Least Square Mean Aided Adaptive Detection in Hybrid Direct-Sequence Time-Hopping Ultrawide Bandwidth Systems

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Abstract—In this contribution an adaptive detection scheme based on least mean square (LMS) principles is proposed and investigated in the context of the hybrid direct-sequence time-hopping ultrawide bandwidth (DS-TH UWB) systems. The bit-error-rate (BER) performance of the hybrid DS-TH UWB system is investigated when communicating over the UWB channels modelled by the Saleh-Valenzuela (S-V) channel model. Furthermore, since both the pure DS- and pure TH-UWB constitute special examples of the hybrid DS-TH UWB, their BER performance is also investigated in this contribution for the sake of comparison with that of the hybrid DS-TH UWB. Our study and simulation results show that the LMS-aided adaptive detection can be a feasible detection scheme for deployment in practical DS-, TH- or hybrid DS-TH UWB systems. It can be shown that, with the aid of a training sequence of reasonable length, the considered UWB schemes are capable of achieving a BER performance which is close to that achieved by the minimum mean-square error (MMSE) detector with perfect channel knowledge.

I. INTRODUCTION

In recent years ultrawide bandwidth (UWB) techniques have drawn wide interest in both research and industry communities [1–3]. Initially, UWB has been implemented with the aid of the time-hopping pulse-position modulation (TH-PPM) techniques without carrier modulation [2, 4]. Then, the direct-sequence spread spectrum (DS-SS) [5], orthogonal frequency-division multiplexing (OFDM) [6], fast frequency-hopping (FFH) [7], etc. techniques have also been introduced for implementation of UWB communications.

In [8] a hybrid direct-sequence time-hopping ultrawide bandwidth (DS-TH UWB) scheme has been proposed and investigated in comparison with the pure TH- and pure DS-UWB schemes, when either single-user correlation detector or MMSE aided multiuser detector is employed. In the hybrid DS-TH UWB the transmitted data is first modulated using the principles of DS spreading and then the locations of the transmitted pulses are determined according to the TH principles [8]. The study in [8] shows that the hybrid DS-TH UWB is capable of inheriting the advantages of both DS-UWB and TH-UWB, while avoiding their disadvantages. The hybrid DS-TH UWB may outperform a corresponding pure TH-UWB or pure DS-UWB system in terms of the achievable bit-error rate (BER) performance, when communicating over Nakagami-m fading channels.

According to the characteristics of the UWB channels, UWB-based multiple-access signals usually conflict strong inter-symbol interference (ISI) and multiuser interference (MUI) due to using extremely high bandwidth and supporting multiple users [9]. Additionally, owing to a high number of resolvable multipaths, in UWB systems the power conveyed by a resolvable multipath component is typically very low. Hence, it is highly challenging to design low-complexity detectors with acceptable detection performance in UWB communications. It is well-known that, the maximum likelihood detector is optimum in terms of achievable BER performance, but impractical for detection of the UWB signals due to its extremely high-complexity, especially when taking into account the above-mentioned characteristics of the UWB channels [10]. Instead, the sub-optimal linear multiuser detectors, such as the MMSE or decorrelating assisted detector, might be employed for detection of the UWB signals [10]. In practice, the MMSE detector is usually preferred against the decorrelating detector, since the MMSE detector can achieve a better BER performance than the decorrelating detector. Furthermore, the MMSE detector can be implemented with the aid of the low-complexity adaptive techniques [10].

Therefore, in this contribution we propose and investigate an adaptive MMSE detection scheme for the hybrid DS-TH UWB systems. Specifically, our adaptive MMSE detection is based on the LMS algorithm [11], which is operated with the aid of a sequence of training symbols at the start of communications. The performance of the hybrid DS-TH UWB system is investigated in the context of the Saleh-Valenzuela (S-V) channel model [12]. Furthermore, since both the pure DS-UWB and pure TH-UWB constitute special examples of the hybrid DS-TH UWB, their BER performance is also investigated in this contribution for the sake of comparison with that of the hybrid DS-TH UWB. Our study and simulation results show that the LMS-aided adaptive MMSE can be an efficient detection scheme for detection of the DS-, TH- as well as the hybrid DS-TH UWB signals. It can be shown that, with the aid of a training sequence of reasonable length, the considered UWB schemes are capable of achieving a BER performance, which is close to that achieved by the MMSE detector employing perfect channel knowledge.

The rest of the paper is organised as follows. Section II describes the system model of the hybrid DS-TH UWB system. The MMSE detection is considered in Section III, while Section IV presents the adaptive implementation of the MMSE detection based on the LMS algorithm. Section V demonstrates our simulation results and, finally, in Section VI the summary is presented.

II. DESCRIPTION OF THE HYBRID DS-TH UWB SYSTEM

A. Transmitted Signal

The transmitter schematic block diagram for the hybrid DS-TH UWB system is the same as that considered in [8], which is also shown in Fig. 1. In our hybrid DS-TH UWB system the binary phase-shift keying (BPSK) baseband modulation is assumed for simplicity. As shown in Fig. 1, each bit is first modulated with the help of a DS spreading sequence. Then, the positions of the transmitted pulses are determined according to the TH pattern. Consequently, by referring to [8] and Fig. 1, the DS-TH UWB signal \( s^{(k)}(t) \) transmitted by the \( k \)th user can be expressed as

\[
s^{(k)}(t) = \sqrt{\frac{E_b}{N_c T_p}} \sum_{j=0}^{\infty} b^{(k)}_j \left( \frac{x}{N_c} \right) d^{(k)}_j \times \psi \left[ t - \left( j - \left\lfloor \frac{j}{N_c} \right\rfloor \right) T_c - c^{(k)}_j T_p \right]
\]

where \( \lfloor x \rfloor \) represents the floor function, which returns the largest integer less than or equal to \( x \), \( \psi(t) \) is the basic time-domain pulse of width \( T_p \), which satisfies \( \int_{-T_p/2}^{T_p/2} \psi^2(t) dt = 1 \). The bandwidth of the hybrid DS-TH UWB system is determined by the basic time-domain pulse. Additionally, the parameters used in (1) or in our forthcoming discourse are listed as follows:

- \( E_b \): Energy per bit;
- \( N_c \): Number of chips per bit, which is defined as the DS spreading factor;
- \( N_c \): Number of time-slots in a chip, which is defined as the TH spreading factor;
- \( T_b \) and \( T_c \): Bit-duration and chip-duration, \( T_b = N_c T_c \);
the pure DS-UWB. By contrast, the hybrid DS-TH UWB with

duration of $T_v$ is considered, which can be represented as [12]

$$\psi(t - |T_v - c_{j}T_{\psi}|)$$

where the abundance of metallic scatterers cause dense multipath

ered [12]. This channel model is suitable for industrial environments,

First divided into $N$ chips having a duration of $T_v$. Then, each chip-
duration of $T_v$ is further divided into $N_v$ time-slots with a duration

$T_v$. Therefore, the bit-duration obeys $T_b = N_cT_v = N_cT_v$. It can

be seen from Fig. 2 that there is a pulse transmitted in the first time-slot

do the propagation channel. This channel model is referred to as the

S-V channel with the channel impulse response (CIR) as shown in

(2), the received signal can be expressed as

$$r(t) = \sqrt{E_b}N_v^{\frac{1}{2}} \sum_{k=1}^{K} \sum_{u=0}^{V-1} \sum_{v=0}^{U-1} h_{u,v}b_{k}^{(k)} d_{j}^{(k)}$$

$$\times \psi_{rec} t = j - \left\lfloor \frac{j}{N_v} \right\rfloor \left( T_v - c_{j}T_{\psi} - T_v - T_v - \tau_k \right)$$

+ $n(t)$

C. Receiver Structure

Let us assume that the hybrid DS-TH UWB system supports $K$

users. When the DS-TH UWB signal shown in (1) is transmitted over

the S-V channel with the channel impulse response (CIR) as shown in

(2), the received signal can be expressed as

$$r(t) = \sqrt{E_b}N_v^{\frac{1}{2}} \sum_{k=1}^{K} \sum_{u=0}^{V-1} \sum_{v=0}^{U-1} h_{u,v}b_{k}^{(k)} d_{j}^{(k)}$$

$$\times \psi_{rec} t = j - \left\lfloor \frac{j}{N_v} \right\rfloor \left( T_v - c_{j}T_{\psi} - T_v - T_v - \tau_k \right)$$

+ $n(t)$

where $n(t)$ represents the additive white Gaussian noise (AWGN),

which is Gaussian distributed with zero-mean and single-sided power

spectrum density of $N_0$ per dimension. $\tau_k$ takes into account the

lack of synchronisation among the users as well as the transmission
delay, while $\psi_{rec}(t)$ represents the time-domain pulse received, which is

usually the second derivative of the transmitted pulse $\psi(t)$ [13].

The receiver schematic block diagram for adaptive detection of the

hybrid DS-TH UWB signal is shown in Fig. 3. The received signal is

first passed through a matched-filter (MF) having the impulse response

$\psi_{rec}(-t)$. The output of the MF is then sampled at a rate of $1/T_v$.

Finally, the observation samples are input to an adaptive filter, in order to

generate the estimates to the transmitted symbols. Let us assume

that a block of $M$ data bits are transmitted. Then, the detector can

collect a total $(MNcN_v + L - 1)$ number of samples, where $(L - 1)$
is due to the $L$ number of resolvable multipaths. In more details, the

$\lambda$th sample can be obtained by sampling the MF’s output at the time

instant $t = T_0 + (\lambda + 1)T_v$, which can be expressed as

$$y_{\lambda} = \left( \sum_{k=1}^{K} b_{k} \right) H_{\lambda} + n(t)$$

Let us define

$$y = [y_0, y_1, \cdots, yM(NcN_v + L - 2)]^T$$

$$n = [n_0, n_1, \cdots, nM(NcN_v + L - 2)]^T$$

Then, according to (5), it can be shown that the element $n_{\lambda}$ in $n$
can be denoted as

$$n_{\lambda} = \left( \sum_{k=1}^{K} b_{k} \right) H_{\lambda} + n(t)$$

which is a Gaussian random variable distributed with zero-mean and a

variance of $\sigma^2 = N_0/2E_b$ per dimension. Furthermore, upon

substituting the received signal in the form of (4) into (5) and after

some simplifications, it can be shown that $y$ can be expressed as

$$y = \sum_{k=1}^{K} c_kH_{\lambda}b_{k} + n$$

![Fig. 1. Transmitter schematic block diagram of hybrid direct-sequence time-
hopping ultrawide bandwidth (DS-TH UWB) systems.]

![Fig. 2. Illustration of the signalling in hybrid DS-TH UWB systems.]

B. Channel Model

In this contribution the IEEE 802.15.4a channel model is consid-
ered [12]. This channel model is suitable for industrial environments,

where the abundance of metallic scatterers cause dense multipath

scattering, resulting in Rayleigh distributed small-scale fading [12].

Specifically, in this contribution the Saleh-Valenzuela (S-V) channel

model is considered, which can be represented as [12]

$$h(t) = \sum_{u=0}^{U-1} \sum_{v=0}^{V-1} h_{u,v} \delta(t - T_v - T_u,v)$$

where $V$ represents the number of clusters and $U$ denotes the number of

resolvable multipaths in a cluster. Hence the total number of resolvable

multipath components can be as high as $L = UV$. In (2) $h_{u,v} = |h_{u,v}|e^{j\phi_{u,v}}$ represents the fading gain of the $uv$th multipath in

the $u,v$th cluster, $T_v$ denotes the arrival time of the $uv$th cluster and $T_u,v$
where \( \mathbf{b}_k = [b^{(k)}_0, b^{(k)}_1, \ldots, b^{(k)}_{M-1}]^T \) contains the \( M \) number of data bits transmitted by the \( k \)th user, the channel matrix of the \( k \)th user, \( \mathbf{H}_k \) is given by

\[
\mathbf{H}_k = \text{diag} \{ \mathbf{h}_k, \mathbf{h}_k, \ldots, \mathbf{h}_k \}
\]

which is a \((ML \times M)\)-dimensional matrix with \( \mathbf{h}_k \) given by the CIR of user \( k \) as

\[
\mathbf{h}_k = \begin{bmatrix}
  h^{(k)}_{(0,0)} & h^{(k)}_{(1,0)} & \cdots & h^{(k)}_{(L-1,V-1)}
\end{bmatrix}^T
\]

The spreading matrix \( \mathbf{C}_k \) of the \( k \)th user is a \([(MNc_Np + L - 1) \times ML]\)-dimensional matrix which can be expressed as

\[
\mathbf{C}_k = \begin{bmatrix}
  \mathbf{C}^{(k)}_0 & 0 & 0 & 0 \\
  0 & \mathbf{C}^{(k)}_1 & 0 & 0 \\
  0 & 0 & \ddots & 0 \\
  0 & 0 & 0 & \mathbf{C}^{(k)}_{M-1}
\end{bmatrix}
\]

where \( \mathbf{0} \) is an all-zero matrix of \((Nc_Np \times L)\)-dimensional.

As the delay-spread of the considered UWB channel spans \( g \) data bits as mentioned in Section II-B, strong inter-symbol-interference (ISI) exists. According to our analysis in Section II, it can be implied that there are \( \min(i, g-1) \) data bits before the desired data bit and \( \min(M-1-i, g-1) \) data bits after the desired data bit, which interfere with the desired \( i \)th bit. Let us consider the bit-by-bit based detection, in order to reduce the detection complexity. Let the observation vector \( y_i \) and the noise vector \( n_i \), corresponding to the \( i \)th data bit of user \( 1 \) be represented by

\[
\begin{align*}
  \mathbf{y}_i &= [y_{i(Nc_Np)}, y_{i(Nc_Np)+1}, \ldots, y_{i(Nc_Np)+L-2}]^T \\
  \mathbf{n}_i &= [n_{i(Nc_Np)}, n_{i(Nc_Np)+1}, \ldots, n_{i(Nc_Np)+L-2}]^T
\end{align*}
\]

Then, \( \mathbf{y}_i \) can be expressed as

\[
\mathbf{y}_i = \mathbf{H}_i \mathbf{C}_i \mathbf{b}_i + \mathbf{w}_i + \mathbf{n}_i
\]

where \( \mathbf{w}_i \) is the additive white Gaussian noise (AWGN) vector following a Gaussian distribution with mean 0 and variance \( \sigma^2 \).

**III. MINIMUM MEAN-SQUARE ERROR DETECTION**

Before considering the LMS-aided adaptive MMSE detector, let us first derive the MMSE detector for the hybrid DS-TH UWB system by assuming that the receiver employs the ideal knowledge about the channel state information (CSI). In this case, the decision variable for \( \mathbf{b}_i^{(1)} \) of the desired user can be expressed as

\[
\hat{z}_i^{(1)} = \mathbf{w}_i^H \mathbf{y}_i, \quad i = 0, 1, \ldots, M - 1
\]

where the optimum weight vector \( \mathbf{w}_i \) is chosen such that it minimises the mean-square error between the transmitted bit \( b_i^{(1)} \) and the decision variable \( \hat{z}_i^{(1)} \), yielding

\[
\mathbf{w}_i = \mathbf{R}_{\mathbf{y}_i}^{-1} \mathbf{r}_{\mathbf{y}_i}^{(1)}
\]

where \( \mathbf{R}_{\mathbf{y}_i} \) denotes the autocorrelation matrix of \( \mathbf{y}_i \), which is given by

\[
\mathbf{R}_{\mathbf{y}_i} = \mathbb{E} [\mathbf{y}_i \mathbf{y}_i^H] = \sum_{k=1}^{K} \mathbf{C}_i^{(k)} \mathbf{h}_k \mathbf{h}_k^H \mathbf{C}_i^{(k)} + 2\sigma^2 \mathbf{I}
\]

\[
+ \sum_{k=1}^{K} \sum_{j=\max(0,i-g)}^{\min(M-1-i,g)} \mathbf{C}_j^{(k)} \mathbf{h}_k \mathbf{h}_j^H \mathbf{C}_i^{(k)} \mathbf{h}_j^H
\]

\[
+ \sum_{k=1}^{K} \sum_{j=i+1}^{\min(M-1,i+g)} \mathbf{C}_j^{(k)} \mathbf{h}_k \mathbf{h}_j^H \mathbf{C}_i^{(k)} \mathbf{h}_j^H \mathbf{C}_j^{(k)} T
\]

where \( \mathbf{I} \) is an identity matrix. In (18) \( \mathbf{r}_{\mathbf{y}_i}^{(1)} \) is the cross-correlation between the signal vector \( \mathbf{y}_i \) and the desired bit \( b_i^{(1)} \), which is given by

\[
\mathbf{r}_{\mathbf{y}_i}^{(1)} = \mathbb{E} [\mathbf{y}_i b_i^{(1)}] = \mathbf{C}_i^{(1)} \mathbf{h}_i
\]
Equations (18) - (20) show that, in order to compute $\mathbf{w}_1$, the knowledge about the signature codes and CSI associated with all the active users is required. Generally, the exact channel knowledge is hard to acquire in UWB communications, since, as mentioned previously, the received UWB signal is usually constituted by many multipath components and each multipath component only conveys very low energy. Additionally, as shown in (18), the MMSE detector needs to invert $\mathbf{R}_y$, which is a $((N_cN_v+L-1)\times(N_cN_v+L-1))$ dimensional matrix. Hence, the detection complexity might be extreme, when the spreading factor $N_cN_v$ is high. In the next section the LMS-aided adaptive MMSE detection for the hybrid DS-TH UWB system is derived, which can substantially reduce the detection complexity.

IV. LEAST MEAN-SQUARE AIDED ADAPTIVE DETECTION

Adaptive algorithms can be employed to find a sub-optimal solution to the optimum weight vector $\mathbf{w}_1$ as seen in (18), while converging to the optimum MMSE solution by iterative computing [11]. There are many adaptive algorithms, which may be applied for detection in UWB systems. In this contribution preference to the LMS algorithm is given due to its robustness and simplicity, despite its relatively slow convergence [11]. Specifically, the LMS algorithm is operated in two modes. The first mode is the training mode, which adjusts the weights of the filter for detection with the aid of a sequence of training symbols. During the training mode, the update equation can be expressed as

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu \mathbf{y}(n)e(n)$$

(21)

where $\mu$ represents the step-size, $e(n)$ is the error signal and can be calculated as $e(n) = d(n) - \mathbf{w}^H(n)\mathbf{y}(n)$, where $\{d(n)\}$ denotes the transmitted training sequences, while $\mathbf{y}(n)$ represents the corresponding received signal.

After the training mode, the adaptive detector is switched to the normal signal detection mode. During this mode, the sub-optimal weight vector $\mathbf{w}$ obtained from the training mode is used to estimate the data transmitted by the desired user. Correspondingly, the decision variable can be expressed as

$$\hat{z}_i^{(1)} = \mathbf{w}^H\mathbf{y}_i$$

(22)

Note that, the training mode shown in (21) can also be operated during the detection mode, but with the aid of the detected data. Furthermore, when comparing the LMS-aided adaptive detector derived in this section with the MMSE detector shown in (18), it can be seen that the LMS-aided adaptive detector does not require the knowledge about the user signatures and also their corresponding channels. Furthermore, the LMS-aided adaptive detector does not compute the inverse of the auto-correlation matrix $\mathbf{R}_y$. Hence, the LMS-aided adaptive detector is more feasible than the original MMSE for implementation in practical UWB systems.

V. SIMULATION RESULTS AND DISCUSSION

In this section mean-square error (MSE) and BER performance of the hybrid DS-TH UWB, pure DS-UWB and pure TH-UWB are investigated. In our simulations the number of resolvable multipaths was assumed to be 15. The total spreading factor was constant and was $N_cN_v = 64$. It is worth mentioning again that the hybrid DS-TH UWB system is reduced to the pure DS-UWB system when $N_c = 64$ and $N_v = 1$, while it is reduced to the pure TH-UWB system when $N_c = 1$ and $N_v = 64$. In our simulations the SV channel model was assumed, where the channel gains were assumed to obey the Rayleigh distribution. The parameters of the SV channel model used in our simulations are summarized in Table. I [12], where ‘LoS’ means that the channel model contains line-of-sight (LoS) propagation paths.

Fig. 4 and Fig. 5 show the learning curves of the LMS algorithm with different step-sizes for the hybrid DS-TH UWB system at $E_b/N_0 = 10$dB, when the DS-spreading factor is $N_c = 16$, the TH-spreading factor is $N_v = 4$, and when supporting single or $K = 7$ users. The ensemble average was taken over 2000 independent
realizations of the channel. It can be observed from Figs. 4 and 5 that the convergence speed of the LMS algorithm depends explicitly on the step-size $\mu$ as the convergence rates are significantly different for different values of the step-sizes. Furthermore, it can be observed that the algorithm using a large value of step-size $\mu$ converges to its steady-state quicker but at a higher MSE as compared to the algorithm which employs small step-size value.

Fig. 6 shows the BER performance of the hybrid DS-TH UWB system when supporting different number of users, while communicating over SV channel modeled by Rayleigh fading. It can be observed from the results that the LMS-aided detector at relatively high SNR is capable of achieving a BER performance that is very close to that achieved by the MMSE detector with perfect channel knowledge. Furthermore, it can be observed that the BER corresponding to the frame length of $FL = 500$ is lower than the BER corresponding to $FL = 1000$. However, this better BER performance is realized at the expense of a lower spectral efficiency than the latter case, as the training sequences were transmitted more frequently in the former case. Additionally, from Fig. 6, it can be observed that the LMS-aided detector is much worse than the ideal MMSE detector at the low SNR region, owing to a bigger step-size. The BER performance at low SNR region may be improved by properly choosing a step-size.

Fig. 7 shows the BER versus SNR performance of various UWB systems using the LMS-aided detection. From the results of Fig. 7 it can be observed that the BER performance of the hybrid DS-TH UWB may be slightly better than that of the pure DS-UWB and the pure TH-UWB. The LMS-aided detection may be employed by all the above-mentioned UWB systems.

VI. SUMMARY

From our study and simulation results, it can be concluded that the LMS-aided adaptive detector constitutes one of efficient detection schemes that can be applied to the DS-,TH- or hybrid DS-TH UWB systems, in order to implement low-complexity detection. For a given step-size, a trade-off exists between the achievable BER performance and the spectral efficiency of the UWB systems. Our future research will be concentrated on using blind or decision directed adaptive detection for the hybrid DS-TH UWB systems, aiming at avoiding the tradeoff between BER performance and spectral efficiency.

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REFERENCES