Channel Estimation and Tracking for MIMO-FBMC Systems

RA-CTI, CTTC

Outline

- Introduction
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  - *Intrinsic* interference in FBMC/OQAM
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- Channel Tracking
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  - LMS-based decision-directed tracking
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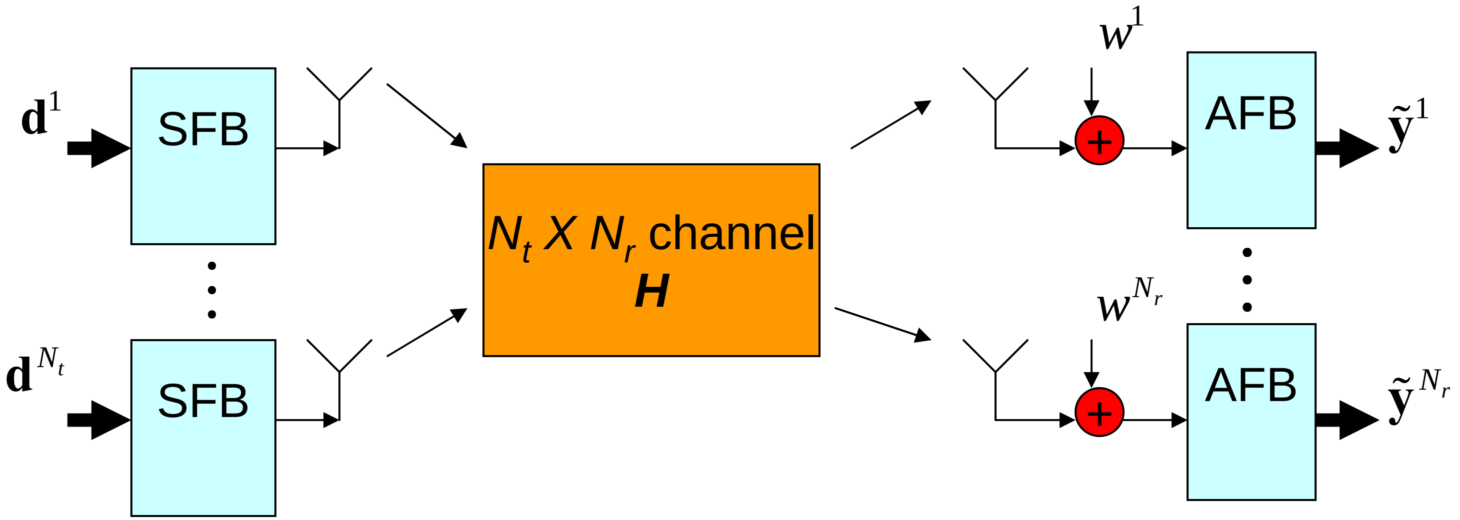
Introduction

MIMO-FBMC system (1)



Assumptions:

- Channel dispersion much less than pulse length
- Channel locally constant (in both time and frequency)

MIMO-FBMC system (2)

$$\underbrace{\begin{bmatrix} \tilde{y}_{k,n}^{1} \\ \tilde{y}_{k,n}^{2} \\ \vdots \\ \tilde{y}_{k,n}^{N_r} \end{bmatrix}}_{\tilde{\mathbf{y}}_{k,n}} = \underbrace{\begin{bmatrix} H_{k,n}^{1,1} & H_{k,n}^{2,1} & \cdots & H_{k,n}^{N_t,1} \\ H_{k,n}^{1,2} & H_{k,n}^{2,2} & \cdots & H_{k,n}^{N_t,2} \\ \vdots & \vdots & \ddots & \vdots \\ H_{k,n}^{1,N_r} & H_{k,n}^{2,N_r} & \cdots & H_{k,n}^{N_t,N_r} \end{bmatrix}}_{\mathbf{H}_{k,n}} \underbrace{\begin{bmatrix} \tilde{x}_{k,n}^{1} \\ \tilde{x}_{k,n}^{2} \\ \vdots \\ \tilde{x}_{k,n}^{N_t} \end{bmatrix}}_{\tilde{\mathbf{x}}_{k,n}} + \underbrace{\begin{bmatrix} \eta_{k,n}^{1} \\ \eta_{k,n}^{2} \\ \vdots \\ \eta_{k,n}^{N_r} \end{bmatrix}}_{\boldsymbol{\eta}_{k,n}} \rightarrow \tilde{\mathbf{y}}_{k,n} = \mathbf{H}_{k,n}\tilde{\mathbf{x}}_{k,n} + \boldsymbol{\eta}_{k,n}$$

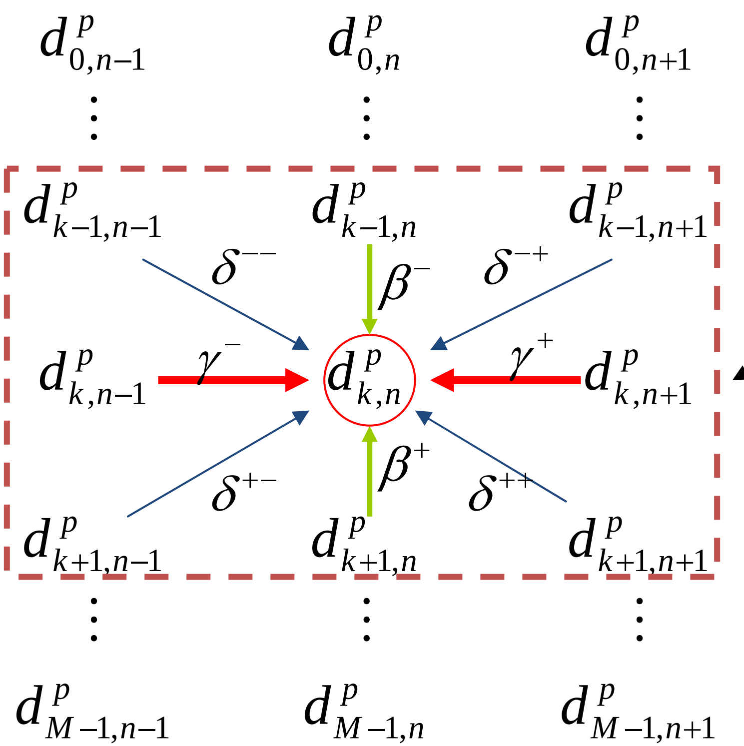
$H_{k,n}^{p,q}$: *M*-point frequency response at TF point (*k,n*) for antenna pair (*p,q*)

$$\tilde{x}_{k,n}^{p} = d_{k,n}^{p} + ju_{k,n}^{p}, \quad p = 1,2,\ldots,N_t$$

transmitted sequence of the *p*th antenna (data & pilots) (real)

intrinsic interference due to the neighboring time-frequency points

Intrinsic interference in FBMC



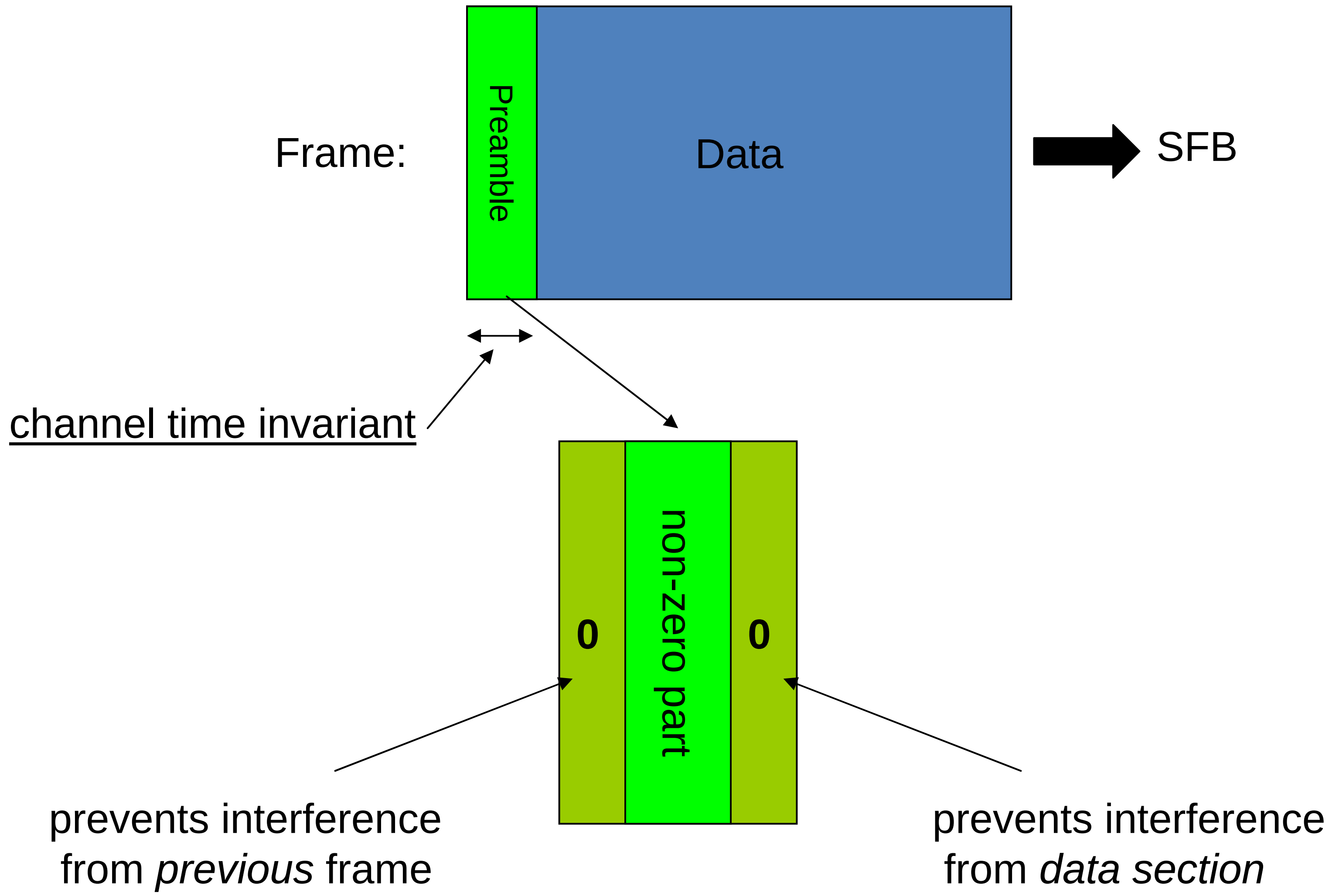
With good TF localization, contributions to intrinsic interference only come from the first-order neighboring TF points

$$t_{1,0} = \beta^-, t_{-1,0} = \beta^+,$$
$$t_{0,-1} = \gamma^-, t_{0,1} = \gamma^+,$$
$$t_{-1,-1} = \delta^{--}, t_{1,-1} = \delta^{+-},$$
$$t_{-1,1} = \delta^{-+}, t_{1,1} = \delta^{++}$$

$$\boxed{\left|\gamma^-\right| = \left|\gamma^-\right| > \left|\beta^-\right| = \left|\beta^-\right| > \left|\delta^{--}\right| = \left|\delta^{+-}\right| = \left|\delta^{-+}\right| = \left|\delta^{++}\right|}$$

Channel Estimation

Preamble-based estimation

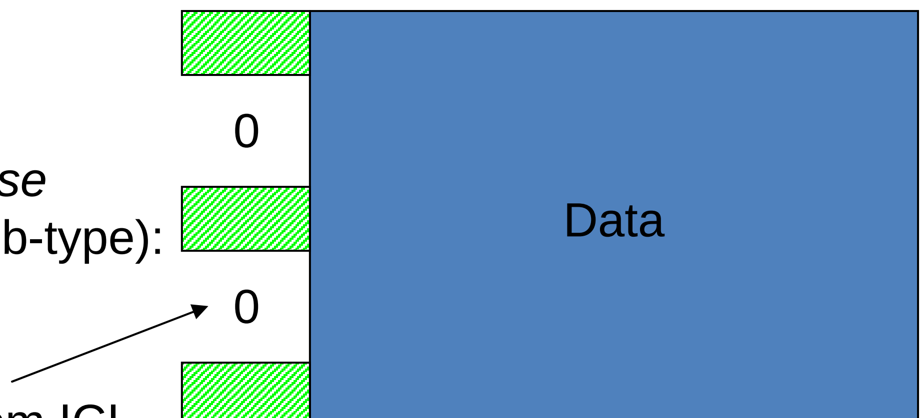


Full and *Sparse* Preambles

Full
(block-type):

<u>Methods:</u>
IAM-R,
IAM-I,
aIAM-I

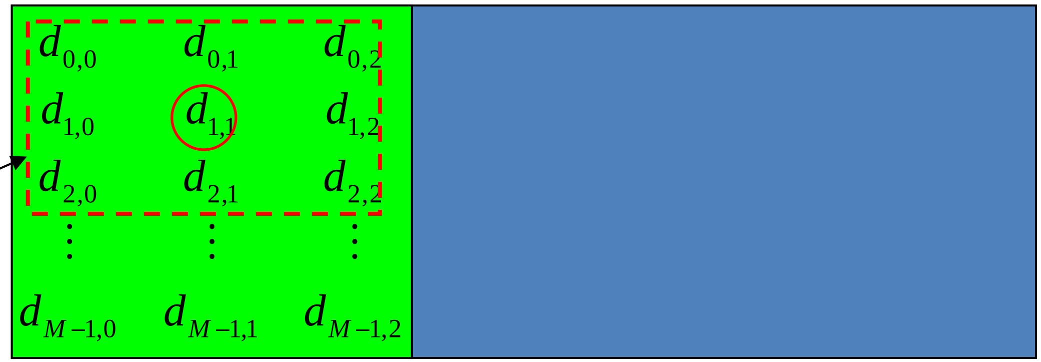
Sparse
(comb-type):



protect from ICI

<u>Methods:</u>
One carrier set,
L_h frequencies,
FDM pilots,
<u>Optimal</u> one-symbol
preamble

Interference Approximation Method (IAM)



constant
frequency response

- Approximate $u_{k,1}$ at the receiver; possible if input at times 0, 2 are also known (training).

- Null 0th and 2nd symbols and choose middle symbol so as to *maximize pseudo-pilots*: $\hat{\tilde{x}}_{k,1} = d_{k,1} + j\hat{u}_{k,1}$

- Compute channel estimate: $\hat{H}_{k,1} = \tilde{y}_{k,1} \big/ \hat{\tilde{x}}_{k,1}$

MIMO IAM-R

Antenna 1

$$\underbrace{\begin{matrix} 0 & 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 \end{matrix}}_{2N_t+1}$$

Signs are carefully chosen so as to maximize pseudo-pilots' magnitude

orthogonal

Antenna 2

$$\underbrace{\begin{matrix} 0 & 1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & 0 \end{matrix}}_{2N_t+1}$$

- Consider times 1, 3:

$$\begin{bmatrix} \tilde{\mathbf{y}}_{k,1} & \tilde{\mathbf{y}}_{k,3} \end{bmatrix} = \mathbf{H}_{k,1} \begin{bmatrix} \tilde{x}_k & \tilde{x}_k \\ \tilde{x}_k & -\tilde{x}_k \end{bmatrix} + \begin{bmatrix} \boldsymbol{\eta}_{k,1} & \boldsymbol{\eta}_{k,3} \end{bmatrix} = \mathbf{H}_{k,1} \tilde{x}_k \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} + \begin{bmatrix} \boldsymbol{\eta}_{k,1} & \boldsymbol{\eta}_{k,3} \end{bmatrix}$$

- Estimate channel:

unitary

$$\hat{\mathbf{H}}_{k,1} = \begin{bmatrix} \tilde{\mathbf{y}}_{k,1} & \tilde{\mathbf{y}}_{k,3} \end{bmatrix} \frac{1}{\tilde{x}_k} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}^{-1} = \mathbf{H}_{k,1} + \begin{bmatrix} \boldsymbol{\eta}_{k,1} & \boldsymbol{\eta}_{k,3} \end{bmatrix} \frac{1}{2\tilde{x}_k} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

pseudo-pilot

MIMO IAM-I

Antenna 1

$$\begin{matrix} 0 & 1 & 0 & 1 & 0 \\ 0 & -j & 0 & -j & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & j & 0 & j & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & -j & 0 & -j & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & j & 0 & j & 0 \end{matrix}$$

Antenna 2

$$\begin{matrix} 0 & 1 & 0 & -1 & 0 \\ 0 & -j & 0 & j & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & j & 0 & -j & 0 \\ 0 & 1 & 0 & -1 & 0 \\ 0 & -j & 0 & j & 0 \\ 0 & -1 & 0 & 1 & 0 \\ 0 & j & 0 & -j & 0 \end{matrix}$$

- Idea: Use *imaginary* pilots to create *imaginary* (or *real*) pseudo-pilots (hence of larger magnitude):

$$\hat{\tilde{x}}_{k,n} = j\left(d_{k,n} + \hat{u}_{k,n}\right)$$

with $d_{k,n}u_{k,n} > 0$.

- *Not* an OQAM input!

Averaged IAM-I (aIAM-I)

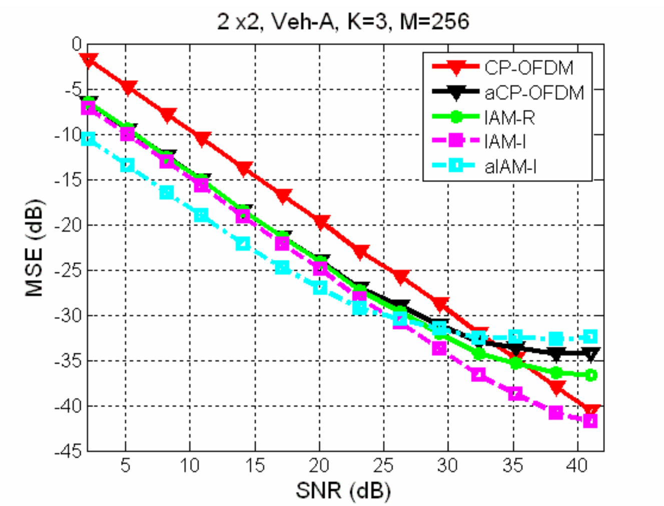
- Idea: Use IAM-I and average the resulting estimates over a small neighborhood. E.g.:

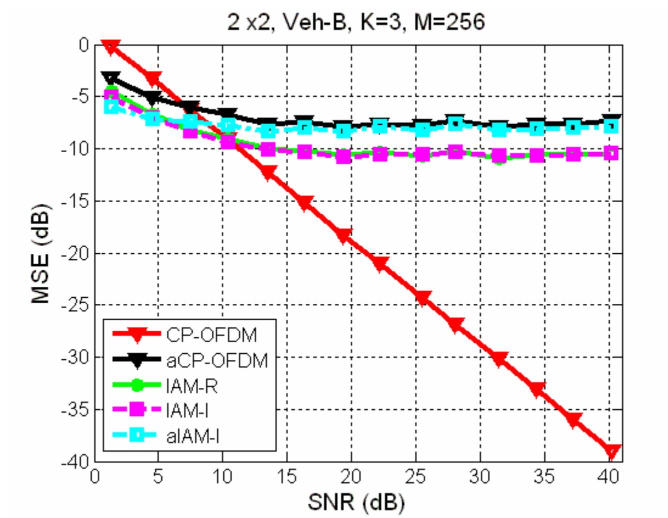
$$\underline{\hat{\mathbf{H}}}_{k,n} = \frac{\hat{\mathbf{H}}_{k-1,n} + \hat{\mathbf{H}}_{k,n} + \hat{\mathbf{H}}_{k+1,n}}{3}$$

- Analogous method for CP-OFDM → *aCP-OFDM*

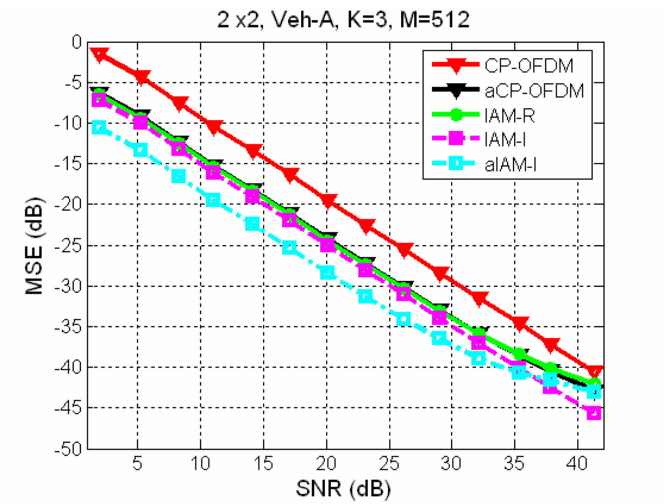
Simulation results (1)

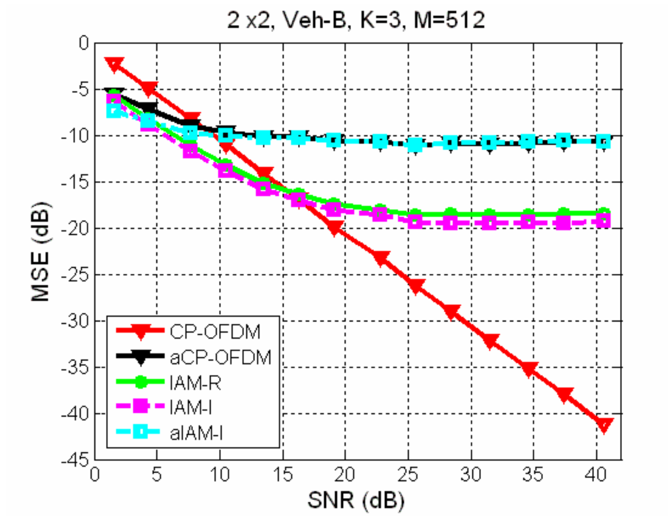
- <u>Simulation with the *same* transmit power</u>





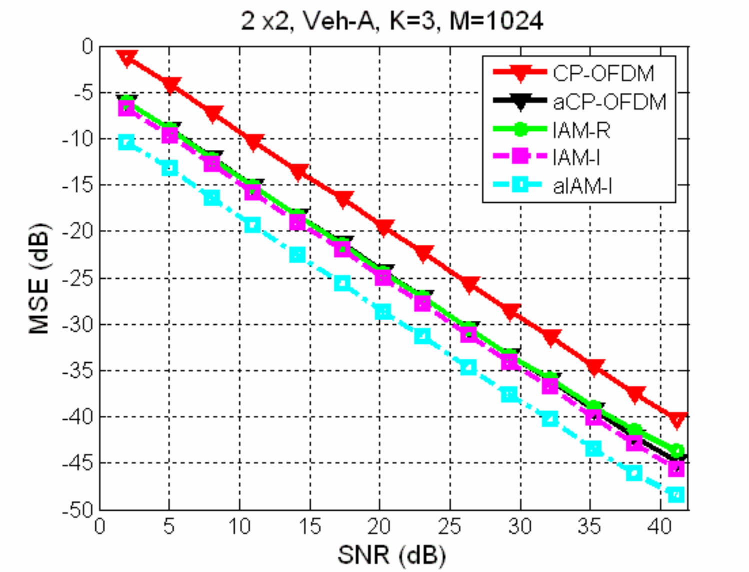
M = 256

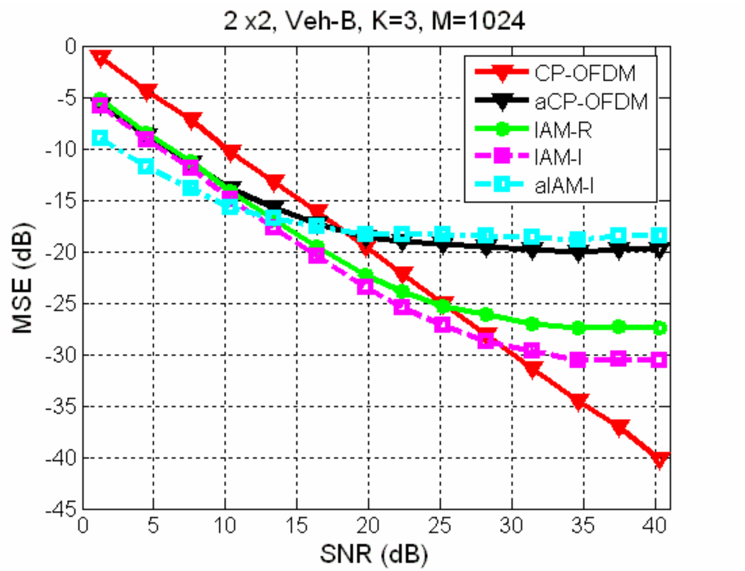




M = 512

Simulation results (2)





$M = 1024$

Simulation results (3)

- IAM-based schemes perform significantly better than CP-OFDM at low and medium SNR values.
- Error floor at high SNR's due to the intrinsic interference
- Relative performance improves with more subcarriers
- aIAM-I exhibits a significant performance gain at practical SNR values in low frequency selectivity channels. When the assumption of locally flat frequency response is no longer valid, its performance deteriorates.

Sparse preambles (1)

- One active carrier set: activate only every 3rd subcarrier ((linearly) interpolate to estimate at the rest of the frequencies)
- Use L_h pilots (equispaced & equipowered (Why?)) with DFT interpolation
- *One* nonzero symbol per antenna, with pilots frequency-division multiplexed (FDM) among the antennas

Sparse preambles (2)

- *MSE-optimal* (for LS) *one-symbol* preamble
- N_t sets of L_h equispaced and equal pilots each per antenna ($M \gg L_h N_t$)
- Associated N_txN_t matrix: unitary

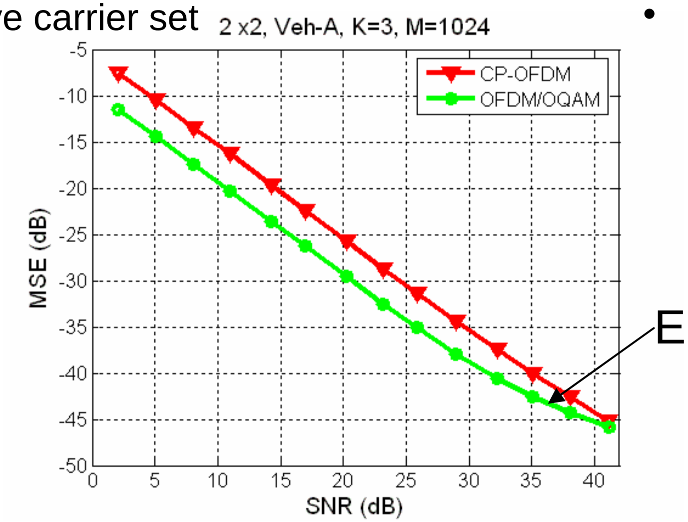
$L_h = 2, N_t = 2$

Antenna 1	Antenna 2
$\begin{matrix} 0 & x & 0 \\ 0 & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & 0 \end{matrix}$	$\begin{matrix} 0 & z & 0 \\ 0 & 0 & 0 \\ 0 & w & 0 \\ 0 & 0 & 0 \\ 0 & z & 0 \\ 0 & 0 & 0 \\ 0 & w & 0 \\ 0 & 0 & 0 \end{matrix}$

$$\begin{bmatrix} x & z \\ y & w \end{bmatrix}$$ unitary

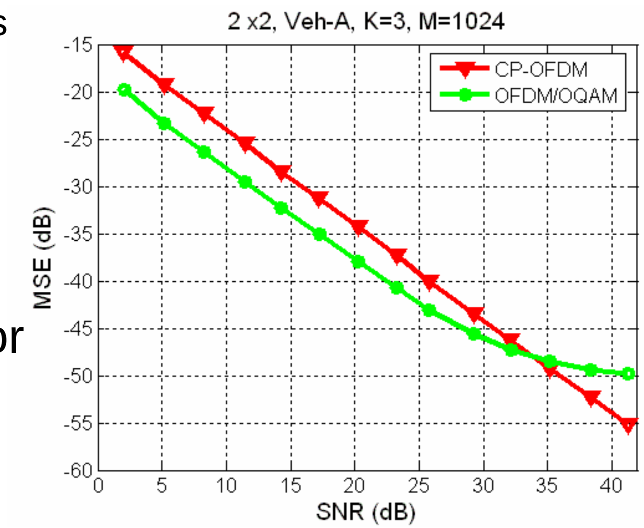
Simulation results

- One active carrier set

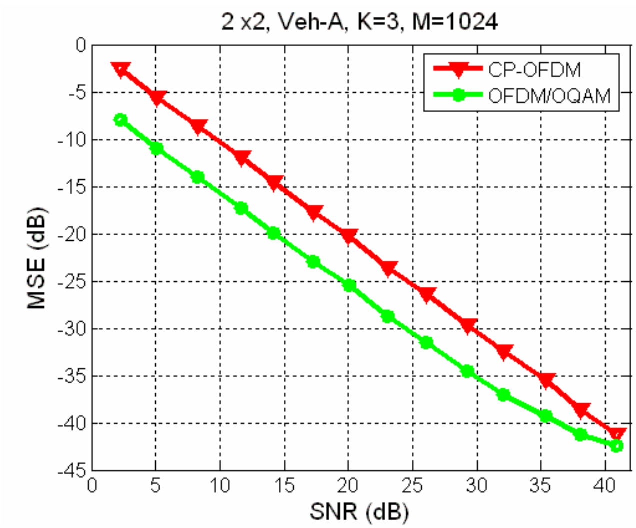


Error floor

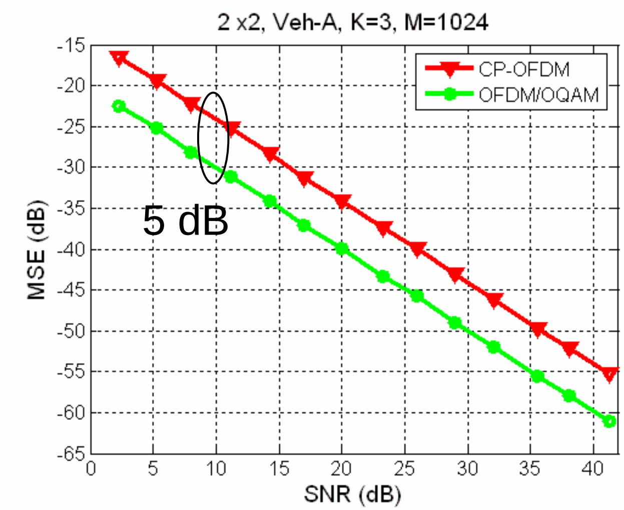
- L_h Pilots



- FDM Pilots



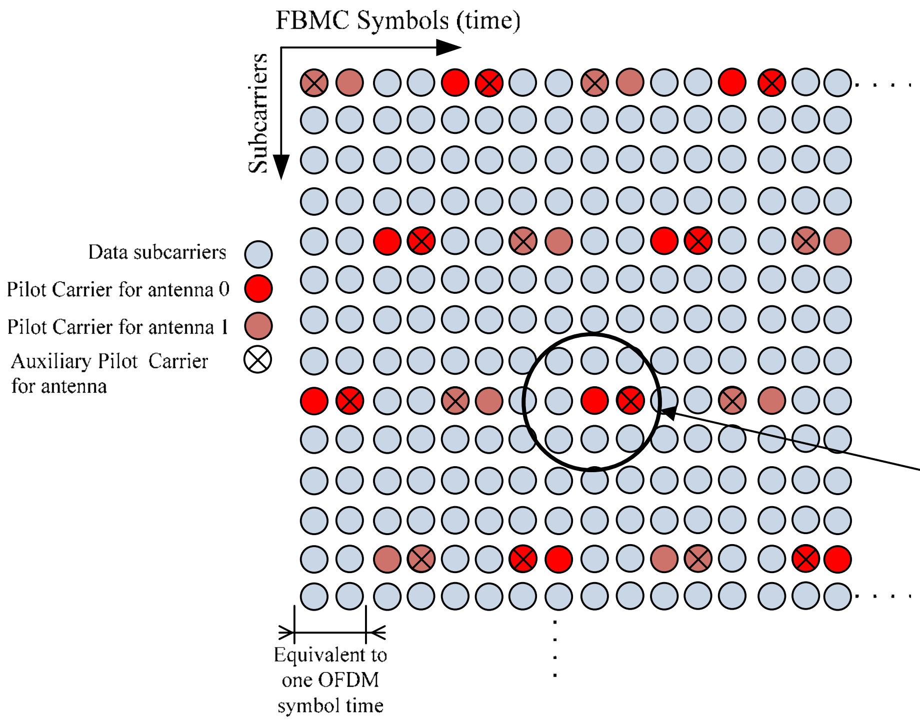
- <u>Optimal</u> One-Symbol



FBMC adaptation to WiMAX DL-PUSC

Auxiliary pilot scheme (1)

The auxiliary pilot (AP) is chosen in such a way that the secondary part (intrinsic interference) of the pilot sample becomes zero:

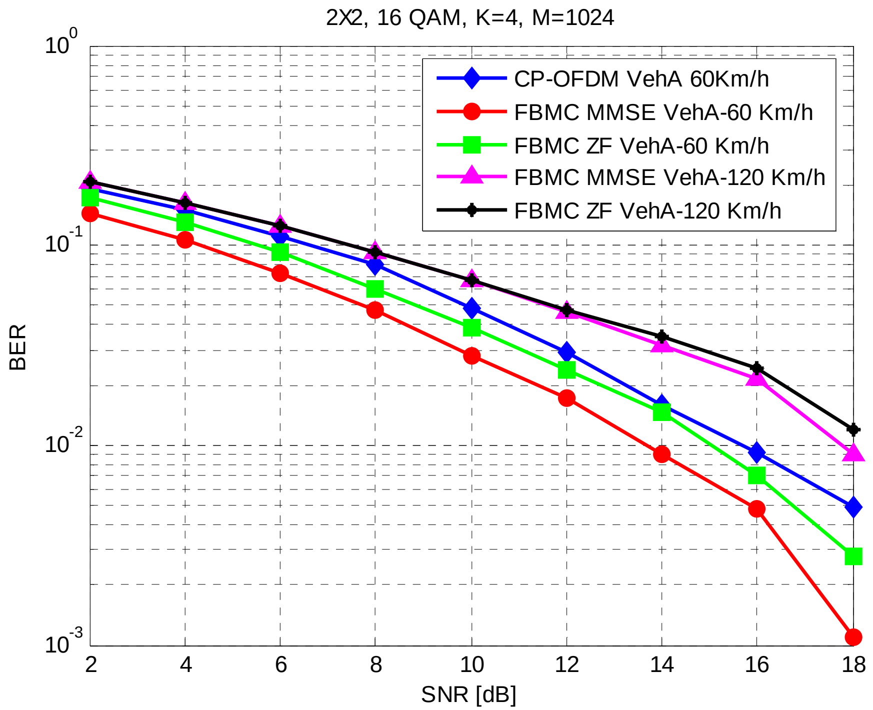


$$d^{p}_{k_a,n_a} = -\frac{\displaystyle\sum_{\substack{(k',n')\in\Omega_{k,n} \\ (k',n')\neq(k_a,n_a)}} d^{p}_{k',n'} t_{k-k',n-n'}}{t_{k-k_a,n-n_a}}$$

Place auxiliary pilots
at the *same* subcarrier
(to minimize the AP magnitude)

FBMC adaptation to WiMAX DL-PUSC

Auxiliary pilot scheme (2)



FBMC 2×2 for Veh-A channel

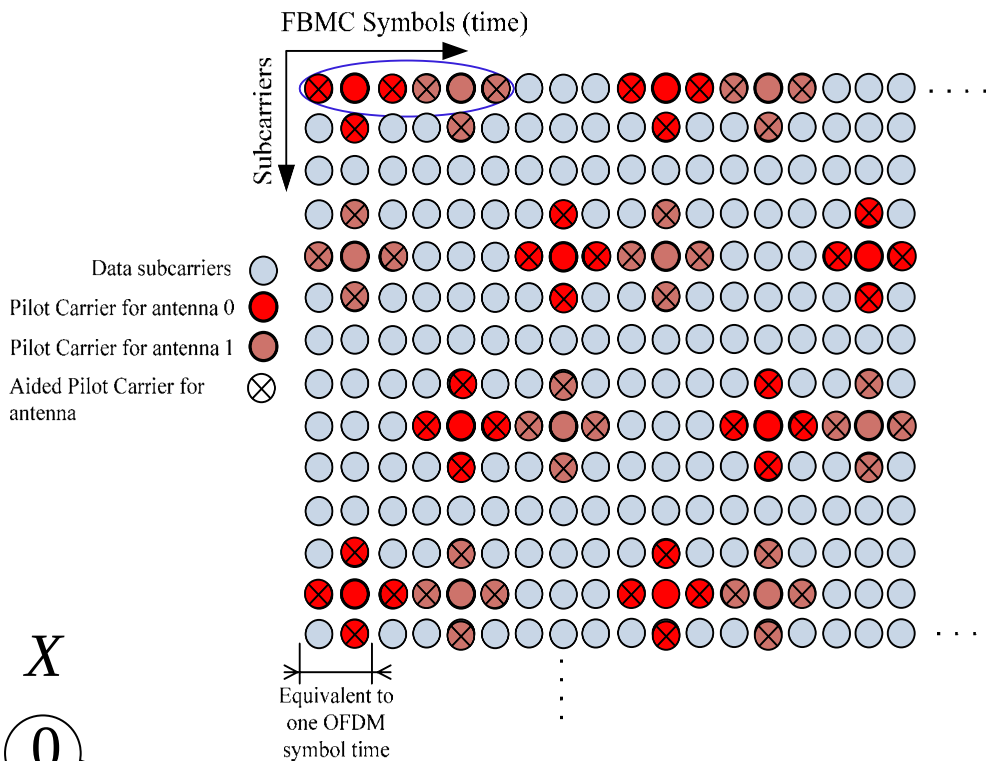
Interference Approximation Method (IAM) (1)

0	1	0
0	1	0
.	-1	.
.	-1	.
.	1	.
.	.	.
.	.	.
.	.	.
.	-1	.
0	-1	0

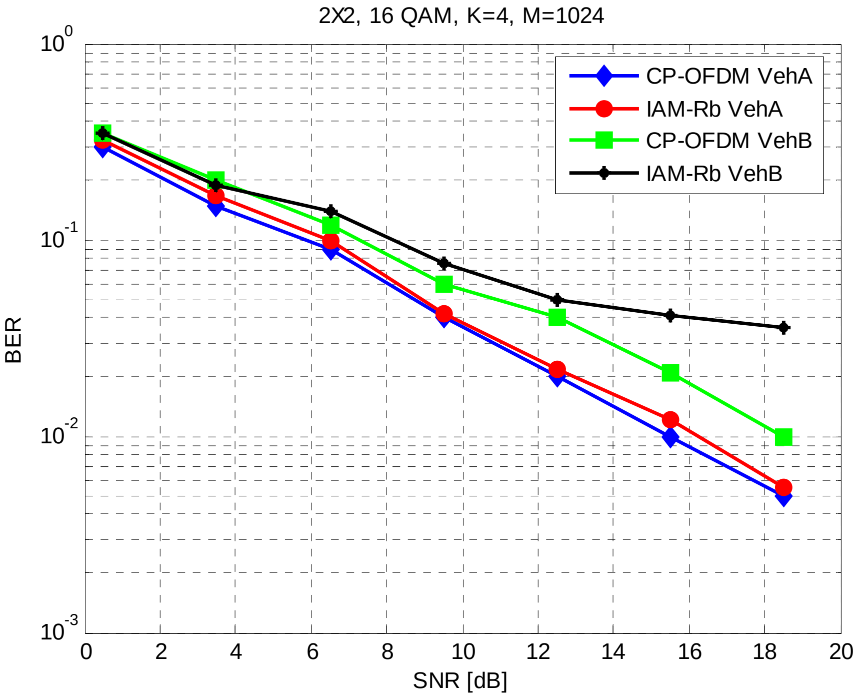
signs alternation

$$\begin{matrix} X & d^{p}_{k-1,n} & X \\ 0 & d^{p}_{k,n} & 0 \\ X & d^{p}_{k+1,n} & X \end{matrix}$$

Cancel strongest interference



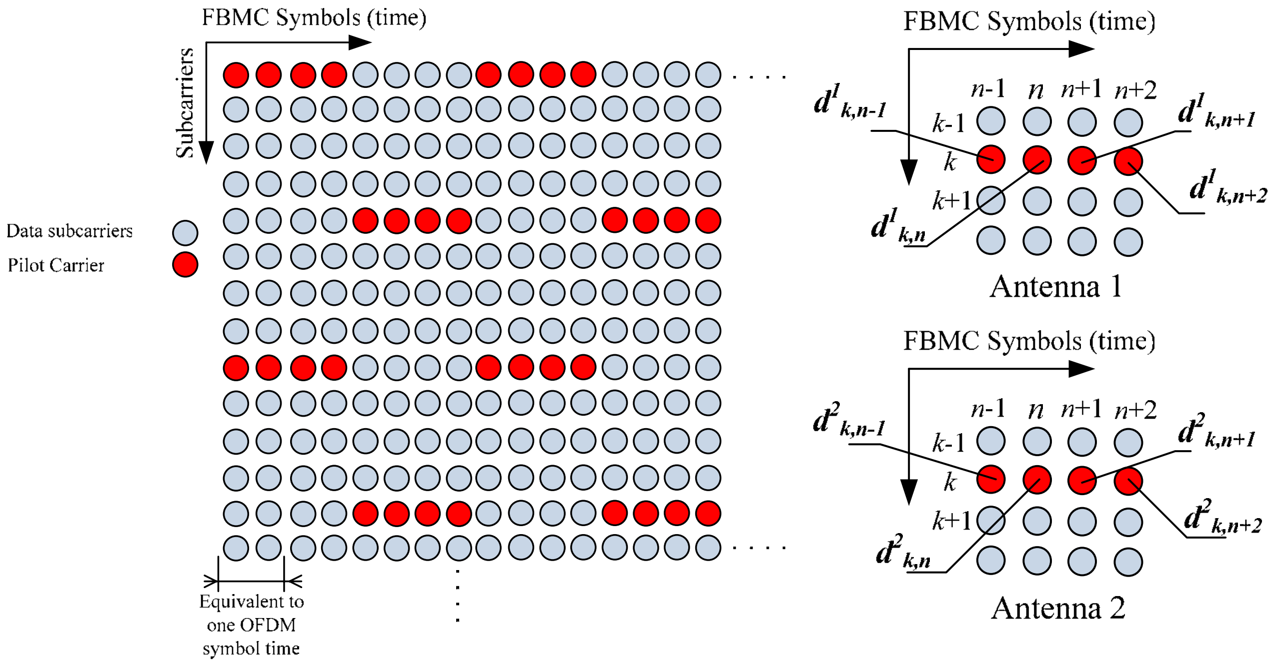
Interference Approximation Method (IAM) (2)



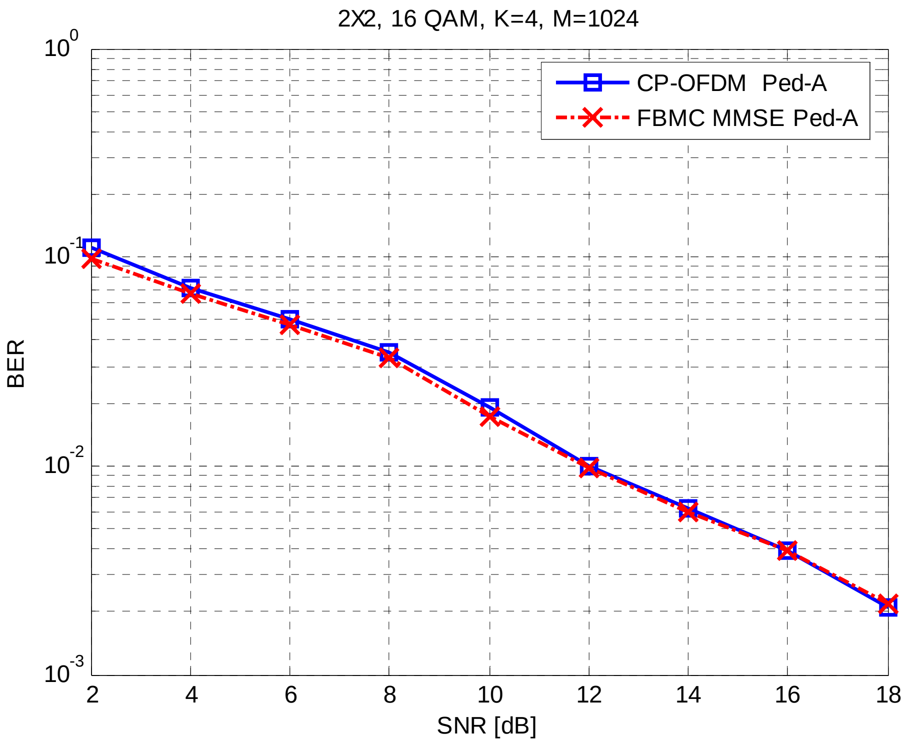
FBMC 2×2 at 60 km/h using ZF equalization.

Scattered pilots (1)

- First, the $d^{p}_{k,n-1}$ symbols are determined to cancel the interference to the position (k,n).
- Then the $d^{p}_{k,n+2}$ symbols are determined to cancel the interference to the position $(k,n+1)$.
- Pilot pairs *orthogonal* among antennas → compute channel by solving a 2x2 system of equations



Scattered pilots (2)



Simplified orthogonal pilot sequence in FBMC MIMO system with 2 transmit antennas

SDM case over Ped-A channel with non iterative MMSE receiver

Channel Tracking

Channel tracking

- User mobility and typical channel coherence times (e.g., coherence time of 2 ms (100 km/h) vs. frame duration of 5 ms in WiMAX)
- Channel remains invariant in the duration of (at least) an FBMC symbol.
- Based on a channel variation model:
  - Kalman filtering (with measurement and state-noise covariances)
  - Frame-by-frame (coarse scale) or symbol-by-symbol (fine scale) tracking (*allocated training pilots*)
  - Complexity issue → for limited mobility
- No channel variation model assumed
  - Decision-directed (*no* pilots) LMS for symbol-by-symbol tracking
  - Low complexity

Kalman filtering (1)

- State equation (AR(1) model):

$$\mathbf{H}[\zeta] = a\mathbf{H}[\zeta - 1] + \mathbf{v}[\zeta]$$

- Measurement equation:

$$\mathbf{y}[\zeta] = \mathbf{D}[\zeta]\mathbf{H}[\zeta] + \mathbf{w}[\zeta]$$

- Process noise covariance: $\mathbf{Q}[\zeta]$

- Measurement noise covariance: $\mathbf{R}[\zeta]$

Kalman filtering (2)

$$\hat{\mathbf{H}}\left[\zeta+1|\zeta\right]=a\hat{\mathbf{H}}\left[\zeta|\zeta\right]$$

$$\mathbf{P}\left[\zeta+1|\zeta\right]=|a|^{2}\,\mathbf{P}\left[\zeta|\zeta\right]+\mathbf{Q}[\zeta]$$

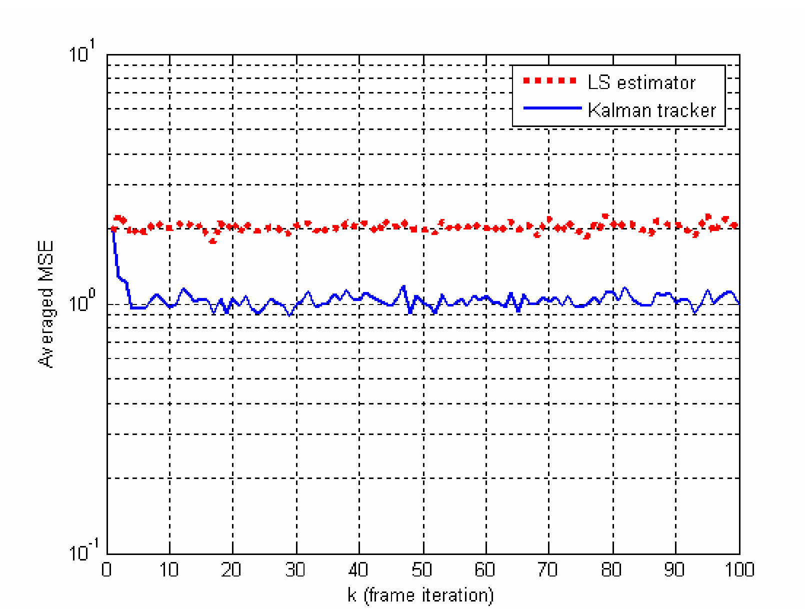
$$\mathbf{K}[\zeta+1]=a\mathbf{P}\left[\zeta+1|\zeta\right]\mathbf{D}[\zeta+1]^{H}\left(\mathbf{D}[\zeta+1]\mathbf{P}\left[\zeta+1|\zeta\right]\mathbf{D}[\zeta+1]^{H}+\mathbf{R}[\zeta+1]\right)^{-1}$$

$$\mathbf{P}\left[\zeta+1|\zeta+1\right]=\left(\mathbf{I}-a\mathbf{K}[\zeta+1]\mathbf{D}[\zeta+1]\right)\mathbf{P}\left[\zeta+1|\zeta\right]$$

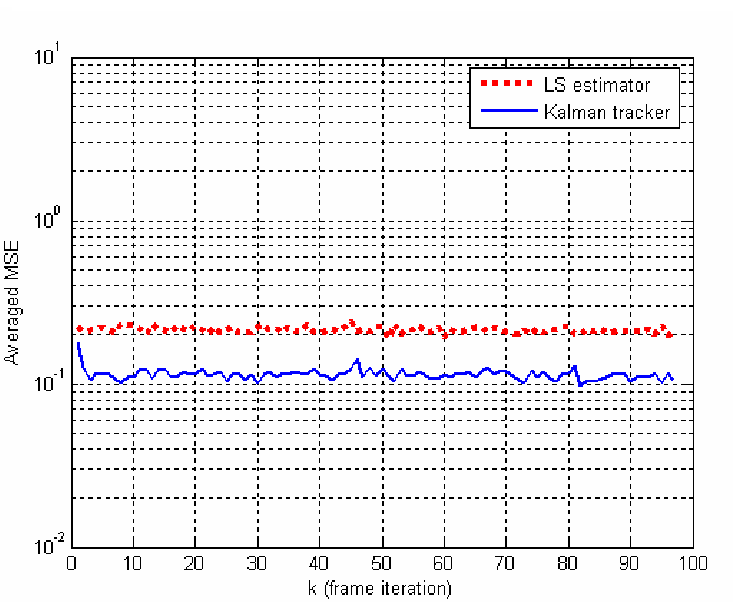
$$\mathbf{e}[\zeta+1]=\mathbf{y}[\zeta+1]-\mathbf{D}[\zeta+1]\hat{\mathbf{H}}\left[\zeta+1|\zeta\right]$$

$$\hat{\mathbf{H}}\left[\zeta+1|\zeta+1\right]=\hat{\mathbf{H}}\left[\zeta+1|\zeta\right]+\mathbf{K}[\zeta+1]\mathbf{e}[\zeta+1]$$

Kalman filtering (3)



SNR = 0 dB



SNR = 10 dB

- MISO system
- frame-by-frame tracking
- 3 dB gain in MSE over no tracking

LMS-based decision-directed tracking (1)

$$\mathbf{h}_n^q = \left[\left(\mathbf{h}_n^{1,q}\right)^T \quad \left(\mathbf{h}_n^{2,q}\right)^T \quad \cdots \quad \left(\mathbf{h}_n^{N_t,q}\right)^T \right]^T$$

$$\mathbf{h}_n = \left[\left(\mathbf{h}_n^{1}\right)^T \quad \left(\mathbf{h}_n^{2}\right)^T \quad \cdots \quad \left(\mathbf{h}_n^{N_r}\right)^T \right]^T$$

$$\mathbf{D}_n^p = \mathrm{diag}\left(x_{k_0,n}^p, x_{k_1,n}^p, \ldots, x_{k_{P-1},n}^p \right)$$

$$\mathbf{T}_n = \left[\mathbf{D}_n^1 \mathbf{F}_{P\times L_h} \quad \mathbf{D}_n^2 \mathbf{F}_{P\times L_h} \quad \cdots \quad \mathbf{D}_n^{N_t} \mathbf{F}_{P\times L_h} \right]$$

$$\mathbf{y}_n = \left[\left(\mathbf{y}_n^{1}\right)^T \quad \left(\mathbf{y}_n^{2}\right)^T \quad \cdots \quad \left(\mathbf{y}_n^{N_r}\right)^T \right]^T$$

$$\boxed{\mathbf{y}_n = \underbrace{\left(\mathbf{I}_{M_R} \otimes \mathbf{T}_n\right)}_{\mathbf{S}_n} \mathbf{h}_n + \boldsymbol{\eta}_n = \mathbf{S}_n \mathbf{h}_n + \boldsymbol{\eta}_n}$$

LMS-based decision-directed tracking (2)

$$\hat{\mathbf{h}}_{n-1} \xrightarrow{\text{DFT}} \hat{\mathbf{H}}_{k,n-1}, \quad k \in \text{selected subcarriers}$$

$$\widehat{\mathbf{x}}_{k,n} = \hat{\mathbf{H}}^{+}_{k,n-1}\mathbf{y}_{k,n}$$ (or some other equalizer (MMSE, V-BLAST, etc.)

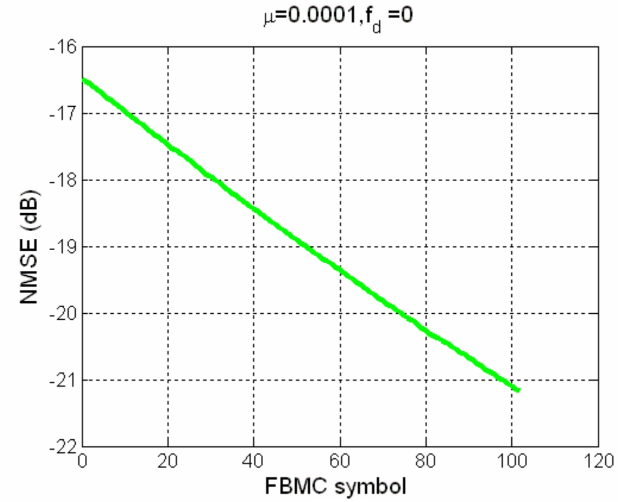
$$\hat{\mathbf{x}}_{k,n} = \hat{\mathbf{d}}_{k,n} + j\hat{\mathbf{u}}_{k,n} = \text{dec}\left[\text{Re}\left(\widehat{\mathbf{x}}_{k,n}\right)\right] + j\,\text{Im}\left(\widehat{\mathbf{x}}_{k,n}\right)$$

$$\hat{\mathbf{x}}_{k,n} \to \hat{\mathbf{D}}_{n} \to \hat{\mathbf{S}}_{n}$$

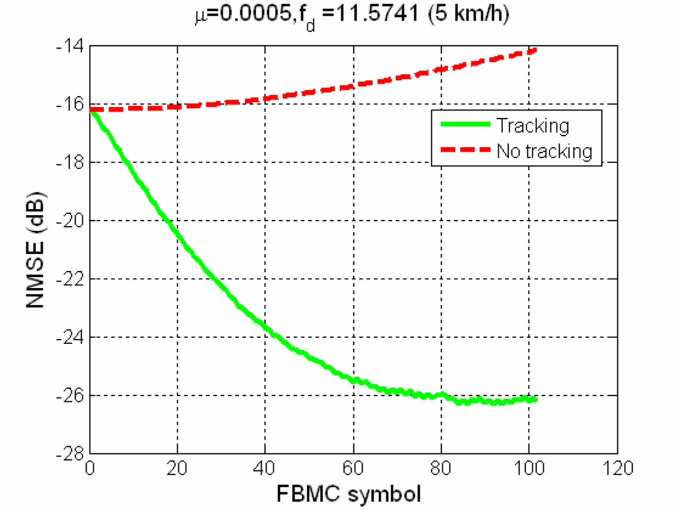
$$\mathbf{e}_{n} = \mathbf{y}_{n} - \hat{\mathbf{S}}_{n}\hat{\mathbf{h}}_{n-1}$$

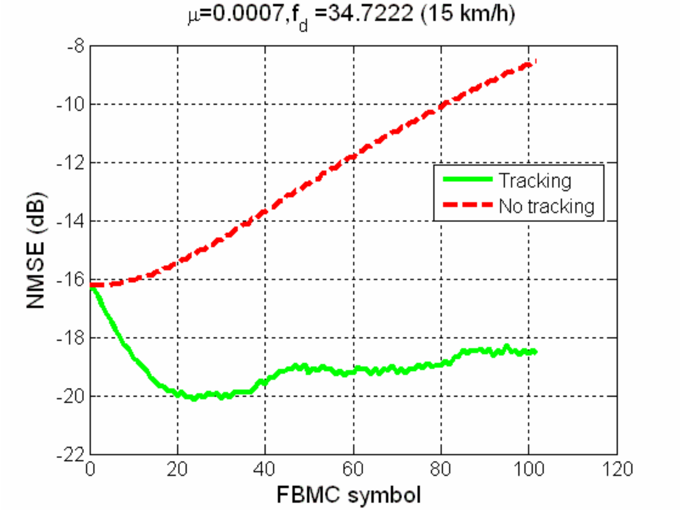
$$\hat{\mathbf{h}}_{n} = \hat{\mathbf{h}}_{n-1} + \mu\hat{\mathbf{S}}_{n}^{H}\mathbf{e}_{n}$$ μ: step size

LMS-based decision-directed tracking (3)



SNR = 20 dB,
M = 512, K = 4





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Future Work

- Refining tracking results (e.g., step size selection, include scattered pilots)

- Extension to multi-user MIMO-FBMC

- Adaptation of existing MIMO equalization techniques (e.g., V-BLAST, sphere decoding) to MIMO-FBMC

- Preamble design for *joint* channel and CFO estimation