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Reduced-Rank Adaptive Least Bit Error-Rate Detection in Hybrid Direct-Sequence Time-Hopping Ultrawide Bandwidth Systems

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***Abstract*— In this paper we consider the low-complexity detection in hybrid direct-sequence time-hopping ultrawide bandwidth (DS-TH UWB) systems. A reduced-rank adaptive LBER detector is proposed, which is operated in the least bit error-rate (LBER) principles within a detection subspace obtained with the aid of the principal component analysis (PCA)-assisted reduced-rank technique. Our reduced-rank adaptive LBER detector is free from channel estimation and does not require the knowledge about the number of resolvable multipaths as well as that about the multipaths' strength. In this paper 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. Our study and simulation results show that this reduced-rank adaptive LBER detector constitutes a feasible detection scheme for deployment in practical pulse-based UWB systems.**

I. Introduction

Pulse-based UWB communications schemes constitute a range of promising alternatives that may be deployed for home, personal-area, sensor network, etc. applications, where the communication devices are required to be low-complexity, high-reliability and minimum power consumption [1]. However, in pulse-based UWB systems the spreading factor is usually very high. The UWB channels are usually very sparse [2], resulting in that a huge number of low-power resolvable multipaths need to be processed at the receiver. As demonstrated in [1, 2], in pulse-based UWB communications the huge number of resolvable multipaths generally consist of a few relatively strong paths and many other weak paths. Unlike in the conventional wideband communications where strong paths usually arrive at the receiver before weak paths, in UWB communications the time-of-arrivals (ToAs) of the strong multipaths are random variables and are not necessary the multipaths arriving at the receiver at the earliest. Due to the above-described issues, therefore, in pulse-based UWB systems it is normally impractical to carry out directly the coherent detection, which depends on accurate channel estimation demanding extreme complexity. In fact, it has been recognized that the complexity might still be extreme, even when the conventional single-user matched-filter (MF) detector [3] is employed. This is because there are a huge number of multipath channels need to be estimated and the detection complexity is at least proportional to the sum of the spreading factor and the number of resolvable multipaths [4].

In this paper we consider the low-complexity detection in hybrid DS-TH UWB systems [5, 6], since the hybrid DS-TH UWB scheme is a generalized pulse-based UWB communication scheme, which includes both the pure DS-UWB and the pure TH-UWB as special cases [1, 5, 6]. The detector proposed is an adaptive detector operated in a reduced-rank detection subspace based on the least bit error-rate (LBER) principles [7, 8], which is hence referred to as the reduced-rank adaptive LBER detector. As our forthcoming discourse shown, the reduced-rank adaptive LBER detector does not depend on channel estimation. It achieves its near-optimum detection with the aid of a training sequence at the start of communication and then maintains its near-optimum detection based on the decision-directed (DD) principles during the communication [9]. The reduced-rank adaptive LBER detector does not require the knowledge about the number of resolvable multipaths as well as that about the locations of the strong resolvable multipaths; It only requires the knowledge (which is still not necessary accurate) about the maximum delay-spread of the UWB channels. Furthermore, the reduced-rank adaptive LBER detector is operated in a reduced-rank detection subspace obtained based on the principal component analysis (PCA) [10]. The detection subspace usually has a rank that is significantly lower than that of the original observation space. Owing to the above-mentioned properties of the reduced-rank adaptive LBER detector, we can argue that it is a low-complexity detection scheme, which is feasible for practical implementation.

Note that, in this contribution the LBER algorithm is preferred instead of the conventional least mean-square (LMS) algorithm [11], since, first, the LBER algorithm works under the minimum BER (MBER) principles, which may outperform the LMS algorithm that is operated in minimum mean-square error (MMSE) sense [8]. Second, the LBER algorithm has similar complexity as the LMS algorithm [8]. Furthermore, it has been observed [8] that the LBER algorithm may provide a higher flexibility for system design in comparison with the LMS algorithm.

II. Description of the Hybrid DS-TH UWB System

The hybrid DS-TH UWB scheme considered in this contribution is the same as that considered in [12], where non-adaptive reduced-rank detection has been investigated.

A. *Transmitted Signal*

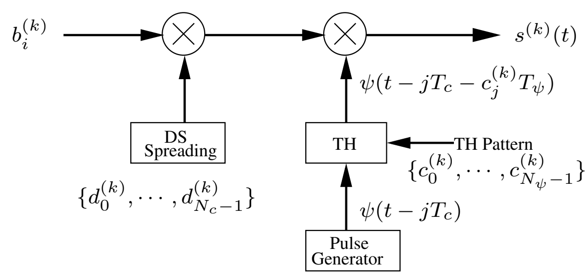

Fig. 1. Transmitter schematic block diagram of hybrid DS-TH UWB system.

The transmitter schematic block diagram for the considered hybrid DS-TH UWB system is shown in Fig. 1. We assume for simplicity that the hybrid DS-TH UWB system employs the binary phase-shift keying (BPSK) baseband modulation. As shown in Fig. 1, a data bit of the kth user is first modulated by a N_c-length DS spreading sequence, which generates N_c chips. The N_c chips are then transmitted by N_c time-domain pulses within one symbol-duration, where the positions of the N_c time-domain pulses are determined by the TH pattern assigned to the kth user. Finally, as shown in Fig. 1, the hybrid DS-TH UWB baseband signal transmitted by the kth user can be written as [5]

$$s^{(k)}(t) = \sqrt{\frac{E_b}{N_c T_\psi}} \sum_{j=0}^{\infty} b^{(k)}_{\lfloor \frac{j}{N_c} \rfloor} d^{(k)}_j \psi \left[t - jT_c - c^{(k)}_j T_\psi \right] \quad (1)$$

where $\lfloor x \rfloor$ represents the largest integer less than or equal to x, $\psi(t)$ is the basic time-domain pulse of width T_ψ, which satisfies $\int_0^{T_\psi} \psi^2(t)dt = T_\psi$. Note that, the bandwidth of the hybrid DS-TH UWB system is approximately equal to the reciprocal of T_ψ of the basic time-domain pulse's width. The other parameters in (1) as well as the other parameters used in this contribution are listed as follows:

- E_b: Energy per bit;
- N_c: Number of chips per bit and DS spreading factor;
- N_ψ: Number of time-slots in a chip and TH spreading factor;
- T_b and T_c: Bit-duration and chip-duration, which satisfies $T_b = N_c T_c$;
- T_ψ: Time-domain pulse width or width of a time-slot, which satisfies $T_c = N_\psi T_\psi$;
- $b^{(k)}_i \in \{+1, -1\}$: The ith data bit transmitted by user k;
- $\{d^{(k)}_j\}$: Random binary DS spreading sequence assigned to the kth user;
- $\{c^{(k)}_j \in \{0, 1, \cdots, N_\psi - 1\}\}$: Random TH sequence assigned to the kth user;
- $N_c N_\psi$: Total spreading factor of hybrid DS-TH UWB system.

Note that, both the pure DS-UWB and pure TH-UWB schemes constitute special cases of the hybrid DS-TH UWB scheme. Specifically, if $N_c > 1$ and $N_\psi = 1$, T_ψ and T_c are then equal and in this case the hybrid DS-TH UWB system is reduced to the pure DS-UWB system. By contrast, when $N_c = 1$ and $N_\psi > 1$, the hybrid DS-TH UWB scheme is then reduced to the pure TH-UWB scheme.

B. Channel Model

In this contribution the Saleh-Valenzuela (S-V) channel model is considered, which has the channel impulse response (CIR) [13]

$$h(t) = \sum_{v=0}^{V-1} \sum_{u=0}^{U-1} h_{u,v} \delta(t - T_v - T_{u,v}) \quad (2)$$

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) $h_{u,v} = |h_{u,v}|e^{j\theta_{u,v}}$ represents the fading gain of the uth multipath in the vth cluster, where $|h_{u,v}|$ and $\theta_{u,v}$ are assumed to obey the Rayleigh distribution [13] and uniform distribution in $[0, 2\pi)$, respectively. In (2) T_v denotes the arrival time of the vth cluster and $T_{u,v}$ the arrival time of the uth multipath in the vth cluster. In the considered UWB channel, the average power of a multipath component at a given delay, say at $T_v + T_{u,v}$, is related to the power of the first resolvable multipath of the first cluster through the relation of [13]

$$\Omega_{u,v} = \Omega_{0,0} \exp\left(-\frac{T_v}{\Gamma}\right) \exp\left(-\frac{T_{u,v}}{\gamma}\right) \quad (3)$$

where $\Omega_{u,v} = E\left[|h_{u,v}|^2\right]$ represents the power of the u resolvable multipath of the vth cluster, Γ and γ are the respective cluster and ray power decay constants.

According to (2), we can know that the maximum delay-spread of the UWB channels considered is $(T_V + T_{U,V})$ and the total number of resolvable multipaths is $L = \lfloor (T_V + T_{U,V})/T_\psi \rfloor + 1$. In order to make the channel model sufficiently general, in this contribution we assume that the maximum delay spread $(T_V + T_{U,V})$ spans $g \geq 1$ data bits, implying that $(g-1)N_c N_\psi \leq (L-1) < g N_c N_\psi$.

C. Receiver Structure

Let us assume that the hybrid DS-TH UWB system supports K uplink users. When the K number of DS-TH UWB signals in the form of (1) are transmitted over UWB channels having the CIR as shown in (2), the received signal at the base-station (BS) can be expressed as

$$r(t) = \sqrt{\frac{E_b}{N_c T_\psi}} \sum_{k=1}^{K} \sum_{v=0}^{V-1} \sum_{u=0}^{U-1} \sum_{j=0}^{MN_c} h^{(k)}_{u,v} b^{(k)}_{\lfloor \frac{j}{N_c} \rfloor} d^{(k)}_j \times \psi_{rec} \left[t - jT_c - c^{(k)}_j T_\psi - T^{(k)}_v - T^{(k)}_{u,v} - \tau_k \right] + n(t) \quad (4)$$

where $n(t)$ represents an additive white Gaussian noise (AWGN) process, which has zero-mean and a single-sided power spectral density of N_0 per dimension, τ_k takes into account the lack of synchronisation among the user signals as well as the transmission delay, while $\psi_{rec}(t)$ is the received time-domain pulse, which is usually the second derivative of the transmitted pulse $\psi(t)$ [14].

The receiver schematic block diagram for the hybrid DS-TH UWB using the considered reduced-rank adaptive LBER detection is shown in Fig. 2. At the receiver, the received signal is first filtered by a MF having an impulse response of $\psi^*_{rec}(-t)$. The output of the MF is then sampled at a rate of $1/T_\psi$. Then, the observation samples are stored in a buffer, which are projected to a reduced-rank detection subspace, once a reduced-rank detection subspace $\boldsymbol{S}_U$ is obtained. Finally, the observations in the detection subspace are input to a traversal filter, which is controlled by the LBER algorithm, in order to generate estimates to the transmitted data bits.

Let us assume that a block of M data bits per user is transmitted. Then, according to Fig. 2, the detector can collect a total of $(MN_c N_\psi + L - 1)$ number of samples, where $(L-1)$ is due to the L number of resolvable multipaths. In more details, the λth sample can be obtained by sampling the MF's output at the time instant of $t = T_0 + (\lambda + 1)T_\psi$, which can be expressed as

$$y_\lambda = \left(\sqrt{\frac{E_b T_\psi}{N_c}} \right)^{-1} \int_{T_0 + \lambda T_\psi}^{T_0 + (\lambda+1)T_\psi} r(t) \psi^*_{rec}(t) dt \quad (5)$$

where T_0 denotes the ToA of the first multipath in the first cluster.

In order to reduce the detection complexity of the hybrid DS-TH UWB system, in this contribution we consider only the bit-by-bit based detection. Let the observation vector $\boldsymbol{y}_i$ and the noise vector $\boldsymbol{n}_i$ related to the ith data bit of the first user (reference user) be represented by

$$\boldsymbol{y}_i = \left[y_{iN_c N_\psi}, y_{iN_c N_\psi + 1}, \cdots, y_{(i+1)N_c N_\psi + L - 2} \right]^T \quad (6)$$

$$\boldsymbol{n}_i = \left[n_{iN_c N_\psi}, n_{iN_c N_\psi + 1}, \cdots, n_{(i+1)N_c N_\psi + L - 2} \right]^T \quad (7)$$

where the elements of $\boldsymbol{n}_i$ are Gaussian random variables distributed with zero-mean and a variance of $\sigma^2 = N_0/2E_b$ per dimension. Then,

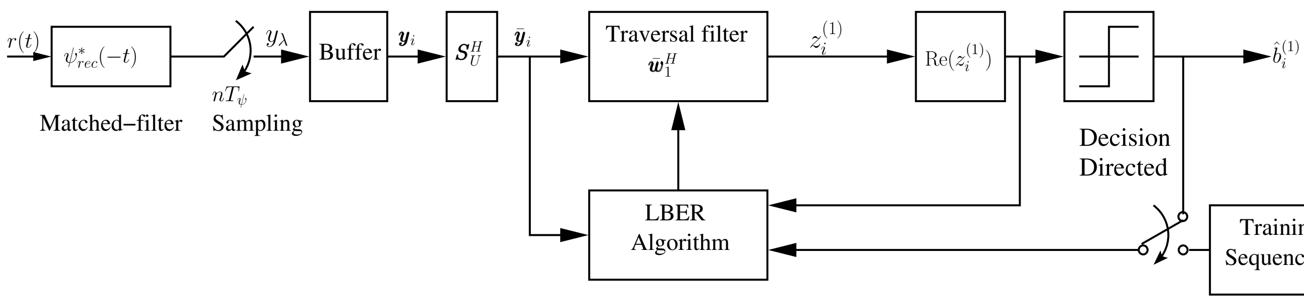

Fig. 2. Receiver schematic block diagram for the hybrid DS-TH UWB systems using reduced-rank adaptive LBER detection.

as shown in [5, 12], $\boldsymbol{y}_i$ can be expressed as

$$\boldsymbol{y}_i = \underbrace{\sum_{k=1}^{K}\sum_{\substack{j=\max(0,i-g)\\ i\neq 0}}^{i-1} \underline{\boldsymbol{C}}_j^{(k)}\boldsymbol{h}_k\boldsymbol{b}_j^{(k)}}_{\text{ISI from the previous bits of } K \text{ users}} + \underbrace{\boldsymbol{C}_i^{(1)}\boldsymbol{h}_1 b_i^{(1)}}_{\text{Desired signal}} + \boldsymbol{n}_i + \underbrace{\sum_{k=2}^{K}\boldsymbol{C}_i^{(k)}\boldsymbol{h}_k b_i^{(k)}}_{\text{Multiuser interference}} + \underbrace{\sum_{k=1}^{K}\sum_{\substack{j=i+1\\ i\neq M-1}}^{\min(M-1,i+g)} \bar{\boldsymbol{C}}_j^{(k)}\boldsymbol{h}_k\boldsymbol{b}_j^{(k)}}_{\text{ISI from the latter bits of } K \text{ users}} \quad (8)$$

where the matrices and vectors have been defined in detail in [5, 12]. From (8), we observe that the ith data bit conflicts both severe inter-symbol interference (ISI) and multiuser interference (MUI), in addition to the Gaussian background noise.

When the conventional linear detectors without invoking reduced-rank techniques are considered, the decision variable for $b_i^{(1)}$ of the reference user can be expressed as

$$z_i^{(1)} = \boldsymbol{w}_1^H\boldsymbol{y}_i,\ i = 0, 1, \ldots, M-1 \quad (9)$$

where $\boldsymbol{w}_1$ is a $(N_cN_\psi + L - 1)$-length weight vector. Since in UWB communications the spreading factor N_cN_ψ might be very high and since the number of resolvable multipath L is usually huge in UWB channels, the vector $\boldsymbol{w}_1$, i.e., the filter length might be very large. Therefore, the complexity of the corresponding detectors might be extreme, even when low-complexity linear detection schemes are considered. Furthermore, using very long filter for detection in UWB systems may significantly degrade the performance of the UWB systems. For example, using a longer traversal filter results in lower convergence speed and, hence, a longer sequence is required for training the filter [11]. Consequently, the data-rate and spectral efficiency of the corresponding communications system decreases. The robustness of an adaptive filter degrades as the filter length increases, since more channel-dependent variables are required to be estimated [15]. Furthermore, when a longer adaptive filter is employed, the computational complexity is also higher, since more operations are required for the corresponding detection and estimation. Therefore, in this paper the reduced-rank adaptive LBER detector is proposed, in order to achieve low-complexity detection in hybrid DS-TH UWB systems.

III. Reduced-Rank Adaptive LBER Detection

In reduced-rank detection the number of coefficients to be determined is reduced through projecting the received signals to a lower dimensional detection subspace [10]. Specifically, let $\boldsymbol{P}_U$ be an $((N_cN_\psi + L - 1) \times U)$ processing matrix with its U columns forming a U-dimensional subspace, where $U < (N_cN_\psi + L - 1)$. Then, for a given received vector $\boldsymbol{y}_i$, the U-length vector in the detection subspace can be expressed as

$$\bar{\boldsymbol{y}}_i = \underbrace{(\boldsymbol{P}_U^H\boldsymbol{P}_U)^{-1}\boldsymbol{P}_U^H}_{\boldsymbol{S}_U^H}\boldsymbol{y}_i \quad (10)$$

where an over-bar is used to indicate that the argument is in the reduced-rank detection subspace.

In this contribution, the PCA-assisted reduced-rank technique [10, 16] is employed for obtaining the processing matrix: Given the rank U of the detection subspace, the U number of eigenvectors corresponding to the U largest eigenvalues of the autocorrelation matrix of $\boldsymbol{y}_i$ are utilized to form the processing matrix $\boldsymbol{P}_U$ [16]. In more detail, the auto-correlation matrix of $\boldsymbol{y}_i$ can be represented using eigen-analysis as

$$\boldsymbol{R}_{y_i} = E[\boldsymbol{y}_i\boldsymbol{y}_i^H] = \boldsymbol{\Phi}\boldsymbol{\Lambda}\boldsymbol{\Phi}^H \quad (11)$$

where $\boldsymbol{\Lambda}$ is a diagonal matrix given by

$$\boldsymbol{\Lambda} = \text{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_{N_cN_\psi+L-1}\} \quad (12)$$

which contains the eigenvalues of $\boldsymbol{R}_{y_i}$, while $\boldsymbol{\Phi}$ is an unitary matrix consisting of the eigenvectors of $\boldsymbol{R}_{y_i}$, which can be written as

$$\boldsymbol{\Phi} = [\boldsymbol{\phi}_1, \boldsymbol{\phi}_2, \cdots, \boldsymbol{\phi}_{N_cN_\psi+L-1}] \quad (13)$$

where $\boldsymbol{\phi}_i$ is the eigenvector corresponding to the eigenvalue λ_i.

Let assume that the eigenvalues are arranged in descent order obeying $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_{N_cN_\psi+L-1}$. Then, the processing matrix $\boldsymbol{P}_U$ in the context of PCA-assisted reduced-rank technique is constructed by the first U columns of $\boldsymbol{\Phi}$, ie., we have $\boldsymbol{P}_U = [\boldsymbol{\phi}_1, \boldsymbol{\phi}_2, \cdots, \boldsymbol{\phi}_U]$.

Given the observations in the detection subspace as shown in (10), the linear detection of $b_i^{(1)}$ can be carried out by forming the decision variable

$$z_i^{(1)} = \bar{\boldsymbol{w}}_1^H\bar{\boldsymbol{y}}_i \quad (14)$$

where $\bar{\boldsymbol{w}}_1$ is now an U-length weight vector. According to the theory of the PCA-based reduced-rank detection [10], the full-rank BER performance can be achieved, provided that the rank U of the detection subspace is not lower than the rank of the signal subspace, which for our hybrid DS-TH UWB system is $K(g+1)$. However, if the rank of the detection subspace is lower than the signal subspace's rank, the reduced-rank detection then conflicts MUI. Consequently, the BER performance of the hybrid DS-TH UWB system using the PCA-based reduced-rank detection deteriorate, in comparison with the full-rank BER performance. Therefore, in the PCA-based reduced-rank detection it is important to have the knowledge about the signal subspace's rank. Note that, in our simulations considered in Section IV, the signal subspace's rank was estimated through eigen-analysis of the autocorrelation matrix $\boldsymbol{R}_{y_i}$, which was estimated with the aid of a block of data bits.

In (14) the weight vector $\bar{\boldsymbol{w}}_1$ can be obtained with the aid of the sample-by-sample adaptive LBER algorithm proposed in [7]. In our reduced-rank adaptive LBER detector for the hybrid DS-TH UWB systems, the reduced-rank adaptive LBER is operated in two modes, namely, the training mode and the decision-directed (DD) mode, respectively. When operated in the training mode, the weight vector $\bar{\boldsymbol{w}}_1$ is adjusted with the aid of a training sequence, which is known to the receiver. Correspondingly, the update equation in the LBER principle can be expressed as [8]

$$\begin{aligned}\bar{\boldsymbol{w}}_1(n+1) &= \bar{\boldsymbol{w}}_1(n) + \mu \frac{\text{sgn}(b_i^{(1)}(n))}{2\sqrt{2\pi}\rho_n} \\ &\times \exp\left(-\frac{|\Re(z_i^{(1)}(n))|^2}{2\rho_n^2}\right)\bar{\boldsymbol{y}}_i(n),\ n=1,2,\ldots \end{aligned} \quad (15)$$

where $\text{sgn}(x)$ is a sign-function, μ is the step-size and ρ_n is the so-called kernel width [8]. In the adaptive LBER algorithm, the step-size μ and the kernel width ρ_n are required to be set appropriately, in order to obtain a high convergence rate as well as a small and steady BER misadjustment. Furthermore, it has been observed [8] that the above-mentioned two parameters can provide a higher flexibility for system design in comparison with the adaptive LMS algorithm, which employs only single adjustable parameter of the step-size [11].

When the training stage is completed and the normal data transmission is started, the reduced-rank adaptive LBER detector is then switched to the DD mode. Under the DD mode, the estimated data bits by the receiver are fed back to the adaptive LBER filter, which is then updated in the LBER principle. Specifically, during the DD mode the update equation can be expressed as

$$\begin{aligned}\bar{\boldsymbol{w}}_1(n+1) &= \bar{\boldsymbol{w}}_1(n) + \mu \frac{\text{sgn}(\hat{b}_i^{(1)}(n))}{2\sqrt{2\pi}\rho_n} \\ &\times \exp\left(-\frac{|\Re(z_i^{(1)}(n))|^2}{2\rho_n^2}\right)\bar{\boldsymbol{y}}_i(n),\ n=1,2,\ldots \end{aligned} \quad (16)$$

where the estimate $\hat{b}_i^{(1)}$ is given by

$$\hat{b}_i^{(1)} = \text{sgn}(\Re\{z_i^{(1)}\}),\ i=0,1,\ldots,M-1 \quad (17)$$

Let us now provide our simulation results in the next section.

IV. Simulation Results and Discussion

In this section the learning and BER performance of the reduced-rank adaptive LBER detector is investigated by simulations. In our simulations the total spreading factor was assumed to be a constant of $N_cN_\psi = 64$, where the DS-spreading factor was set to $N_c = 16$ and the TH-spreading factor was hence $N_\psi = 4$. The normalised Doppler frequency-shift of the UWB channels was fixed to $f_dT_b = 0.0001$. In our simulations the S-V channel model used in [13] was considered and the channel gains were assumed to obey the Rayleigh distribution. In more detail, the parameters of the S-V channel model used in our simulations are summarized in the following Table.

$1/\Lambda$	Γ	γ
14.11 ns	2.63 ns	4.58 ns

TABLE I
Parameters for the S-V channel model used in simulations.

Fig. 3 shows the ensemble-average squared error-rate (SER) learning curve of the reduced-rank adaptive LBER detector for the hybrid DS-TH UWB system supporting $K = 5$ users, when different step-size values are considered. Note that, the SER drawn in Fig. 3 is defined as

$$\text{SER} = \left|\frac{\text{sgn}(b_i^{(1)}(n))}{2\sqrt{2\pi}\rho_n}\exp\left(-\frac{|\Re(z_i^{(1)}(n))|^2}{2\rho_n^2}\right)\right|^2 \quad (18)$$

which is proportional to the BER achieved by the reduced-rank adaptive LBER detector. In our simulations the signal-to-noise ratio (SNR) per bit was set to $E_b/N_0 = 10$dB, the ensemble-average SER was obtained from the average over 2000 independent realizations, the weight vector was initialized to $\bar{\boldsymbol{w}}(0) = \mathbf{1}$ of an all-one vector, and the rank of the detection subspace was chosen as $U = 20$. It can be observed from Fig. 3 that the convergence speed of the reduced-rank adaptive LBER detector is depended on the step-size μ. Explicitly, there exists an optimum step-size value, which results in that the reduced-rank adaptive LBER detector converges to the lowest BER. As shown in Fig. 3, when an inappropriate step-size is used, the convergence speed may become lower and the reduced-rank adaptive LBER detector may converge to a relatively higher SER.

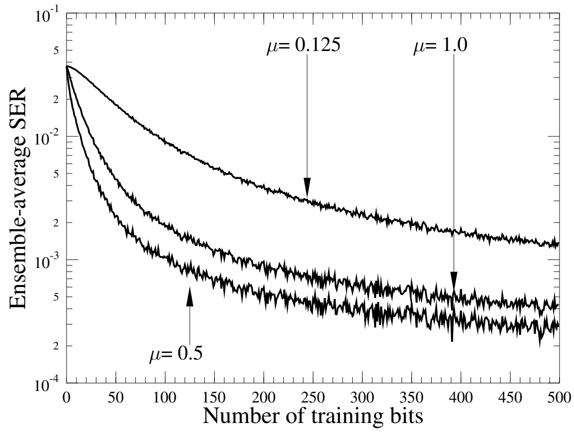

Fig. 3. Learning curves of the reduced-rank adaptive LBER detector for the hybrid DS-TH UWB system supporting $K = 5$ users, when the detection subspace has a rank of $U = 20$. The parameters used in the simulations were $E_b/N_0 = 10$dB, Doppler frequency-shift of $f_dT_b = 0.0001$, $\rho_n = \sqrt{10}\sigma_n$, $g = 1$, $N_c = 16$, $N_\psi = 4$ and $L = 15$.

Fig. 4 shows the BER versus SNR per bit performance of the hybrid DS-TH UWB system using reduced-rank adaptive LBER detection, when communicating over the UWB channels experiencing correlated Rayleigh fading. The hybrid DS-TH UWB system considered supported $K = 5$ users and the normalised Dopper frequency-shift was assumed to be $f_dT_b = 0.0001$. Furthermore, we assumed that $g = 1$, implying that the desired bit conflicts ISI from one bit transmitted before the desired bit and also from one bit transmitted after the desired bit. Note that, given the parameters as shown in the caption of the figure, it can be shown that the rank of the signal subspace is $K(g+1) = 10$. From the results of Fig. 4, we observe that, when the rank of the detection subspace is lower than that of the signal subspace, i.e., when $U \leq 10$, the BER performance of the hybrid DS-TH UWB system improves, as the rank of the detection subspace increases. The best BER performance is attained, when the rank of the detection subspace reaches the rank of the signal subspace. When the rank of the detection subspace is higher than that of the signal subspace, no further SNR gain is achievable. Furthermore, when the rank of the detection subspace is lower than that of the signal subspace, error-floor is observed, explaining that the MUI cannot be fully suppressed by the reduced-rank adaptive LBER detector.

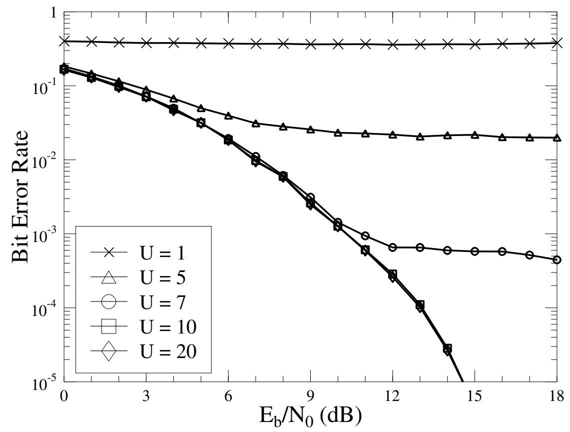

Fig. 4. BER performance of the hybrid DS-TH UWB systems using reduced-rank adaptive LBER detection, when communicating over the UWB channels modelled by the S-V channel model associated with correlated Rayleigh fading. The parameters used in the simulations were $K = 5$, $f_dT_b = 0.0001$, $\mu = 0.5$, $\rho_n = \sqrt{10\sigma_n}$, $g = 1$, $N_c = 16$, $N_\psi = 4$ and $L = 15$. The frame length was fixed to 1000 bits, where the first 160 bits were used for training.

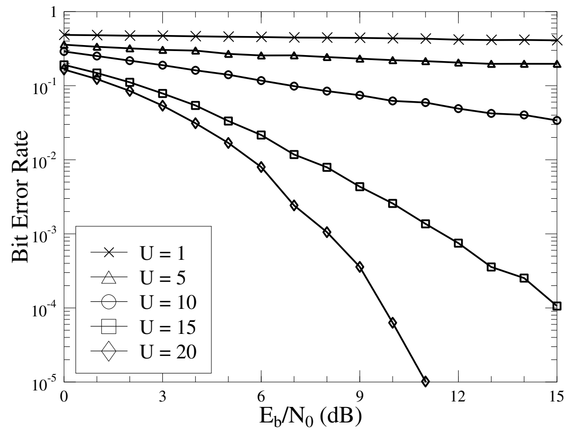

Fig. 5. BER performance of the hybrid DS-TH UWB systems using reduced-rank adaptive LBER detection, when communicating over the UWB channels modelled by the S-V channel model associated with correlated Rayleigh fading. The parameters used in the simulations were $K = 5$, $f_dT_b = 0.0001$, $\mu = 0.5$, $\rho_n = \sqrt{10\sigma_n}$, $g = 3$, $N_c = 16$, $N_\psi = 4$ and $L = 150$. The frame length was fixed to 1000 bits, where the first 160 bits were used for training.

Fig. 5 shows the BER versus SNR per bit performance of the hybrid DS-TH UWB system using reduced-rank adaptive LBER detection, when communicating over the UWB channels experiencing correlated Rayleigh fading, which results in severe ISI. In contrast to Fig. 4, where we assumed that $g = 1$ and the number of resolvable multipaths was $L = 15$, in the context of Fig. 5 we assumed that $g = 3$ and $L = 150$. The other parameters used for Fig. 5 were the same as those used for Fig. 4. Note that, for the parameters considered in Fig. 5, the rank of the signal subspace is $K(g + 1) = 20$. Again, as the results of Fig. 5 shown, the BER performance improves as the rank of the detection subspace increases, until it reaches the rank of the signal subspace. In comparison with Fig. 4, we can see that, for a given E_b/N_0 value, the full-rank BER shown in Fig. 5 is lower than the corresponding full-rank BER shown in Fig. 4. This is because the UWB channel considered associated with Fig. 5 has $L = 150$ number of resolvable multipaths, which results in a higher diversity gain than the UWB channel considered associated with Fig. 4, which has $L = 15$ number of resolvable multipaths.

V. Conclusions

In conclusions, our study and simulation results show that the reduced-rank adaptive LBER detector constitutes one of the efficient detectors for the hybrid DS-TH UWB systems. The reduced-rank technique can be employed for achieving low-complexity detection in the DS-TH UWB systems and for improving their efficiency. The reduced-rank adaptive LBER detector is capable of achieving the full-rank BER performance with the detection subspace having a rank that is significantly lower than $(N_cN_\psi + L - 1)$ of the original observation space.

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