Location-aware Adaptation and Precoding for Low Complexity IR-UWB Receivers

Heinrich Luecken, Thomas Zasowski, Christoph Steiner, Florian Troesch, and Armin Wittneben
Communication Technology Laboratory, ETH Zurich, 8092 Zurich, Switzerland
{lueckenh, zasowski, steinech, troeschf, wittneben}@nari.ee.ethz.ch

***Abstract*—An environment is considered with many low complexity wireless mobile stations communicating to higher complexity stationary cluster heads. The cluster heads can determine the rough position of the mobile stations using geo-regioning. The mobile stations are not able to perform a channel estimation due to complexity reasons. We present two approaches to utilize regional channel knowledge available at the cluster head for improvement of the data detection performance at the mobile station. First, by feeding back the average power delay profile of the channel from the cluster head to the mobile station, the mobile station can adapt a filter according to this information. Second, at cluster head side the covariance matrix of the channel impulses response vectors is used for precoding optimization. Based on channel impulse responses measured in a realistic environment the performance of both approaches is evaluated. Performance gains of 1 to 3 dB compared to energy detection can be obtained.**

I. Introduction

Ultra wideband (UWB) impulse radio (IR) communication attracted much interest for the use in wireless sensor networks (WSN) and body area networks (BAN) due to low complexity and energy efficient system realizations. In particular noncoherent receivers can be implemented very efficiently and promise low power consumption to meet stringent constraints on battery autonomy. The high bandwidth of UWB enables localization with high spatial resolution. The location knowledge can be used for performance enhancement of data transmission.

We consider a wireless network with cluster heads (CH) and mobile stations (MS) as shown in Fig. 1. The environment is separated into several regions $R_1, \ldots, R_N$. The CH know the covariance matrices including the average power delay profile (APDP) of the channel impulse response vectors of each region of the environment. The CH are able to perform geo-regioning, i.e., to localize MS based on their channel impulse responses (CIR). It has been shown in [1] that estimation based on the covariance matrices of the CIR is a very promising technique for performing the region estimation. That way, the rough position of the MS can be determined by only one CIR.

For many applications, joint localization and data communication is desirable, e.g. tracking items in a production hall, airport or hospital combined with query of sensor data. The CH are not limited in terms of complexity and can decode the received signal coherently. It is assumed that MS have low complexity and are not able to estimate the channel since low cost and low energy consumption are essential for them. Therefore, we consider noncoherent receivers at the MS. It has been shown in [2] that nonlinear energy detection receivers can be implemented requiring a very low power consumption of less than 1 mW. Here, a more general receiver structure is considered that consists of a squaring device, followed by a linear filter.

To improve the data detection performance of the MS two approaches are investigated. Since the MS is not able to estimate the channel, this functionality is shifted to the CH. Due to the geo-regioning capabilities, a CH is able to estimate region and APDP of a MS by receiving one CIR only. This information about the APDP is fed back from the CH to the MS. The MS adapts its receive filter behind the squaring device according to the APDP. According to [3] the APDP knowledge is used to improve the data detection performance at the MS side. To save complexity and memory at the MS only the APDP instead of the whole covariance matrix is considered for the case of receiver adaptation. The geo-regioning based APDP acquisition requires much less effort compared to a standard estimation of the APDP, where several pulses have to be transmitted frequently.

Alternatively to utilization of the APDP at the MS, the knowledge of the covariance matrix of the channel is also beneficial at the CH. Knowing the channel statistics of a region, a precoding can be performed to improve the data detection performance at the MS. Application of several precoding schemes for UWB impulse radio have been proposed, such as time-reversal [4]. In [5] a reduced complexity time-reversal technique is investigated. However, we propose to perform precoding based on the covariance matrix of the channel for a certain region. For this approach we assume a fixed receive filter, which further reduces complexity and no feedback is required. Based on this system model the received signal contribution is maximized.

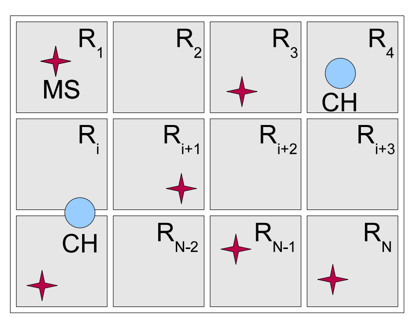

Fig. 1. Network scenario with cluster heads (CH), mobile stations (MS), and regions $(R_1, \ldots, R_N)$.

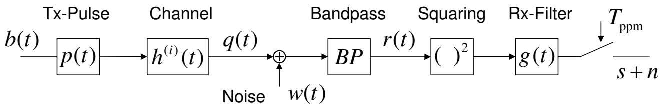

Fig. 2. Block diagram of transmitter, channel and receiver of region i

The remainder of this paper is organized as follows. In Section II, the considered system model is described. Section III shows the algorithms used for adaptation of the receive filter based on the APDP. Precoding optimization based on the covariance matrix of the channel over the region is presented in Section IV. Finally, the performance of the two approaches is evaluated in Section V and conclusions are given in Section VI.

II. System Model

A block diagram of the considered system is shown in Fig. 2. For data transmission UWB IR using binary PPM is considered. It is assumed that only one pulse is transmitted per symbol. Depending on the binary PPM symbol $a_n \in \{0, 1\}$ the pulse lies either in the first or the second PPM half frame of duration T_{ppm}. Thus, the data signal $b(t)$ is modeled as

$$b(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT_{\text{symb}} - a_n T_{\text{ppm}})$$

where $T_{\text{symb}} = 2T_{\text{ppm}}$ denotes the symbol period. The PPM data $b(t)$ is fed to a transmit pulse shaping filter denoted by $p(t)$ and transmitted over the channel to region i, with CIR realization $h^{(i)}(t)$. The signal at the receiver antenna is denoted by $q(t)$. Subsequently, white Gaussian noise $w(t)$ of power spectral density $N_0/2$ is added. The non-linear receiver consists of an ideal bandpass filter of bandwidth B and center frequency f_c, a squaring device and a receive filter $g(t)$. The output is sampled with period T_{ppm}, where perfect synchronization to the PPM frame is assumed. Data detection is performed by subtracting the value of the first half frame from the second. If the result is less than zero it is decided that a 0 was transmitted, otherwise a 1. It is assumed that no inter symbol interference (ISI) occurs.

III. Receiver Adaptation

First, we consider the situation that the low-complexity receiver knows the APDP of the channel and adapts its receive filter $g(t)$ accordingly. This is done as follows. In an initialization phase the cluster heads determine the fingerprints of all regions including their characteristic APDP. After this step they are able to estimate the position of MS and with it the APDP of the channel impulse response. This information is disseminated to the nodes such that they can adapt their receiver. For this approach the transmit pulse is assumed to be flat in frequency over the considered bandwidth.

The impulse responses $h^{(i)}(t)$ of the channel for region i is modeled as (according to [3])

$$h^{(i)}(t) = \sigma_i(t) \cdot V(t), \text{ with } \sigma_i(t) = 0 \text{ for } t \geq T_{\text{ppm}}, t < 0$$

where $V(t)$ is a zero-mean Gaussian random process with unit variance and flat power spectral density in the bandwidth B around center frequency f_c. The second moment of the channel impulse response

$$\mathsf{E}[h^{(i)}(t)^2] = \mathsf{E}[(\sigma_i(t) \cdot V(t))^2] = \sigma_i^2(t)$$

yields the APDP $\sigma_i^2(t)$ of Region i. Based on this channel model, as derived in [3], the symbol-wise maximum-likelihood decision metric in case of APDP knowledge is given by

$$L = \int_{kT_{\text{symb}}}^{(k+1)T_{\text{symb}}} r^2(t) \frac{\sigma_i^2(t) - \sigma_i^2(t - T_{\text{ppm}})}{\sigma_i^2(t) - \sigma_i^2(t - T_{\text{ppm}}) + N_0 B} dt.$$

The decision rule can be interpreted as an energy detector where the integration window is weighted by the APDP. That way, mapping the decision rule to the considered receiver architecture yields for the impulse response $g_{i,\text{APDP}}(t)$ of the receive filter

$$g_{i,\text{APDP}}(t) = \begin{cases} \frac{\sigma_i^2(T_{\text{ppm}} - t)}{\sigma_i^2(T_{\text{ppm}} - t) + N_0 B} & \text{for } 0 \leq t < T_{\text{ppm}} \\ 0 & \text{else.} \end{cases} \tag{1}$$

The MS has to adapt its receive filter according to (1) depending on which region it is currently located in.

IV. Transmitter Adaptation

This section presents how the CH can use the region information to perform a transmit pulse shaping. We assume that the receive filter $g(t)$ is fixed and the transmit pulse $p(t)$ can be chosen arbitrarily. We follow the approach to maximize the received signal contribution at the output of the receive filter, which is denoted by s. The maximization is performed with respect to the pulse shape $p(t)$, subject to a power constraint on $p(t)$. At high SNR and if the receive filter is assumed to be a constant time window, this optimization is equivalent to maximizing the SNR at the receive filter output. However, for an arbitrary receive filter $g(t)$ the noise contribution n depends on the transmit pulse $p(t)$.

For analysis, we consider now an equivalent discrete system in vector notation. The sampling period T_s must fulfill $1/T_s \geq 4(B + f_c)$ to account for the squaring operation. The samples of the transmit pulse shape $p[k] = p(kT_s)$ are stacked into a vector as

$$\vec{p} = [p[1], p[2], \ldots, p[N]]^T, \text{ with } N = T_{\text{ppm}}/T_s$$

and likewise for the signal at the receive antenna $\vec{q}$. Then, the convolution with a CIR of region i can be written as the matrix multiplication $\vec{q} = \mathbf{H}^{(i)} \cdot \vec{p}$ with

$$\mathbf{H}^{(i)} = \begin{bmatrix} h^{(i)}[1] & 0 & \cdots & 0 \\ h^{(i)}[2] & h^{(i)}[1] & & \vdots \\ \vdots & & \ddots & 0 \\ h^{(i)}[N] & \cdots & h^{(i)}[2] & h^{(i)}[1] \end{bmatrix} = \begin{bmatrix} \vec{h}_1^T \\ \vec{h}_2^T \\ \vdots \\ \vec{h}_N^T \end{bmatrix}.$$

Only N rows of the convolution matrix are considered, corresponding to the duration of a PPM half frame. The remaining contribution is omitted and can be neglected, since it is not captured by the time window of the receive filter. Accordingly, the samples of the receive signal without noise are given by

$$q[k] = \vec{h}_k^T \cdot \vec{p}. \tag{2}$$

The signal contribution s at the receive filter output is obtained by squaring (2), convolution with the receive filter impulse response $g[k]$ and sampling at time $k = N$. This yields

$$s = \sum_{k=1}^{N} g[N-k] \cdot (q[k])^2.$$

Substituting (2) and further manipulations lead to the quadratic form

$$\begin{aligned} s &= \sum_{k=1}^{N} g[N-k] \cdot \left(\vec{p}^T \vec{h}_k \vec{h}_k^T \vec{p}\right) \\ &= \vec{p}^T \left(\sum_{k=1}^{N} g[N-k] \cdot \vec{h}_k \vec{h}_k^T\right) \vec{p} = \vec{p}^T \mathbf{Q} \vec{p}. \end{aligned}$$

Now, we can substitute the power constraint $\vec{p}^T\vec{p} = \text{const}$, which leads to the scaled $\tilde{s}$ given by

$$\tilde{s} = \frac{\vec{p}^T \mathbf{Q} \vec{p}}{\vec{p}^T \vec{p}}.$$

The desired pulse shape $\vec{p}_{\text{pre}}$, which maximizes the average received signal contribution can now be written as the unconstrained maximization problem

$$\vec{p}_{\text{pre}} = \arg\max_{\vec{p}} \mathsf{E}_h[\tilde{s}] = \arg\max_{\vec{p}} \frac{\vec{p}^T \hat{\mathbf{Q}} \vec{p}}{\vec{p}^T \vec{p}}. \tag{3}$$

The expectation is taken with respect to the CIR realization of region i. Hence, the $N \times N$-matrix $\hat{\mathbf{Q}}$ is given by

$$\hat{\mathbf{Q}} = \sum_{k=1}^{N} g[N-k] \cdot \mathsf{E}[\vec{h}_k \vec{h}_k^T]. \tag{4}$$

The matrix $\mathsf{E}[\vec{h}_k \vec{h}_k^T]$ contains elements of the covariance matrix of the CIR taps. The regional covariance matrix of the channel is known to the CH due to its geo-regioning capabilities. Since $\mathsf{E}[\vec{h}_k \vec{h}_k^T]$ is symmetric, $\hat{\mathbf{Q}}$ is symmetric as well and its eigenvalues are real. Therefore, the right hand side of (3) is determined by the eigenvector that corresponds to the largest eigenvalue of $\hat{\mathbf{Q}}$.

V. Performance Results

This section describes the performance evaluation of a system with geo-regioning based APDP selection and a system that makes use of the presented precoding scheme. The results are obtained by simulations based on a set of CIRs measured in a rich multipath indoor environment. The measurement area is subdivided into 22 regions, containing LOS and NLOS situations, with a region size of 27 cm $\times$ 56 cm each. Fig. 3 shows the floor plan of the measurement scenario with the different regions and the position of the CH.

We consider a system bandwidth of $B = 3$ GHz, using a center frequency of $f_c = 4.5$ GHz. The PPM half frame time is chosen to be $T_{\text{ppm}} = 25$ ns, which avoids ISI and results in a peak data rate of 20 Mbps. The channel is assumed to be static for one block-length of 256 bit and is chosen randomly out of a set of 600 measured CIRs per region. To omit the influence of path loss the energy of each CIR is normalized.

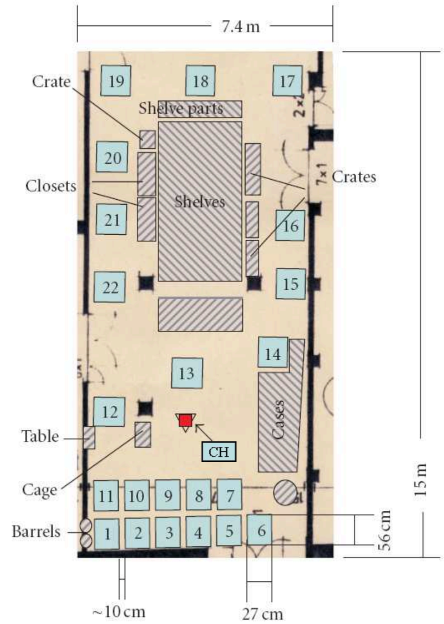

Fig. 3. Floor plan of the measurement scenario

A. Receiver adaptation based on regional APDP

To evaluate the performance of the system in case of APDP knowledge at the receiver, the transmit pulse is assumed to be flat in frequency over the considered system bandwidth. In Fig. 4 the bit error rate (BER) performance of the proposed system is shown versus the signal-to-noise ratio E_b/N_0, with E_b denoting the energy per bit and $\frac{N_0}{2}$ the noise power spectral density. For comparison, the performance of a receiver with full channel state information (coherent detection), one with the instantaneous power delay profile (IPDP) information, i.e., the knowledge of the squared channel impulse response taps [6], and an energy detector (ED) without channel state information is presented. The ED corresponds to the considered receiver using a rectangular receive filter. The BER curves of ED and IPDP-weighting are upper and lower bounds for the receiver using the APDP. In case of large regions where the APDP is not representative, the APDP performance approaches the ED BER while the IPDP performance is achieved for small regions with very similar CIRs. The performance is plotted for two regions with particularly different characteristics. Region 9 can be referred to as a typical LOS situation whereas Region 17 shows NLOS characteristics.

Without ISI and due to a fixed integration duration the ED BER performance is independent of the environment as shown in [7]. For the LOS Region 9 the performance of the IPDP and APDP based receivers is better compared to NLOS. The energy is spread over less paths and parts containing mainly noise are omitted for decision because of the weighting with the APDP. The similarity of different CIRs within Region 9

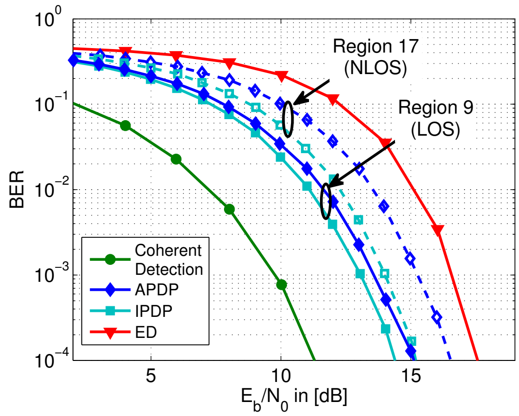

Fig. 4. Performance Comparison of APDP, IPDP and ED

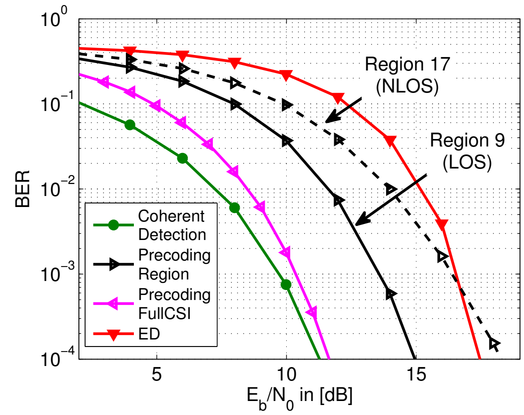

Fig. 5. Performance of Precoding compared to ED and coherent detection

results in an APDP performance that is very close to the one of the receiver with IPDP. In the NLOS case the performance difference is evident due to a larger variance of the CIRs. Note, however, that the performance is still better than for the ED.

B. Transmitter adaptation based on covariance matrix

To evaluate the performance of the presented precoding scheme, we assume a fixed receive filter. To account for stringent complexity requirements at the MS we choose a first-order low-pass filter after the squaring device for integration. The impulse response $g_{\mathrm{LP}}(t)$ of the first-order low-pass filter is given by

$$g_{\mathrm{LP}}(t) = \begin{cases} \sqrt{4\pi f_{\mathrm{cutoff}}} \cdot e^{-t2\pi f_{\mathrm{cutoff}}} & \text{for } t > 0 \\ 0 & \text{otherwise.} \end{cases}$$

The cutoff frequency of the low-pass filter is denoted by f_{cutoff}. We have chosen $f_{\mathrm{cutoff}} = 300$ MHz. According to (4), the matrix $\hat{\mathbf{Q}}$ is determined for each region. Fig. 5 shows the performance of the presented precoding scheme averaged over channel realizations within the region. Again, for comparison the energy detector and coherent detection performance is shown. These reference curves are obtained with the frequency flat pulse. Furthermore, the performance of precoding according to (3) is shown, when full channel state information at the transmitter is available. For this case, the actual value of the CIR may be used instead of the covariance matrix, i.e. the expectation in (4) is omitted.

The performance evaluation shows that performance gains up to 3 dB can be reached by application of the precoding scheme compared to energy detection. That way, the precoding reaches the performance of the regional APDP receiver adaptation for the chosen region size and first order low-pass receive filter. However, considering the NLOS situation of region 17 a performance gain compared to the energy detector can only be observed in the low SNR regime. This behavior is caused by choosing $\max \mathsf{E}_h[\tilde{s}]$ as objective function for precoding optimization. In high SNR regime the typical error event is determined by a bad channel realization. The precoding introduces additional fading to the system which leads to this suboptimal behavior in terms of BER. However, considering the low SNR regime a performance gain in the order of 1-2 dB can still be reached.

VI. Conclusions

It has been shown that knowledge of regional channel statistics can improve the performance of non-coherent detectors. For adaptation at receiver side the regional APDP of the channel is used, known from localization based on geo-regioning. For transmit pulse shaping an algorithm has been derived that maximizes the received signal component at the output of the considered non-linear detector. Both approaches have been evaluated based on measured channel impulse responses. Performance gains of 1 to 3 dB compared to energy detection can be obtained. Hence, in a system of unbalanced complexity constraints, such as WSN, it turns out to be a promising concept to use geo-regioning information to enhance data transmission performance.

VII. Acknowledgements

The work presented in this paper was partially supported by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS), a center supported by the Swiss National Science Foundation under grant number 5005-67322.

References

[1] C. Steiner, F. Althaus, F. Troesch, and A. Wittneben, "Ultra-wideband geo-regioning: A novel clustering and localization technique," *Eurasip Journal on Advances in Signal Processing*, November 2007.

[2] F. Troesch, C. Steiner, T. Zasowski, T. Burger, and A. Wittneben, "Hardware aware optimization of an ultra low power UWB communication system," *IEEE International Conference on Ultra-Wideband, ICUWB 2007*, pp. 174–179, September 2007.

[3] M. Weisenhorn and W. Hirt, "ML receiver for pulsed UWB signals and partial channel state information," *IEEE International Conference on Ultra-Wideband, ICU 2005*, pp. 379–384, September 2005.

[4] T. Strohmer, M. Emami, J. Hansen, G. Papanicolaou, and A. Paulraj, "Application of time-reversal with MMSE equalizer to UWB communications," *Global Telecommunications Conference, 2004. GLOBECOM '04. IEEE*, vol. 5, pp. 3123–3127 Vol.5, Nov.-3 Dec. 2004.

[5] N. Guo, B. Sadler, and R. Qiu, "Reduced-complexity UWB time-reversal techniques and experimental results," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 12, pp. 4221–4226, December 2007.

[6] T. Zasowski, F. Troesch, and A. Wittneben, "Partial channel state information and intersymbol interference in low complexity UWB PPM detection," *IEEE International Conference on Ultra-Wideband, ICUWB 2006*, pp. 369–374, September 2006.

[7] F. Trösch, F. Althaus, and A. Wittneben, "Modified pulse repetition coding boosting energy detector performance in low data rate systems," *IEEE International Conference on Ultra-Wideband, ICU 2005*, pp. 508–513, September 2005.