LATENCY TIME OPTIMIZATION FOR FIR AND BLOCK TRANSMIT FILTERS

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ABSTRACT

We address the problem of optimizing the latency time for transmit filters which can have FIR or block structure. When we allow the transmission system to have latency time, we gain an additional degree of freedom which can be exploited to improve the performance substantially. Contrary to the latency time optimization for FIR filters, the optimization for block transmit filters is very complex. We present a suboptimum approach for block transmit filters which leads to results close to optimum but with low complexity.

1. INTRODUCTION

Conventionally, the distortions caused by the channel are combatted by receive processing. However, we have to keep the *mobile stations* simple. Thus, transmit processing is advantageous for the downlink, as the receivers perform an *a priori* known processing and the transmitter has to adapt to the properties of the channel. The *transmit matched filter* (TxMF, [1]) maximizes the desired signal portion, the *transmit zero-forcing filter* (TxZF, [2, 3, 4, 5, 6, 7]) removes interference, and the *transmit Wiener filter* (TxWF, [8]) minimizes the *modified mean square error* (*modified* MSE).

An additional degree of freedom can be gained by introducing a latency time. The time period between transmission and detection of a symbol is not fixed anymore and the optimization of the latency time can further improve the performance of the system. In [9], Krauss et al. stated that latency time optimization leads to an SNR improvement of 3 – 4 dB for FIR receive filters. To our knowledge, no comparable result has been reported for FIR transmit filters yet.

Our contribution is to show that the latency time optimization for FIR transmit filters implies similar gains as for FIR receive filters. Moreover, we will investigate the potential of latency time optimization for block filters. Because the latency time optimization for block filters is very complex, we discuss different suboptimum approaches.

We explain the system models for FIR and block transmit processing in Section 2 and the respective latency time optimizations in Sections 3 and 4. In Section 5, we discuss suboptimum latency time optimizations for the TxZF and the TxWF, and show the simulation results in Section 6.

2. SYSTEM MODEL

We use $\mathrm{E}[\bullet]$, '$*$', '$\otimes$', $(\bullet)^{\mathrm{T}}$, and $(\bullet)^{\mathrm{H}}$ for expectation, convolution, Kronecker product, transpose, and conjugate transpose, respectively. All random processes are assumed to be zero-mean and stationary. The covariance matrix of $\boldsymbol{x}[n]$ is $\boldsymbol{R}_{\boldsymbol{x}} = \mathrm{E}\left[\boldsymbol{x}[n]\boldsymbol{x}^{\mathrm{H}}[n]\right]$, whereas $\sigma_y^2 = \mathrm{E}\left[|y[n]|^2\right]$ is the variance of $y[n]$. We denote the $N \times N$ identity matrix by $\mathbf{1}_N$, the $N \times M$ zero matrix by $\mathbf{0}_{N\times M}$, and use the selection matrix $\boldsymbol{S}_{(q,M,N)} = \left[\mathbf{0}_{M\times q}, \mathbf{1}_M, \mathbf{0}_{M\times N-q}\right] \in \{0,1\}^{M\times M+N}$.

2.1. FIR Transmit Filtering

The data $s[n]$ are convolved with the FIR transmit filter $\boldsymbol{p}[n] = \sum_{\ell=0}^{L} \boldsymbol{p}_\ell \delta[n-\ell] \in \mathbb{C}^{N_\mathrm{a}}$ prior to transmission over the channel $\boldsymbol{h}[n] = \sum_{q=0}^{Q} \boldsymbol{h}_q \delta[n-q] \in \mathbb{C}^{N_\mathrm{a}}$, where N_a denotes the number of antennas. Thus, we get for the estimate

$$\hat{s}[n] = \boldsymbol{h}^{\mathrm{T}}[n] * \boldsymbol{p}[n] * s[n] + \eta[n] = \boldsymbol{p}^{\mathrm{T}}\boldsymbol{H}\boldsymbol{s}[n] + \eta[n], \tag{1}$$

where we added the Gaussian noise $\eta[n]$ and defined the filter vector $\boldsymbol{p} = [\boldsymbol{p}_0^{\mathrm{T}}, \ldots, \boldsymbol{p}_L^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{C}^{(L+1)N_\mathrm{a}}$, the channel matrix $\boldsymbol{H} = \sum_{q=0}^{Q} \boldsymbol{S}_{(q,L+1,Q)} \otimes \boldsymbol{h}_q \in \mathbb{C}^{(L+1)N_\mathrm{a}\times Q+L+1}$, and $\boldsymbol{s}[n] = [s[n], \ldots, s[n-Q-L]]^{\mathrm{T}} \in \mathbb{C}^{Q+L+1}$. The desired value of $\hat{s}[n]$ (cf. Fig. 1) is $s[n-\nu]$ with latency ν.

2.2. Block Transmit Processing

With the transmit filter $\boldsymbol{P} \in \mathbb{C}^{NN_\mathrm{a}\times N}$, the channel matrix $\boldsymbol{H}_\mathrm{b} = \sum_{q=0}^{Q} \boldsymbol{S}_{(q,N,Q)}^{\mathrm{T}} \otimes \boldsymbol{h}_q^{\mathrm{T}} \in \mathbb{C}^{Q+N\times NN_\mathrm{a}}$ and the receive noise vector $\boldsymbol{\eta} = [\eta[0], \ldots, \eta[Q+N-1]]^{\mathrm{T}} \in \mathbb{C}^{Q+N}$, the estimate can be expressed as (see Fig. 2)

$$\hat{\boldsymbol{s}}_\mathrm{b} = \boldsymbol{S}_{(\mu,N,Q)}\left(\boldsymbol{H}_\mathrm{b}\boldsymbol{P}\boldsymbol{s}_\mathrm{b} + \boldsymbol{\eta}\right), \tag{2}$$

where $\boldsymbol{s}_\mathrm{b} = [s[0], \ldots, s[N-1]]^{\mathrm{T}} \in \mathbb{C}^N$ contains the N symbols of one block and we introduced a latency time μ.

3. LATENCY TIME OPTIMIZATION FOR FIR TRANSMIT FILTERS

Although Montalbano et al. [3] mentioned the possibility to optimize the latency time for FIR transmit filters, they did

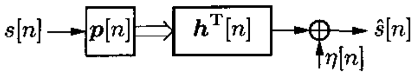

Figure 1: System Model for FIR Transmit Processing

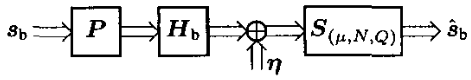

Figure 2: System Model for Block Transmit Processing

not deal with the problem. We follow the idea of Krauss et al. in [9] for FIR receive filters to further optimize the objective function by the choice of the latency time.

3.1. FIR Transmit Zero-Forcing Filter – FIR TxZF

The FIR TxZF removes interference, uses the whole available transmit power E_{tr}, and maximizes the gain β of the combination of the channel $\boldsymbol{h}[n]$ with the transmit filter $\boldsymbol{p}[n]$:

$$\boldsymbol{p}_{\mathrm{ZF}}^{\mathrm{T}} = \arg\min_{\boldsymbol{p}^{\mathrm{T}},\nu} \beta^{-2} \text{ s. t.: } \mathrm{E}\left[\|\boldsymbol{p}[n] * s[n]\|_2^2\right] = E_{\mathrm{tr}} \quad (3)$$
$$\text{and } \boldsymbol{h}^{\mathrm{T}}[n] * \boldsymbol{p}[n] = \beta\delta[n-\nu].$$

The solution of above optimization for fixed ν reads as

$$\boldsymbol{p}_{\mathrm{ZF}}^{\mathrm{T}}(\nu) = \beta_{\mathrm{ZF}}(\nu)\boldsymbol{e}_{\nu+1}^{\mathrm{T}} \left(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\right)^{-1} \boldsymbol{H}^{\mathrm{H}}, \quad (4)$$

where $\beta_{\mathrm{ZF}}(\nu)$ is necessary to satisfy the transmit power constraint, $\boldsymbol{e}_\nu$ denotes the ν-th column of $\mathbf{1}_{Q+L+1}$, and we assumed white symbols, i. e. $\boldsymbol{R}_s = \sigma_s^2\mathbf{1}_{Q+L+1}$. The optimum latency time further maximizes the gain $\beta_{\mathrm{ZF}}(\nu)$:

$$\nu_{\mathrm{ZF}} = \arg\min_{\nu} \boldsymbol{e}_{\nu+1}^{\mathrm{T}} \left(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\right)^{-1} \boldsymbol{e}_{\nu+1}. \quad (5)$$

Therefore, the optimum $\nu_{\mathrm{ZF}}+1$ is the index of the minimum diagonal element of the inverse of $\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}$.

3.2. FIR Transmit Matched Filter – FIR TxMF

The desired signal portion in the estimate $\hat{s}[n]$ is maximized by the TxMF which can be written as [1]

$$\boldsymbol{p}_{\mathrm{MF}}^{\mathrm{T}}(\nu) = \beta_{\mathrm{MF}}(\nu)\boldsymbol{e}_{\nu+1}^{\mathrm{T}}\boldsymbol{H}^{\mathrm{H}}, \quad (6)$$

where $\beta_{\mathrm{MF}}(\nu)$ is used to fulfill $\mathrm{E}[\|\boldsymbol{p}[n] * s[n]\|_2^2] = E_{\mathrm{tr}}$ and the optimum ν_{MF} is simply the channel order Q.

3.3. FIR Transmit Wiener Filter – FIR TxWF

The FIR TxWF minimizes the *modified* MSE and uses the whole available transmit power E_{tr}:

$$\boldsymbol{p}_{\mathrm{WF}}^{\mathrm{T}} = \arg\min_{\boldsymbol{p}^{\mathrm{T}},\nu} \mathrm{E}\left[\left|s[n-\nu] - \beta^{-1}\hat{s}[n]\right|^2\right] \quad (7)$$
$$\text{s. t.: } \mathrm{E}\left[\|\boldsymbol{p}[n] * s[n]\|_2^2\right] = E_{\mathrm{tr}}.$$

The solution of above optimization for fixed latency ν can be expressed as

$$\boldsymbol{p}_{\mathrm{WF}}^{\mathrm{T}}(\nu) = \beta_{\mathrm{WF}}(\nu)\boldsymbol{e}_{\nu+1}^{\mathrm{T}}\boldsymbol{H}^{\mathrm{H}}\left(\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}} + \xi\mathbf{1}_{(L+1)N_s}\right)^{-1}, \quad (8)$$

where $\xi = \sigma_\eta^2/E_{\mathrm{tr}}$ and $\beta_{\mathrm{WF}}(\nu)$ guarantees that the transmit power constraint is satisfied. The optimum latency time further minimizes the *modified* MSE and can be found by setting $\nu_{\mathrm{WF}}+1$ equal to the index of the principal diagonal element of $\boldsymbol{H}^{\mathrm{H}}(\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}} + \xi\mathbf{1}_{(L+1)N_s})^{-1}\boldsymbol{H}$.

4. LATENCY TIME OPTIMIZATION FOR BLOCK TRANSMIT FILTERS

Contrary to the block receive filters (e. g. [10]), the block transmit filters depend on the latency time μ, as the receiver only employs N of $N+Q$ received symbols as estimate $\hat{\boldsymbol{s}}_{\mathrm{b}}$.

4.1. Block Transmit Zero-Forcing Filter – TxZF

With an optimization similar to Eqn. (3), the TxZF for fixed latency time μ can be found to be

$$\boldsymbol{P}_{\mathrm{ZF}}(\mu) = \beta_{\mathrm{b,ZF}}(\mu)\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}\left(\boldsymbol{E}_\mu\boldsymbol{H}_{\mathrm{b}}\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}\right)^{-1}, \quad (9)$$

where $\beta_{\mathrm{b,ZF}}(\mu)$ is used to satisfy $\mathrm{E}[\|\boldsymbol{P}\boldsymbol{s}_{\mathrm{b}}\|_2^2] = E_{\mathrm{tr,b}}$ and we introduced $\boldsymbol{E}_\mu = \boldsymbol{S}_{(\mu,N,Q)}$. The optimum latency time is

$$\mu_{\mathrm{ZF}} = \arg\min_{\mu} \operatorname{tr}\left(\left(\boldsymbol{E}_\mu\boldsymbol{H}_{\mathrm{b}}\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}\right)^{-1}\right). \quad (10)$$

The necessary search is very complex ($O(QN^3)$), because for every value of $\mu = 0,\ldots,Q$, we have to compute the inverse of the $N \times N$ matrix $\boldsymbol{E}_\mu\boldsymbol{H}_{\mathrm{b}}\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}$.

4.2. Block Transmit Matched Filter – TxMF

The TxMF can be expressed as

$$\boldsymbol{P}_{\mathrm{MF}}(\mu) = \beta_{\mathrm{b,MF}}(\mu)\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}} \quad \text{with} \quad (11)$$
$$\mu_{\mathrm{MF}} = \arg\max_{\mu} \operatorname{tr}\left(\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}\boldsymbol{E}_\mu\boldsymbol{H}_{\mathrm{b}}\right), \quad (12)$$

where $\beta_{\mathrm{b,MF}}(\mu)$ is needed to set the transmit power to $E_{\mathrm{tr,b}}$.

4.3. Block Transmit Wiener Filter – TxWF

With $\boldsymbol{A}_{\mathrm{WF}}(\mu) = \boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}\boldsymbol{E}_\mu\boldsymbol{H}_{\mathrm{b}} + \xi_{\mathrm{b}}\mathbf{1}_{NN_s}$, where we introduced $\xi_{\mathrm{b}} = \operatorname{tr}(\boldsymbol{E}_\mu\boldsymbol{R}_\eta\boldsymbol{E}_\mu^{\mathrm{T}})/E_{\mathrm{tr,b}}$, the TxWF reads as

$$\boldsymbol{P}_{\mathrm{WF}}(\mu) = \beta_{\mathrm{b,WF}}(\mu)\boldsymbol{A}_{\mathrm{WF}}^{-1}(\mu)\boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}}\boldsymbol{E}_\mu^{\mathrm{T}}, \quad (13)$$

which can be obtained with an optimization like in Eqn. (7) and whose optimum latency time can be found with

$$\mu_{\mathrm{b,WF}} = \arg\max_{\mu} \operatorname{tr}\left(\boldsymbol{E}_\mu \boldsymbol{H}_{\mathrm{b}} \boldsymbol{A}_{\mathrm{WF}}^{-1}(\mu) \boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}} \boldsymbol{E}_\mu^{\mathrm{T}}\right). \qquad (14)$$

Similar to the TxZF, the complexity of above latency time optimization is $O(QN^3)$.

5. SUBOPTIMUM LATENCY TIME OPTIMIZATIONS FOR BLOCK TRANSMIT FILTERS

5.1. A Priori Fixed Latency Time

The simplest and most commonly used latency time "optimization" is to use an *a priori* fixed latency. Many authors set the latency to zero (e. g. [2, 4, 7]) and Kowalewski et al. chose a fixed latency time equal to the channel order in [6]. Note that this approach is very sensitive to the *power delay profile* (PDP) of the channel. Thus, the transmitter must know the actual PDP to decide the value of the fixed latency.

5.2. Maximum Amplitude Latency Time

Another heuristic approach is to set the latency time to the delay of the channel path with the largest amplitude [5]:

$$\mu_{\mathrm{b,max}} = \arg\max_{\mu} \|\boldsymbol{h}_\mu\|_2^2. \qquad (15)$$

Consequently, this approach tries to maximize the gain of the channel leading to a receive signal with large amplitude.

5.3. Trace Approximation Latency Time

When we replace the trace of the inverse (cf. Eqn. 10) by the reciprocal of the trace, we end up with the trace approximation latency time for the TxZF:

$$\mu_{\mathrm{ZF,trace}} = \arg\min_{\mu} \operatorname{tr}^{-1}\left(\boldsymbol{E}_\mu \boldsymbol{H}_{\mathrm{b}} \boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}} \boldsymbol{E}_\mu^{\mathrm{T}}\right), \qquad (16)$$

which is equal to the TxMF latency time optimization in Eqn. (12). Since $\operatorname{tr}(\boldsymbol{B}^{-1}) \geq N^2 \operatorname{tr}^{-1}(\boldsymbol{B})$ with a Hermitian $N \times N$ matrix $\boldsymbol{B}$, we minimize a lower bound, which does not assure that the original function is minimized.

The trace approximation approach to obtain the latency time for the block transmit Wiener filter reads as

$$\mu_{\mathrm{WF,trace}} = \arg\max_{\mu} \operatorname{tr}^{-1}\left(\boldsymbol{A}_{\mathrm{WF}}(\mu)\right) \operatorname{tr}\left(\boldsymbol{B}_{\mathrm{WF}}(\mu)\right), \qquad (17)$$

where we introduced $\boldsymbol{B}_{\mathrm{WF}}(\mu) = \boldsymbol{H}_{\mathrm{b}}^{\mathrm{H}} \boldsymbol{E}_\mu^{\mathrm{T}} \boldsymbol{E}_\mu \boldsymbol{H}_{\mathrm{b}}$. Hence, we maximize an upper bound instead of the original function, because $\operatorname{tr}((\boldsymbol{C}+\xi'\mathbf{1}_N)^{-1}\boldsymbol{C}) \leq N \operatorname{tr}^{-1}(\boldsymbol{C}+\xi'\mathbf{1}_N)\operatorname{tr}(\boldsymbol{C})$ with Hermitian $\boldsymbol{C} \in \mathbb{C}^{N\times N}$ and $\xi' \in \mathbb{R}_0^+$.

Both trace approximation latency time optimizations reduce the compexity to $O(QN^2)$, but are more complex than the other two suboptimum approaches.

6. SIMULATION RESULTS

For all simulations, we have used $N_{\mathrm{a}} = 2$ antennas, and white noise, i. e. $\boldsymbol{R}_\eta = \sigma_\eta^2 \mathbf{1}_{Q+N}$. We considered two PDPs: 1) exponential PDP with $\{\mathrm{E}[\|\boldsymbol{h}_0\|_2^2],...,\mathrm{E}[\|\boldsymbol{h}_5\|_2^2]\} = \{-3.1, -4.1, -12.1, -13.1, -18.1, -23.1\}$ dB; 2) uniform PDP with $\boldsymbol{h}_k = \mathbf{0}$ for one random $k \in \{0,...,4\}$ and $\mathrm{E}[\|\boldsymbol{h}_q\|_2^2] = 1/4, \forall q = 0,...,4, q \neq k$. We set the transmit power to $E_{\mathrm{tr}} = \sigma_s^2$ (FIR) or $E_{\mathrm{tr,b}} = N\sigma_s^2$ (block) and show the mean of 10000 realizations each with $N = 50$ QPSK symbols.

In Fig. 3, we compare the FIR transmit filters of order $L = Q = 5$ with two FIR receive filters of the same length. Obivously, the transmit filters lead to similar results as the receive filters. Moreover, the FIR TxZF and the FIR TxWF profit from latency time optimization, since the filters with fixed latency $\nu_{\mathrm{fix}} = 5$ are much worse.

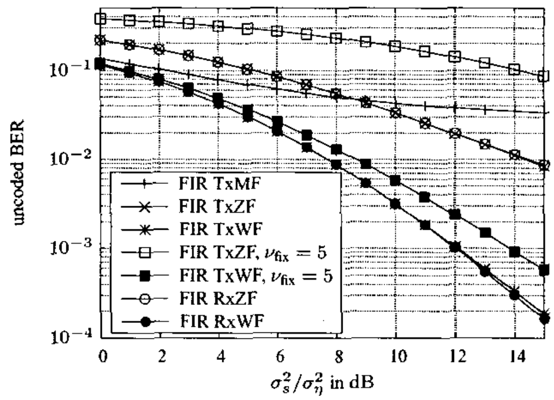

Figure 3: FIR Transmit Filters for Exponential PDP

We show the results for the block TxZFs in Fig. 4. Due to the exponential PDP, the TxZF with fixed latency $\mu_{\mathrm{fix}} = 1$ is as close to the optimum TxZF as the TxZF with latency time $\mu_{\mathrm{WF,trace}}$ of the trace approximation approach. Even the TxZF with latency μ_{max} equal to the delay of the strongest path outperforms the often used TxZF with $\mu_{\mathrm{fix}} = 0$. For $\mu_{\mathrm{fix}} > 1$, the performance deteriorates with increasing μ_{fix} due to the small power of the latter channel taps.

Since we get similar results for the block TxWFs (cf. Fig. 5) with exponential PDP, where especially the TxWF with μ_{max} is close to optimum, we also present the results for the TxWFs with uniform PDP in Fig. 6. The TxWFs with $\mu_{\mathrm{fix}} = 0$ and $\mu_{\mathrm{fix}} = 1$ lead to the same results as the TxWFs with $\mu_{\mathrm{fix}} = 4$ and $\mu_{\mathrm{fix}} = 3$, respectively, because of the symmetry of the PDP. However, the best fixed latency time for uniform PDP is $\mu_{\mathrm{fix}} = 2$ which is different from the optimum $\mu_{\mathrm{fix}} = 1$ for exponential PDP (cf. Fig. 5). Additionally, the TxWF with μ_{max} and $\mu_{\mathrm{WF,trace}}$ nearly reach the performance of the optimum TxWF.

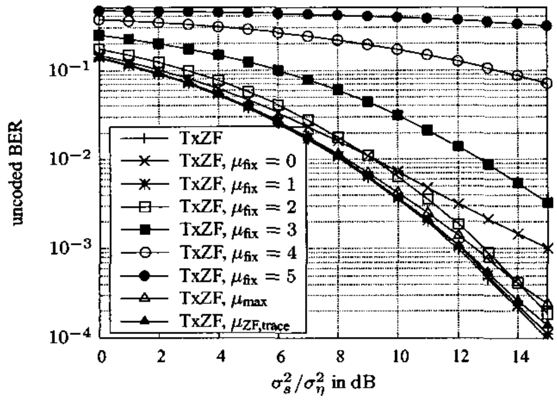

Figure 4: Block TxZFs for Exponential PDP

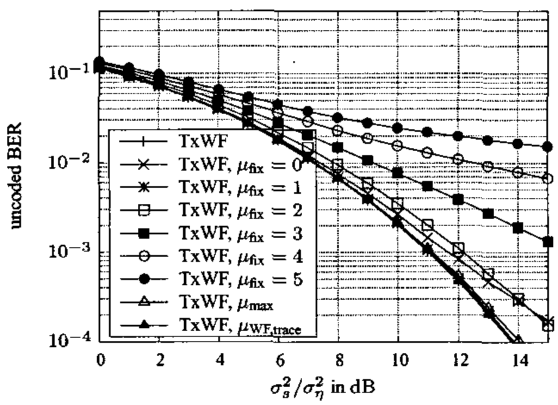

Figure 5: Block TxWFs for Exponential PDP

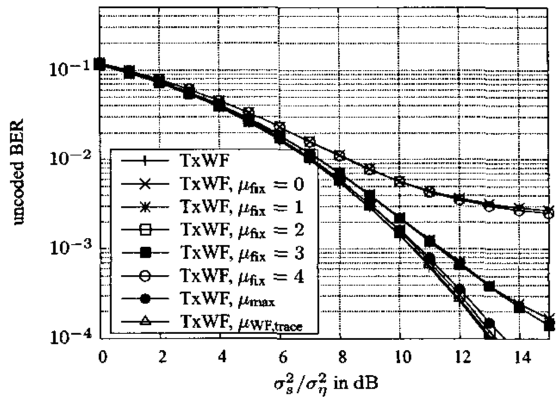

Figure 6: Block TxWFs for Uniform PDP

7. CONCLUSIONS

We have proposed to include latency time optimization in the design of FIR and block transmit filters. Simulations have shown that latency time optimization is crucial for FIR and block transmit filters. Moreover, the simulations justify to use the trace approximation latency time optimization and the latency time according to the path with the maximum amplitude, since both suboptimum approaches seem to be very robust against power delay profile changes.

8. REFERENCES

[1] R. Esmailzadeh and M. Nakagawa, "Pre-RAKE Diversity Combination for Direct Sequence Spread Spectrum Mobile Communications Systems," *IEICE Transactions on Communications*, vol. E76-B, no. 8, pp. 1008–1015, August 1993.

[2] B. R. Vojčić and W. M. Jang, "Transmitter Precoding in Synchronous Multiuser Communications," *IEEE Transactions on Communications*, vol. 46, no. 10, pp. 1346–1355, October 1998.

[3] G. Montalbano, I. Ghauri, and D. T. M. Slock, "Spatio-Temporal Array Processing for CDMA/SDMA Downlink Transmission," in *Proc. Asilomar Conference on Signals, Systems, and Computers*, November 1998, vol. 2, pp. 1337–1341.

[4] M. Meurer, P. W. Baier, Y. Lu, A. Papathanassiou, and T. Weber, "TD-CDMA Downlink: Optimum Transmit Signal Design Reduces Receiver Complexity and Enhances System Performance," in *Proc. ICT 2000*, May 2000, pp. 300–305.

[5] M. Joham and W. Utschick, "Downlink Processing for Mitigation of Intracell Interference in DS-CDMA Systems," in *Proc. ISSSTA 2000*, September 2000, vol. 1, pp. 15–19.

[6] F. Kowalewski and P. Mangold, "Joint Predistortion and Transmit Diversity," in *Proc. Globecom '00*, November 2000, vol. 1, pp. 245–249.

[7] A. Noll Barreto and G. Fettweis, "Capacity Increase in the Downlink of Spread Spectrum Systems through Joint Signal Precoding," in *Proc. ICC 2001*, June 2001, vol. 4, pp. 1142–1146.

[8] M. Joham, K. Kusume, M. H. Gzara, W. Utschick, and J. A. Nossek, "Transmit Wiener Filter for the Downlink of TDD DS-CDMA Systems," in *Proc. ISSSTA 2002*, September 2002, vol. 1, pp. 9–13.

[9] T. P. Krauss, M. D. Zoltowski, and G. Leus, "Simple MMSE Equalizers for CDMA Downlink to Restore Chip Sequence: Comparison to Zero-Forcing and RAKE," in *Proc. ICASSP 2000*, June 2000, vol. V, pp. 2865–2868.

[10] G. K. Kaleh, "Channel Equalization for Block Transmission Systems," *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 1, pp. 110–121, January 1995.