielefeld, G. Fabeck, and R. Mathar, "Power-aware distributed detection in IR-UWB sensor networks," in *Proc. IEEE Sensor Array and Multich. Signal Process. Workshop (SAM)*, Jul. 2008, pp. 261–265.

[3] G. Fabeck, D. Bielefeld, and R. Mathar, "Power-aware sensor selection for distributed detection in wireless sensor networks," in *IEEE Veh. Technol. Conf. Fall (VTC-Fall)*, 2009.

[4] B. Blaszczyszyn and B. Radunovic, "Using transmit-only sensors to reduce deployment cost of wireless sensor networks," 2008, pp. 1202–1210.

[5] B. Radunovic, H. Truong, and M. Weisenhorn, "Receiver architectures for UWB-based transmit-only sensor networks," in *Proc. Int. Conf. Ultra-Wideband (ICU)*, 2005, pp. 379–384.

[6] H. Arslan, Z. Chen, and M.-G. Di Benedetto, Eds., *Ultra Wideband Wireless Communication*. Hoboken, New Jersey: Wiley-Interscience, 2006.

[7] P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme ina DS/CDMA system," *IEEE J. Sel. Areas Commun.*, vol. 12, no. 5, pp. 796–807, Jun. 1994.

[8] K. Pedersen, T. Kolding, I. Seskar, and J. Holtzman, "Practical implementation of successive interference cancellation in DS/CDMA systems," in *Proc. IEEE Int. Conf. Univ. Pers. Comm. Record*, vol. 1, 1996, pp. 321–325.

[9] N. Boubaker and K. Letaief, "Combined multiuser successive interference cancellation and partial rake reception for ultra-wideband wireless communications," in *Proc. IEEE Veh. Technol. Conf. Fall (VTC-Fall)*, vol. 2, 2004, pp. 1209–1212.

[10] C. Liu, "A low-complexity multiuser detector for time-hopping impulse-radio systems," in *Proc. IEEE Int. Conf. Comm. Techn.*, 2008, pp. 249–252.

[11] E. Fishler and H. Poor, "Low-complexity multiuser detectors for time-hopping impulse-radio systems," *IEEE Trans. Signal Process.*, vol. 52, no. 9, pp. 2561–2571, 2004.

[12] K. Puttegowda, G. Verma, S. Bali, and R. Buehrer, "On the effect of cancellation order in successive interference cancellation for CDMA systems," in *Proc. IEEE Veh. Technol. Conf. Fall (VTC-Fall)*, vol. 2, 2003, pp. 1035–1039 Vol.2.

[13] R. Buehrer, "Equal BER performance in linear successive interference cancellation for CDMA systems," *IEEE Trans. Commun.*, vol. 49, no. 7, pp. 1250–1258, 2001.

[14] M. Win and R. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, no. 4, pp. 679–689, Apr. 2000.