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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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Outline

- ❑ Motivation;
- ❑ Description of hybrid direct-sequence time-hopping ultrawide bandwidth (DS-TH UWB) system;
- ❑ Conventional linear detection;
- ❑ Reduced-rank detection;
- ❑ Reduced-rank adaptive least-bit-error-rate (LBER) detection;
- ❑ Simulation results;
- ❑ Conclusions.

Motivation

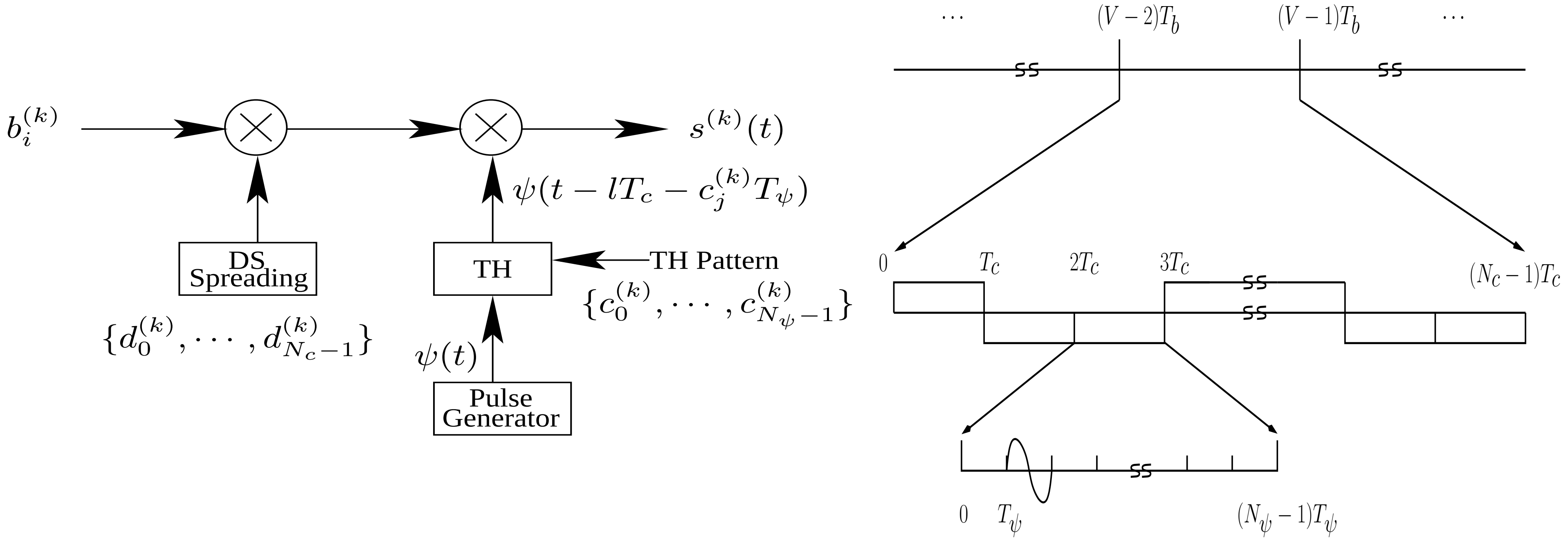
- UWB channels are highly frequency-selective, yielding a huge number of resolvable multipaths with each path conveying very low signal power. Hence, channel estimation is extremely difficult;
- Unlike conventional wideband channels where strong paths usually arrive at the receiver before weak paths, in UWB channels the time-of-arrivals (ToAs) of multipaths are random variables.
- The reduced-rank adaptive detectors do not require the knowledge about the number of resolvable multipaths as well as the knowledge about the locations of the resolvable multipaths;
- The reduced-rank adaptive LBER detector is free from channel estimation and operated in the minimum BER principle.

Hybrid DS-TH UWB Systems

Hybrid DS-TH UWB is an UWB scheme combining both the DS and TH techniques and enjoying the following advantages:

- It is capable of inheriting the advantages of both the DS-UWB and TH-UWB systems, while avoiding simultaneously their disadvantages;
- It is a generalized pulse-based UWB scheme, which includes both the DS-UWB and TH-UWB schemes as its special examples;
- It outperforms the corresponding pure TH-UWB or pure DS-UWB system in terms of the achievable BER performance;
- It provides more degrees-of-freedom for system design and reconfiguration than the pure DS-UWB or pure TH-UWB system.

Hybrid DS-TH UWB: Transmitter Model



- The transmitted data is first modulated based on the principles of DS spreading and then the locations of the transmitted pulses are determined according to the TH principles.

Transmitted and Received Signal

Transmitted signal:

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

Saleh-Valenzuela (S-V) Channel Model:

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

Received signal:

$$r(t) = \sqrt{\frac{E_b}{N_c T_\psi}} \sum_{k=1}^{K} \sum_{v=0}^{V-1} \sum_{u=0}^{U-1} \sum_{j=0}^{MN_c-1} h_{u,v}^{(k)} b^{(k)}_{\lfloor \frac{j}{N_c} \rfloor} d_j^{(k)} \\ \times \psi_{rec} \left[t - jT_c - c_j^{(k)} T_\psi - T_v^{(k)} - T_{u,v}^{(k)} - \tau^{(k)} \right] + n(t)$$

Representation of Received Signal

- The observation vector for the ith bit of the first user can be expressed as

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

- where $\boldsymbol{n}_i$ is the Gaussian noise vector, the components of $\boldsymbol{n}_i$ are Gaussian distributed with mean zero and a common variance of $\sigma^2 = N_0/2E_b$ per dimension.

- $\underline{\mathbf{C}}_j^{(k)}$ and $\bar{\boldsymbol{C}}_j^{(k)}$ are the spreading matrices corresponding to the bits transmitted before and after bit i, respectively.

Conventional Linear Detection

- ❑ Decision variable: $z_i^{(1)} = \boldsymbol{w}_1^H \boldsymbol{y}_i,\ i = 0, 1, \cdots, M-1$, where $\boldsymbol{w}_1$ is a $(N_c N_\psi + L - 1)$-length weight vector;
- ❑ In UWB communications the spreading factor $N_c N_\psi$ might be very high and the number of resolvable multipaths L is usually huge. Hence, the filter length might be very large. Consequently, the complexity of the corresponding detectors might be extreme, even when linear detectors are considered;
- ❑ Additionally, using very long filter for detection in UWB systems may significantly degrade the performance of the UWB systems, such as convergence speed, robustness, spectral-efficiency, etc.
- ❑ In this case, reduced-rank techniques can be employed to reduce the number of coefficients to be estimated by the adaptive detector, resulting in lower detection complexity.

Reduced-Rank Detection

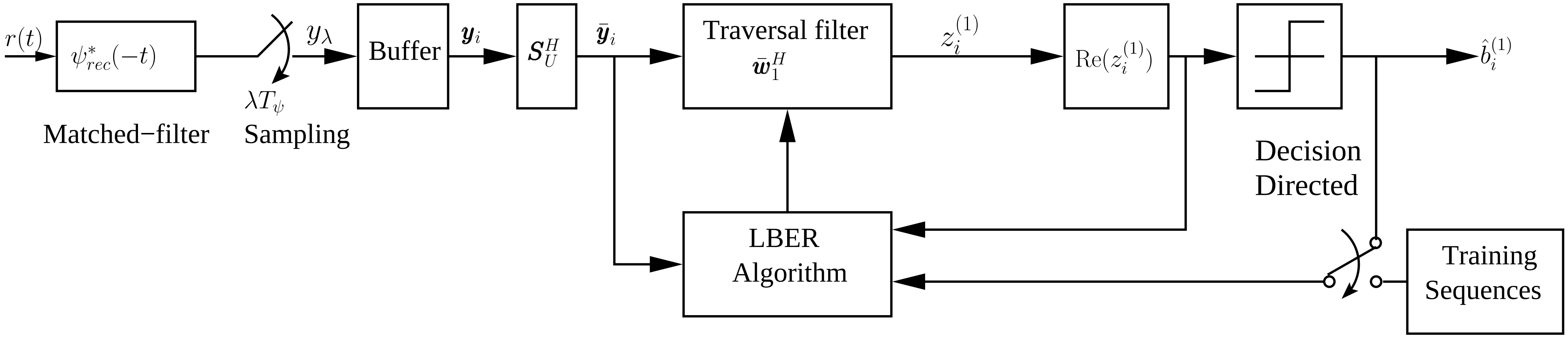
- The received signal is projected on to a lower dimensional subspace with the help of a projection matrix $\boldsymbol{S}_U$, yielding: $\bar{\boldsymbol{y}}_i = \underbrace{(\boldsymbol{P}_U^H \boldsymbol{P}_U)^{-1} \boldsymbol{P}_U^H}_{\boldsymbol{S}_U^H} \boldsymbol{y}_i$;
- The decision variable for the ith data bit of the desired user is formed as $z_i^{(1)} = \bar{\boldsymbol{w}}_1^H \bar{\boldsymbol{y}}_i$;
- The processing matrix $\boldsymbol{P}_U$ can be detected based on various reduced-rank techniques, such as the principal component analysis (PCA) method.

Principal Component Analysis (PCA)

The eigen-decomposition of the auto-correlation matrix is carried out and the eigen vectors corresponding to the U largest eigenvalues are retained for forming the processing matrix $\boldsymbol{P}_U$. The details are as follows:

- Eigen-decomposition of the auto-correlation matrix: $\boldsymbol{R}_{y_i} = \boldsymbol{\Phi}\boldsymbol{\Lambda}\boldsymbol{\Phi}^H$,
- where $\boldsymbol{\Phi} = [\boldsymbol{\phi}_1, \boldsymbol{\phi}_2, \cdots, \boldsymbol{\phi}_{N_c N_\psi + L - 1}]$ is the unitary matrix consisting of the eigenvectors of $\boldsymbol{R}_{y_i}$,
- $\boldsymbol{\Lambda} = \text{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_{N_c N_\psi + L - 1}\}$ is a diagonal matrix containing the corresponding eigenvalues;
- Assuming that the eigenvalues have been arranged in a descending order, ie., $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_{N_c N_\psi + L - 1}$, then the processing matrix $\boldsymbol{P}_U$ in the principles of PCA is constituted by the first U columns of $\boldsymbol{\Phi}$, ie., $\boldsymbol{P}_U = [\boldsymbol{\phi}_1, \boldsymbol{\phi}_2, \cdots, \boldsymbol{\phi}_U]$.

Reduced-Rank Adaptive LBER Detector



- ❏ The reduced-rank adaptive LBER detector is operated in two modes;
  - ✓ Training mode: The weight vector is adjusted with the aid of a training sequence:

$$\bar{\boldsymbol{w}}_1(i+1) = \bar{\boldsymbol{w}}_1(i) + \mu \frac{\mathrm{sgn}(b_i^{(1)})}{2\sqrt{2\pi}\rho} \exp\left(-\frac{|\Re(z_i^{(1)})|^2}{2\rho^2}\right) \bar{\boldsymbol{y}}_i, \ i = 0, 1, 2, \ldots \tag{2}$$

    - ✦ μ: step-size;
    - ✦ $\mathrm{sgn}(x)$: sign-function;
    - ✦ ρ: kernel width;
    - ✦ $b_i^{(1)}$: training bit.
  - ✓ Decision-directed (DD) mode: The weight vector $\bar{\boldsymbol{w}}_1$ obtained from the training mode is further updated with the aid of the data bits estimated at the receiver:

$$\bar{\boldsymbol{w}}_1(i+1) = \bar{\boldsymbol{w}}_1(i) + \mu \frac{\mathrm{sgn}(\hat{b}_i^{(1)})}{2\sqrt{2\pi}\rho} \exp\left(-\frac{|\Re(z_i^{(1)})|^2}{2\rho^2}\right) \bar{\boldsymbol{y}}_i, \ i = 0, 1, 2, \ldots \tag{3}$$

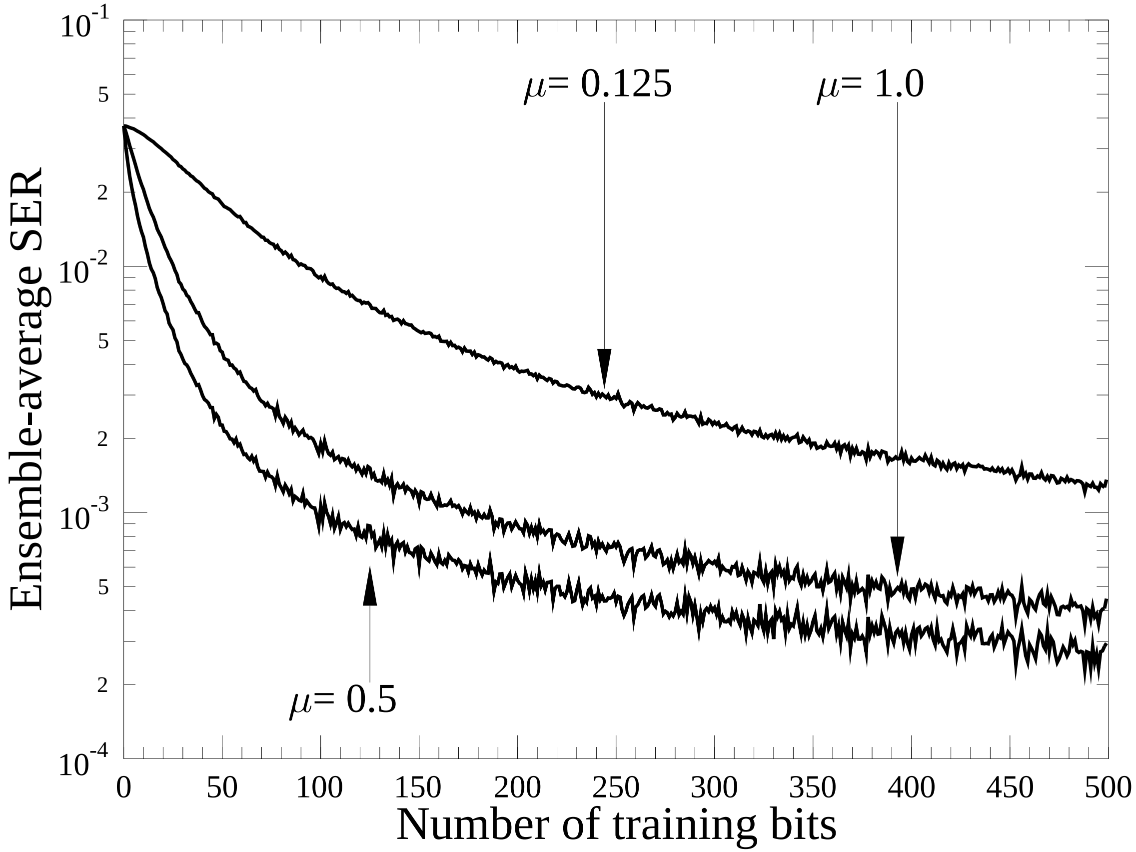
where $\hat{b}_i^{(1)}$ represents the estimate to $b_i^{(1)}$.

Simulation Results: Parameters

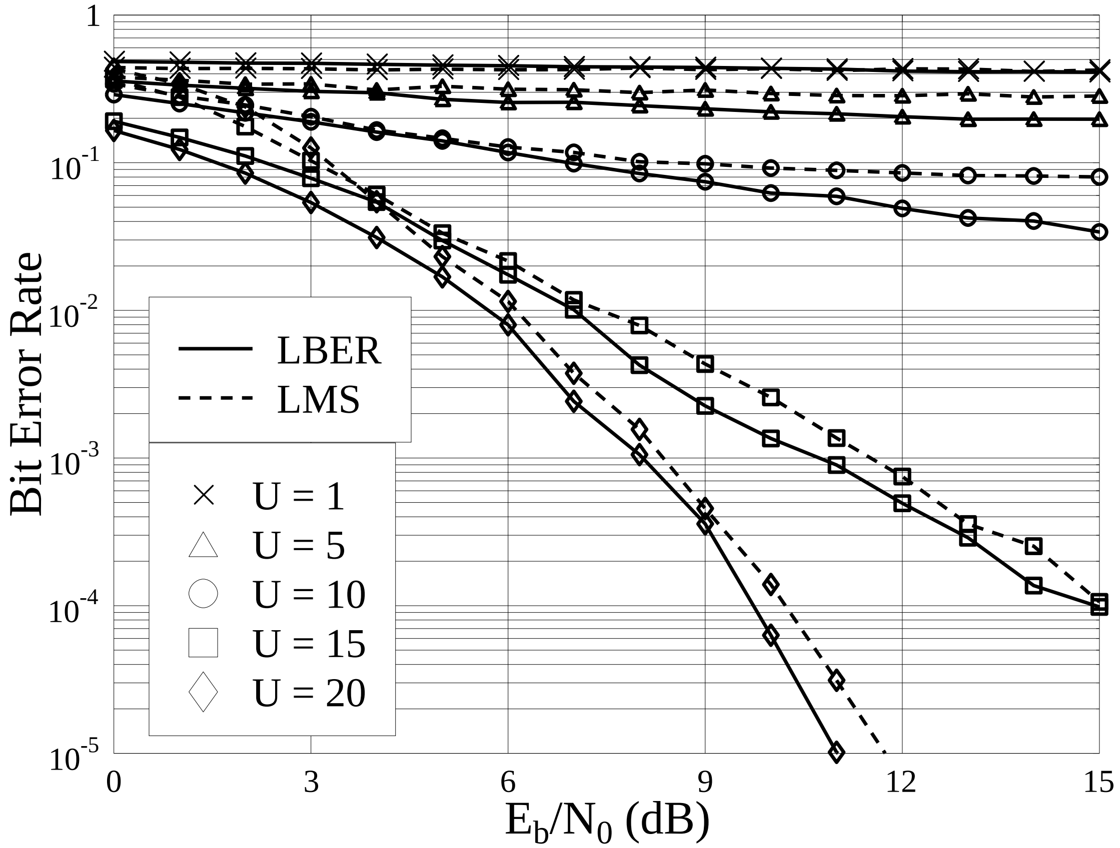
- ❑ DS spreading factor: $N_c = 16$;
- ❑ TH spreading factor: $N_\psi = 4$;
- ❑ Total number of resolvable multipaths: $L = 15$ or 150;
- ❑ Normalised Doppler frequency-shift: $f_d T_s = 0.0001$.
- ❑ Parameters for the S-V channel model:

$1/\Lambda$	Γ	γ
14.11ns	2.63ns	4.58ns

- ❑ Frame length 1000 bits, with first 160 bits for training; Projection matrix $\boldsymbol{S}_U$ constructed based on the block of 160 training data.



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 $U = 10$. The parameters used in the simulations were $E_b/N_0 = 10$dB, Doppler frequency-shift of $f_dT_b = 0.0001$, $\rho = \sqrt{10}\sigma$, $g = 1$, $N_c = 16$, $N_\psi = 4$ and $L = 15$.



BER performance comparison of reduced-rank adaptive LBER and LMS detectors, 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 $K = 5$, $f_d T_b = 0.0001$, $\mu = 0.5$, $\rho = \sqrt{10}\sigma$, $g = 3$, $N_c = 16$, $N_\psi = 4$ and $L = 150$. The frame length was fixed to 1000 bits, where the first 160 bits were used for training.

Conclusions

❑ The PCA-based reduced-rank adaptive LBER detector constitutes one of efficient detection schemes for hybrid DS-TH-UWB systems;

❑ The detector is free from channel estimation and does not require any knowledge about the channel impulse response (CSI) of the UWB channels;

❑ It is capable of providing a good trade-off between the achievable BER performance and the affordable complexity.