Self-interference Handling in OFDM Based Wireless Communication Systems

Tevfik Yücek

yucek@eng.usf.edu

University of South Florida

Department of Electrical Engineering

Tampa, FL, USA

(813) 974 0759

Agenda

- Introduction
- System description
- Frequency selectivity and delay spread estimation
- ICI Handling
- Summary

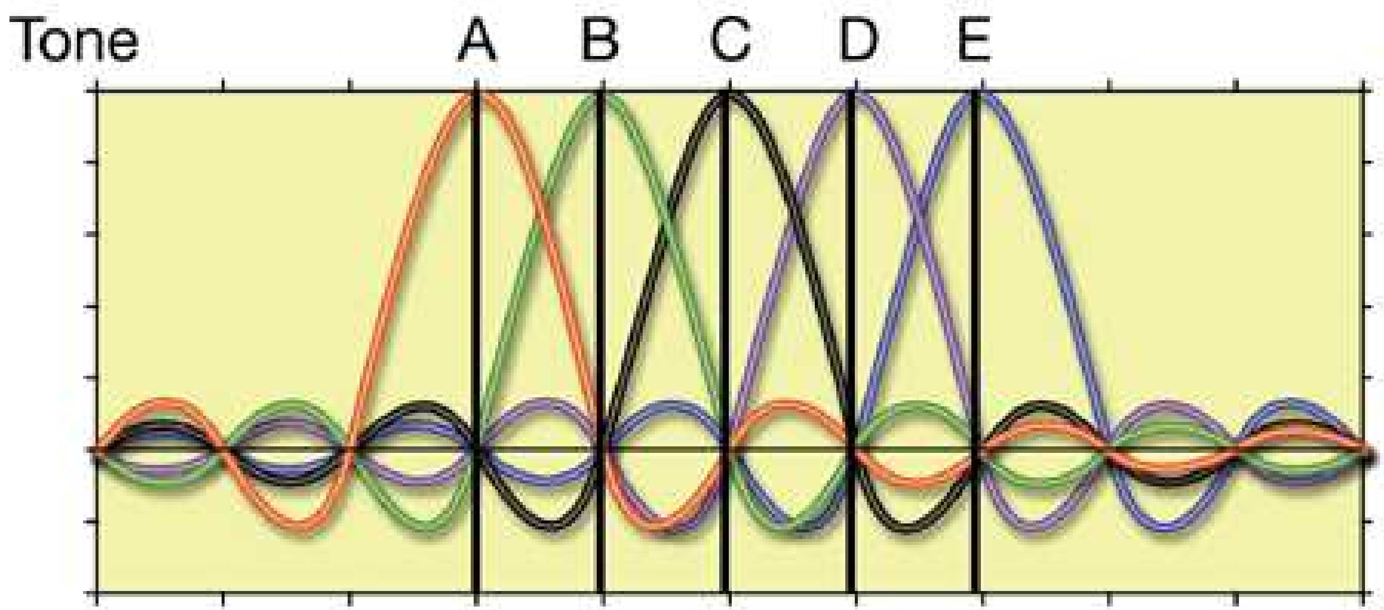
Application areas

- Military HF radio (1950's-1960's)
- ADSL
- DAB, DVB-T
- Wireless LAN: IEEE 802.11a/g, HyperLAN/2, HiSWANa
- **Strong** candidate for IEEE 802.15.3 and 4G cellular

Why OFDM ?

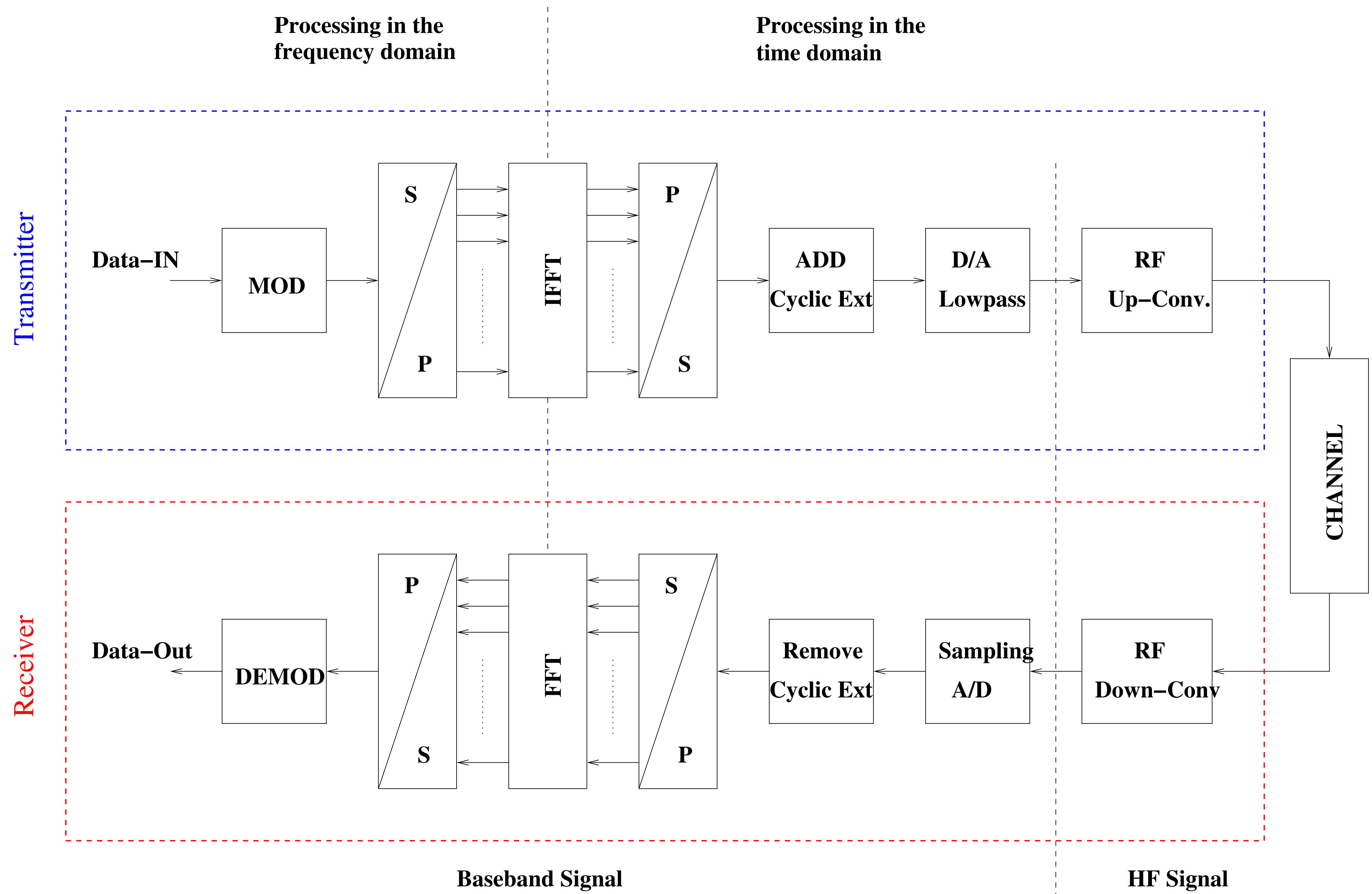
- Why OFDM ?
  - Resistant to multipath (especially important for high data rate transmission)
  - Offers a natural resistance to narrowband interference
- Problems
  - Transmitter and receiver (timing) synchronization
  - Frequency synchronization
  - Large peak-to-average power ratio

How it works?

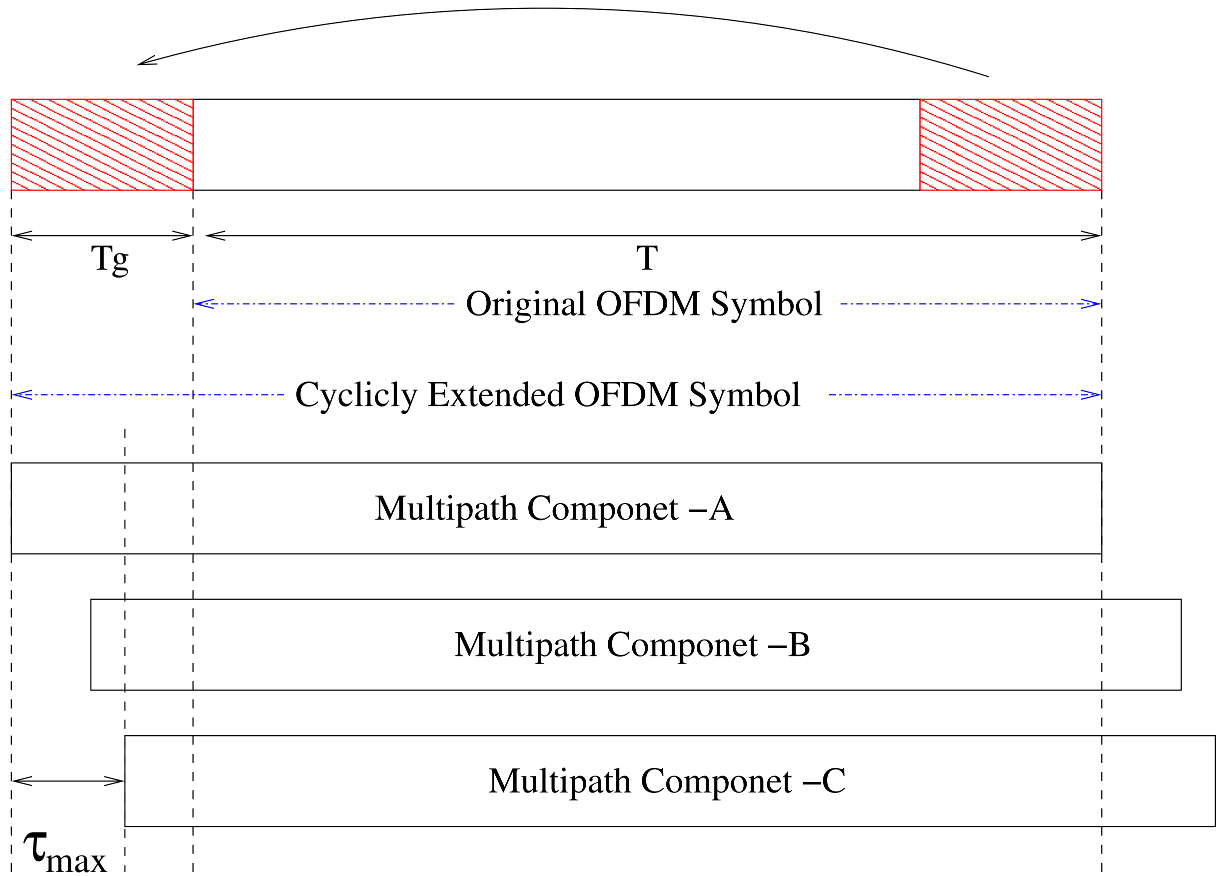


- Data is transmitted in parallel over different sub-carriers
- Each sub-carrier will observe flat fading
- More sensitive to frequency errors

OFDM system model



Cyclic prefix extension



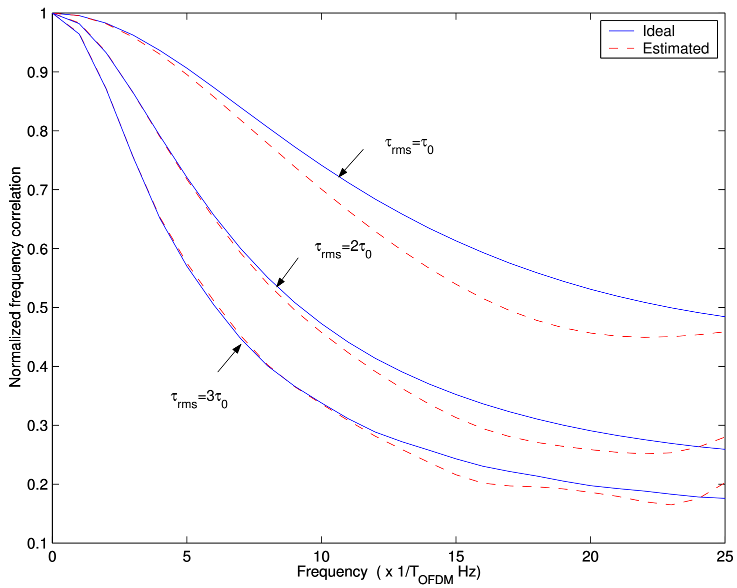
- More than one transmission path between transmitter and receiver
- Received signal is the sum of many versions of the transmitted signal with varying delay and attenuation
- A copy of the last part of the OFDM symbol of length equal to or greater than the maximum delay spread of the channel.

Agenda

- Introduction
- System description
- Frequency selectivity and delay spread estimation
  - Averaged parameter estimation
  - Instantaneous parameter estimation
- ICI Handling
- Summary

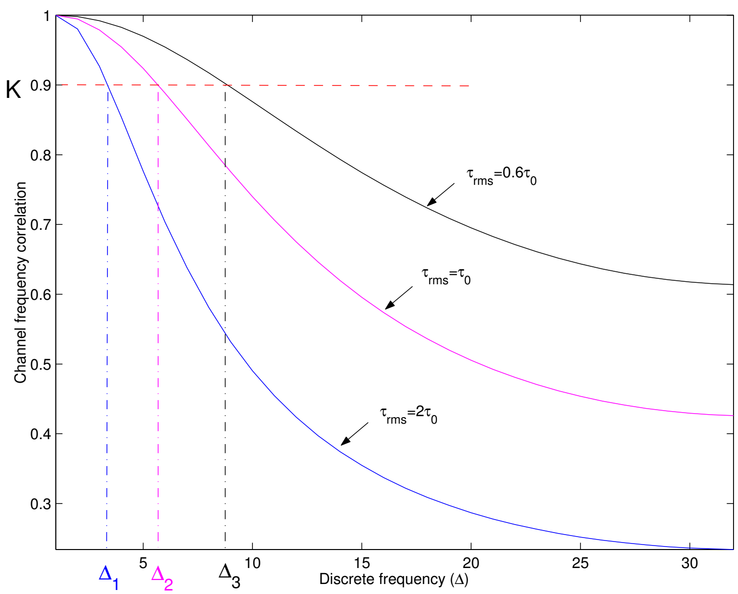
Motivation & Prior work

- Applications
  - Adaptation of the length of the cyclic prefix
  - Adaptation of subcarrier bandwidth
  - Adaptation of bandwidth of the channel estimation filters
- Prior work
  - Using CIR
    - Time domain channel estimation is required
    - Taking IDFT of channel frequency response
  - Using CFR
    - Frequency Domain Level Crossing Rate (LCR)



- In coherent OFDM systems often channel frequency response is available
- CFC estimate is obtained using channel frequency response estimates
- The correlation values obtained over each OFDM symbol
- These estimates averaged over many OFDM symbols
- Note that CFC is Fourier transform of PDP
- PDP can be obtained by IDFT, then related parameters can be calculated from PDP (but, computationally complex)
- Direct relation between time-domain channel parameters and CFC is desired

Delay spread estimation

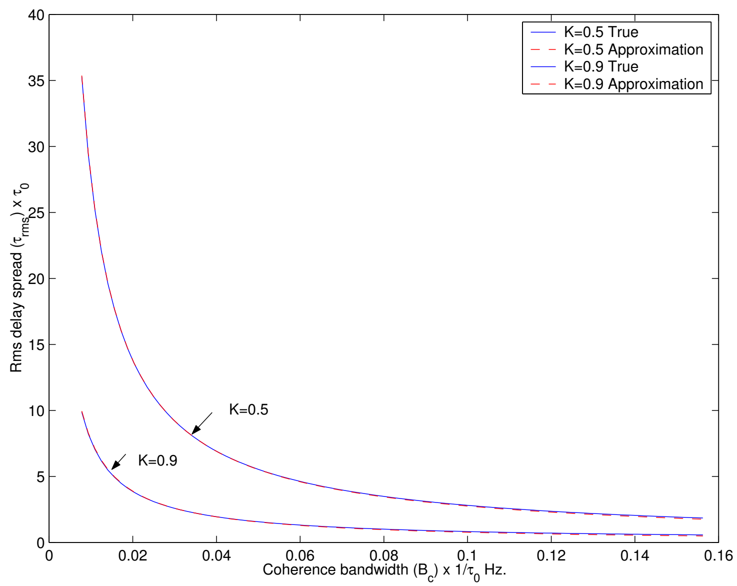


- Coherence bandwidth: Range of frequencies over which two frequency components have correlation above K.
- Coherence bandwidth is obtained by using CFC (see figure)
- Exact relation between coherence bandwidth and RMS delay spread is derived for exponential power delay profile
- RMS delay spread is calculated using this relation
- Algorithm is tested for other power delay profiles as well

Delay spread estimation

For given K and the corresponding Δ value, RMS delay spread is derived as

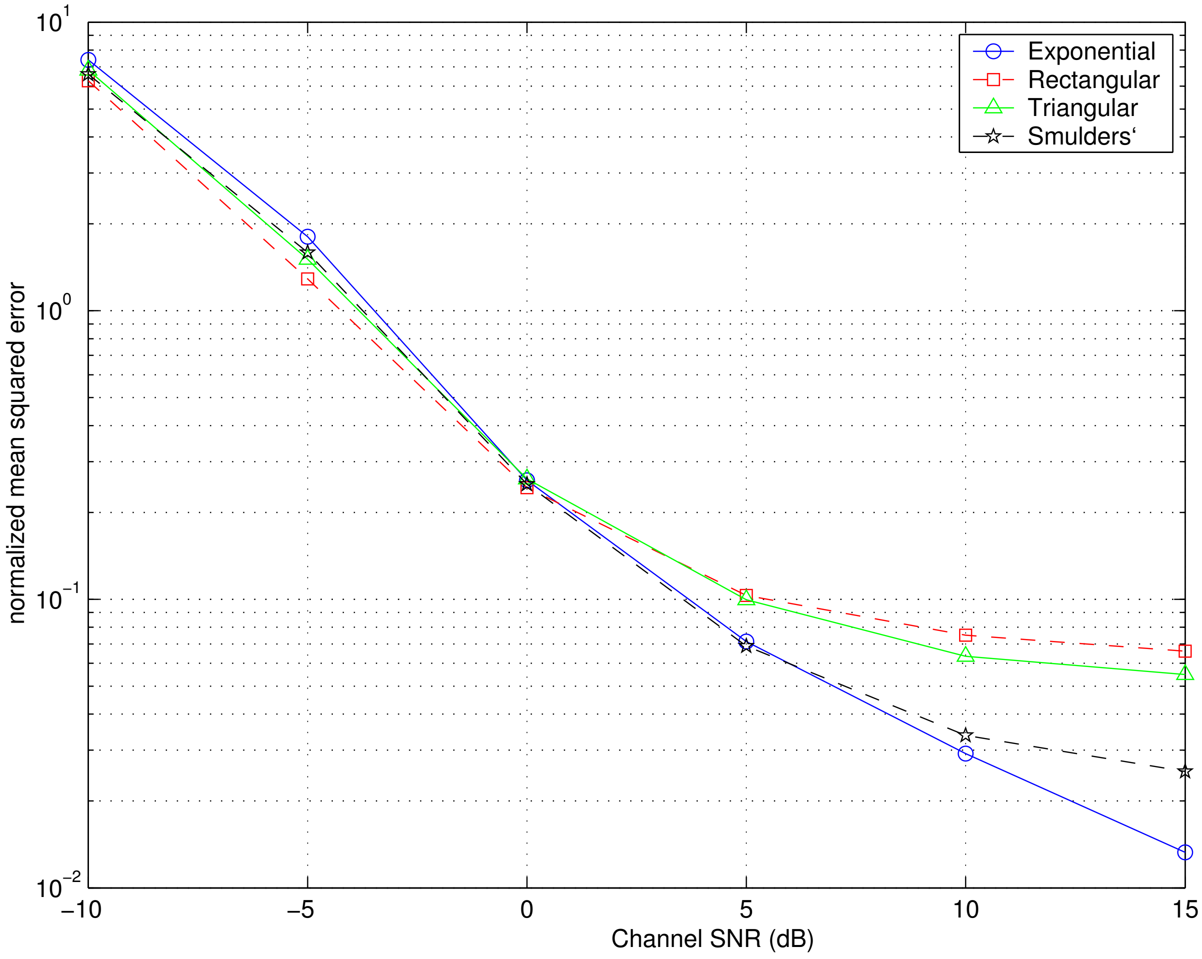
$$\tau_{RMS} = \frac{\tau_0}{\ln \frac{2-2K^2\cos\frac{2\pi\Delta}{N} + \sqrt{(2K^2\cos\frac{2\pi\Delta}{N}-2)^2 - 4(1-K^2)^2}}{2(1-K^2)}}$$

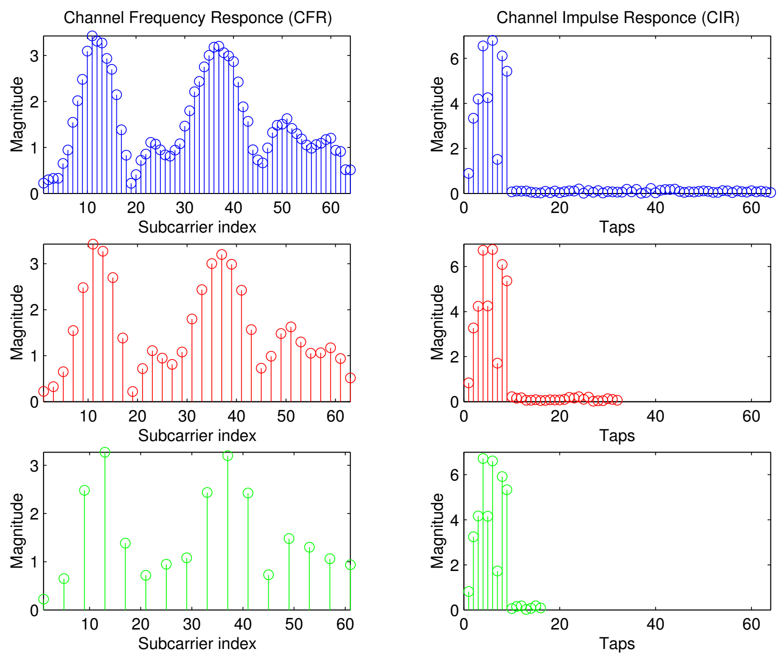


- An approximation to above found in the form $\tau_{RMS} \approx \frac{C}{\Delta}\tau_0$, and gives accurate and less complex results.
- A bound relationship between B_c and τ_{RMS} is given by Fleury (96) as

$$B_c \geq \frac{\cos^{-1} K}{2\pi\tau_{RMS}}$$

Simulation results





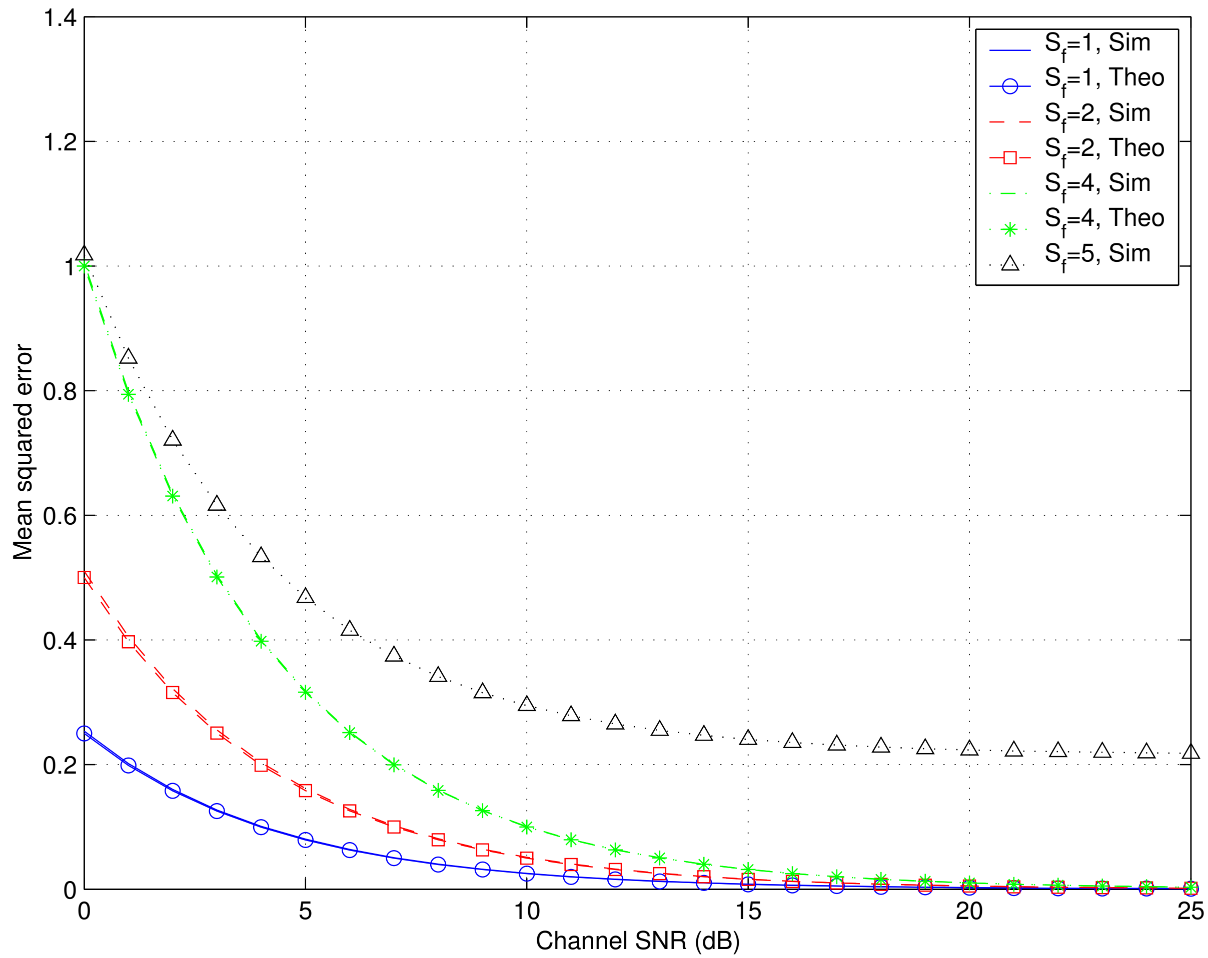
- Useful for estimating for short term parameters

- CIR estimate is used for this purpose
- CIR obtained from CFR
- CFR can be sampled to reduce computational complexity
- Nyquist rate for sampling

$$\tau_{max} \Delta f S_f \leq 1$$

τ_{max} : maximum excess delay
Δf : subcarrier spacing
S_f : sampling interval

Results

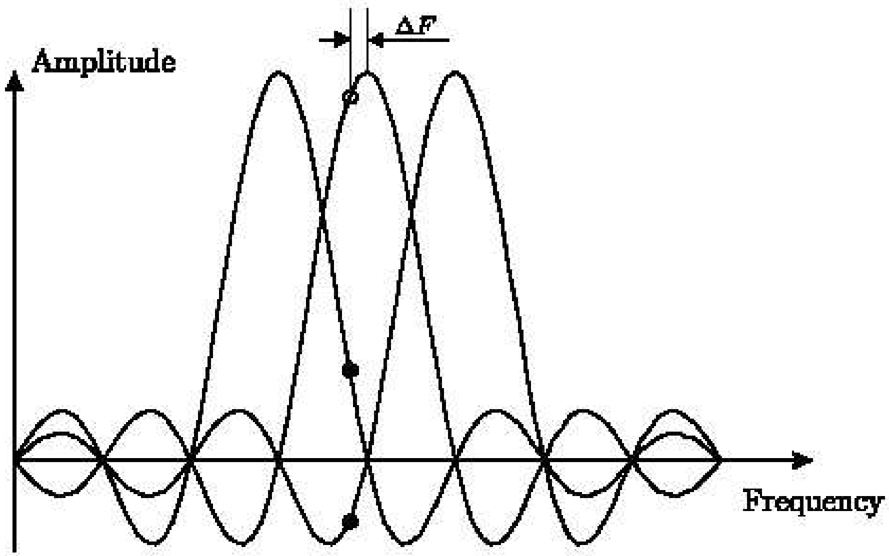


- Mean squared error is increasing as sampling frequency is decreasing. However, computational complexity is reducing.

Agenda

- Introduction
- System description
- Frequency selectivity and delay spread estimation
- ICI Handling
  - ICI Cancellation
  - ICI Cancellation based channel estimation
- Summary

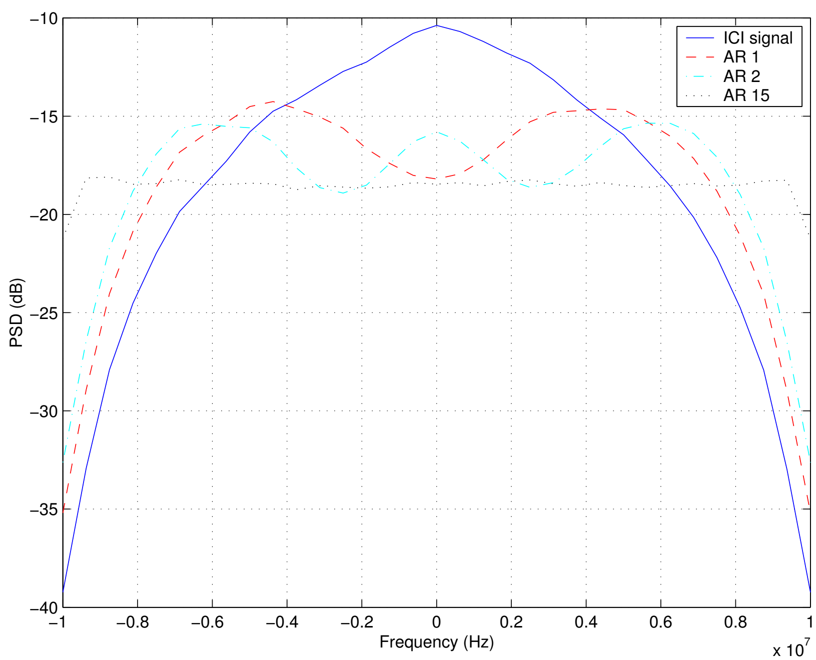
Motivation



- Loss of orthogonality among subcarriers causes inter-carrier interference (ICI).
  - Frequency offset, Doppler shift, or phase noise.
- ICI affects both channel estimation and detection.
- Previous channel estimation algorithms treat ICI as part of the additive noise.

ICI cancellation using AR modeling

- ICI is colored in nature
- ICI is whitened by fitting an AR process and filtering



- $Received = Desired + ICI + Noise$
- Desired signal is estimated
- $ICI + Noise$ is modeled as AR process and whitened

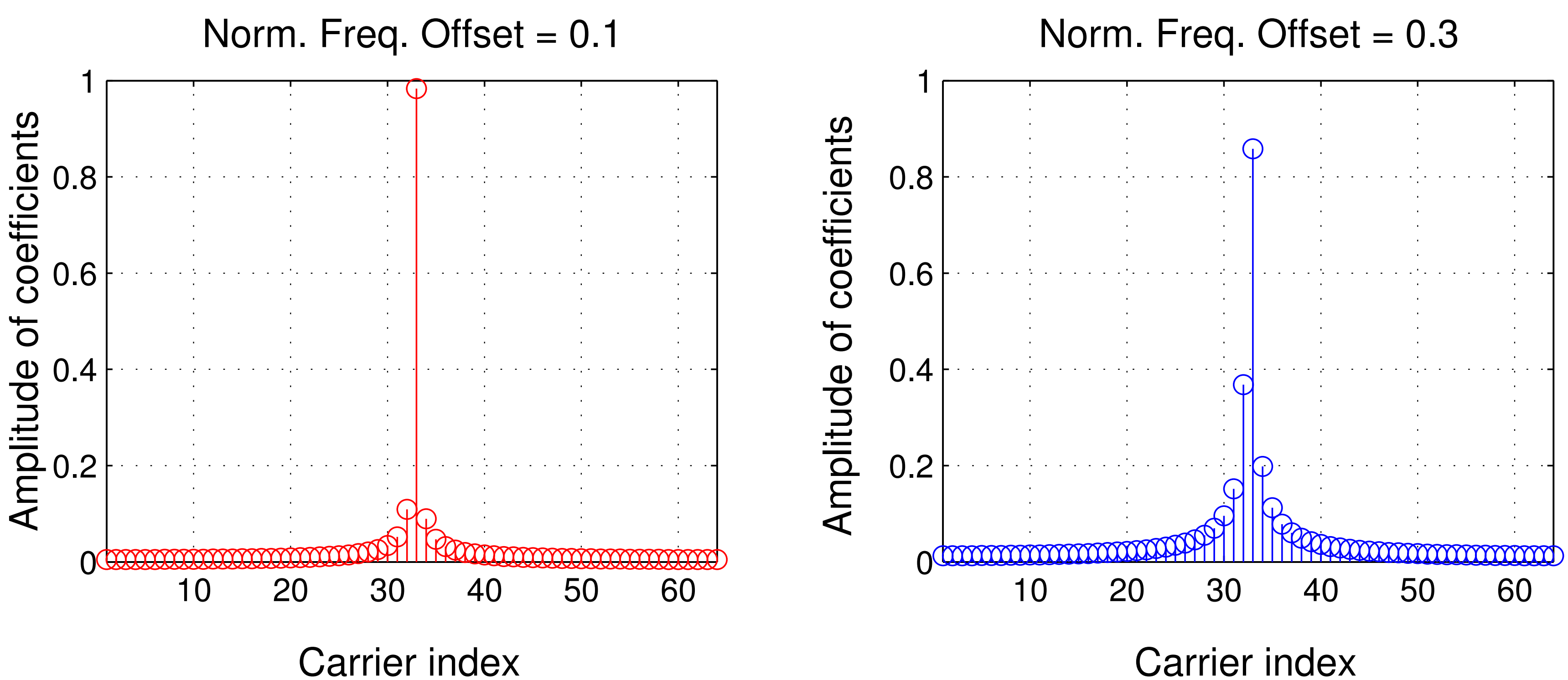
Prior work

- Channel estimation
  - Least-squares (LS)
  - Minimum mean-square error (MMSE)
  - Maximum-Likelihood (ML)
- Channel estimation & ICI
  - Linear minimum mean-square error (LMMSE)
  - Time domain filtering to suppress ICI

Basic idea

$$\mathbf{y} = \mathbf{S}_{\epsilon_p}\mathbf{X}\mathbf{h} + \mathbf{n}$$

$$\begin{aligned}(\mathbf{S}_{\epsilon_h}\mathbf{X})^{-1}\mathbf{y} &= (\mathbf{S}_{\epsilon_h}\mathbf{X})^{-1}\mathbf{S}_{\epsilon_p}\mathbf{X}\mathbf{h} + (\mathbf{S}_{\epsilon_h}\mathbf{X})^{-1}\mathbf{n} \\ \mathbf{h}_{\epsilon_h} &= \mathbf{X}^{-1}\underbrace{\mathbf{S}_{\epsilon_h}{}^{-1}\mathbf{S}_{\epsilon_p}}_{\mathbf{S}_{\epsilon_p-\epsilon_h}=\mathbf{S}_{\epsilon_r}}\mathbf{X}\mathbf{h} + \mathbf{n}_{\epsilon_h}\end{aligned}$$



Basic idea

- Properties of $\mathbf{S}_{\epsilon_p}$
  - $\mathbf{S}^H\mathbf{S} = \mathbf{I}$ (Unitary matrix). $\Rightarrow \mathbf{S}^{-1} = \mathbf{S}^H$.
  - $\mathbf{S}_{\epsilon_1}\mathbf{S}_{\epsilon_2} = \mathbf{S}_{\epsilon_1+\epsilon_2}$
  - $\mathbf{S}_{-\epsilon} = \mathbf{S}_{\epsilon}^H$
  - Circulant matrix (rows and columns)
- Selection method for best hypothesis
  - Channel frequency correlation decreases as frequency offset increases.

$$R_{\mathbf{h}_{\epsilon_h}}(\tau) = \begin{cases} R_h(0) + \frac{\sigma_n^2}{\sigma_s^2} & \tau = 0 \\ R_h(\tau)|\mathbf{S}_{\epsilon_r}(0)|^2 & \tau \neq 0 \end{cases}$$

$$|\mathbf{S}_{\epsilon_r}(0)| = \frac{\sin(\pi\epsilon_r)}{N\sin(\pi\epsilon_r/N)}$$

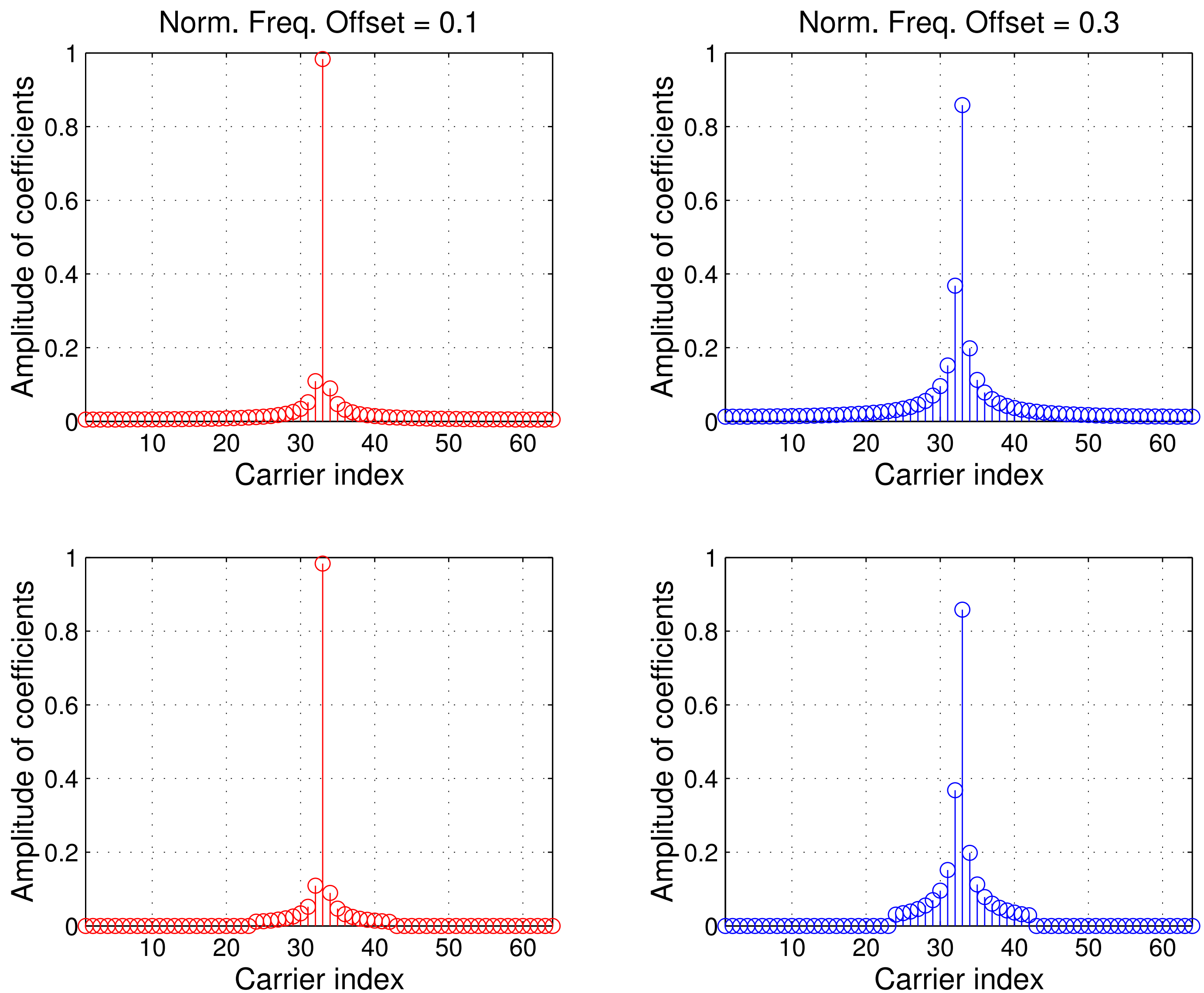
  - Only first correlation value, $R_{\mathbf{h}_{\epsilon_h}}(1)$, is used.

Searching algorithm

- Binary search is used to decrease the computational complexity.
  - Choose the max and min frequency offset hypothesis.
  - Find corresponding channel correlation values.
  - Move point with smaller correlation to the middle point between previous points.
  - Repeat for a pre-defined number of times.
- We only need the interference matrices only for ϵ_{max}, $\epsilon_{max}/2$, ϵ_{max}/4, ϵ_{max}/8, $\ldots$
- ϵ_{max} can be chosen adaptively.

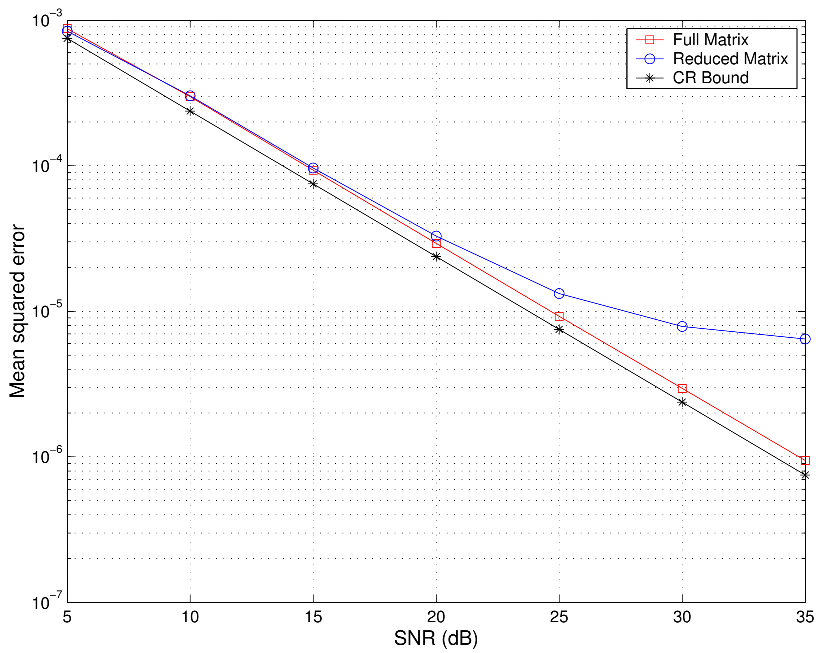
Reducing complexity

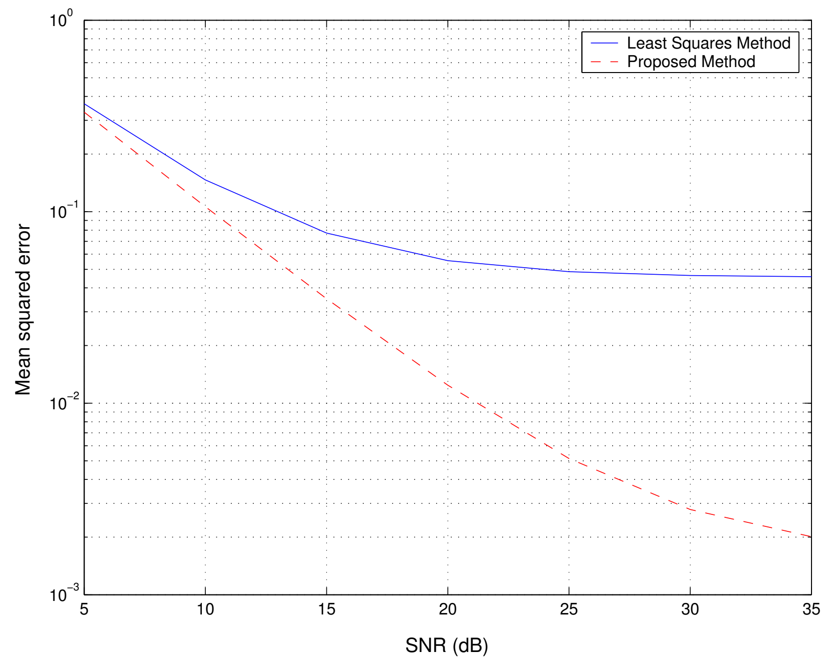
- In $\mathbf{S}$, most of the energy is concentrated around the diagonal, *i.e.* interference is mostly due to neighboring subcarriers.



Results

- OFDM system with 64 subcarriers
- 6-tap symbol-spaced CIR with exponential PDP
- 8 iterations used in search alg. $(8 + 1 = 9$ hypotheses).
- Reduced matrix considers only 32 neighboring subcarriers





Summary

- Average RMS delay spread of the channel is calculated from the channel frequency correlation estimate.
- Exact relation between coherence bandwidth and RMS delay spread is derived
- Time domain CIR is obtained by taking IFFT of the sampled CFR.
- The optimal sampling rate for sampling the channel response is investigated and simulation results for different sampling rates are given.
- An ICI cancellation method based on AR modeling is explained.
- A novel frequency-domain channel estimator which mitigates the effects of ICI by jointly finding the frequency offset and CFR is described.

Thank You!

QUESTIONS ?

University of South Florida

BACKUP SLIDES

System model

An OFDM based system is considered

$$x_m(n) = \sum_{k=0}^{N-1} S_m(k) e^{j2\pi nk/N}$$

$$y_m(n) = \sum_{l=0}^{L-1} x_m(n-l) h_m(l) + z_m(n)$$

$$Y_m(k) = S_m(k) H_m(k) + Z_m(k)$$

$$\hat{H}_m(k) = \frac{Y_m(k)}{S_m(k)} = H_m(k) + w_m(k)$$

S_m : Symbols to be transmitted

x_m : Transmitted signal

h_m : Channel impulse response

y_m : Received signal (time)

z_m : Noise (time)

Y_m : Received signal (Frequency)

H_m : Channel frequency response

Z_m : Noise in frequency domain

$\hat{H}_m$: Channel frequency response estimate

Effect of impairments (Long Term Est.)

- **Additive noise:** effect of noise on the CFC appears as a DC term whose magnitude depends on noise variance (this can be removed by noise variance estimator)

$$\tilde{\phi}_H(\Delta) = \begin{cases} \phi_H(\Delta) & \text{if } \Delta \neq 0 \\ \phi_H(0) + \sigma_w^2 & \text{if } \Delta = 0. \end{cases}$$

- **Constant Phase Shift in Channel:** constant phase shift does not effect proposed algorithm as it does not change the correlation

$$\breve{H}_m = H_m e^{j\Phi}.$$

$$\begin{aligned} \breve{\phi}_H(\Delta) &= E_{m,k}\{\breve{H}_m^*(k)\breve{H}_m(k+\Delta)\} \\ &= \phi_H(\Delta), \end{aligned}$$

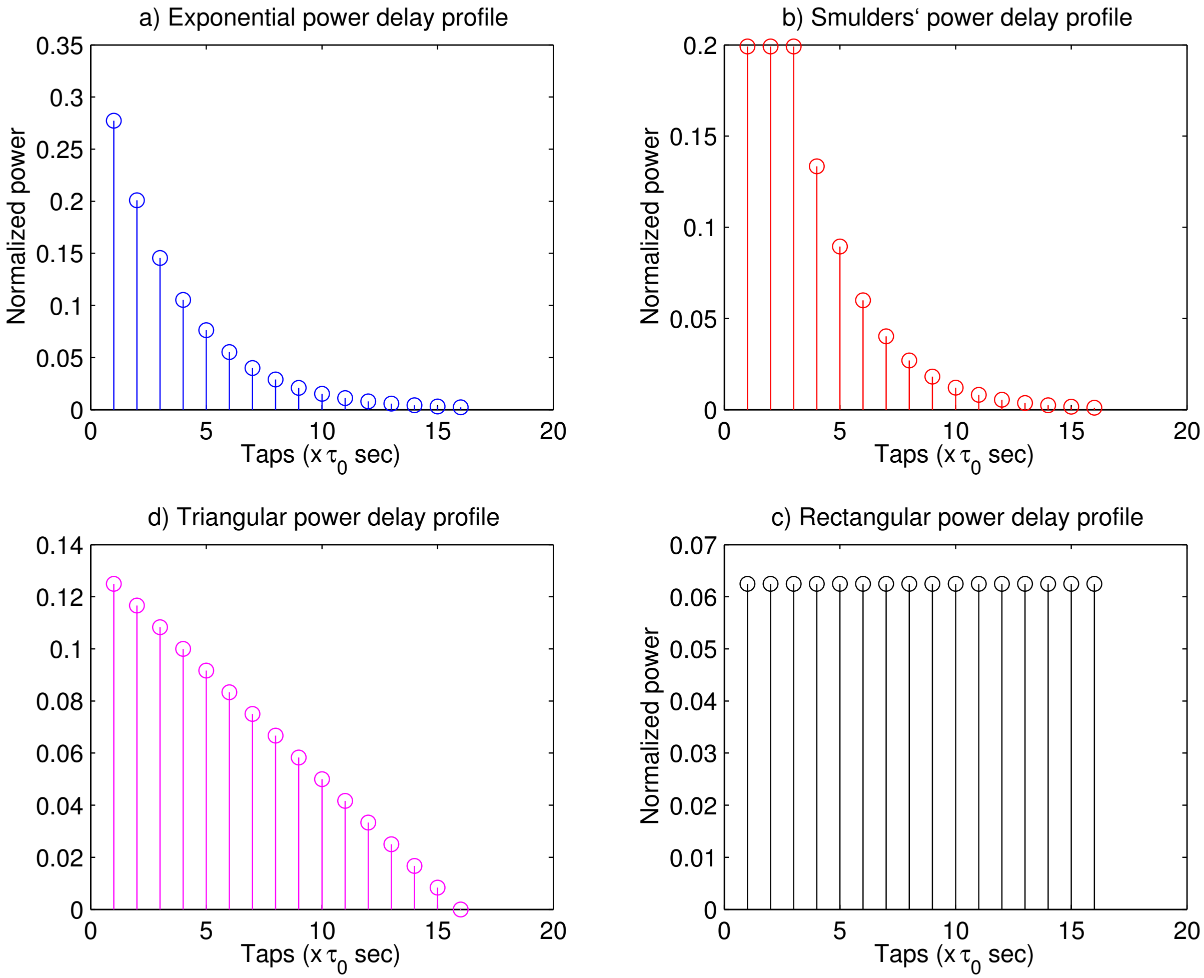
Effect of impairments (Long Term Est.)

- **Carrier-dependent Phase Shift in Channel:** It causes a constant phase shift in the CFC. However, this is not a problem since we are using the magnitude of CFC.

$$\bar{H}_m(k) = H_m(k)e^{-j\frac{2\pi k\theta}{N}},$$

$$\begin{aligned}\bar{\phi}_H(\Delta) &= E_{m,k}\{\bar{H}^*_m(k)\bar{H}_m(k+\Delta)\} \\ &= \phi_H(\Delta)e^{-j\frac{2\pi\Delta\theta}{N}}.\end{aligned}$$

Tested PDPs


a) Exponential power delay profile
Normalized power
Taps (x τ_0 sec)
b) Smulders' power delay profile
Normalized power
Taps (x τ_0 sec)
d) Triangular power delay profile
Taps (x τ_0 sec)
c) Rectangular power delay profile
Normalized power
Taps (x τ_0 sec)

Effect of impairments (Short Term Est.)

- Additive Noise : When IDFT is taken the power of noise decreases within a desired window since signals energy is concentrated on CIR while noise energy is spread.
- Constant Phase Shift in Channel : Not a problem since the time domain statistics depends on the *magnitude of CIR* which is not changing.

$$\breve{h}_m(l) = h_m(l)e^{j\Phi}$$

- Carrier-dependent Phase Shift in Channel : Biases time domain parameter estimates, by causing additional ISI which is not due to medium. Requires accurate timing and synchronization to reduce this effect.

System model

$$\mathbf{y} = \mathbf{S}_{\epsilon_p}\mathbf{X}\mathbf{h} + \mathbf{n}$$

$\mathbf{y}$: vector of received symbols

$\mathbf{X}$: diagonal matrix with the transmitted symbols on its diagonal

$\mathbf{h}$: vector representing the CFR to be estimated

$\mathbf{n}$: AWGN vector with mean zero and variance of σ_n^2

$\mathbf{S}_{\epsilon_p}$: interference (crosstalk) matrix that represents the leakage between subcarriers, *i.e.* ICI.

- Elements of $\mathbf{S}_{\epsilon_p}$ can be found using

$$\mathbf{S}_{\epsilon_p}(m,n) = \frac{\sin \pi(m-n+\epsilon_p)}{N \sin \frac{\pi}{N}(m-n+\epsilon_p)} e^{j\pi \frac{N-1}{N}(m-n+\epsilon_p)}$$