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L2-Orthogonal ST-Code Design for Multi-h CPM with fast Decoding

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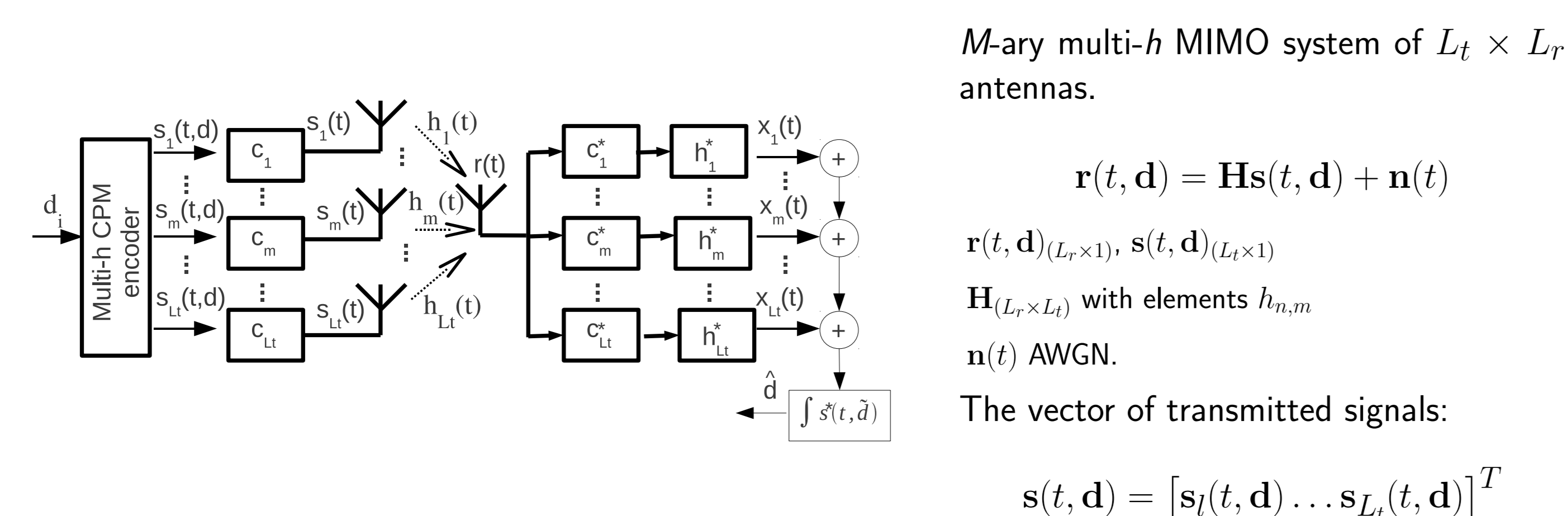
Abstract

- ⊕ CPM: favorable trade-off between power and bandwidth efficiency.
- ⊕ Multi-h CPM: generalization to further decrease the need for bandwidth.
- ⊖ Difficult decoding in multi-path environments with no diversity.

How to overcome these limitations:

- ⊕ **IDEA:** To combine CPM with Space-Time Block Coding (STBC).
- Non trivial extension to L^2 -orthogonal Space-Time codes provides full diversity and better spectral compactness.[1][2]
- Decoding complexity greatly decreased.[1][2]

The System Model



The baseband general form [3]

$$s(t, \mathbf{d}) = \sqrt{\frac{E_s}{T}} \exp(j\phi(t, \mathbf{d}))$$

The information-carrying phase function

$$\phi(t, \mathbf{d}) = 2\pi \sum_{k=0}^{K-1} h_{[k]} d_k q(t - (k-1)T)$$

modulation indices h_1, \dots, h_H , cycle in time with period H as:

$$[k] = \text{mod}(k, H) + 1$$

$h_{[k]}$ quotient between two relative prime integers.

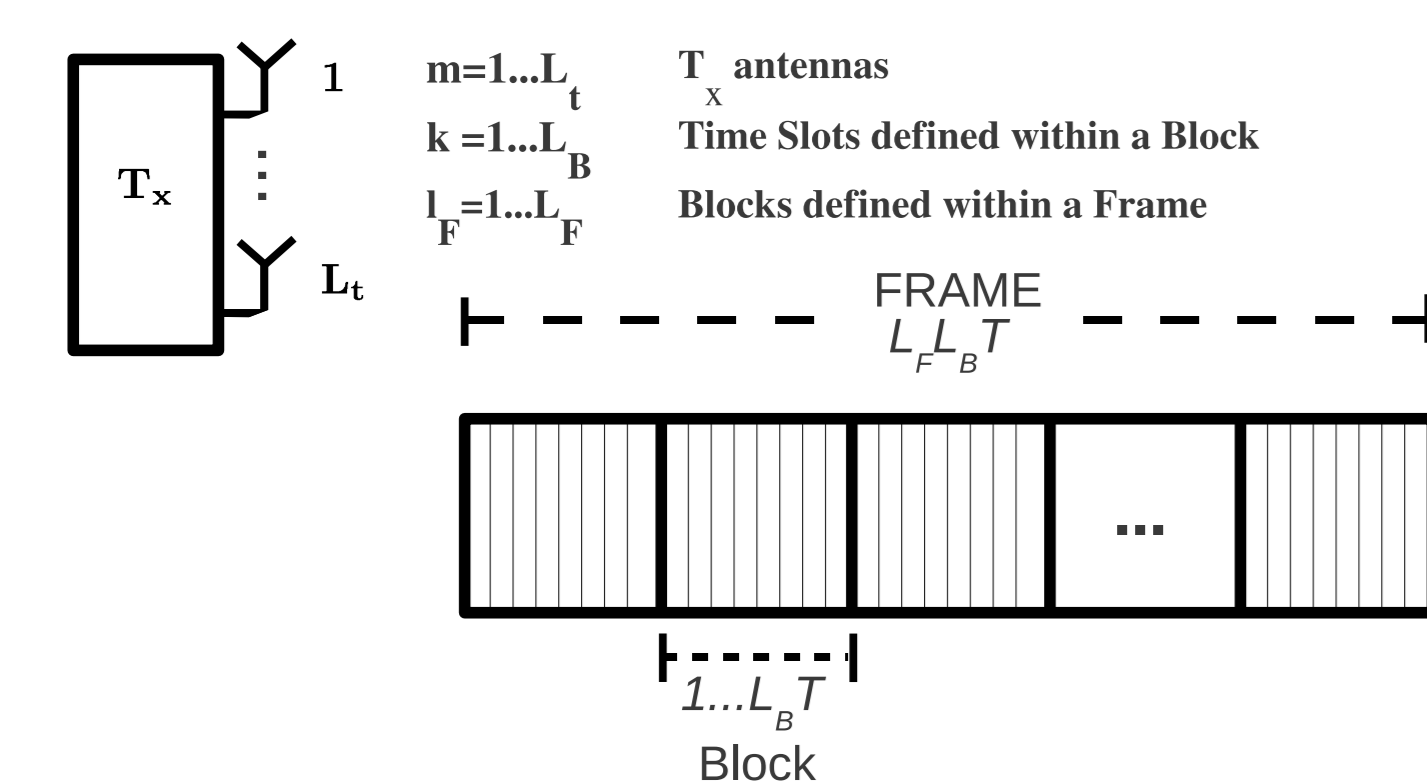
$$H_k = (h_1, h_2, \dots, h_k) = \left(\frac{p_1}{q}, \frac{p_2}{q}, \dots, \frac{p_k}{q} \right)$$

The phase continuity is ensured by the phase pulse $q(t)$,

$$q(t) = \begin{cases} 0 & t < 0 \\ \bar{q}(t) & \text{elsewhere} \\ 1/2 & t \geq \gamma T \end{cases}$$

$\bar{q}(0) = 0$, $\bar{q}(\gamma T) = 1/2$ and $\lim_{t \rightarrow \gamma T} \bar{q}(t) = \bar{q}(\gamma T)$ for $0 \leq \tau < \gamma T$. γ is the overlapping factor and the symbol index is given by $k = \lceil t/T \rceil$

L^2 Orthogonality



The phase continuity is ensured by an antenna dependent phase memory:

$$\theta_{m,k} = \theta_{m,k-1} + \frac{h_{[k-\gamma]}}{2} d_{m,k-\gamma} + c_{m,k}(T) - c_{m,k}(0).$$

Auto-correlation coefficients cancel and cross-correlation coefficients between antennas put to 0

$$\sum_{k=1}^{L_B} \int_{(k-1)T}^{kT} \exp(j2\pi[\theta_{m,k} + \sum_{i=k-\gamma+1}^k h_{[i]} d_{m,i} q(t - (i-1)T) + c_{m,k}(t) - \theta_{m',k} - \sum_{i=k-\gamma+1}^k h_{[i]} d_{m',i} q(t - (i-1)T) - c_{m',k}(t)]) dt = 0$$

To ease the design, two assumptions are introduced,

1. $c_{m,k}(t) = c_{m,k'}(t)$
2. $d_{m,k} = d_{m',k}$

For any arbitrary number of transmit antennas, we introduce correction functions $c_{m,k}$ as:

$$c_m^{lin}(t) = \frac{m-1}{L_B T} t \quad \text{for } (k-1)T < t < kT$$

For $m = 1, \dots, L_t$ and the transmitted signal takes the form of

$$s_m(t, \mathbf{d}) = s(t, \mathbf{d}) \exp(j2c_m^{lin}(t))$$

L^2 Decoding

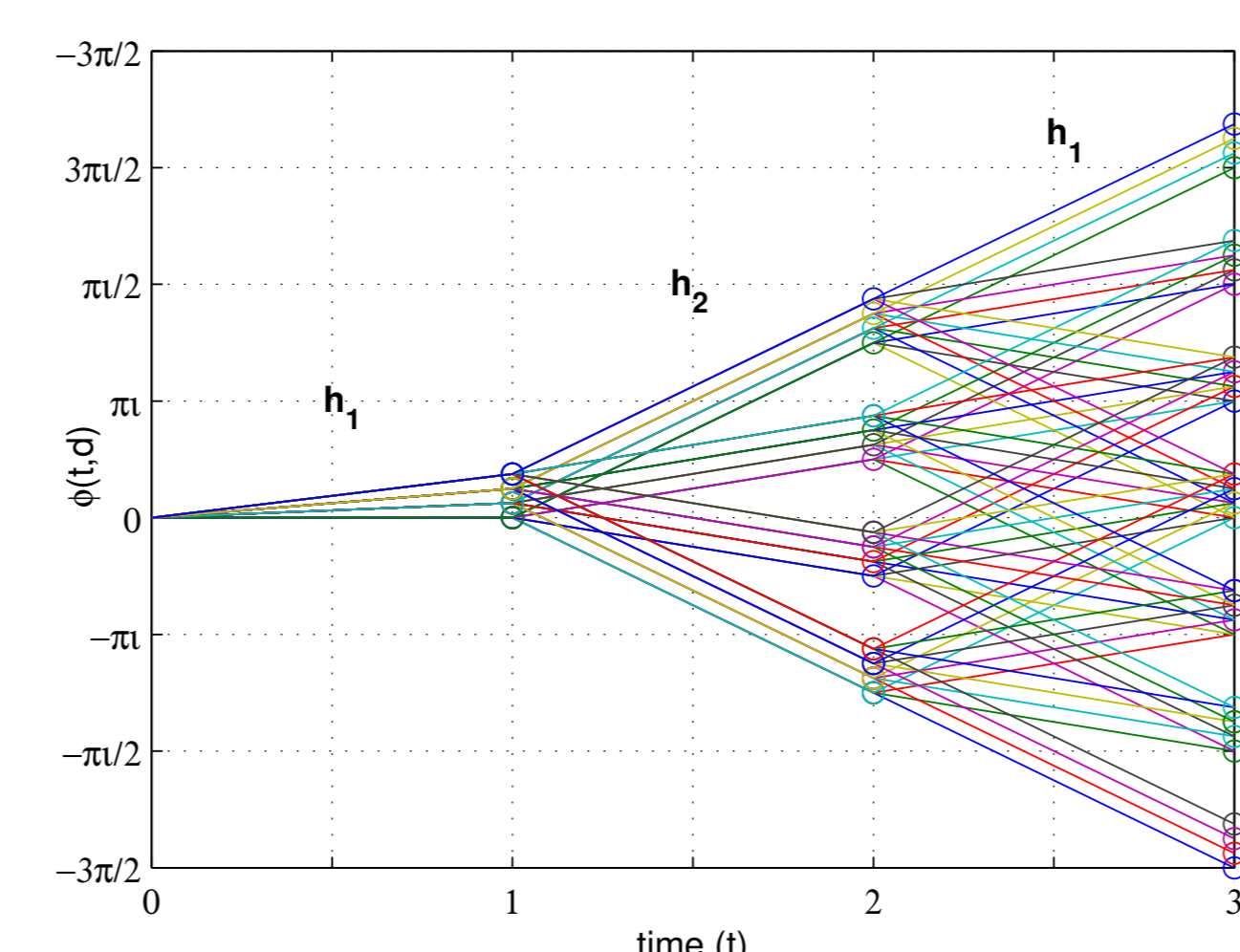


FIG. 1: Inner-block phase transition for $h_1 = \frac{1}{4}$ and $h_2 = \frac{3}{4}$.

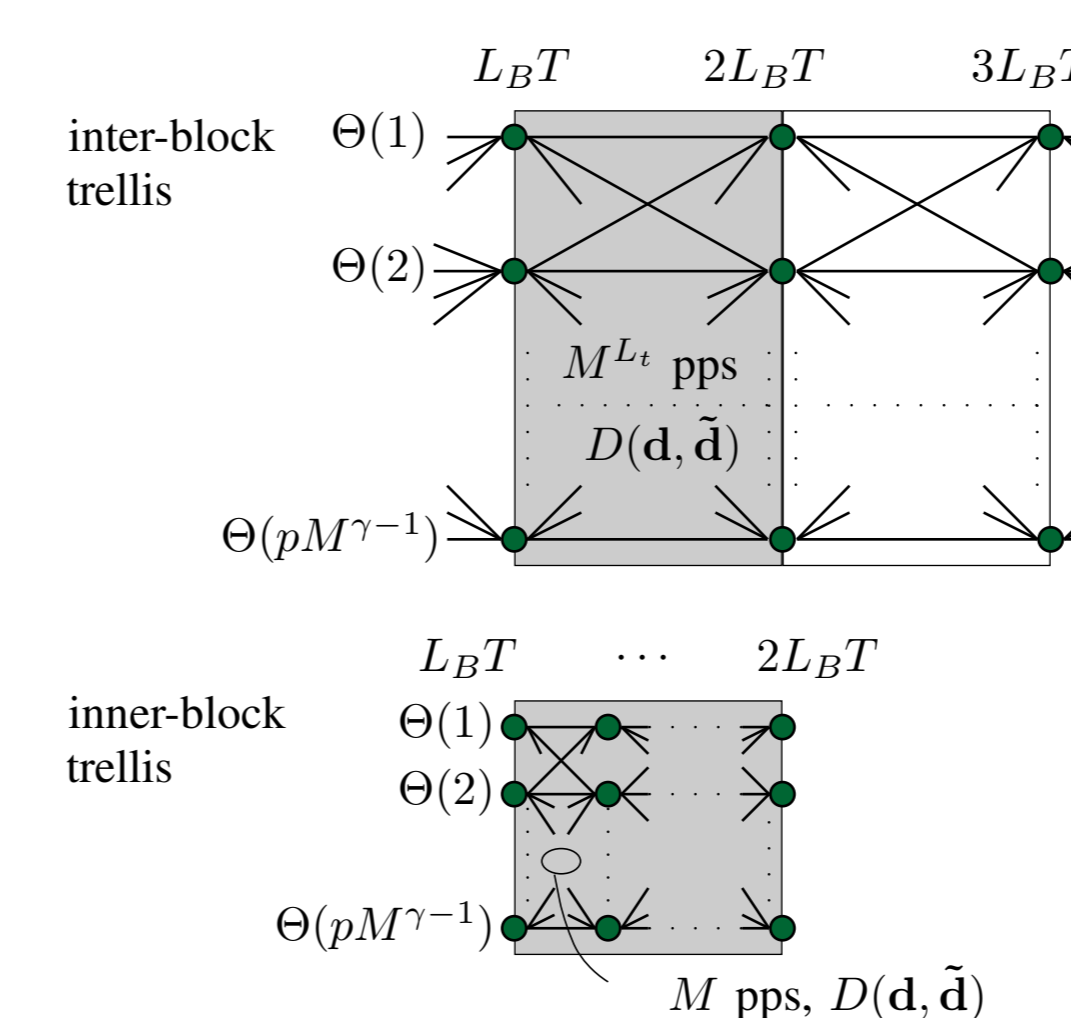


FIG. 2: Simplified detection with $k = 1$ (pps per state).

Classical correlation based multi-h detector expressed blockwise:

$$D(\mathbf{d}, \hat{\mathbf{d}}|\Theta(k)) = \sum_{k=1}^{L_F} \sum_{n=1}^{N_s} \int_{kT L_B}^{(k+1)T L_B} \text{Re} \left\{ r(t, \mathbf{d}_{[n]}) \dots \mathbf{d}_{L_B[n]} \cdot \left(\sum_{m=1}^{L_t} h_m^* s_m^*(t, \theta, \hat{\mathbf{d}}_{[n]}) \dots \hat{\mathbf{d}}_{L_B[n]} \right) \right\} dt$$

⊖ **Impractical:**

- $pM^{(L_t L_B N_s + \gamma - 1)}$ matched filters of length $N_s L_B T$ employed $pM^{\gamma-1}$ times.
- pM^{L_B-1} states and $M^{L_B T}$ symbols to decode with N_s samples each.

⊕ **Orthogonality:** the cross correlation terms are canceled out with blockwise decoding.

$$D_B(\mathbf{d}, \hat{\mathbf{d}}|\Theta(k)) = \sum_{m=1}^{L_T} \int_{(l-1)T}^{lT} \text{Re} \{ r(t, \mathbf{d}) h_m^* c_m^*(t) s^*(t, \hat{\mathbf{d}}) \} dt.$$

To get decoding with complexity **growing linearly** w.r.t number of transmit antennas, we introduce

$$x(t, \mathbf{d}) = r(t, \mathbf{d}) \sum_{m=1}^{L_T} h_m^* c_m^*(t).$$

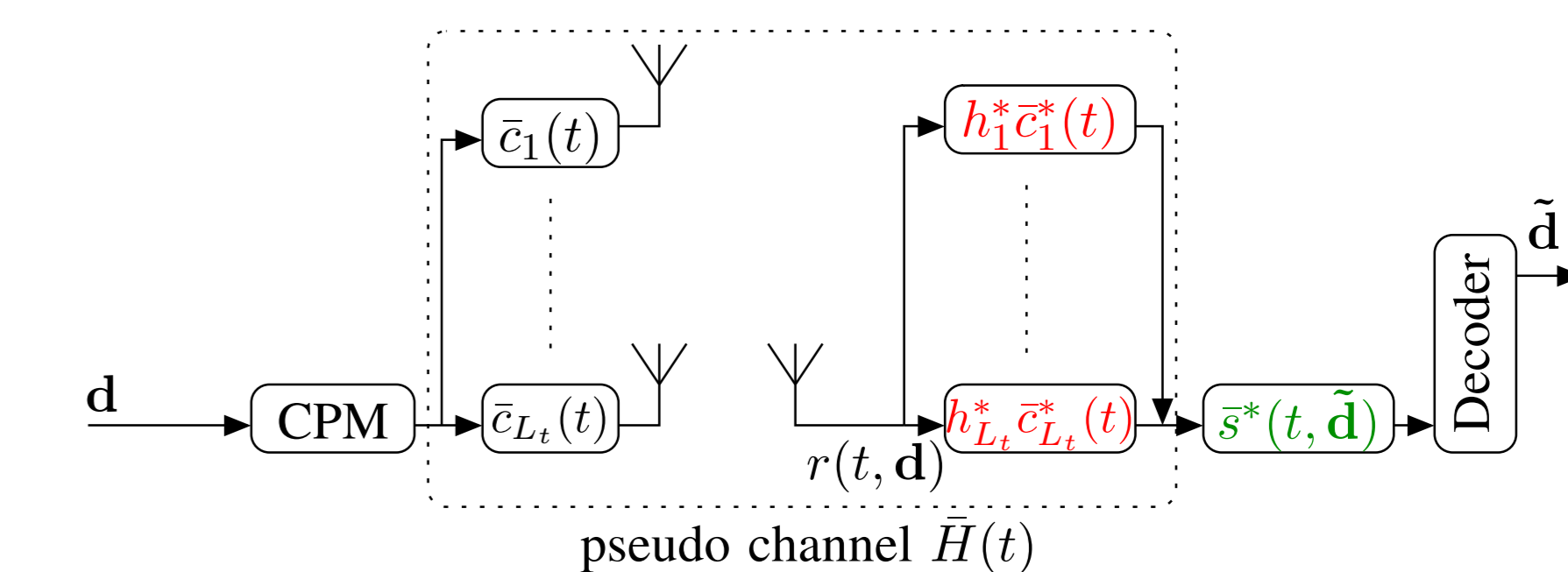
A simplified expression for a classical multi-h decoder [4] then is given by

$$D(\mathbf{d}, \hat{\mathbf{d}}|\Theta(k)) = \int_{(l-1)T}^{lT} \text{Re} \{ x(t, \mathbf{d}) \cdot s(t, \hat{\mathbf{d}})_{\Theta(k)} \} dt$$

Hence our detector based on the correlations gives us an expression which maximizes the minimum distance as

$$D_r(\mathbf{d}, \hat{\mathbf{d}}|\Theta(k)) = \arg \max_{\Theta(1) \rightarrow \Theta(pM^{\gamma-1})} \left\{ \int_{(l-1)T}^{lT} \text{Re} \{ x(t, \mathbf{d}) s(t, \hat{\mathbf{d}}) \} dt \right\}.$$

The simplified detector can now be represented in a similar form as in [5],



Simulation Results

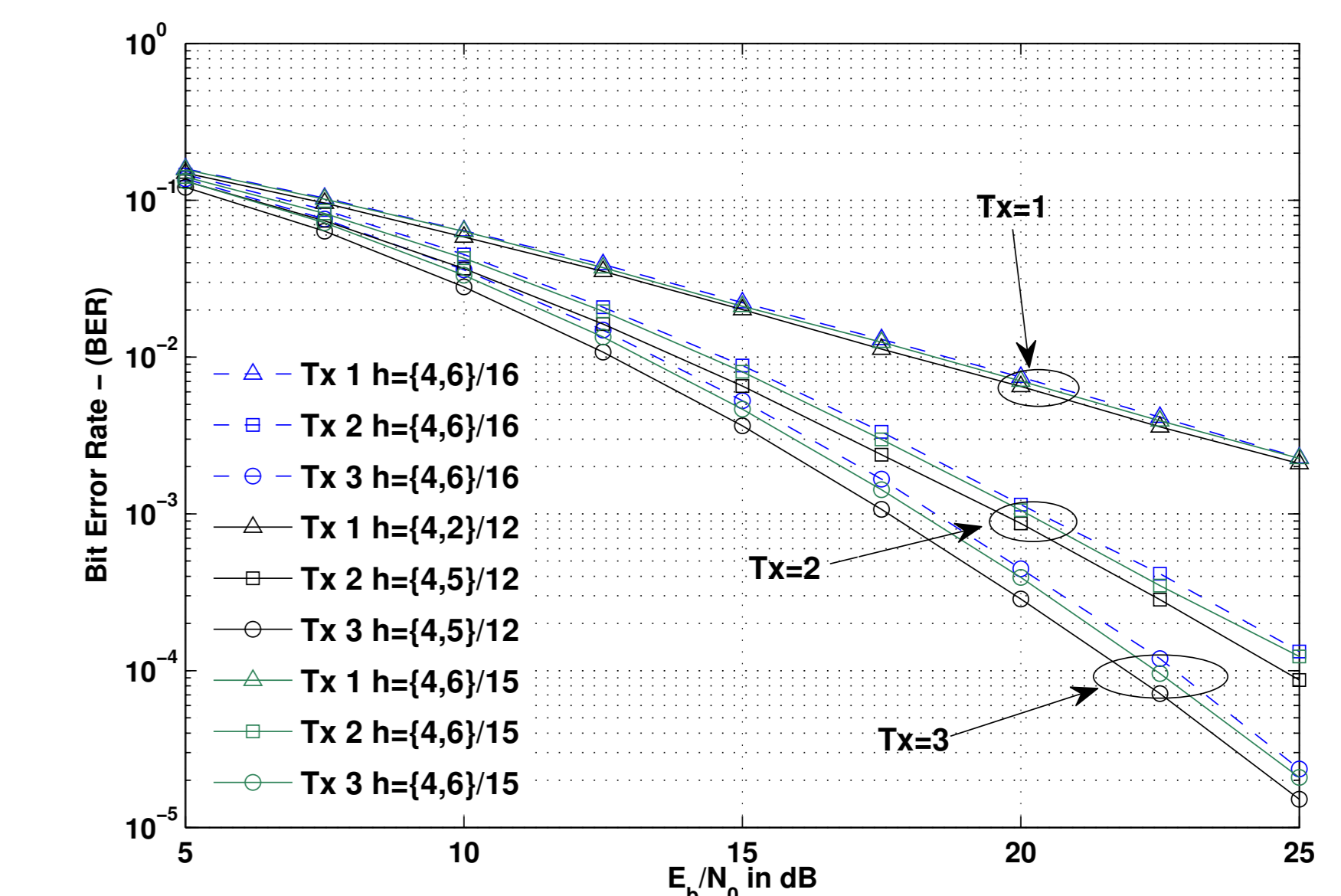


FIG. 3: BER for $T_x = 1, 2, 3$, $L_B = 2$ and $h_i = \{4, 5\}/12$, $h_i = \{4, 6\}/16$, $h_i = \{4, 6\}/15$.

Conclusions

- ✓ L^2 -orthogonal STBC provide full diversity by the construction of orthogonal waveforms.
- ✓ We have shown that the inner trellis is equivalent to the inter-trellis for multi-h CPM.
- ✓ By choosing $H \leq L_B$ we get the largest minimum distance in a block.
- ✓ L^2 -orthogonal STBC satisfies the needs for energy and spectral efficiency.
- ✓ Decoding complexity increases as PM instead of PMM^{L_T} .

References

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- [4] J. B. Anderson and D. P. Taylor. A bandwidth-efficient class of signal-space codes. *IEEE Trans. Inf. Theory*, 1978.
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