Software Radio Implementation for MIMO/OFDM High-Speed Wireless LAN/MAN with Space-Time Coding and BLAST Technologies

Weidong Xiang

University of Michigan-Dearborn

Project Background

- Software Radio Laboratory, *Georgia Institute of Technology*, *2000-2004*
- Implement high-speed wireless prototype integrating parallel transmission technologies
- Yamacraw project

Outline

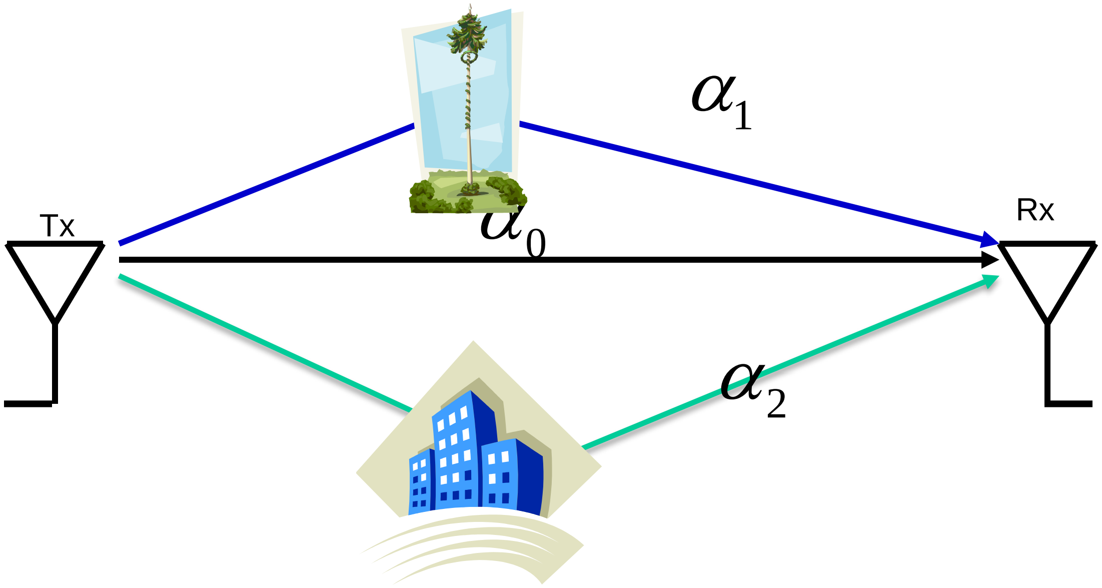
1. Background
2. A 2×2 real-time space-time coding wireless prototype
3. A 4×4 OFDM/BLAST high-speed prototype
4. Summary

Gigabit Wireless !?

- Motivation: explore the practical solution for high speed wireless link

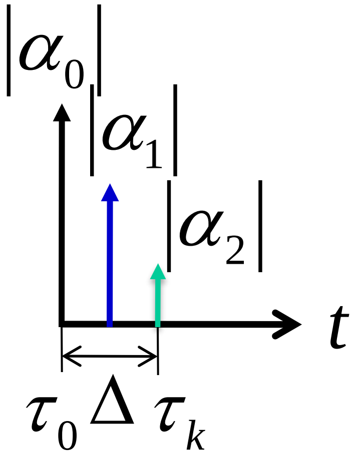
What is the highest data rate for a wireless link ?

Multipath Fading

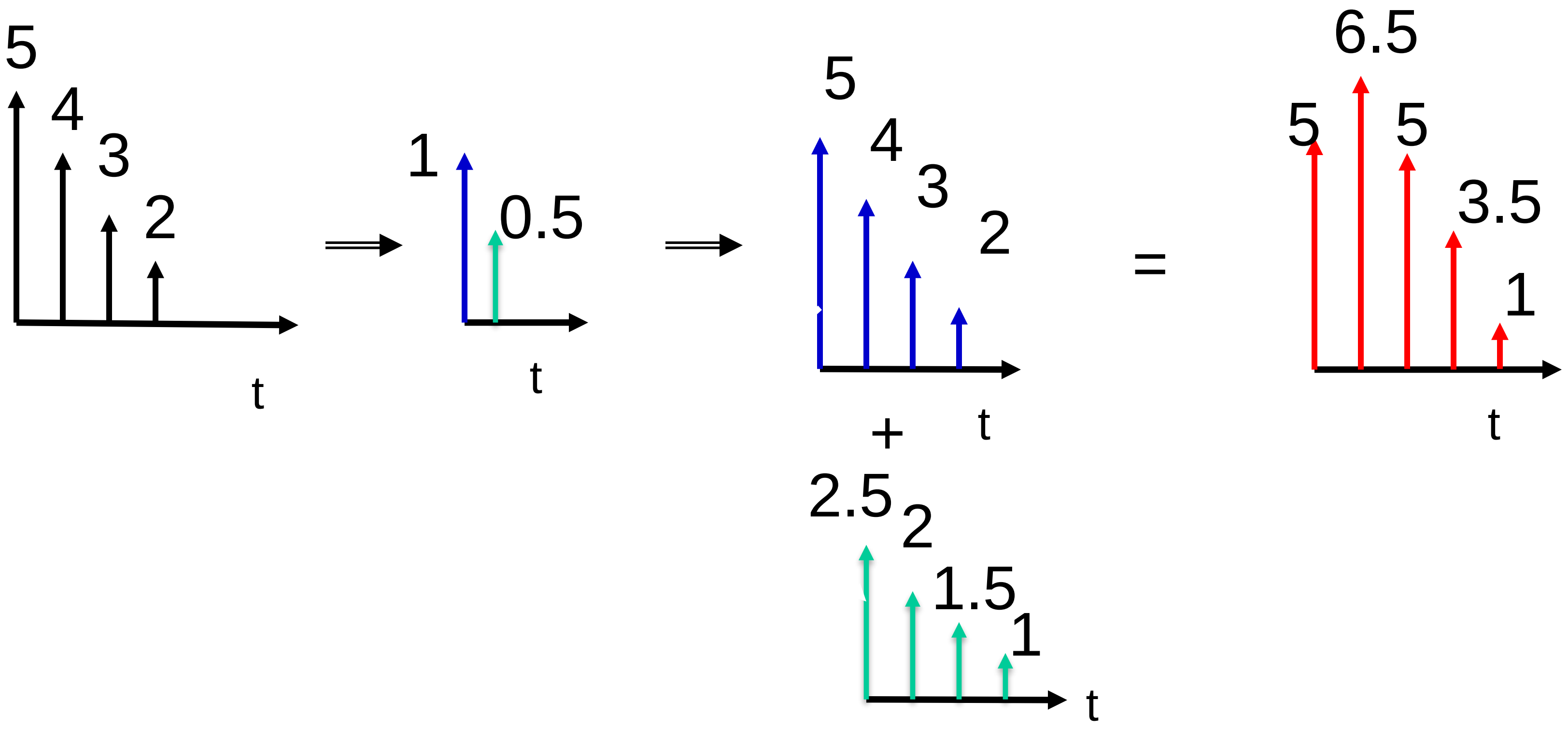


Channel Impulse Response (CIR)

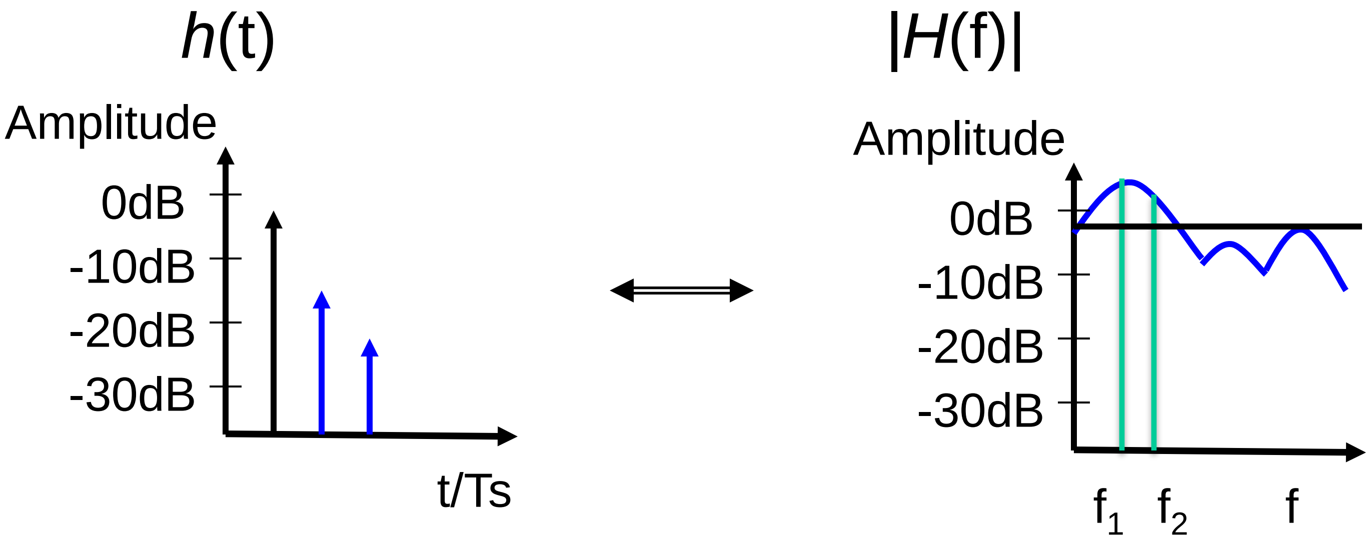
$$h(t) = \sum_{k=0}^{L-1} \alpha_k \delta(t - \tau_k)$$



Inter-Symbol Interference (ISI)



Frequency Selective Fading

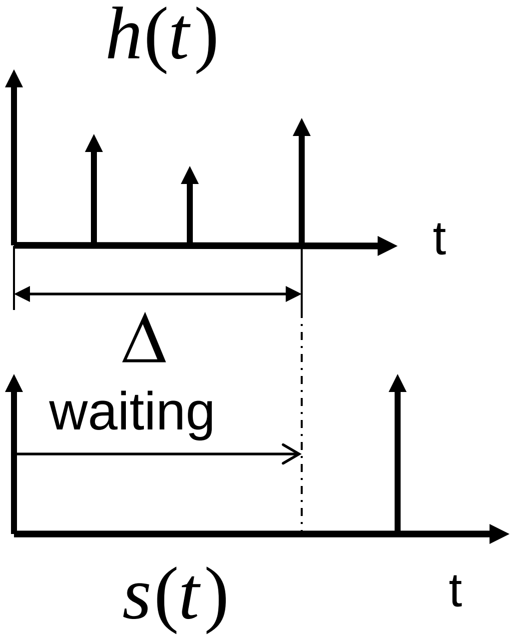


- Flat fading if there is no multipath fading
- Correlation expresses the degree of similar variation at f_1 and f_2

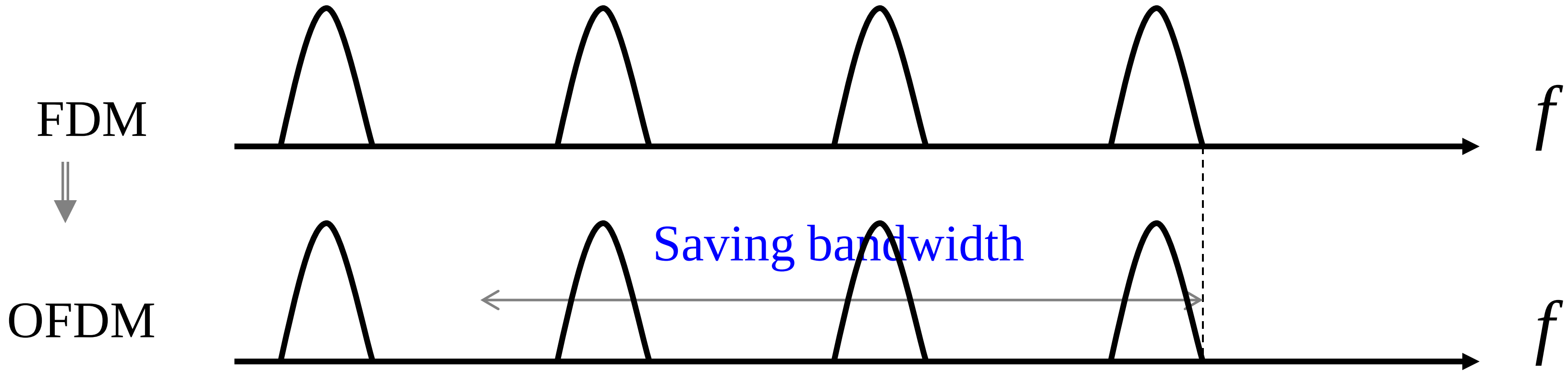
Data Rate Cap

- Unavoidable multipath fading
- Maximal ISI-free data rate

$$1/(1+\Delta)$$



Orthogonal Frequency Division Multiplexing (OFDM)



Orthogonal Condition

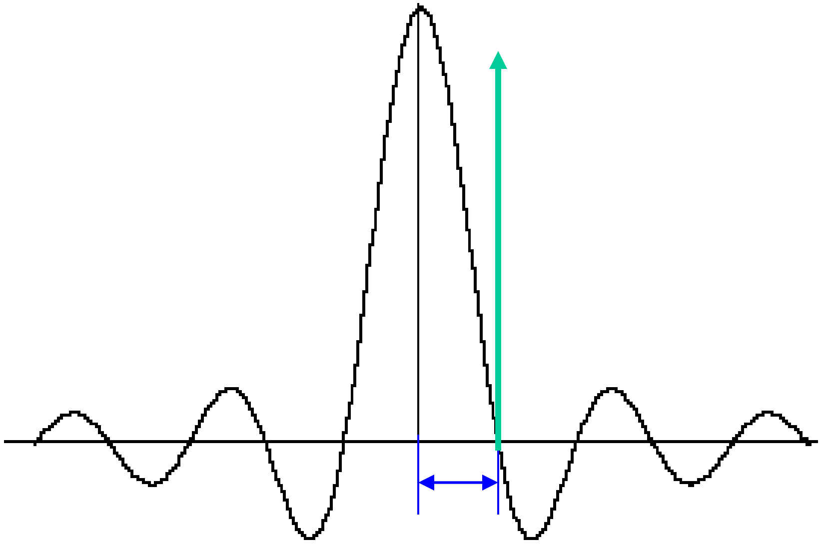
$$\Delta f = \frac{1}{NT}$$

OFDM Modem

- Modulation IFFT
- Demodulation FFT

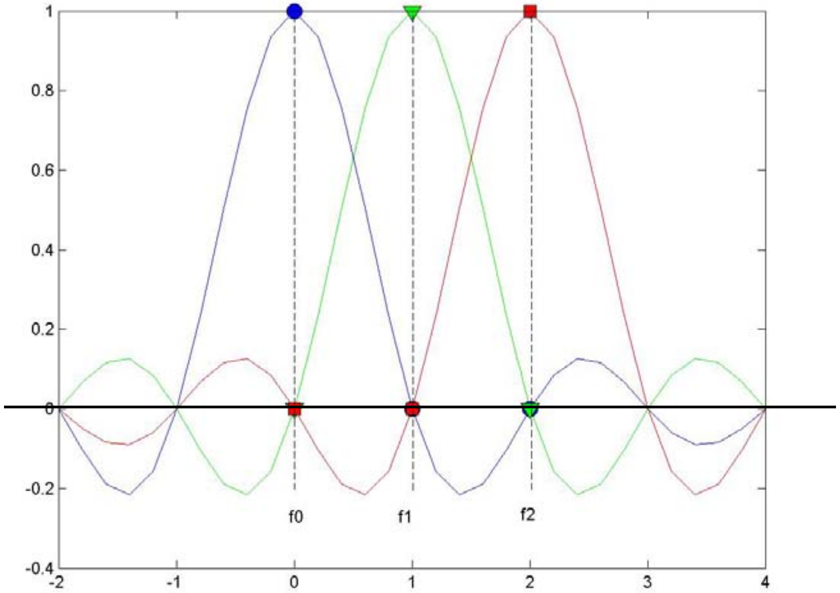
OFDM Spectrum

The spectrum of a sub-channel



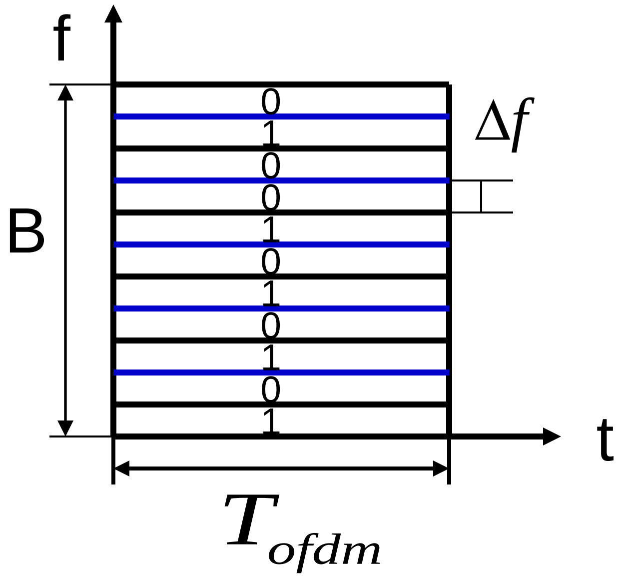
$$\frac{1}{2}\Delta f = R_b$$

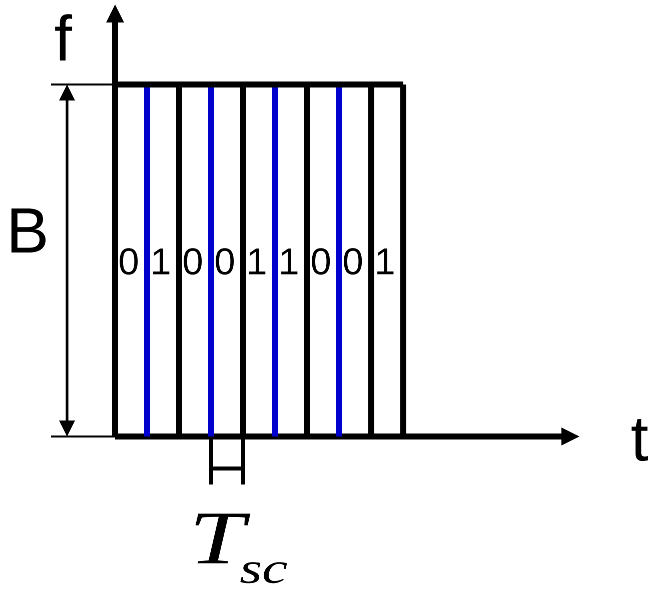
OFDM spectrum



The key to keep the sub-channel orthogonal each other is to keep an appropriate channel spacing

OFDM vs. Single Carrier





$$B = N\Delta f$$

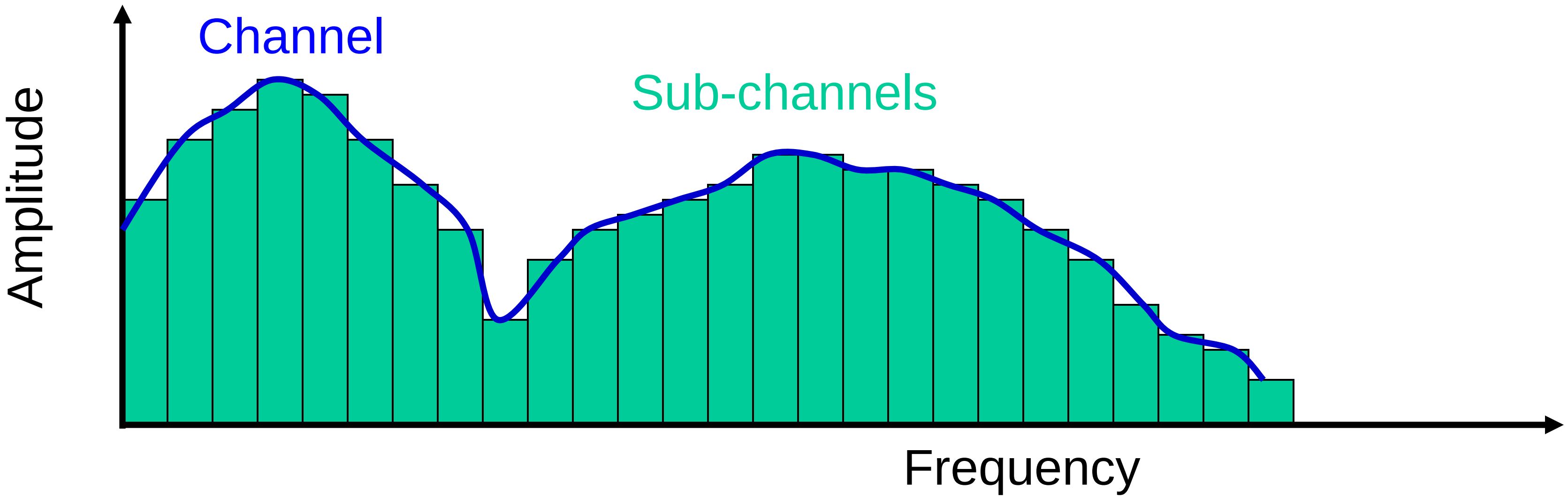
$$T_{ofdm} = NT_{sc}$$

$$\Delta f = \frac{1}{T_{ofdm}}$$

$$B = \frac{1}{T_{sc}}$$

Where *N* is total number of subcarriers

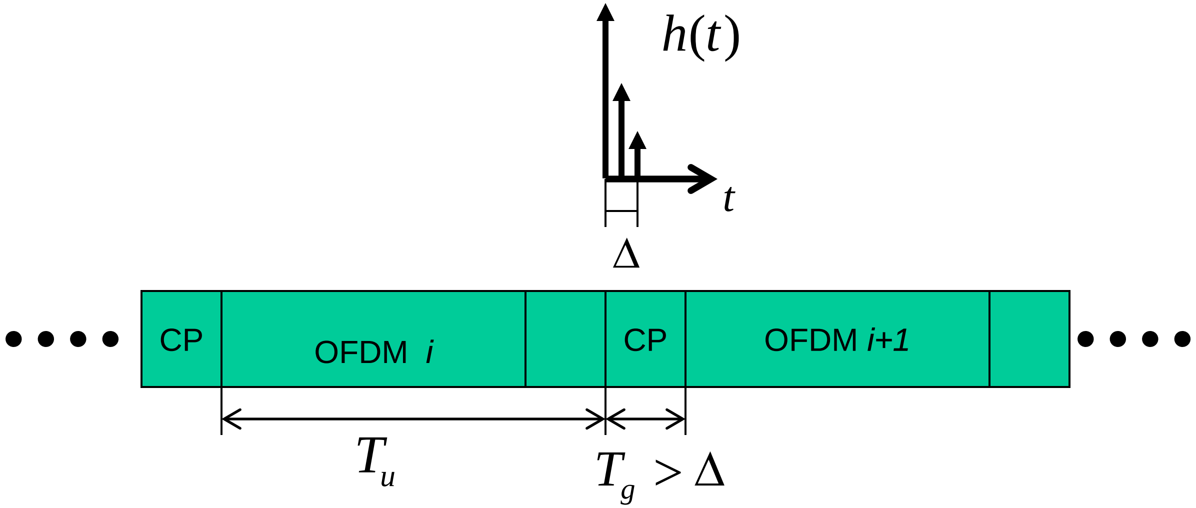
OFDM: A Multicarrier Modulation



- Parallel Transmission
- Sub-channel experiences flat fading
- Simple frequency domain equalization

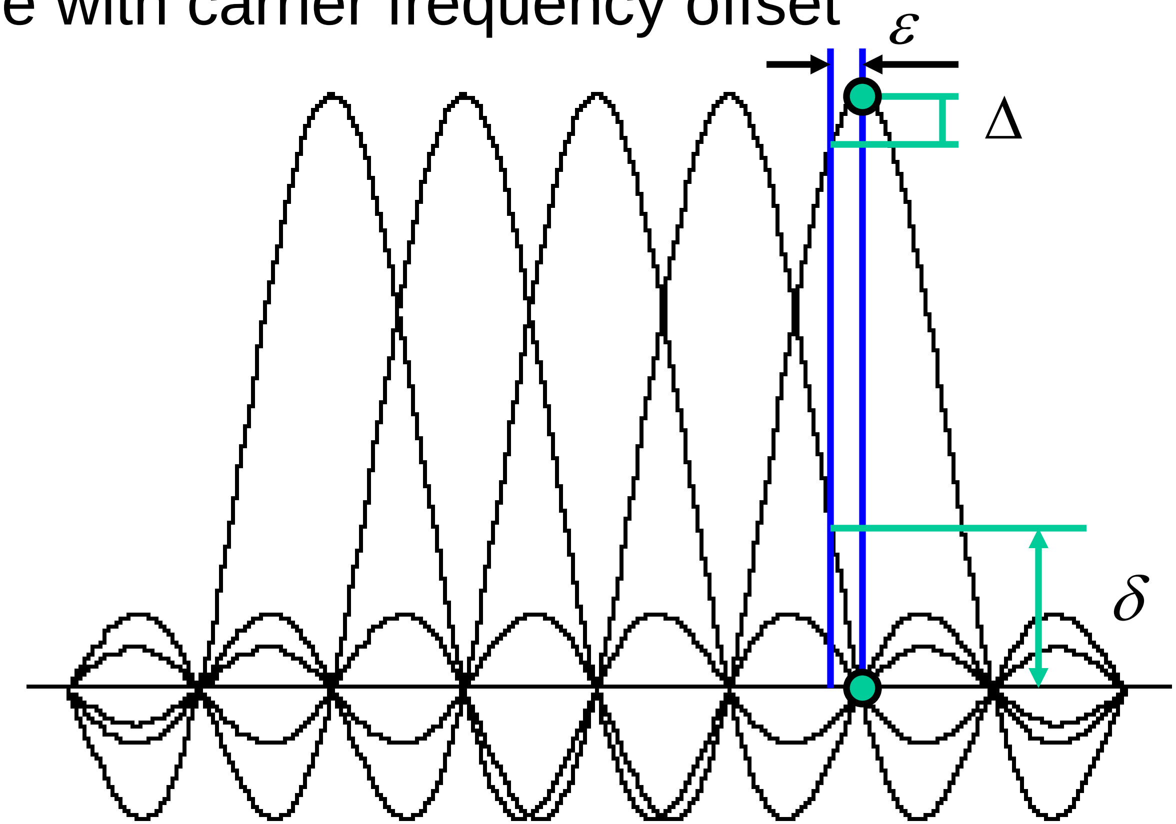
Cycle Prefix (CP)

CP is adopted to remove ISI



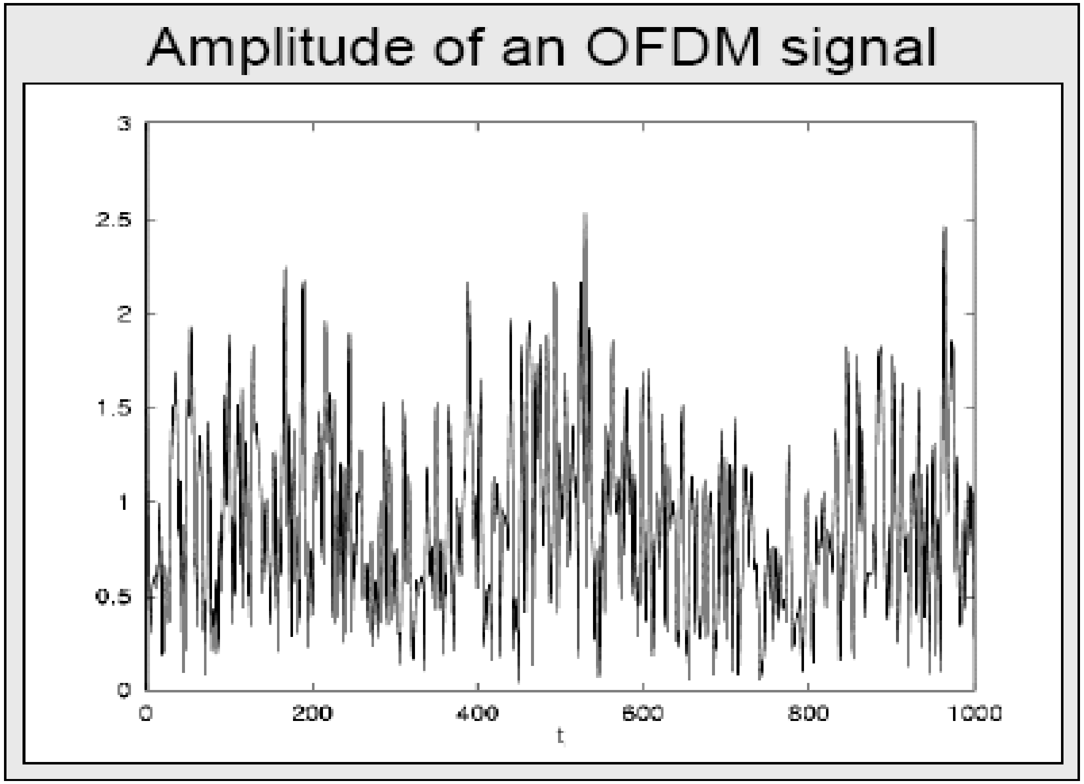
Challenges of OFDM

Sensitive with carrier frequency offset

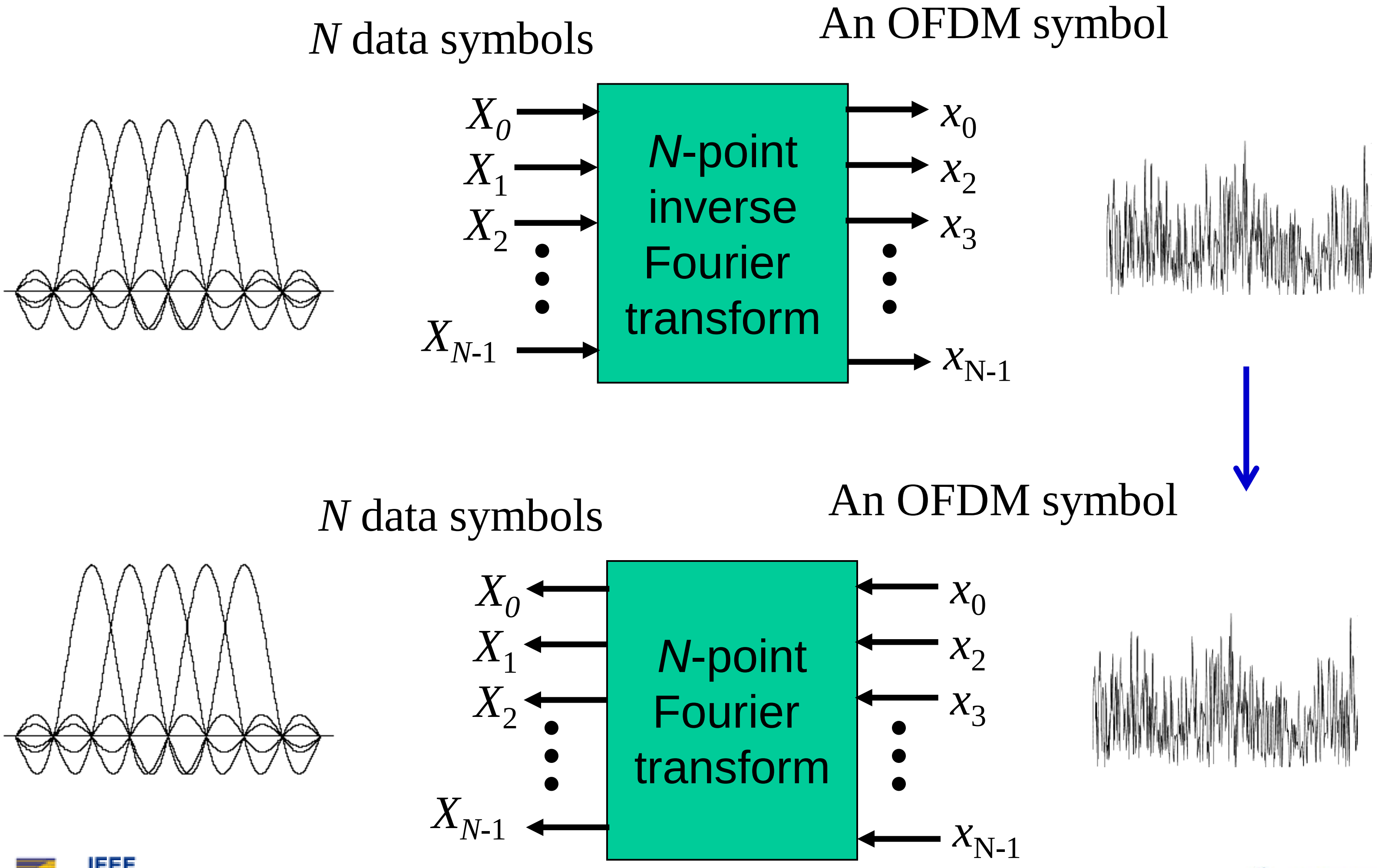


Challenges of OFDM

- PAPR (peak-to-average power ratio)
- Linearity of circuits, especially power amplifier


Amplitude of an OFDM signal

OFDM Modulation and Demodulation



N data symbols

An OFDM symbol

X_0

X_1

X_2

$X_{N\text{-}1}$

N-point inverse Fourier transform

x_0

x_2

x_3

$x_{N\text{-}1}$

N data symbols

An OFDM symbol

X_0

X_1

X_2

$X_{N\text{-}1}$

N-point Fourier transform

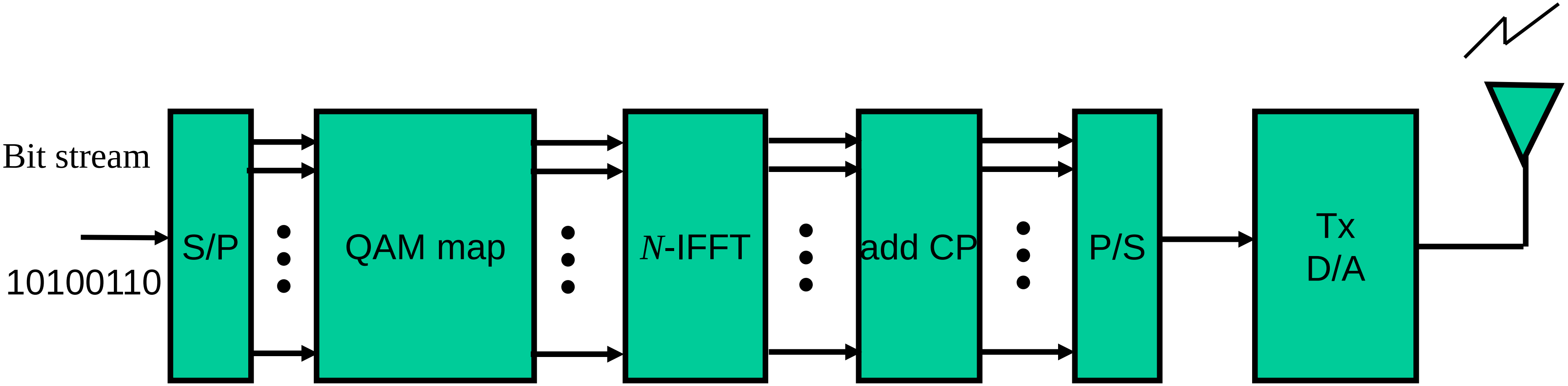
x_0

x_2

x_3

$x_{N\text{-}1}$

An OFDM Transceiver



Bit stream

10100110

S/P

QAM map

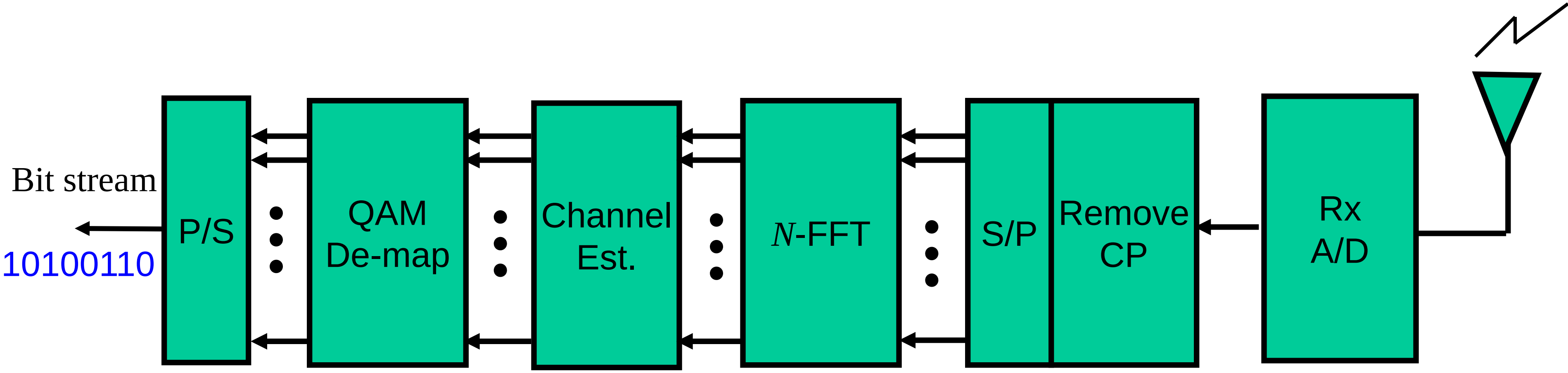
N-IFFT

add CP

P/S

Tx
D/A

Tx



Bit stream

10100110

P/S

QAM
De-map

Channel
Est.

N-FFT

S/P

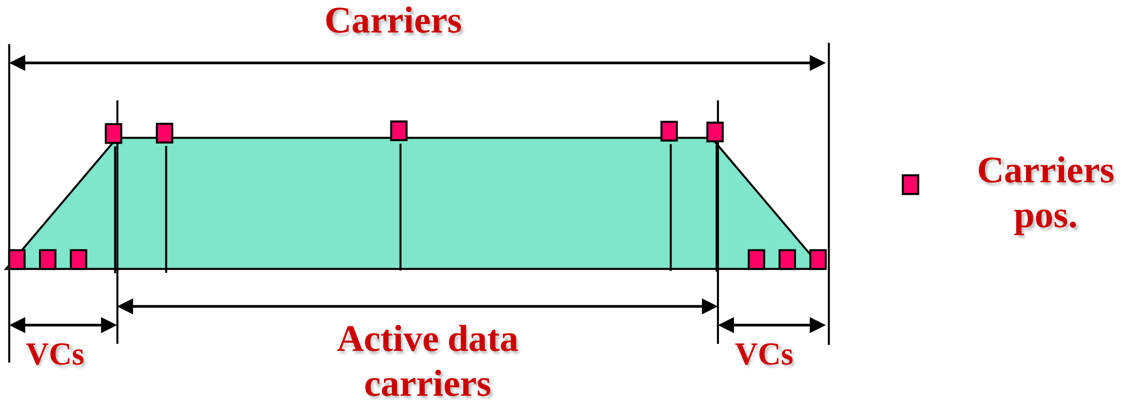
Remove
CP

Rx
A/D

Rx

Overhead

- CP (time domain)
- Virtual carriers (VCs, frequency domain)
    - Example: IEEE 802.11a, 12 VCs in 64 SCs

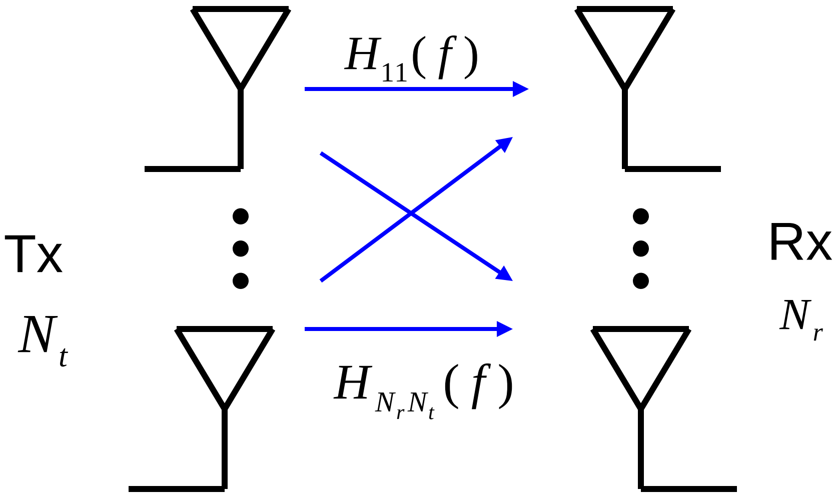


Applications of OFDM

- Digital broadcasting – DAB/DVB
- High speed WLAN – IEEE 802.11a,g/HiperLAN2
- High speed WMAN – IEEE 802.16
- IEEE 802.11p wireless access in vehicular environments
- ADSL
- Considered promising candidate for 4G

Multiple Input Multiple Output (MIMO)

$H_{i,j}(f)$ the path gain of the link between i-th Tx and j-th Rx.



$$H(f) = \left[H_{i,j}(f)\right]$$

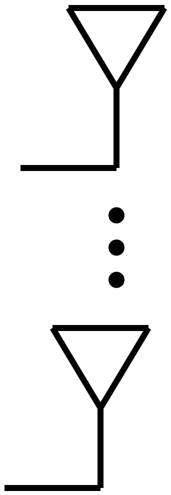
Channel matrix is to be with

$$N_r \times N_t \times N$$

$$Y(f) = H(f)X(f) + N(f)$$

Space-Time Coding (STC)

$$X = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} \qquad XX^T = 2I_{2\times 2}$$



$-s_2^*, s_1$

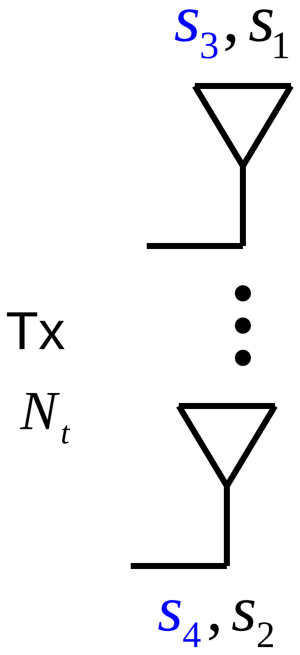
Tx

N_t

s_1^*, s_2

Bell Laboratory Layered Space-Time (BLAST)

$$X = \begin{bmatrix} s_1 & s_3 \\ s_2 & s_4 \end{bmatrix}$$



Singular Value Decomposition (SVD)

$$Y = HX + N$$

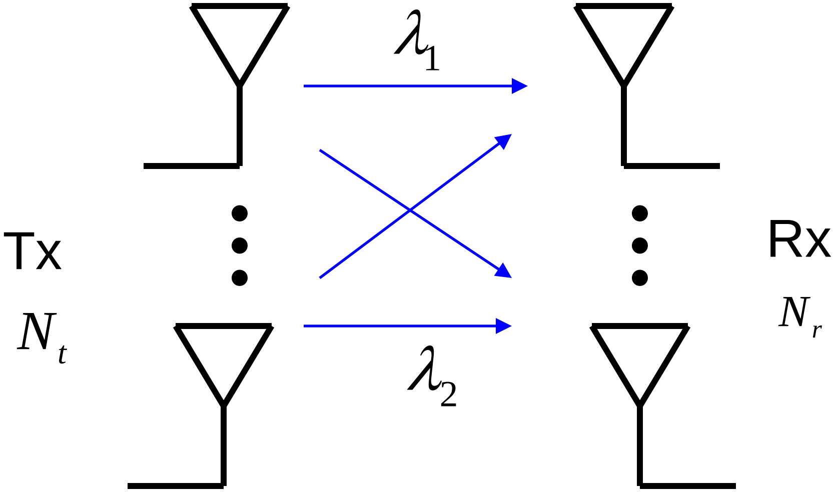
$$Y = U\Lambda VX + N$$

$$U^{-1}YV^{-1} = \Lambda VXV^{-1} + U^{-1}NV^{-1}$$

$$\bar{Y} = \Lambda\bar{X} + \bar{N}$$

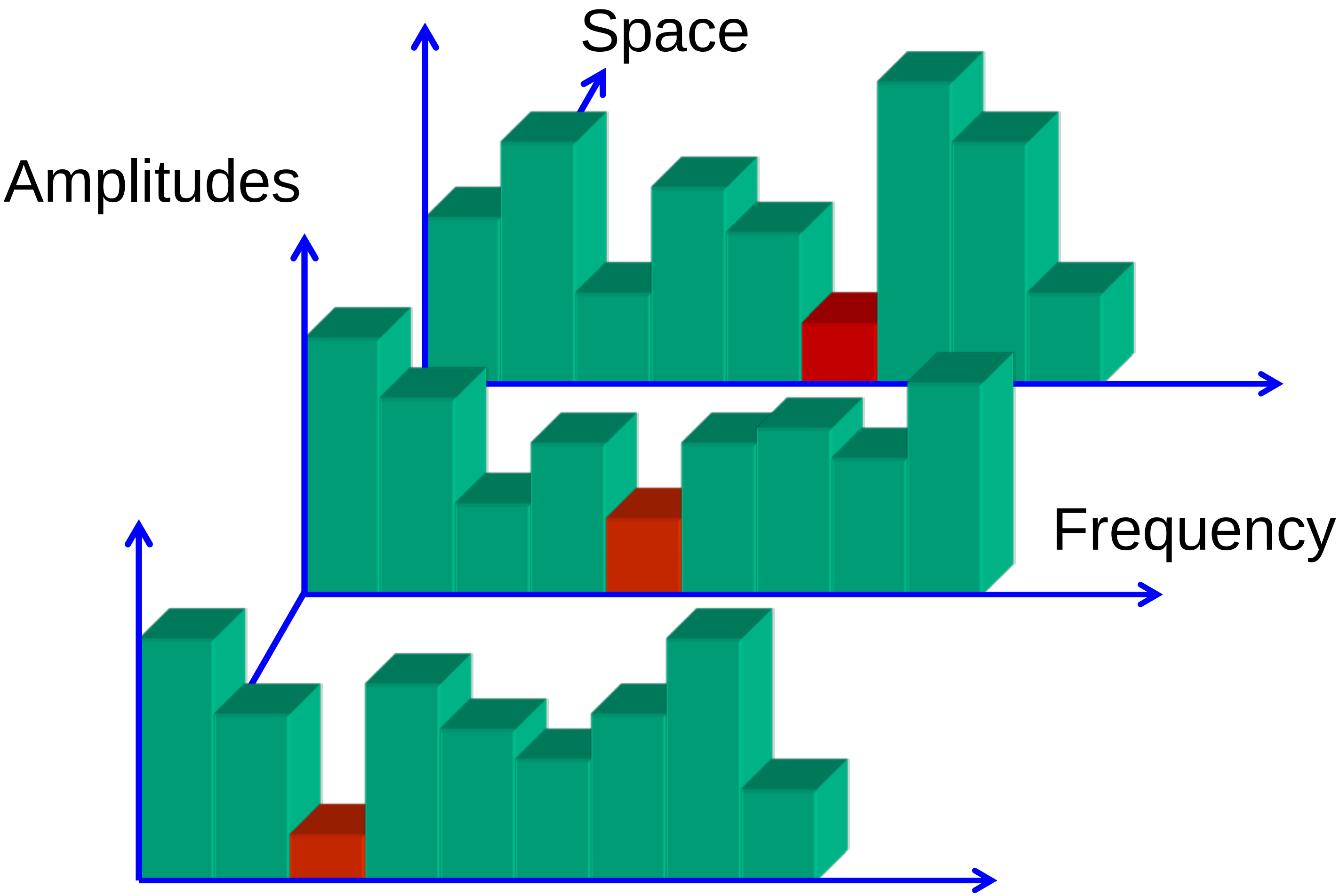
Λ is the diagonalized channel matrix

MIMO Equivalent Channels



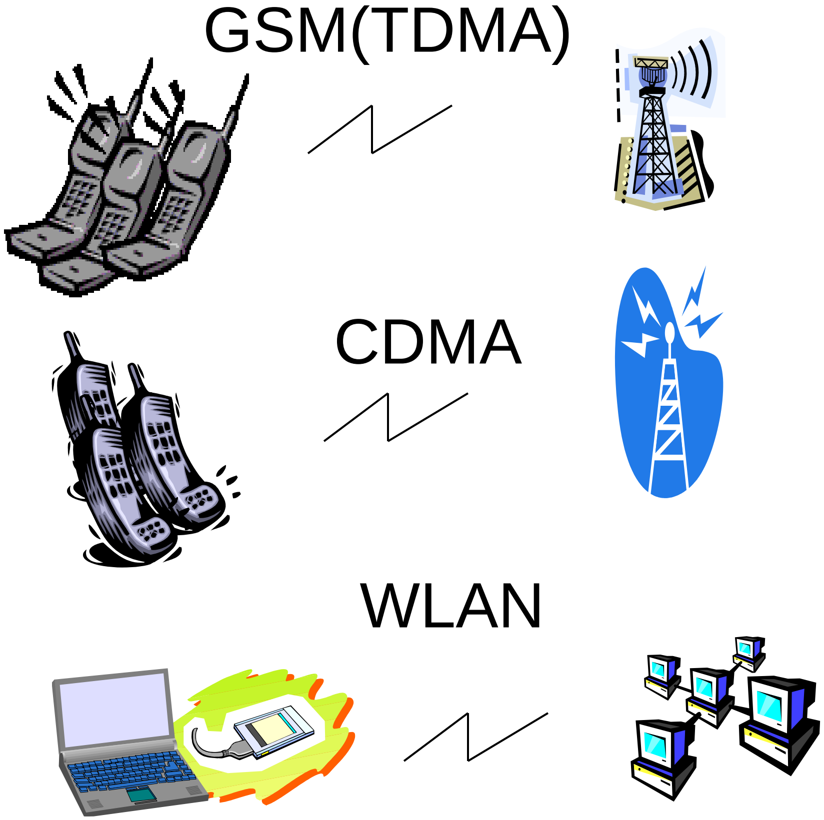
$$\Lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$$

OFDM/MIMO



What is the Problem with Current Wireless System ?

- Surplus coexisting standards
- Incompatibility with heterogeneous systems



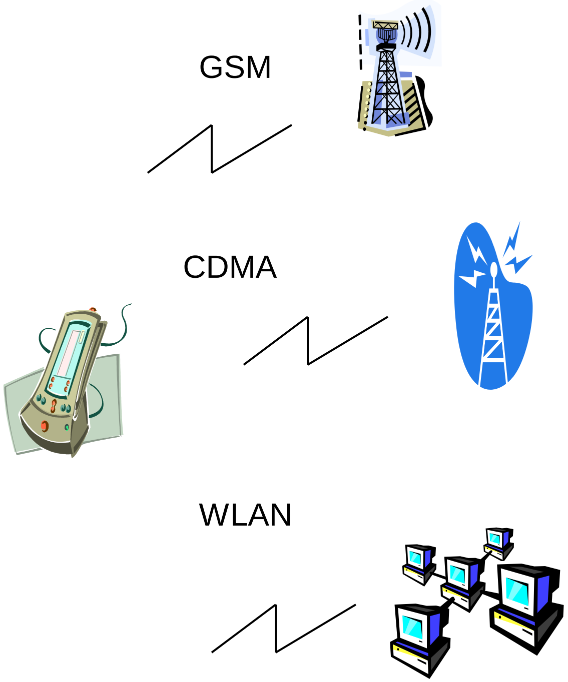
GSM(TDMA)

CDMA

WLAN

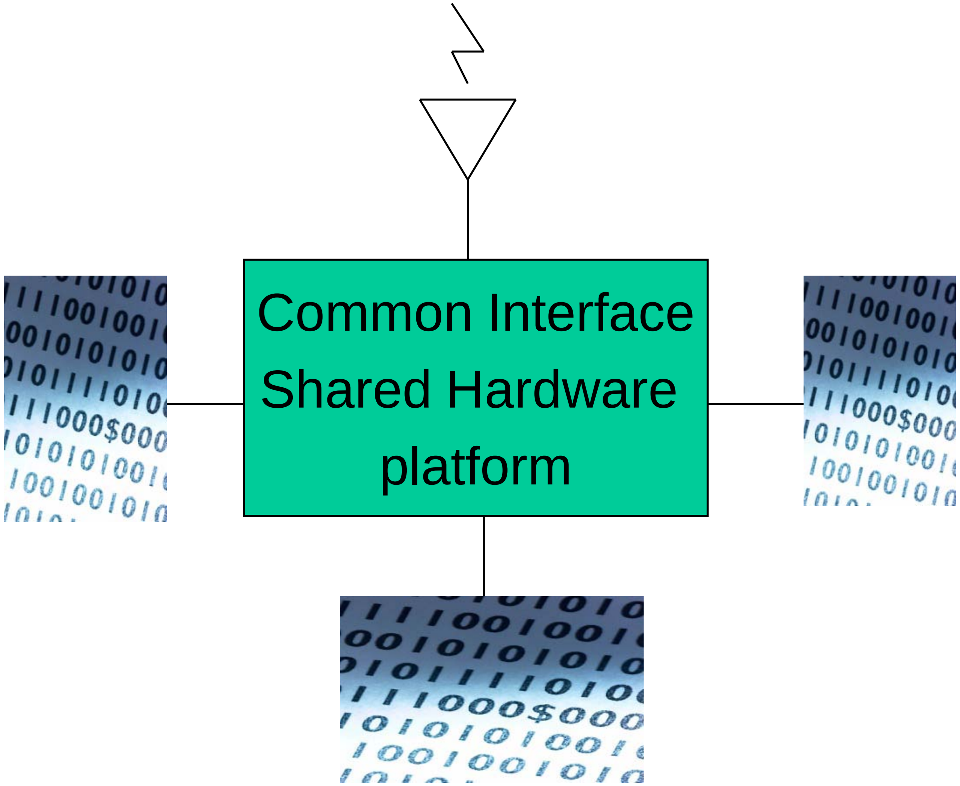
Software Radio (SWR)

- Re-configurability
- Multiple modes
- User defined function



Understanding SWR

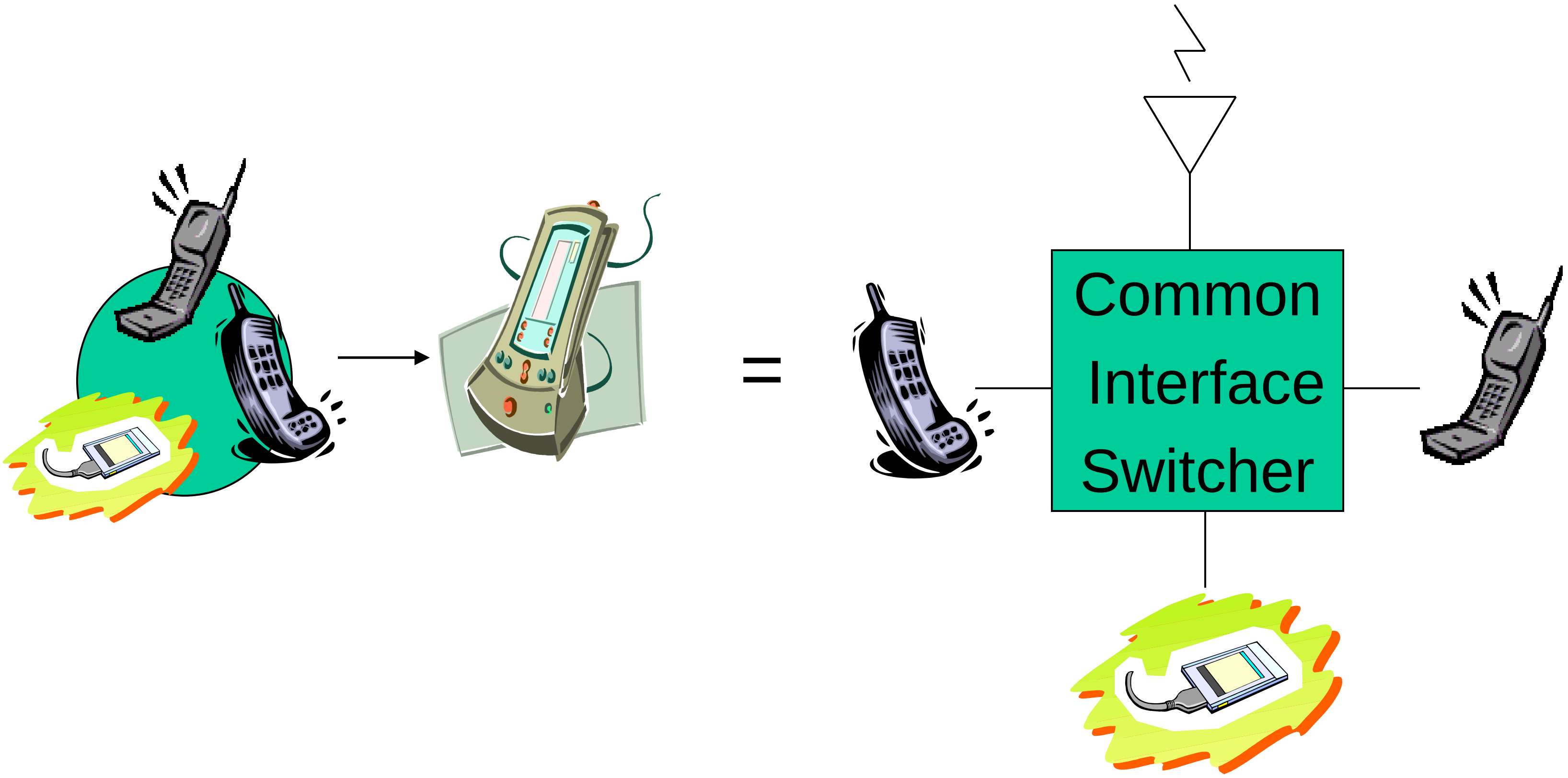
- Software defined radio
- A design philosophy
- Comparison with computer



Applications of SWR

- Military
- Base station
- Not available for handset !?

A Transition SWR Approach
Software Controlled Radio

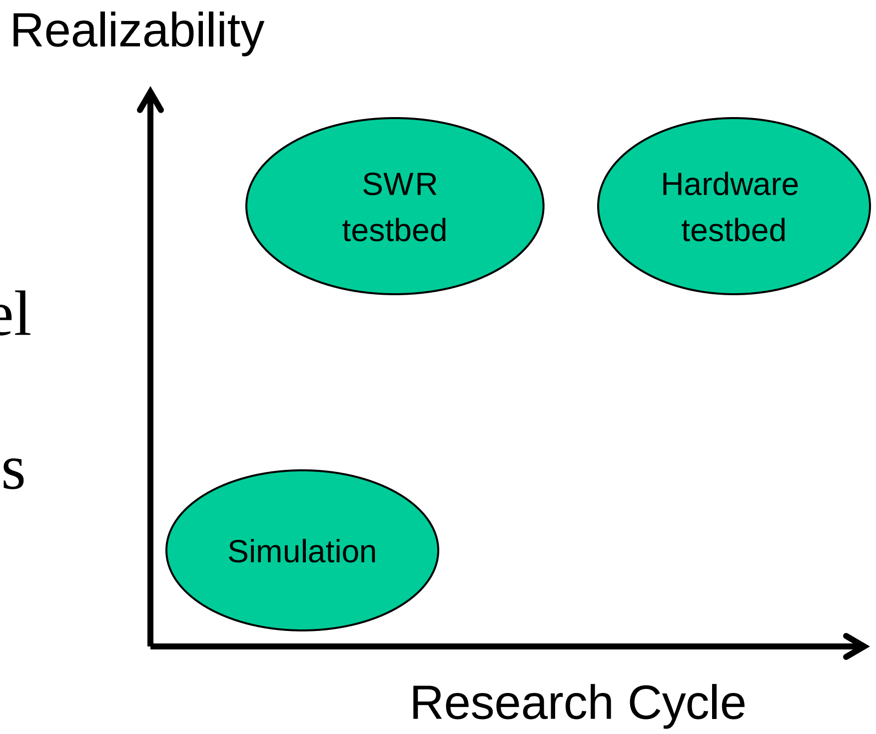


=

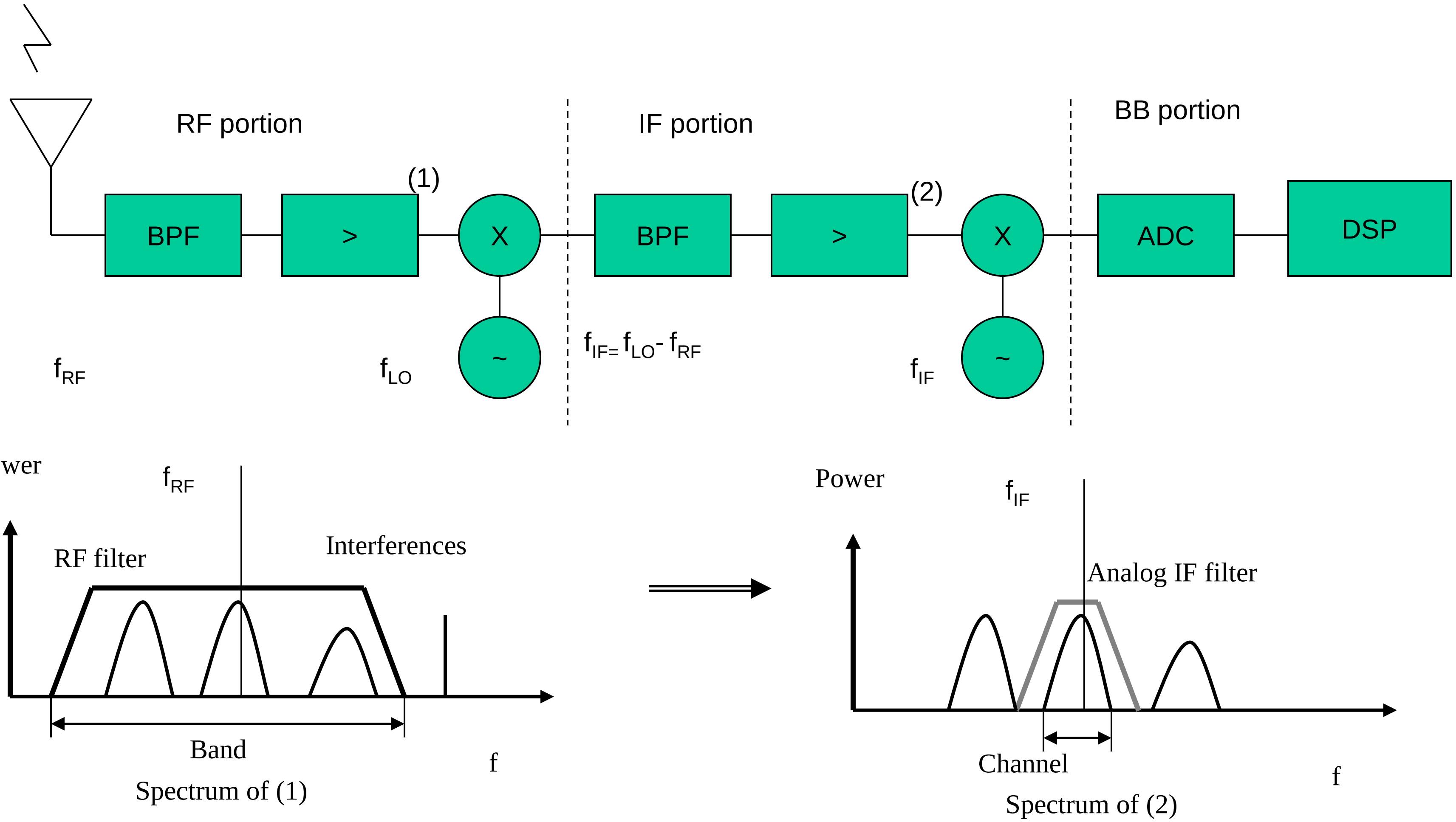
Common Interface Switcher

SWR Testbed

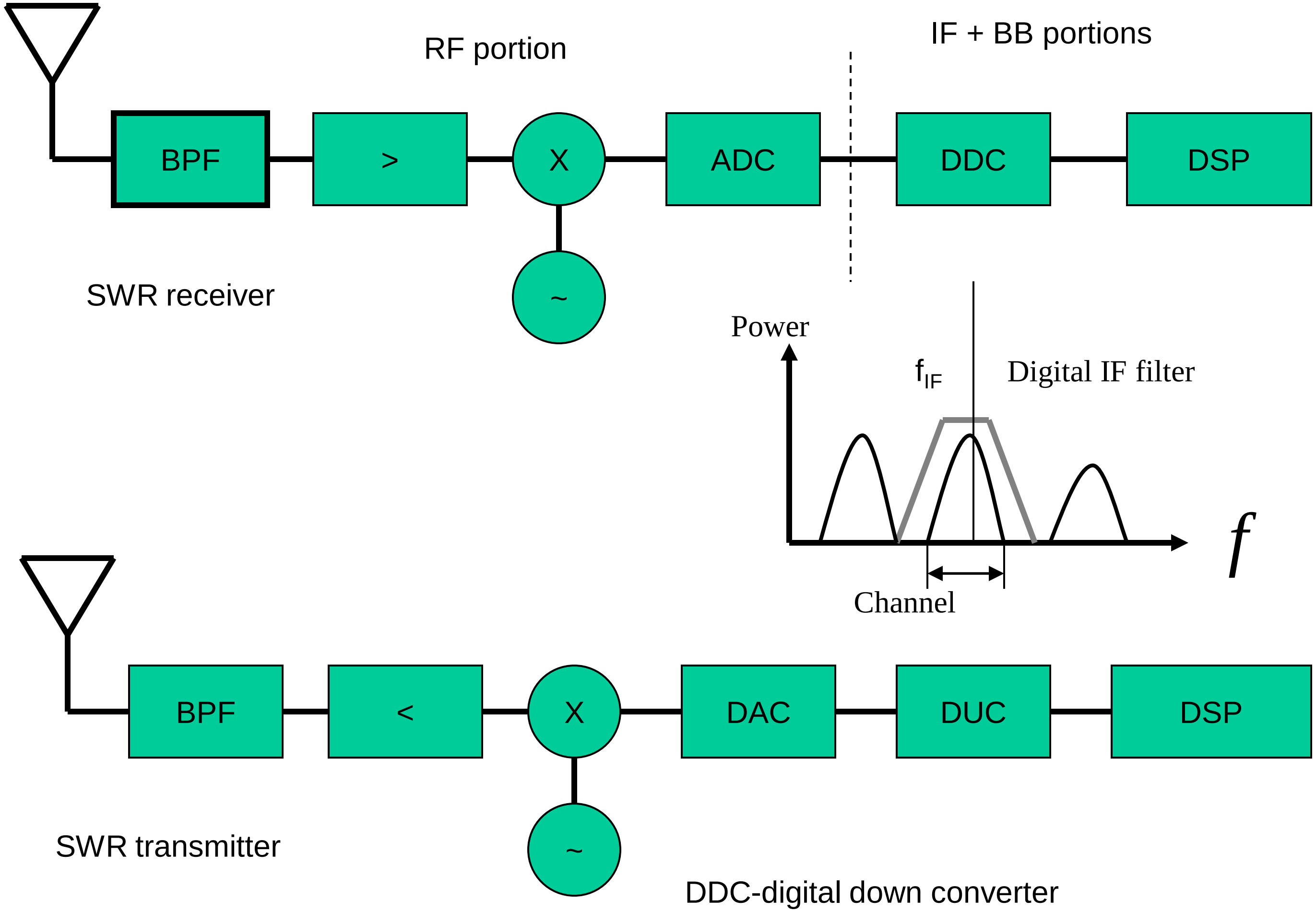
- Scalable
- Open architecture
- Supporting heterogeneous parallel processing
- Flexible high-speed I/O interfaces



Superheterodyne Receiver



Realizable SWR Configuration



DDC-digital down converter

DUC-digital up converter

SWR Considerations

- RF Front End
- Low Noise
- High Linearity
- ADC/DAC/DDC/DUC
- Wide Band
- High Dynamic Range
- High Spur Free Dynamic Range (SFDR)

DSP - TMS320C6701

•System Clock 167MHz

•1GFLOPS

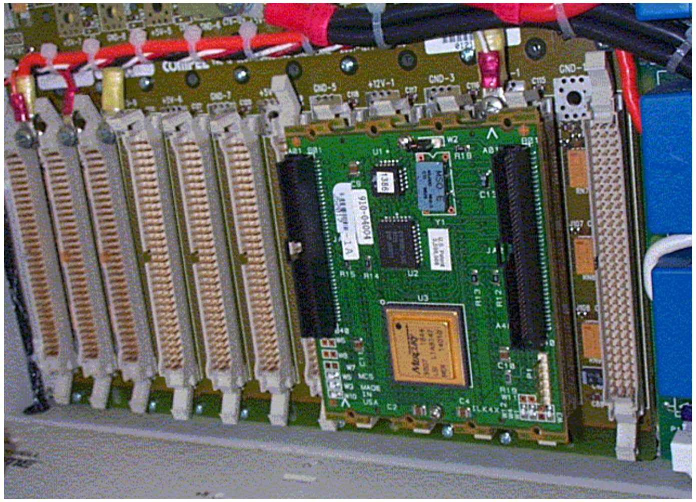
•8 Software Pipelines

•4 DMA Channels

•16K×32 Internal Data Memory (IDRAM)

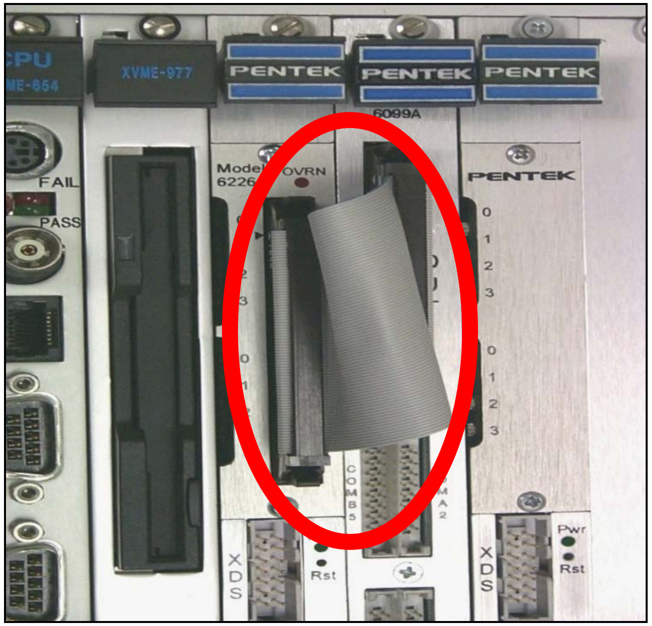
Raceway Interface

SWR feature interface: *online re-configurable*



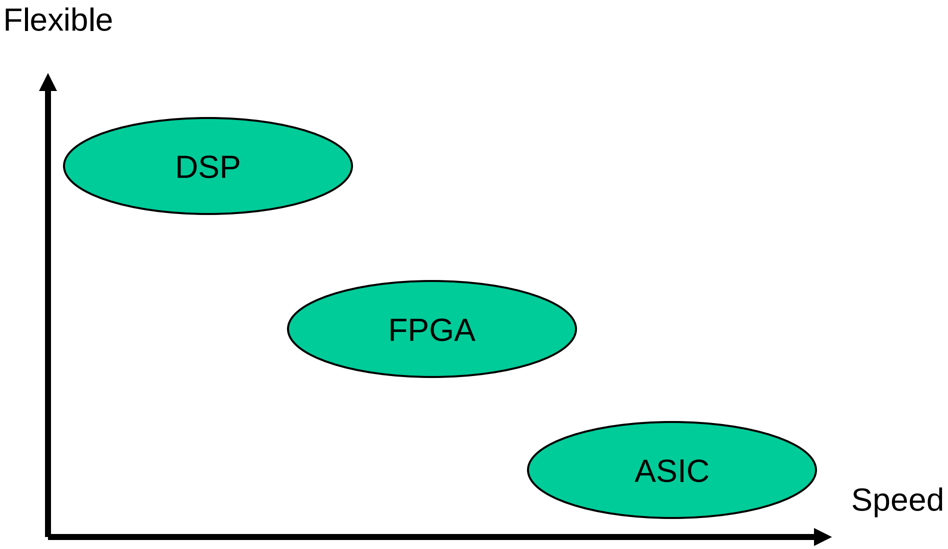
Front Panel Data Port (FPDP)

- The fastest interface between DSP and computer
- 160MB/s
- 10 feet



SWR Considerations

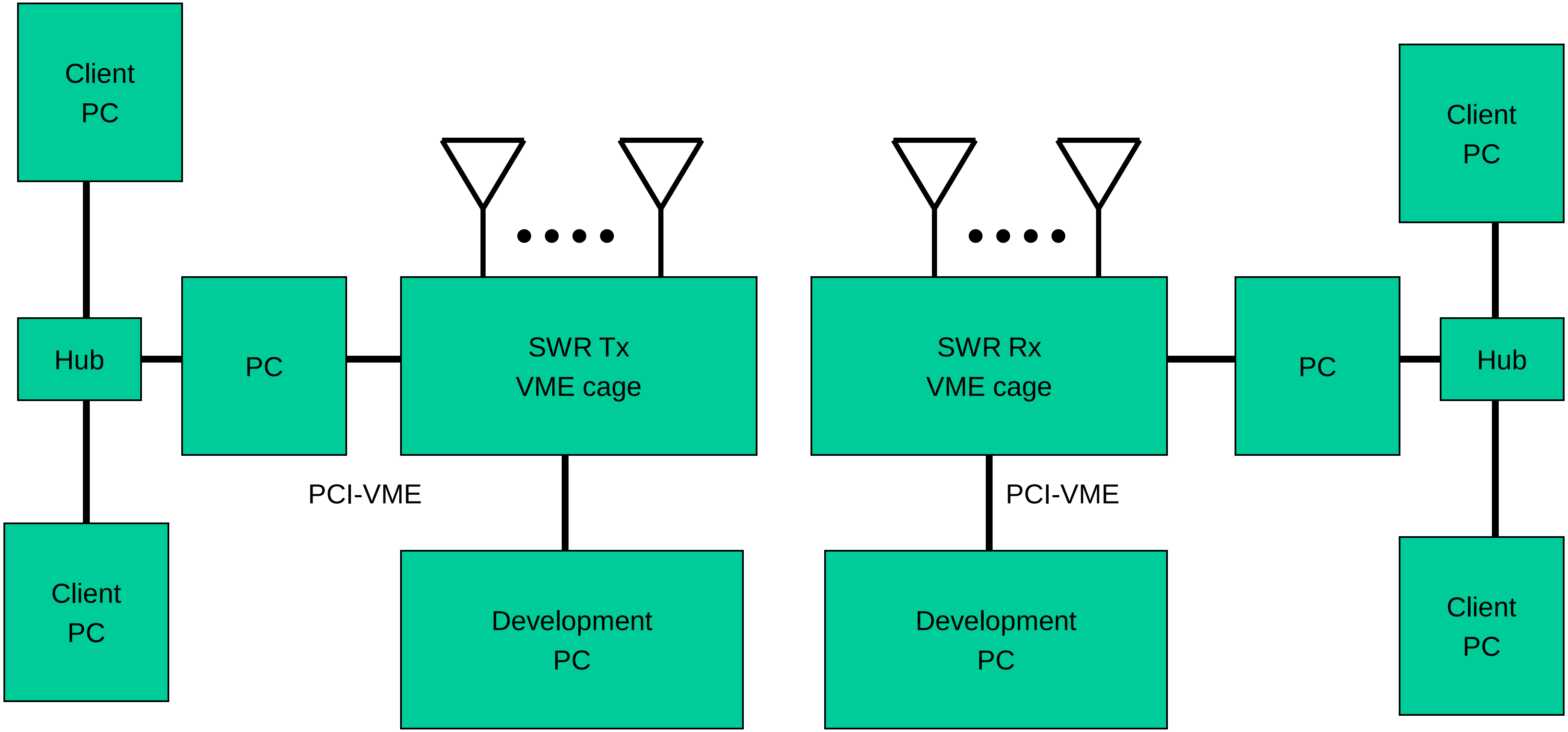
- Operation Mechanism
- Application Specific Integrated Circuits (ASIC)
- Field Programmable Gate Arrays (FPGA)
- Digital Signal Processor (DSP)



Comparison of PCI- and VME-Based SWR Testbeds

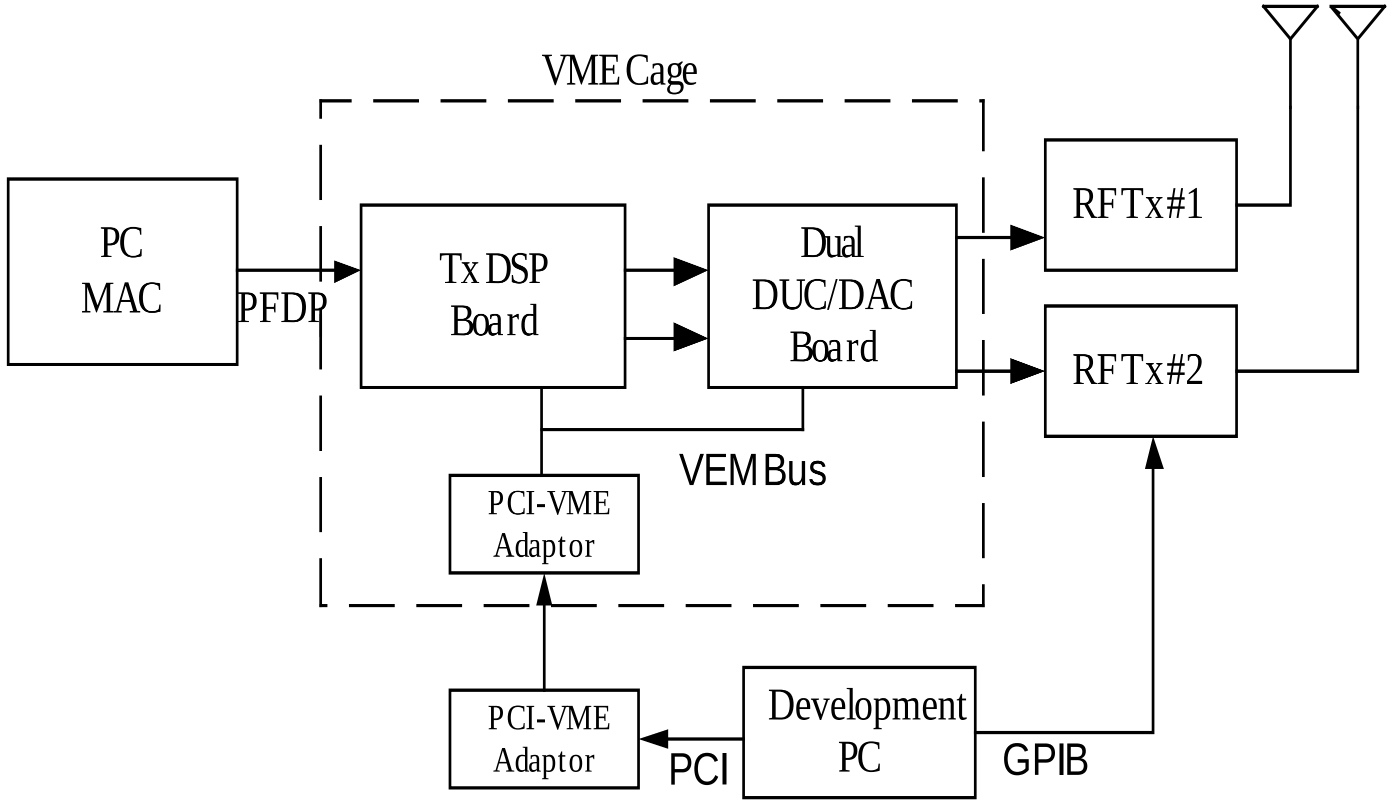
	PCI	VME
Bits	32	32
Bus data rate	132MB/s	80MB/s
Number of slots	4	21
Cost	Low	High
Power consumption	Low	High
Flexibility	Low	High
Application	Dedicated	General
Providers: *Pentek, ICS and Sundance*		

A SWR Testbed Diagram

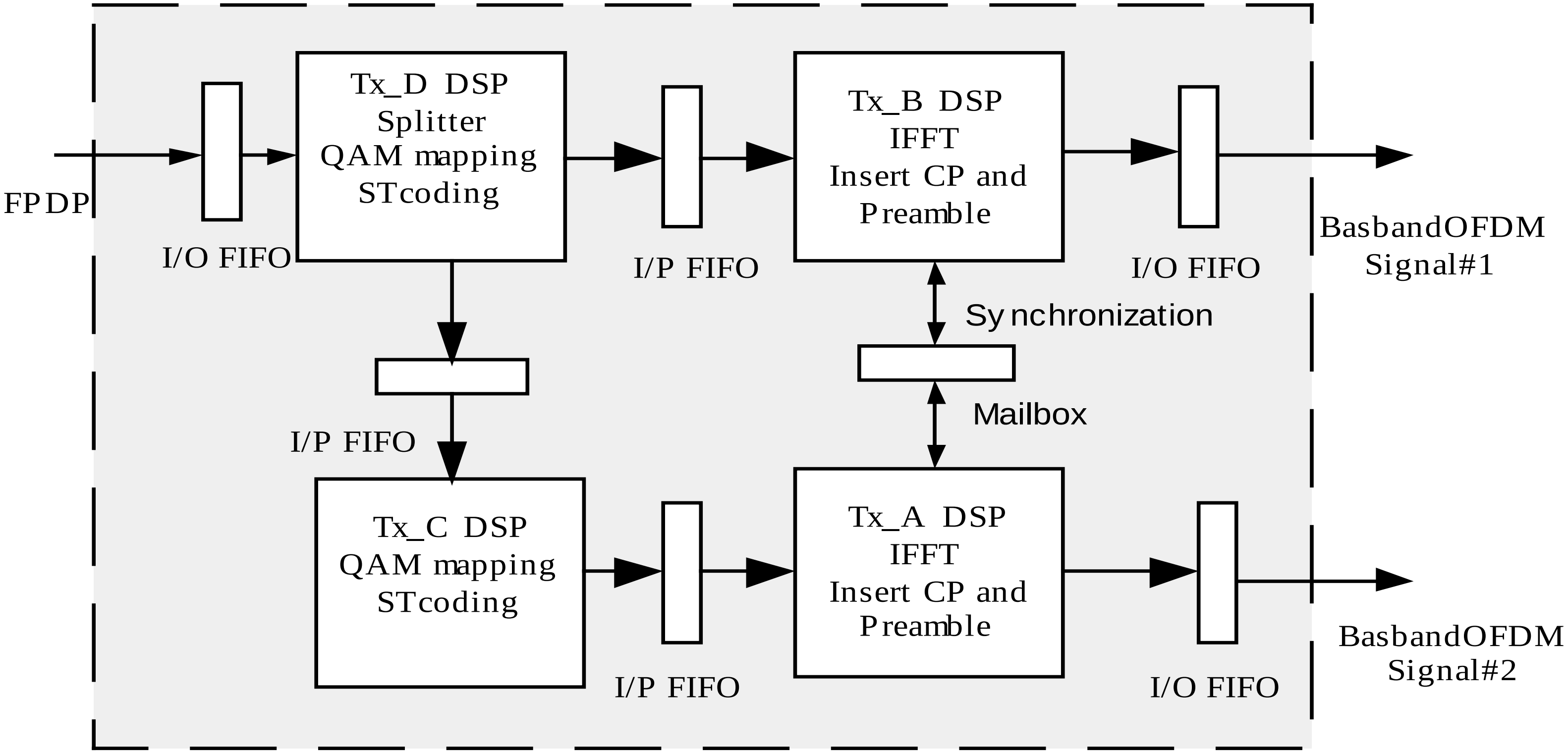


A 2×2 Real-Time Space-Time Coding Wireless Prototype

Diagram of Transmitter



The Tx DSP Board



Tx DSP Board

Receiver

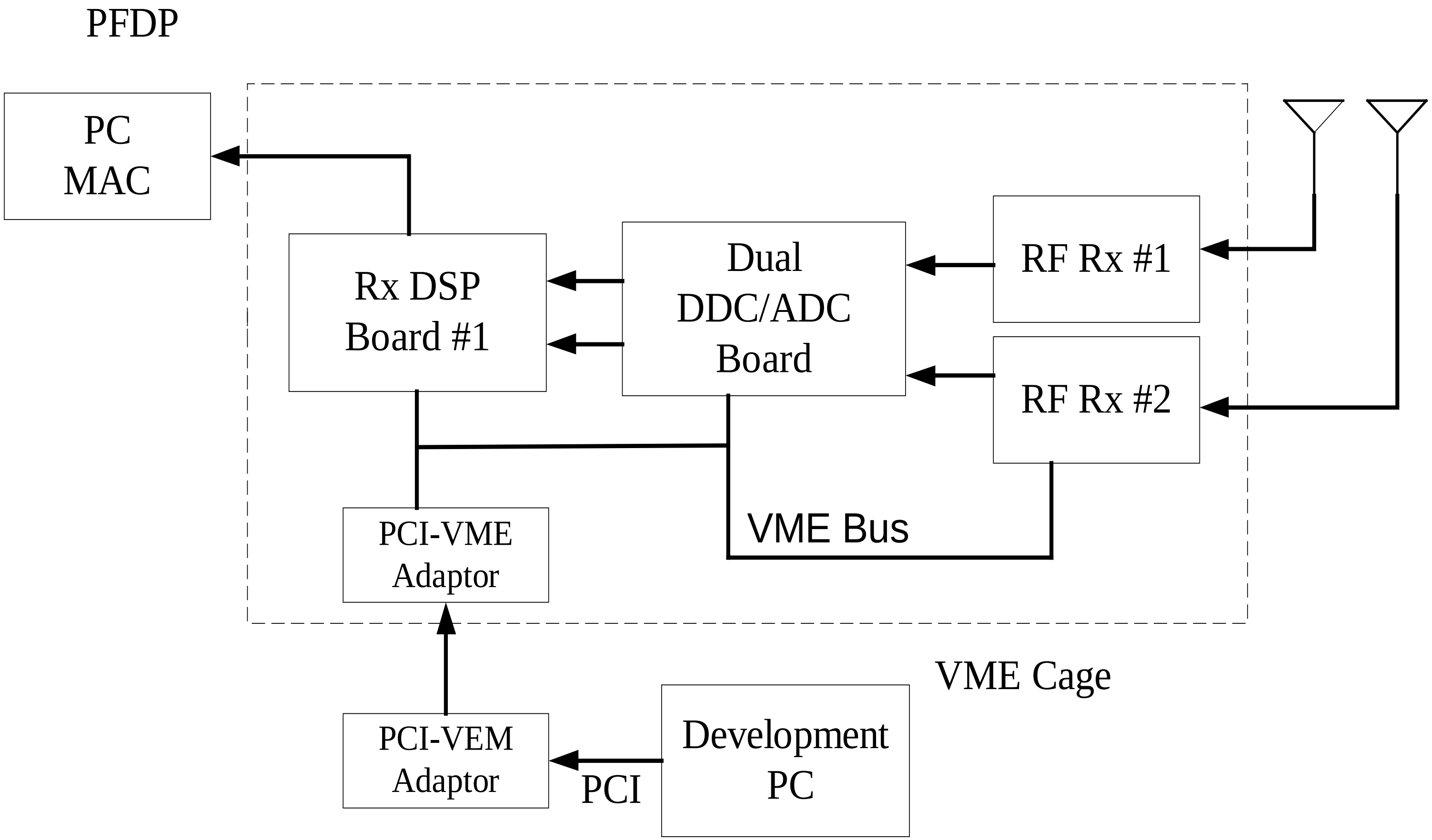
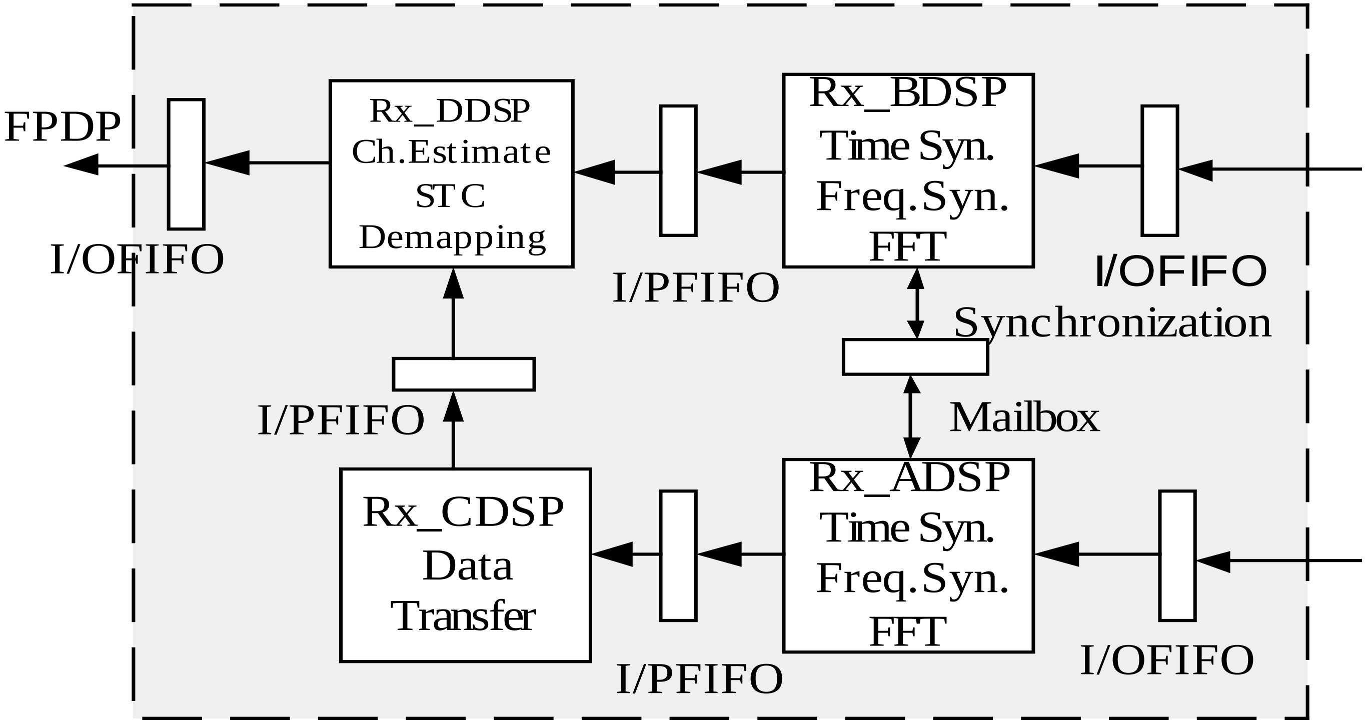

PFDP
PC MAC
Rx DSP Board #1
Dual DDC/ADC Board
RF Rx #1
RF Rx #2
PCI-VME Adaptor
VME Bus
VME Cage
PCI-VEM Adaptor
PCI
Development PC

Diagram of Rx DSP Board



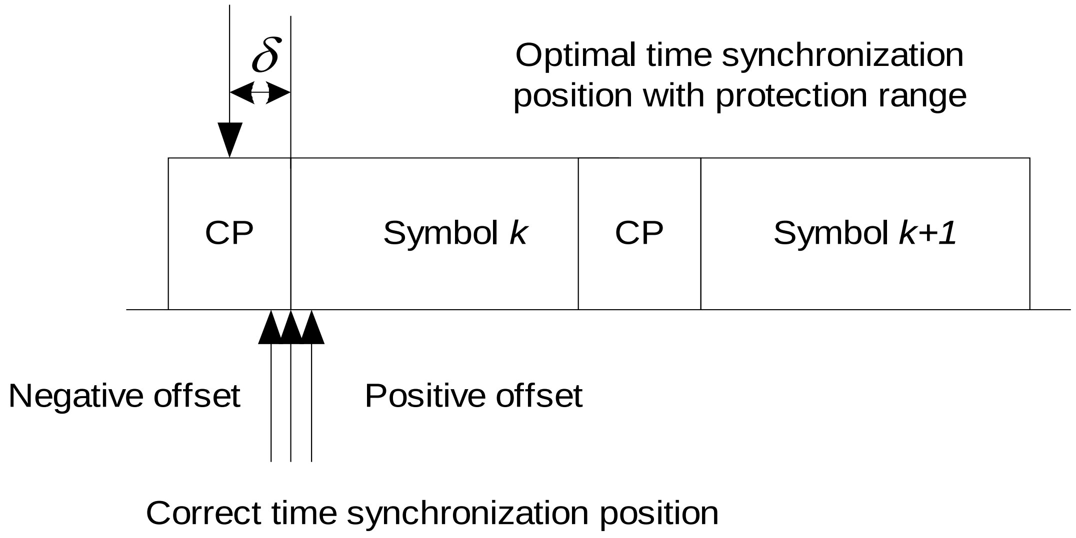
RxDSPBoard

System Specification

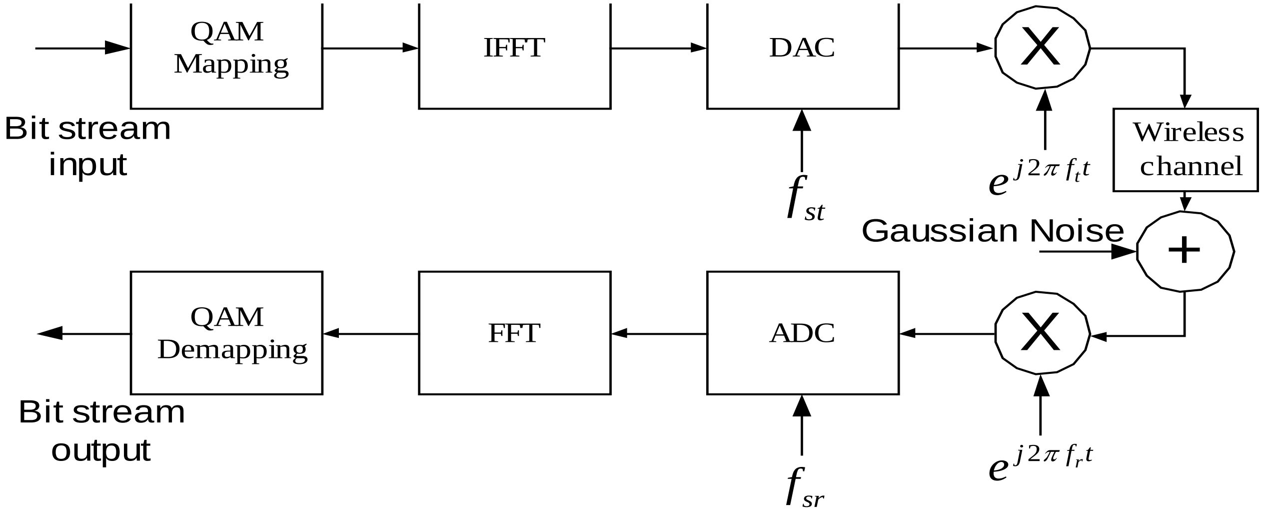
FFT Block Size	256
Cyclic Prefix	64
Number of Subcarriers	200
Carrier Frequency	2435MHz
Sample Rate	8MSPS
Modulation	64QAM
Data Rate	30Mbit/s
Frame Preamble	Based on IEEE 802.16

Synchronizations in OFDM System

- Time Synchronization



Frequency and Sampling Clock Synchronization



QAM Mapping

IFFT

DAC

X

Wireless channel

Bit stream input

f_{st}

$e^{j2\pi f_t t}$

Gaussian Noise

+

QAM Demapping

FFT

ADC

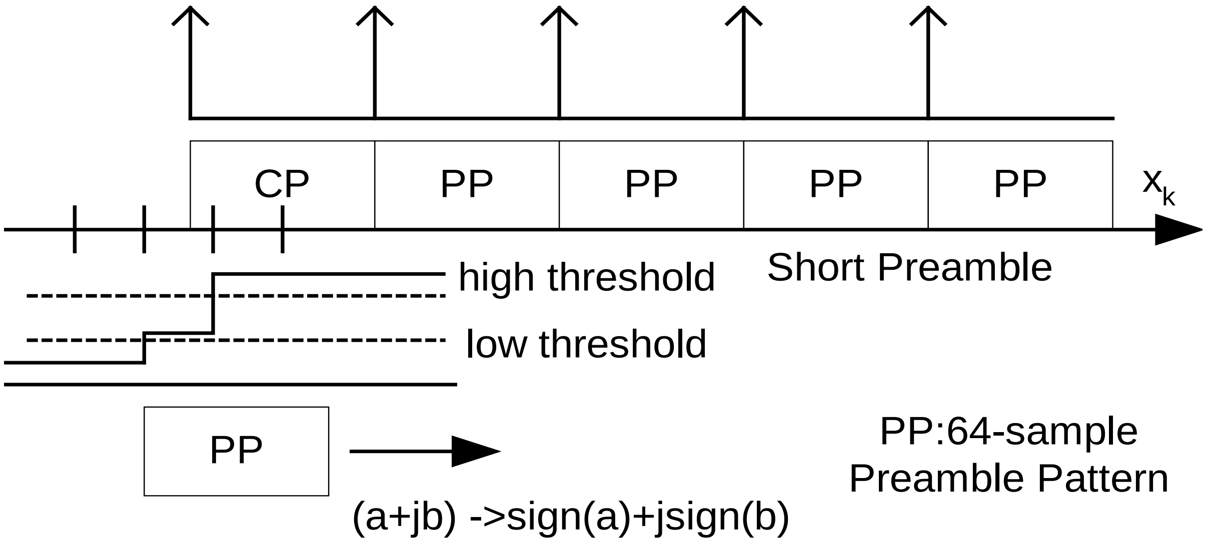
X

Bit stream output

f_{sr}

$e^{j2\pi f_r t}$

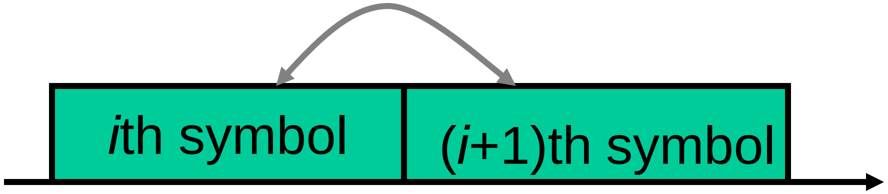
Time Synchronization



- Locate the start of an OFDM symbol
- Cross-correlator requires huge computation
- Coarse scan, quantization

Frequency Synchronization

- Frequency offset causes the loss of orthogonality which leads to ISI
- Moose's method



$$Y_{k,i} = R_k + W_{k,i}$$

$$Y_{k,i+1} = R_k e^{j2\pi\varepsilon} + W_{k,i+1}$$

$$\hat{\varepsilon} = \frac{1}{2\pi} angle(\sum_{k=0}^{N-1} Y_{k,i}^{*} Y_{k,i+1})$$

$$D(\hat{\varepsilon}) = \frac{1}{4\pi^2 N \times SNR}$$

Probability Density Function (PDF) of Estimate Error

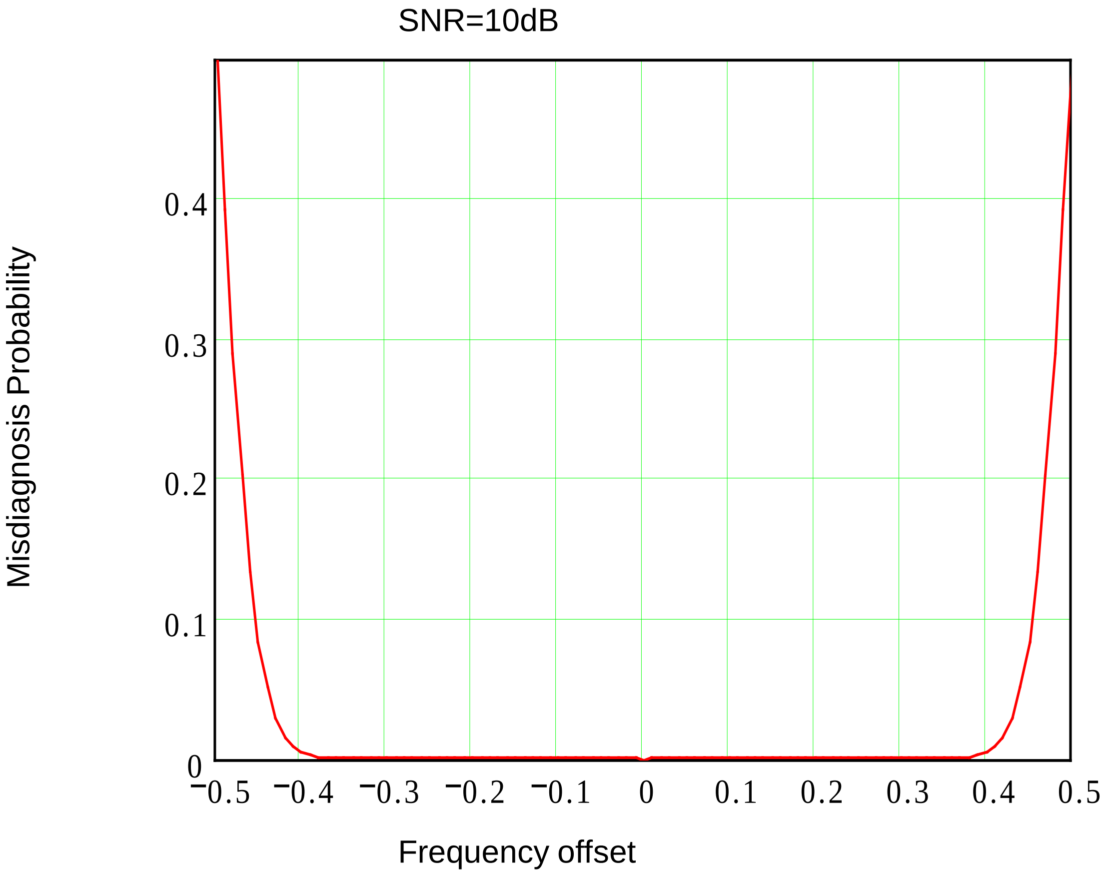
$$\sum_{k=0}^{N-1} Y_{k,i}^{*} Y_{k,i+1}$$

$$= \sum_{k=0}^{N-1} (R_k^{*} R_k e^{j2\pi\varepsilon} + R_k^{*} W_{k,i+1} + R_k W_{k,i}^{*} e^{j2\pi\varepsilon} + W_{k,i}^{*} W_{k,i+1})$$

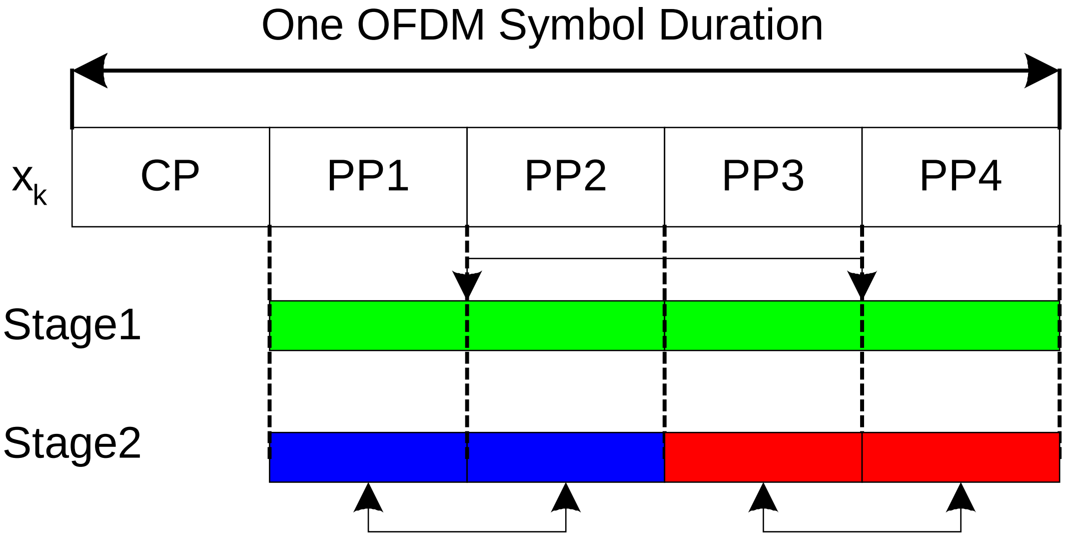
$$D(\hat{\varepsilon} - \varepsilon) = \frac{1}{12} e^{-\beta}$$

$$+ \frac{1}{8\pi^{5/2}} \int_{-\pi}^{\pi} \sqrt{\beta} e^{-\beta \sin(\theta)^2} \cos(\theta)(1 + erf(\sqrt{\beta}\cos(\theta))\theta^2 d\theta$$

Misdiagnosis Probability



A Multi-Stage Carrier Frequency Offset Estimator



$$\hat{\varepsilon} = \sum_{i=1}^{n} \Lambda(\hat{\varepsilon}_i)\alpha_i$$

$$\hat{\varepsilon}_i = \frac{2^{i-1}}{\pi} angle\left(\sum_{l=0}^{2^{i-1}-1} \sum_{k=lN/2^{i-1}}^{N/2^i+lN/2^{i-1}-1} x_k^* x_{k+N/2^i}\right) \qquad \sum_{i=1}^{n} \alpha_i = 1$$

Applied to IEEE 802.16 OFDM Short Preamble

$$D(\hat{\varepsilon}_1) = 2/(\pi^2 N\gamma) \qquad Cov(\hat{\varepsilon}_1, \hat{\varepsilon}_2) = 0$$

$$D(\hat{\varepsilon}_2) = 8/(\pi^2 N\gamma)$$

$$D(\hat{\varepsilon}) = \alpha_1^2 D(\hat{\varepsilon}_1) + (1-\alpha_1)^2 D(\hat{\varepsilon}_2)$$

$$\alpha_1 = 4/5, \quad \alpha_2 = 1/5$$

$$D(\hat{\varepsilon}) = \frac{8}{5}\frac{1}{\pi^2 N\gamma}$$

Sampling Clock Synchronization

$$Y_{m,i} = \frac{1}{N}\sum_{n=0}^{N-1}\sum_{k=0}^{N-1} X_{k,i}H_{k,i}e^{j\frac{2\pi}{N}n(k+k\beta-m)}e^{j\frac{2\pi}{N}\alpha_i k\beta} + W_{m,i}$$

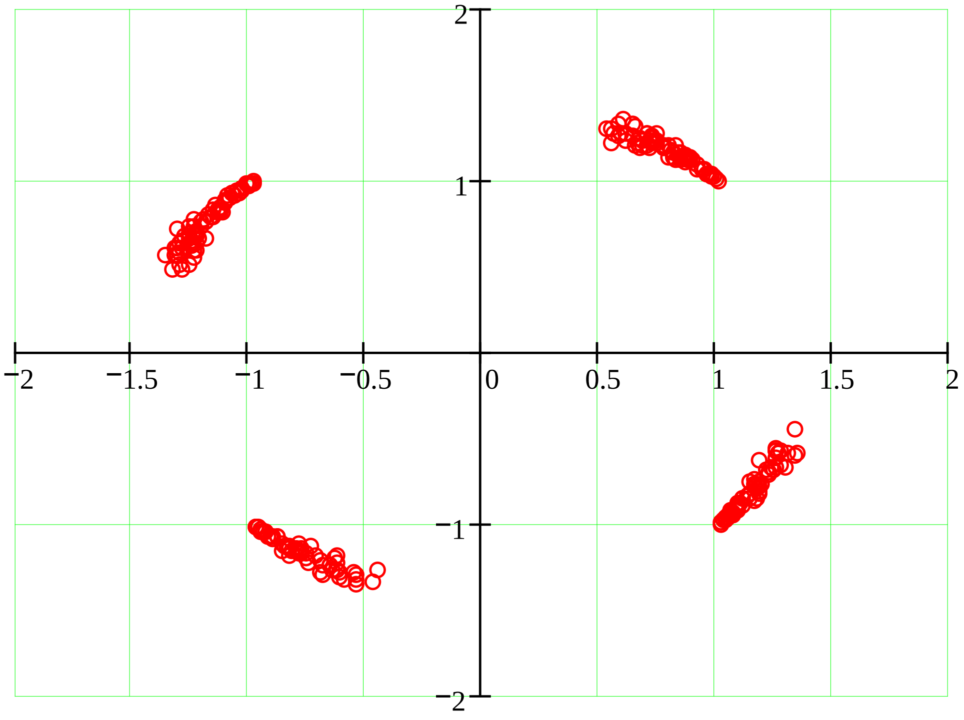
$$= X_{m,i}H_{m,i}e^{j\frac{\pi}{N}m\beta(2\alpha_i+N-1)}\frac{\sin(\pi m\beta)}{N\sin(\frac{\pi}{N}m\beta)}$$

$$+\sum_{k=0,k\neq m}^{N-1} X_{k,i}H_{k,i}e^{j\frac{\pi}{N}m\beta(2\alpha_i+N-1)}e^{-j\pi\frac{k-m}{N}}\frac{\sin(\pi k\beta)}{N\sin(\frac{\pi}{N}(k+k\beta-m))}$$

$$+W_{m,i}$$

$$\beta = \Delta f_s / f_{sr}$$

The Impairment of Sampling Clock Offset



A Cascade Frequency and Sampling Clock Offsets Estimation Method

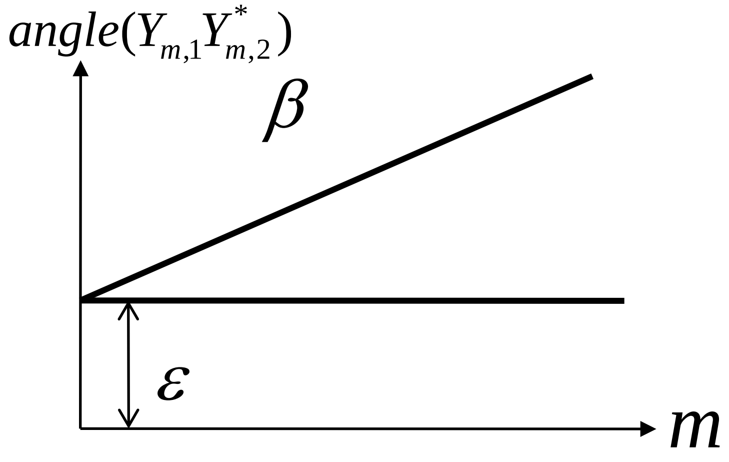
$$Y_{m,1} = R_m + W_{m,1}$$

$$Y_{m,2} = R_m e^{j2\pi(m\beta+\varepsilon)} + W_{m,2}$$

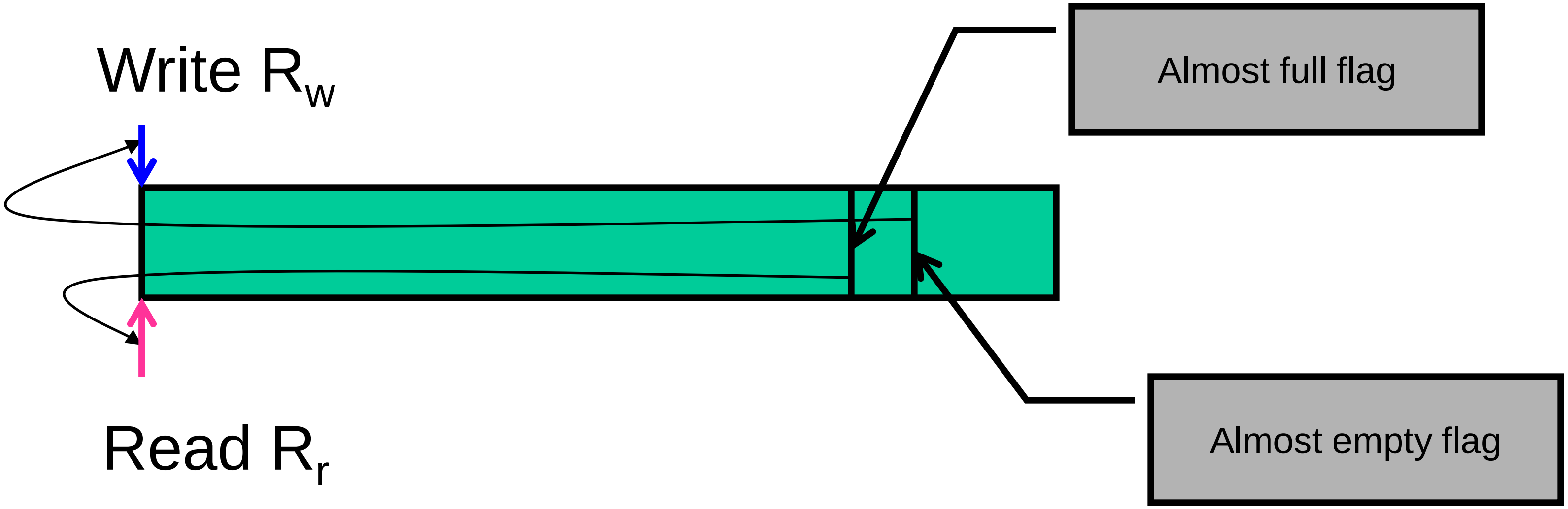
$$\hat{\varepsilon}_1 \approx \varepsilon + \frac{N-1}{2}\beta$$

$$\hat{\beta} = \frac{1}{2\pi} angle\left(\sum_{m=0}^{N/2-1} Y_{m,1}Y^*_{m,2}Y^*_{m+N/2,1}Y_{m+N/2,2}\right)$$

$$\hat{\varepsilon} = \hat{\varepsilon}_1 - \frac{N-1}{2}\hat{\beta}$$

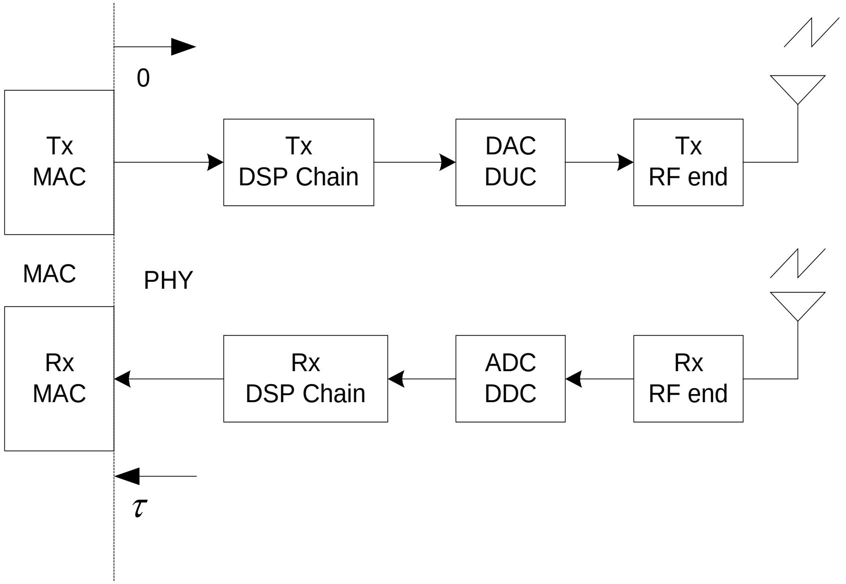


FIFO Based Data Delivery



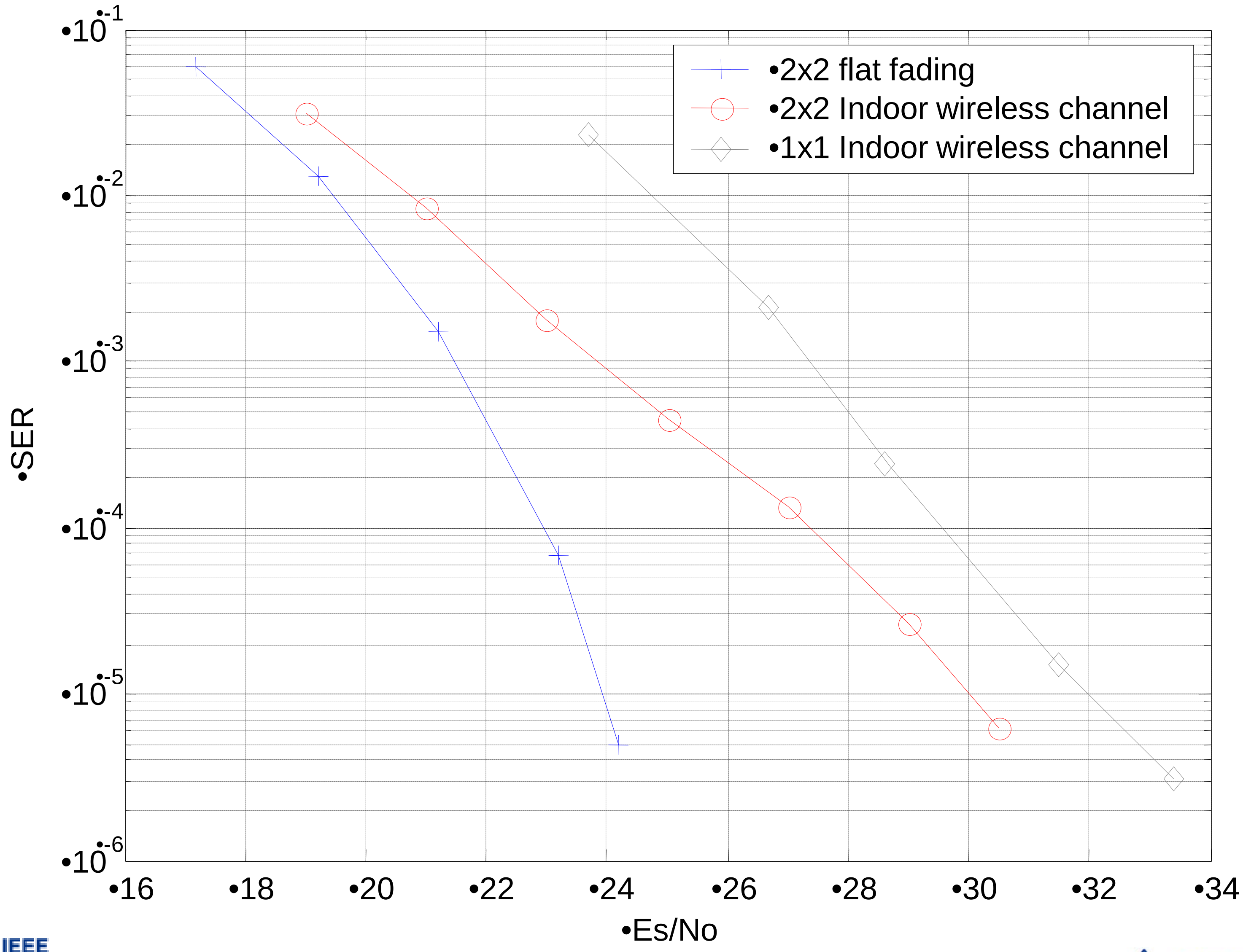
$$\Delta t = N\left(\frac{1}{R_w} - \frac{1}{R_r}\right)$$

End-to-End Processing Latency

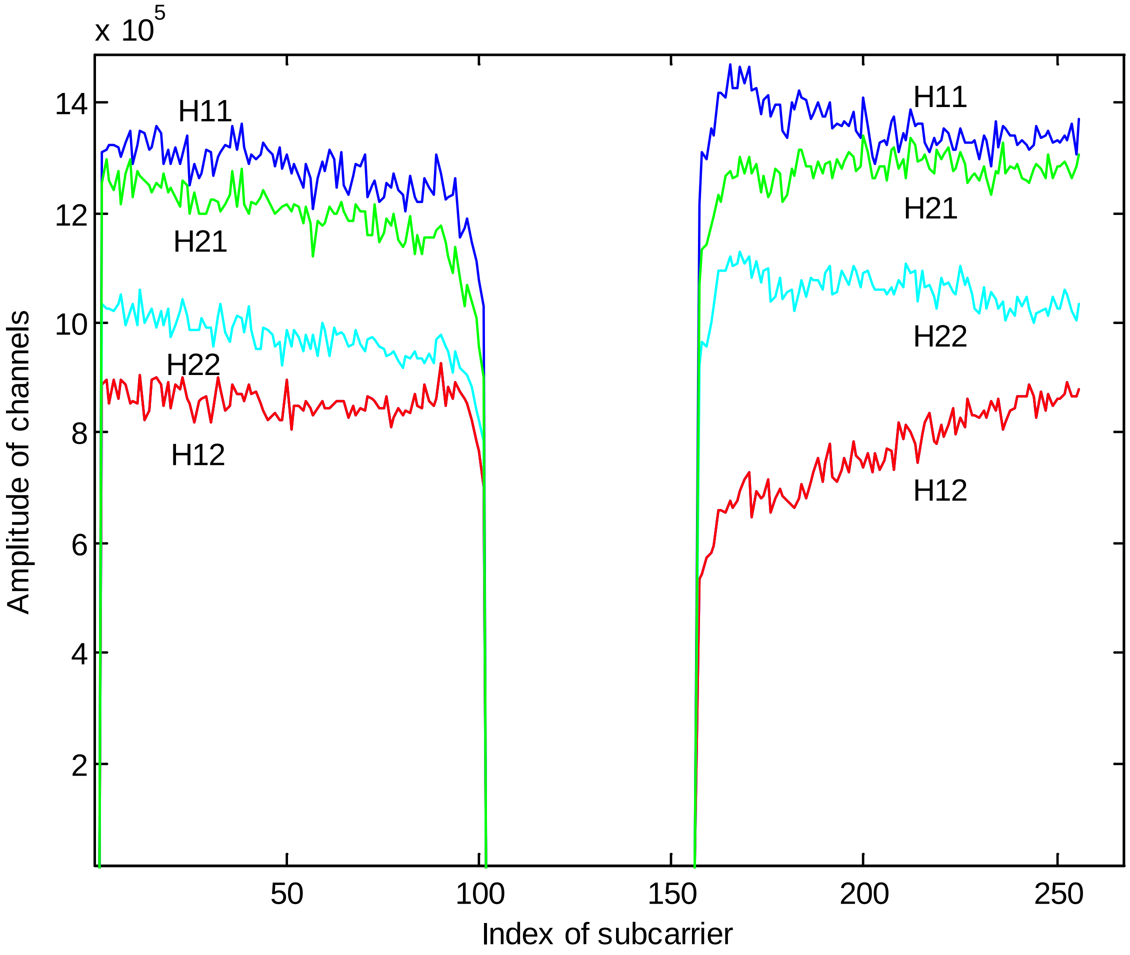


$$\tau = \frac{1}{R_s}\left(\sum_{i=0}^{L-1} length(FIFO_i)\right) + \frac{d}{c}$$

Experimental Results



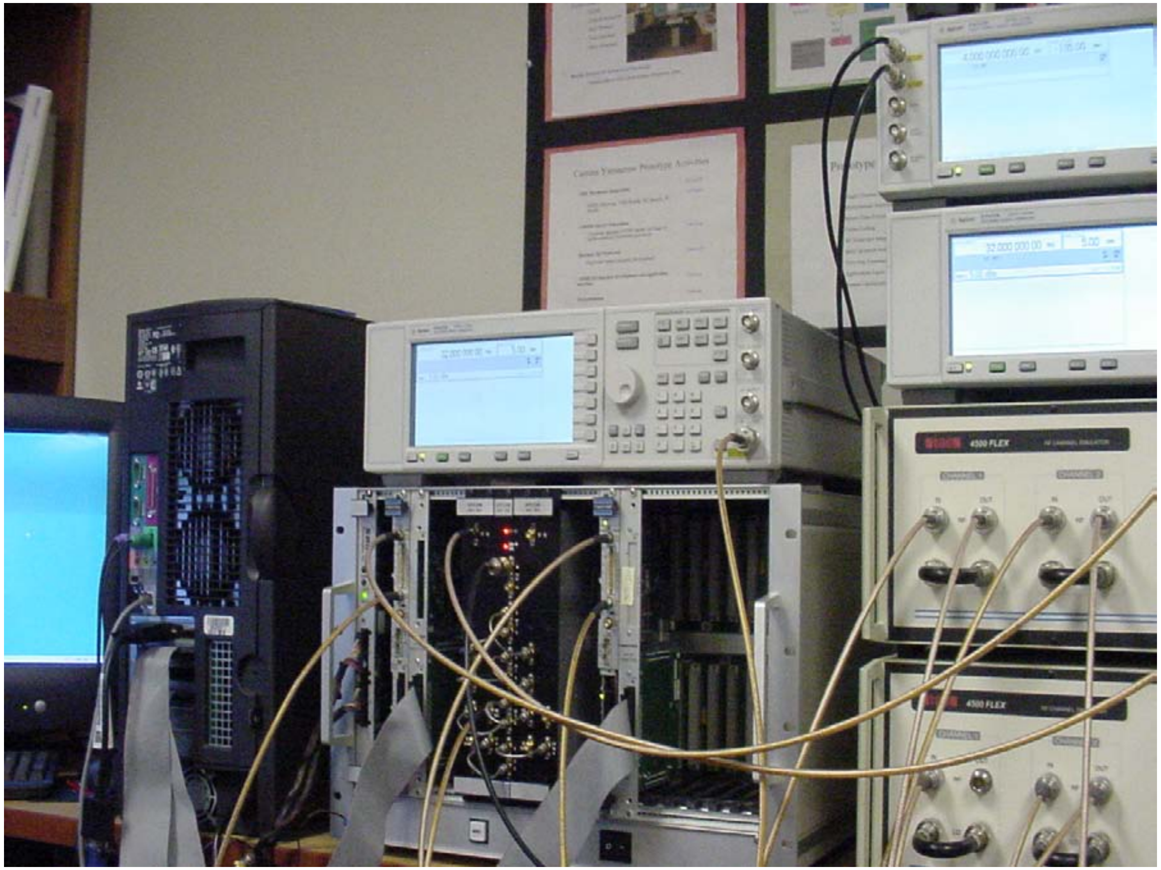
Actual CIRs


x 10^5
14
12
10
8
6
4
2
50
100
150
200
250
Amplitude of channels
Index of subcarrier
H11
H21
H22
H12
H11
H21
H22
H12

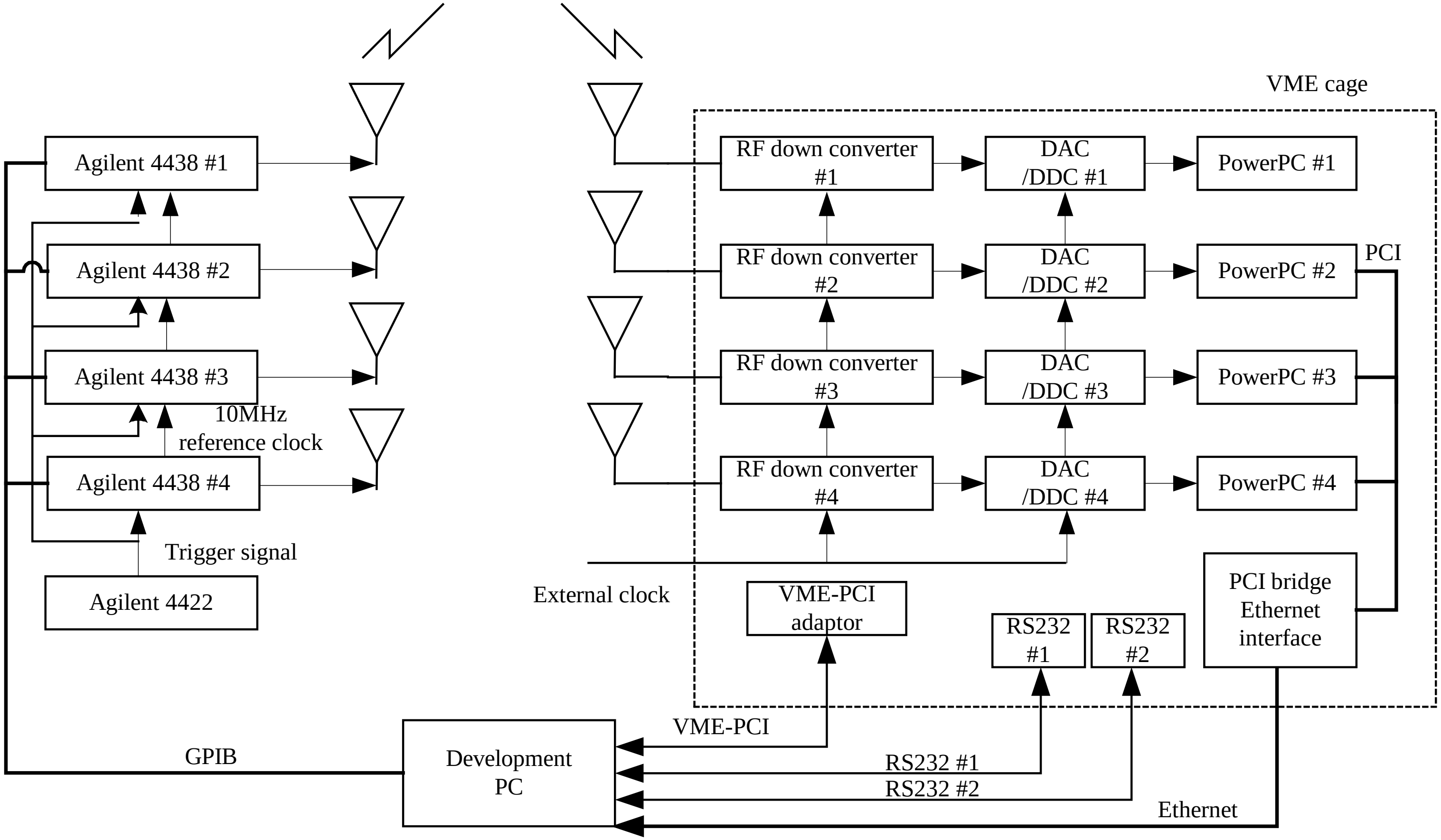
The Measured Time Consumption For Key Algorithms

Based on one OFDM symbol	Unit K cycles 1 Cycle=6ns
DMA transfer	1
IQ unpack	1.2
Time synchronization	4.1
Frequency offset estimate	3
IFFT/FFT	4.8
Channel estimate	10
Channel compensation	8
QAM mapping/de-mapping	5

A VME Cage with FPDP Interfaces Connected to a Gateway PC



A 4×4 OFDM/BLAST High-Speed Prototype



VME cage

Agilent 4438 #1
Agilent 4438 #2
Agilent 4438 #3
Agilent 4438 #4
10MHz
reference clock
Trigger signal
Agilent 4422

RF down converter #1
RF down converter #2
RF down converter #3
RF down converter #4

DAC /DDC #1
DAC /DDC #2
DAC /DDC #3
DAC /DDC #4

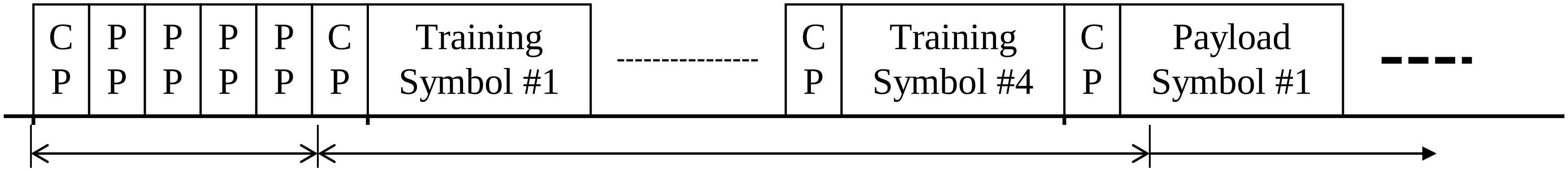
PowerPC #1
PowerPC #2
PowerPC #3
PowerPC #4
PCI

External clock
VME-PCI adaptor
RS232 #1
RS232 #2
PCI bridge Ethernet interface

GPIB
Development PC
VME-PCI
RS232 #1
RS232 #2
Ethernet

DAC: digital-to-analog converter
DDC: digital down converter

Frame Structure



CP | PP | PP | PP | PP | CP | Training Symbol #1 | ---------------- | CP | Training Symbol #4 | CP | Payload Symbol #1 | ----

Short Preamble

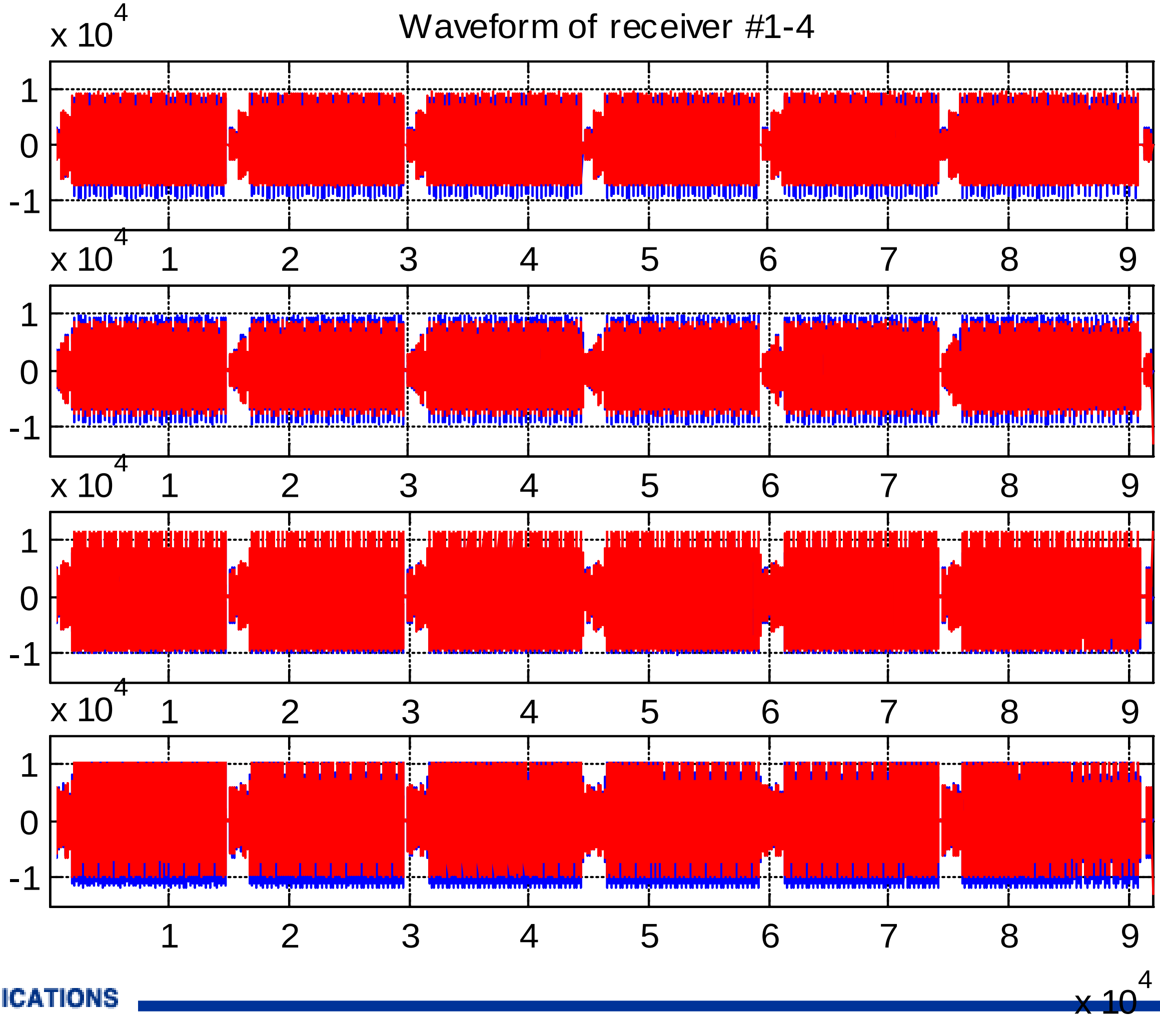
Four training symbols

40 Playload Symbols

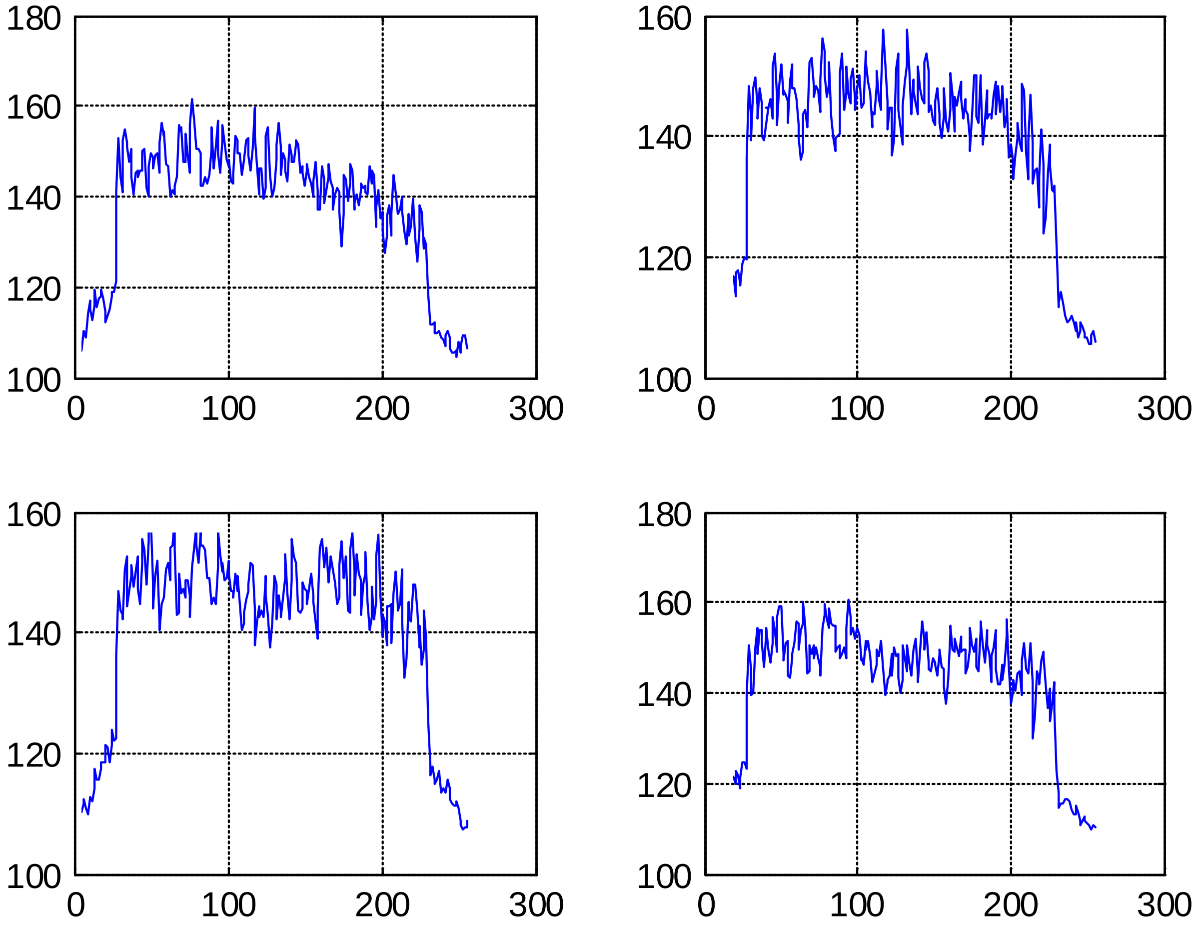
Four Training Signals

$$\begin{bmatrix} Tr_{1,1} & Tr_{1,2} & Tr_{1,3} & Tr_{1,4} \\ Tr_{2,1} & Tr_{2,2} & Tr_{2,3} & Tr_{2,4} \\ Tr_{3,1} & Tr_{3,2} & Tr_{3,3} & Tr_{3,4} \\ Tr_{4,1} & Tr_{4,2} & Tr_{4,3} & Tr_{4,4} \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \end{bmatrix} Pl$$

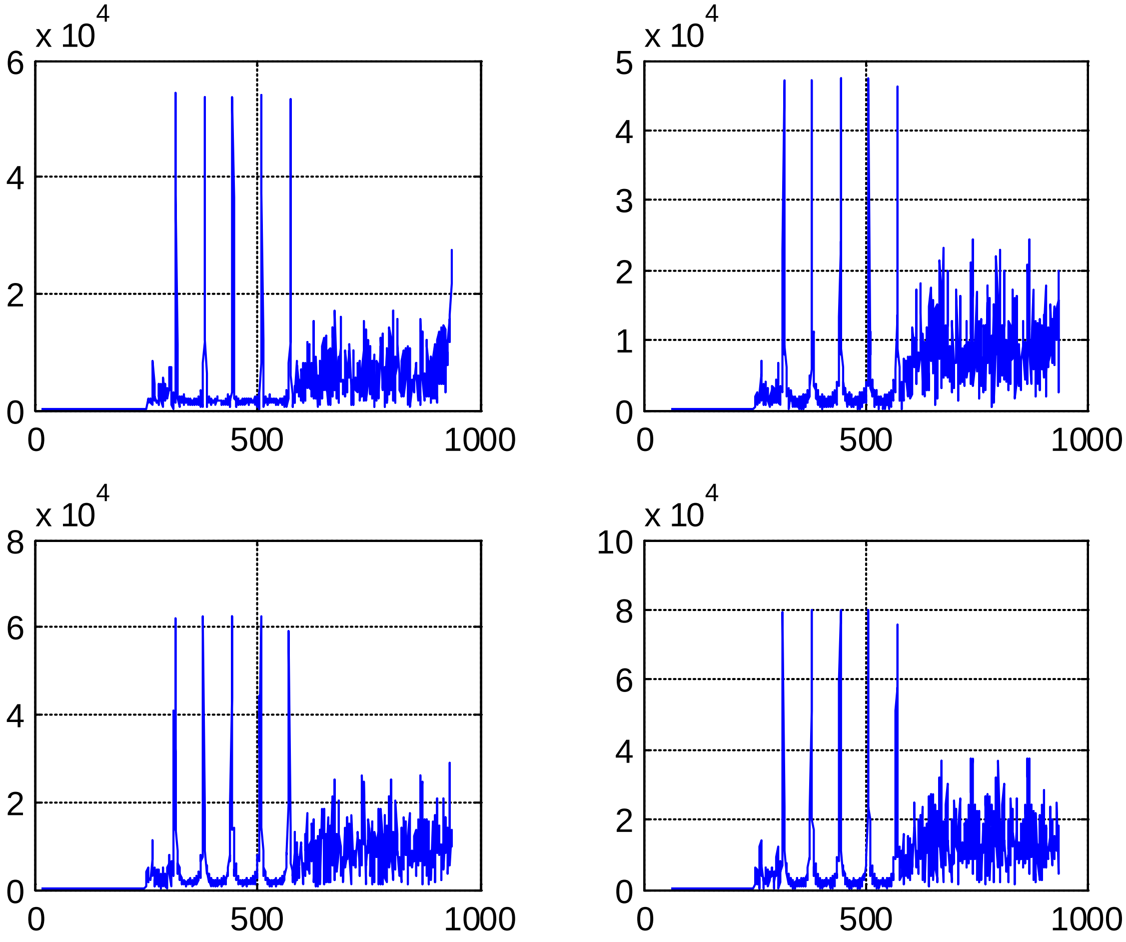
A snapshot: time waveforms



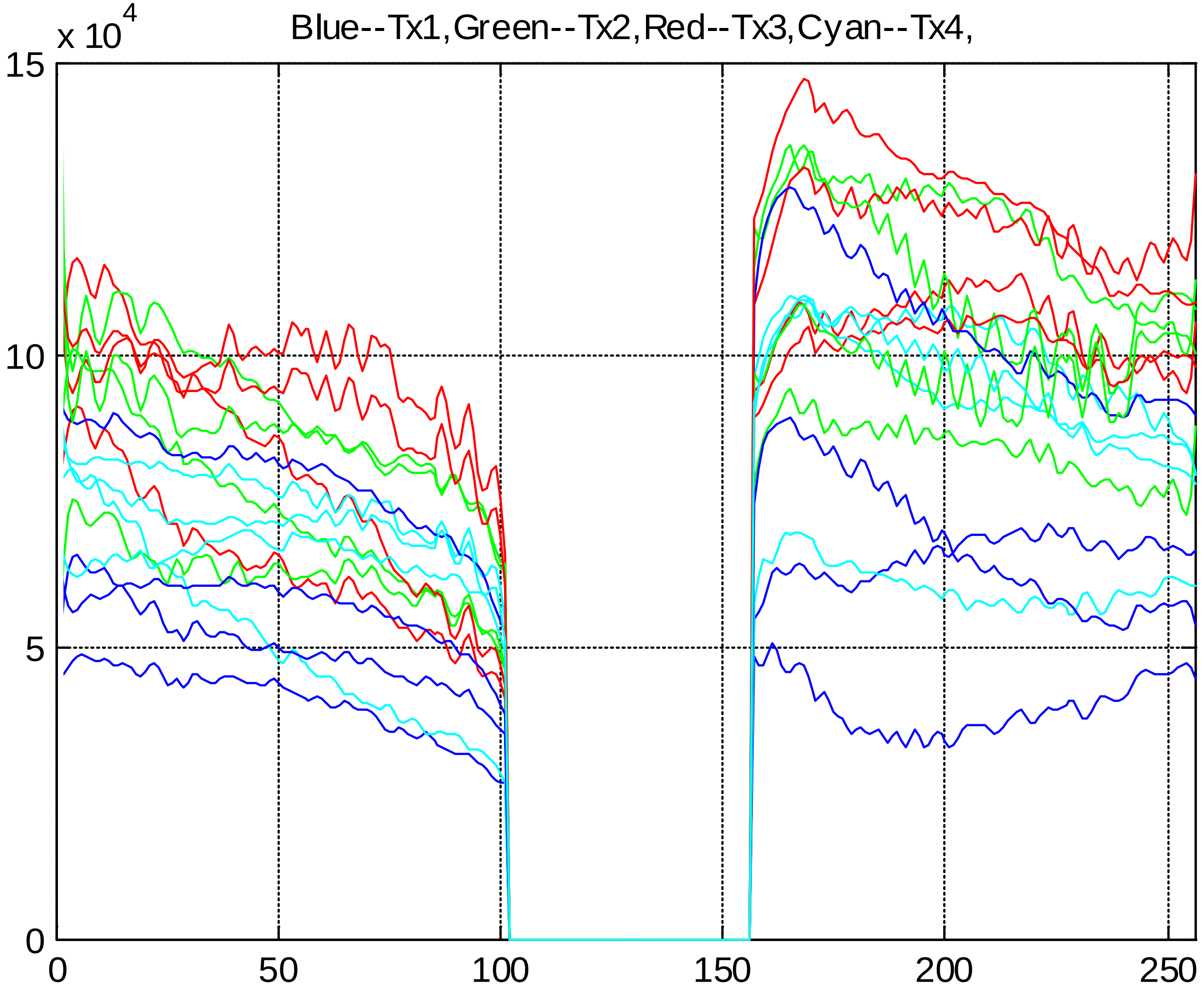
A snapshot: spectrums



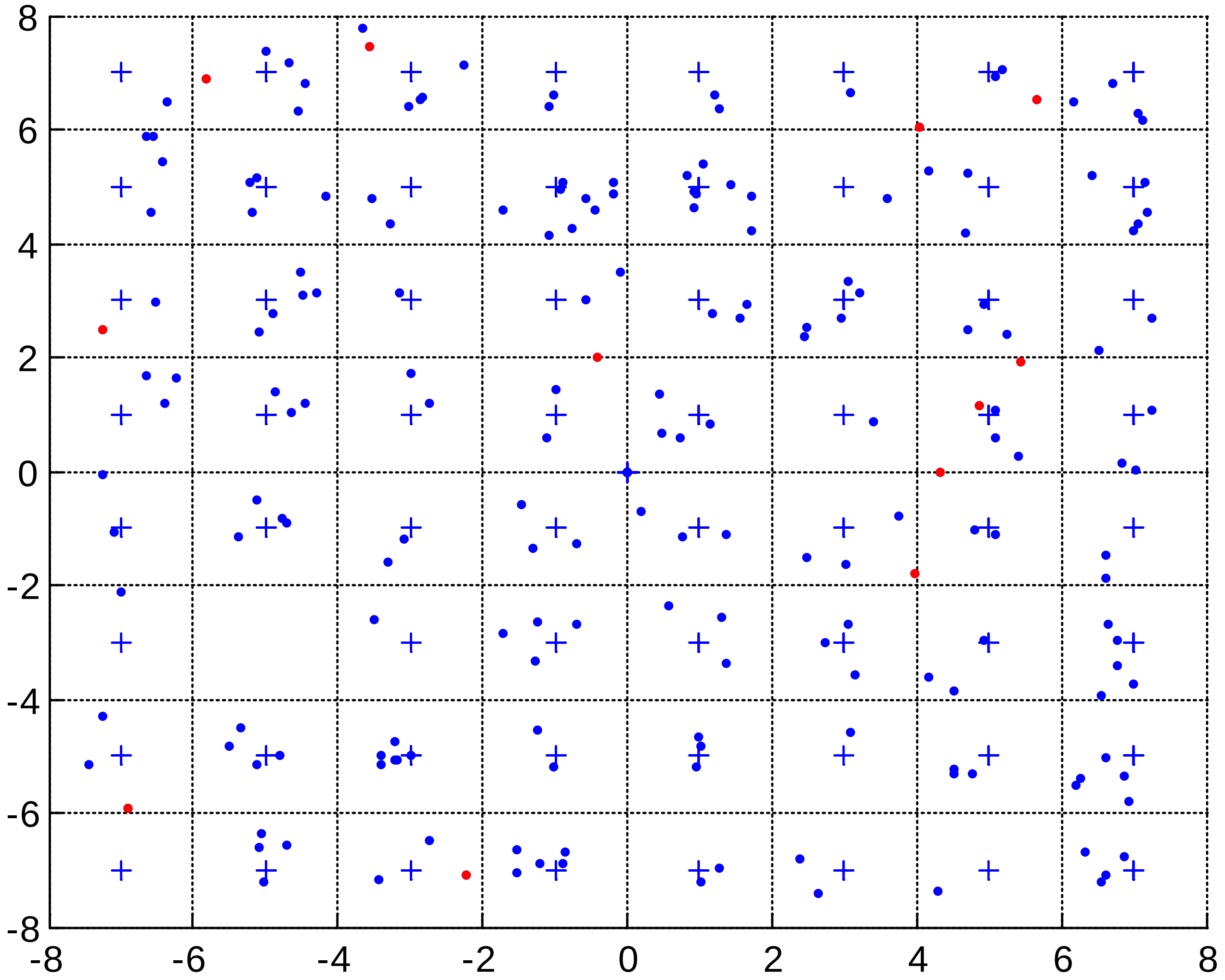
A snapshot: correlator outputs



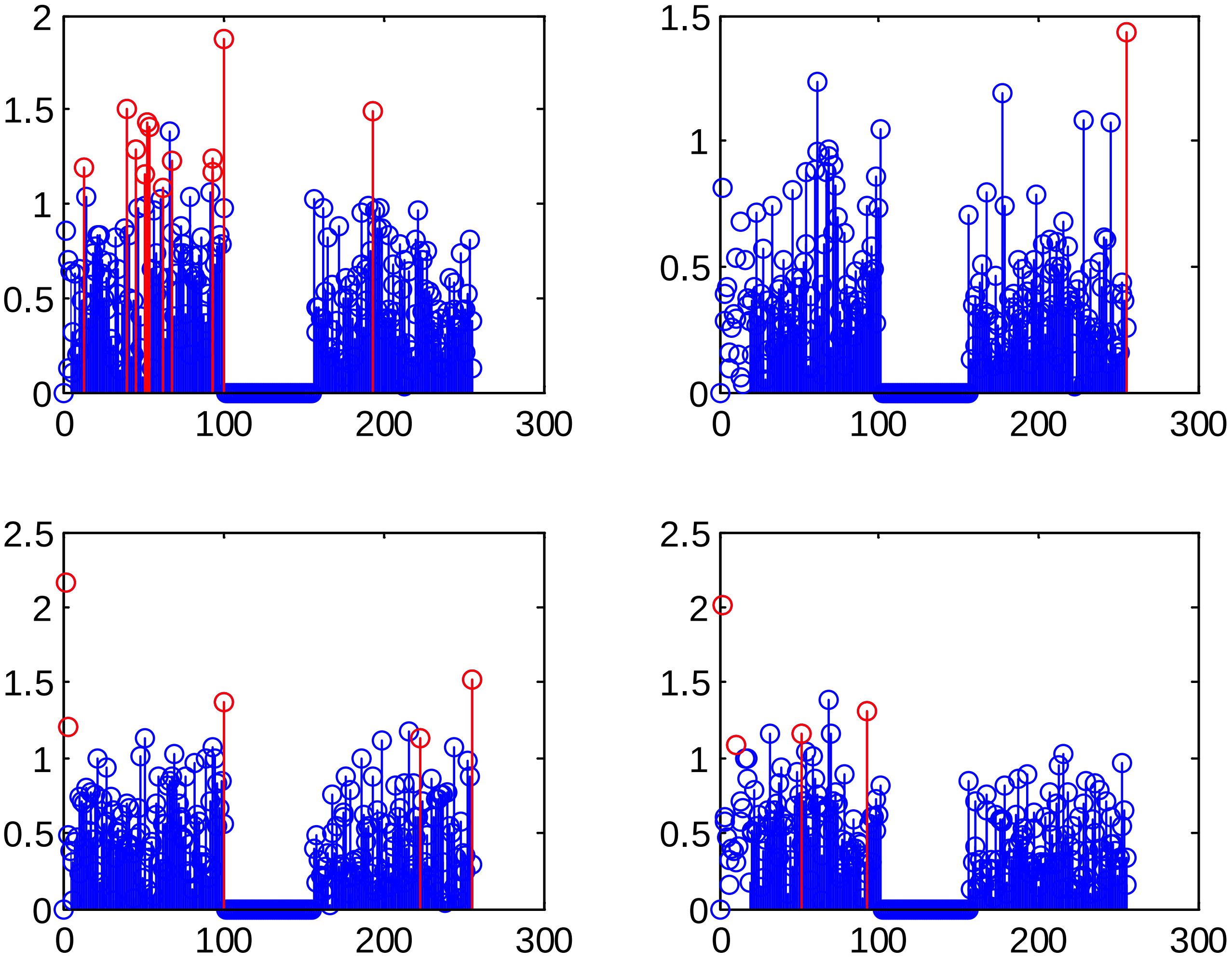
A snapshot: frequency responses



A snapshot: modulated constellations



A snapshot: error distances

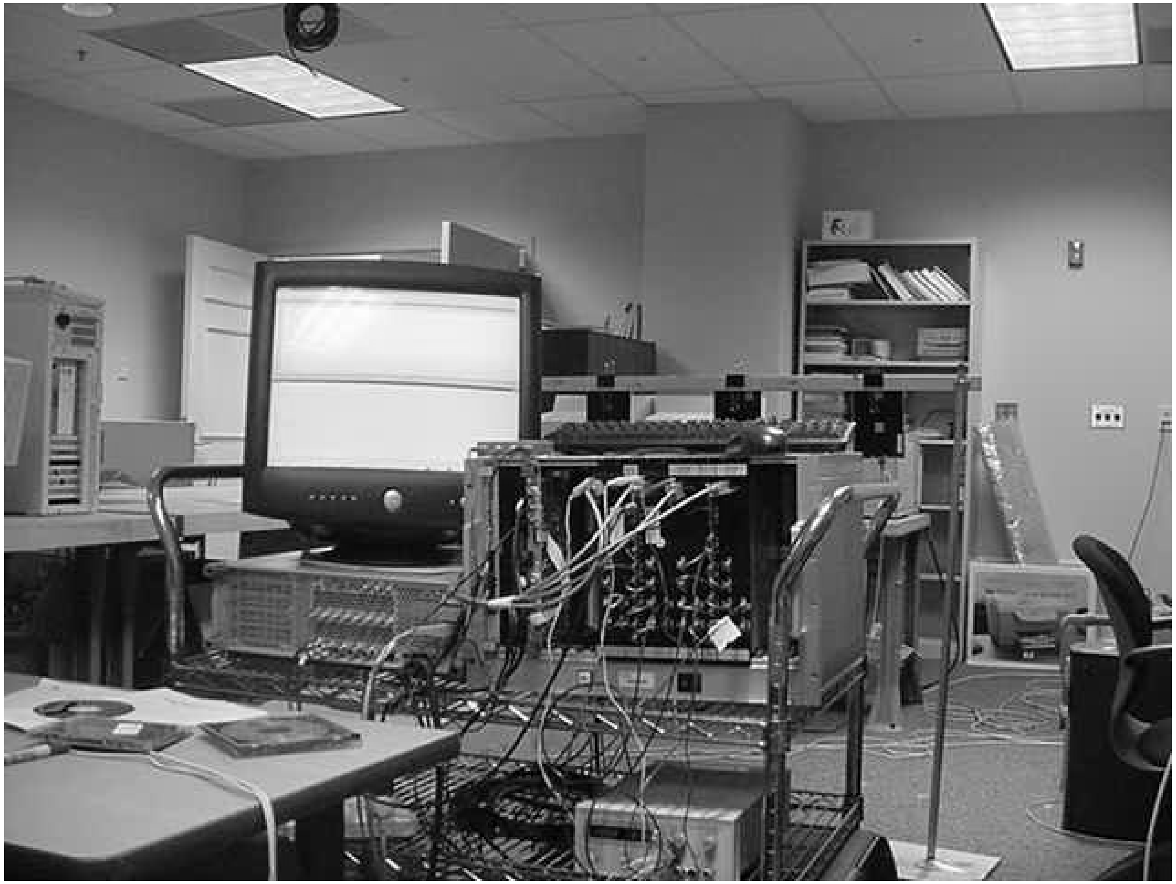


System Specifications

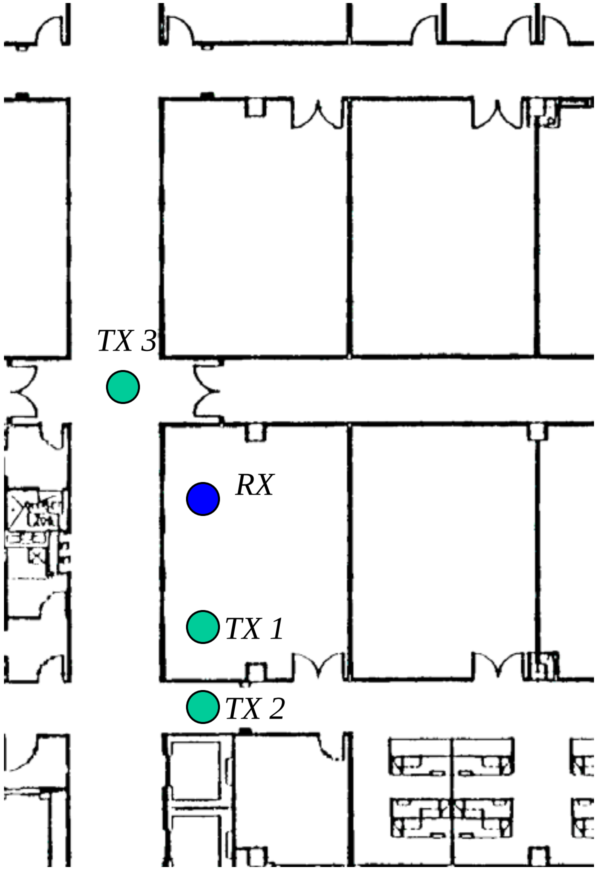
FFT Block Size	256
Cyclic Prefix	64
Number of subcarriers	200
Carrier Frequency	2435MHz
Signal Bandwidth	27.3438MHz
Sample Rate	35MSPS
Modulation	64QAM
Data Rate	525Mbit/s
Coding rate	215/255 (RS)
Spectrum efficiency	19.2bit/Hz/S
Frame Preamble	Based on IEEE 802.16

Transmitters of the 4×4 MIMO OFDM Testbed

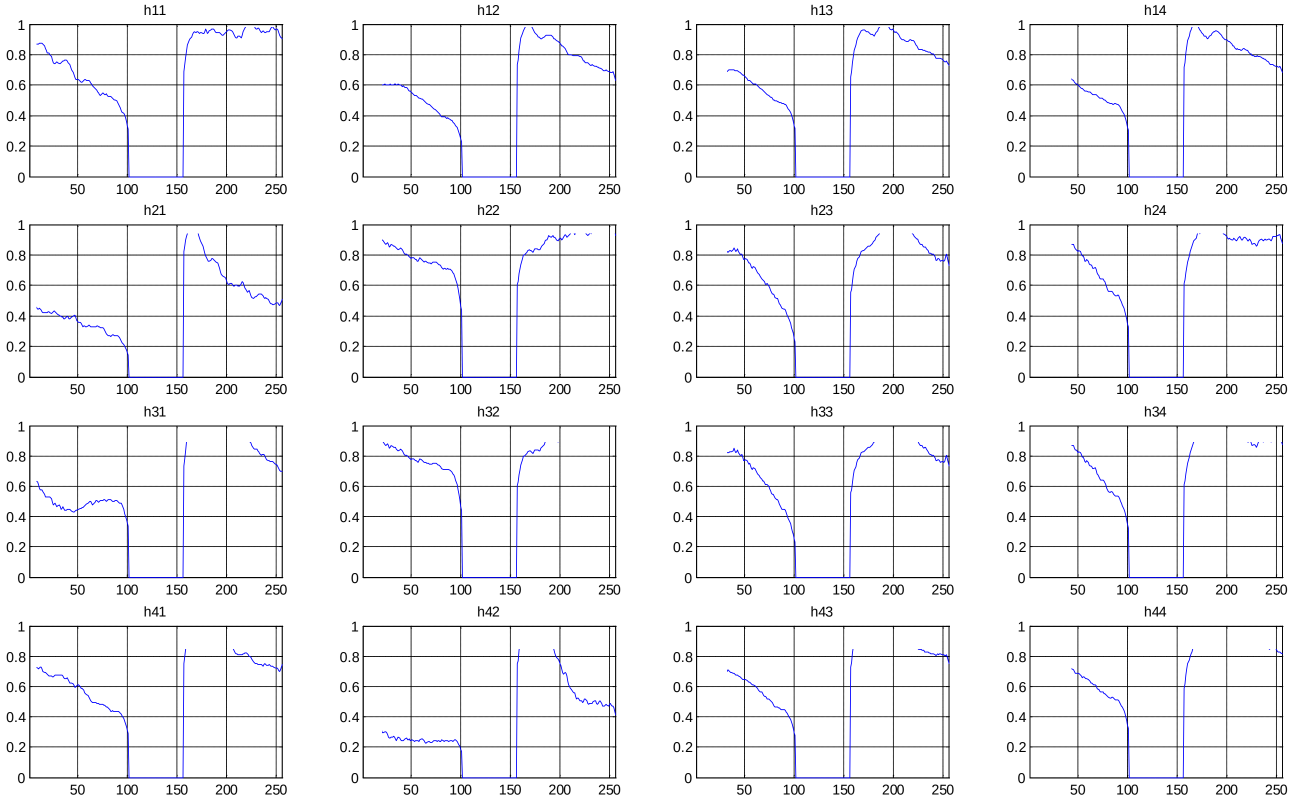
Receivers of the 4×4 MIMO OFDM Testbed



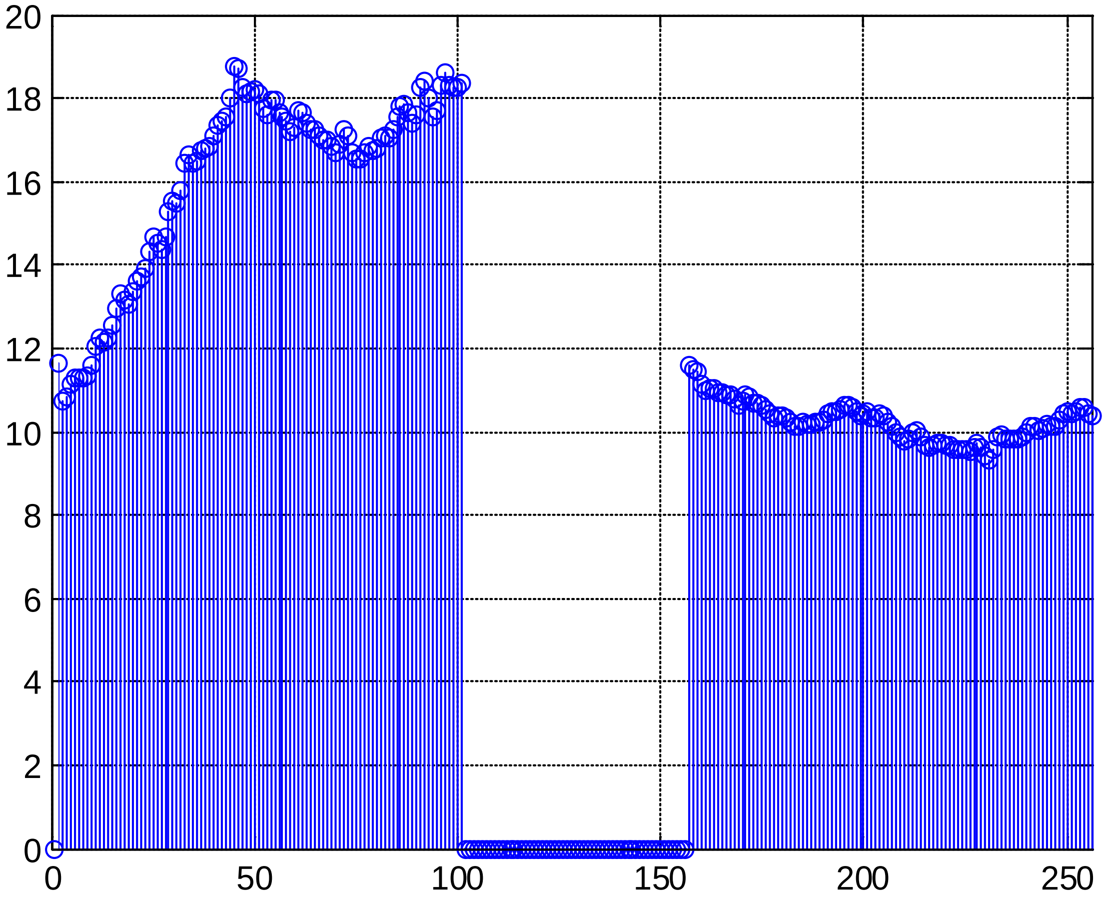
The LOS and NLOS Measurements



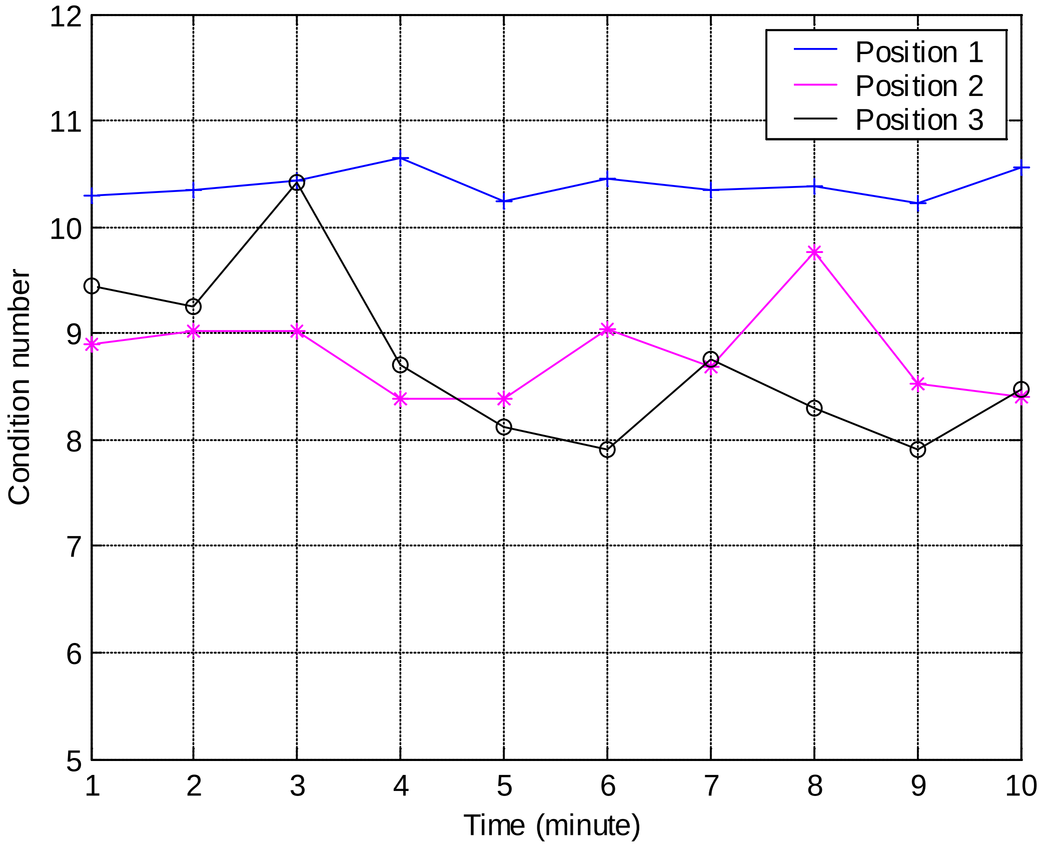
A Measurement of 16 CIRs at Position 1



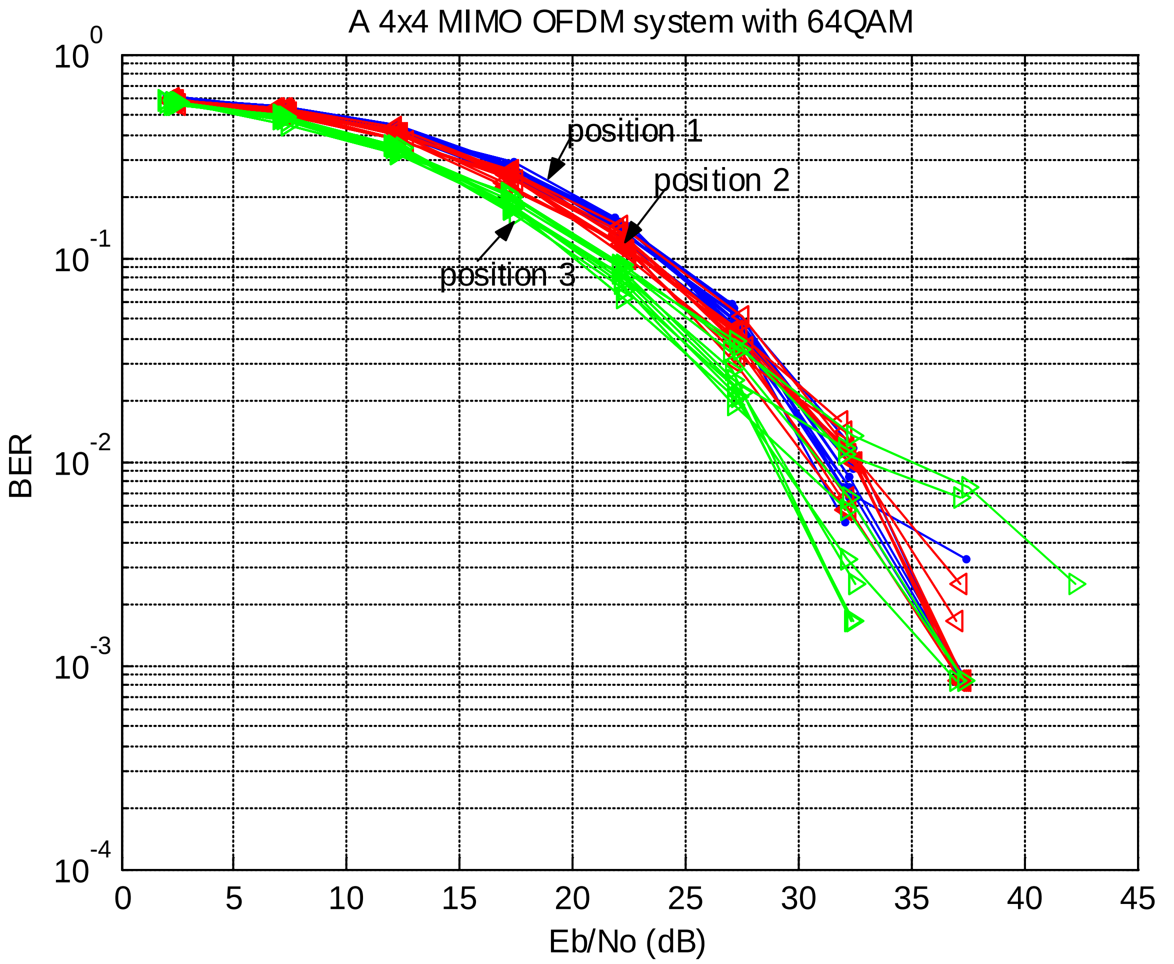
Condition Numbers at Different Subcarriers for the MIMO Channels at Position 1.



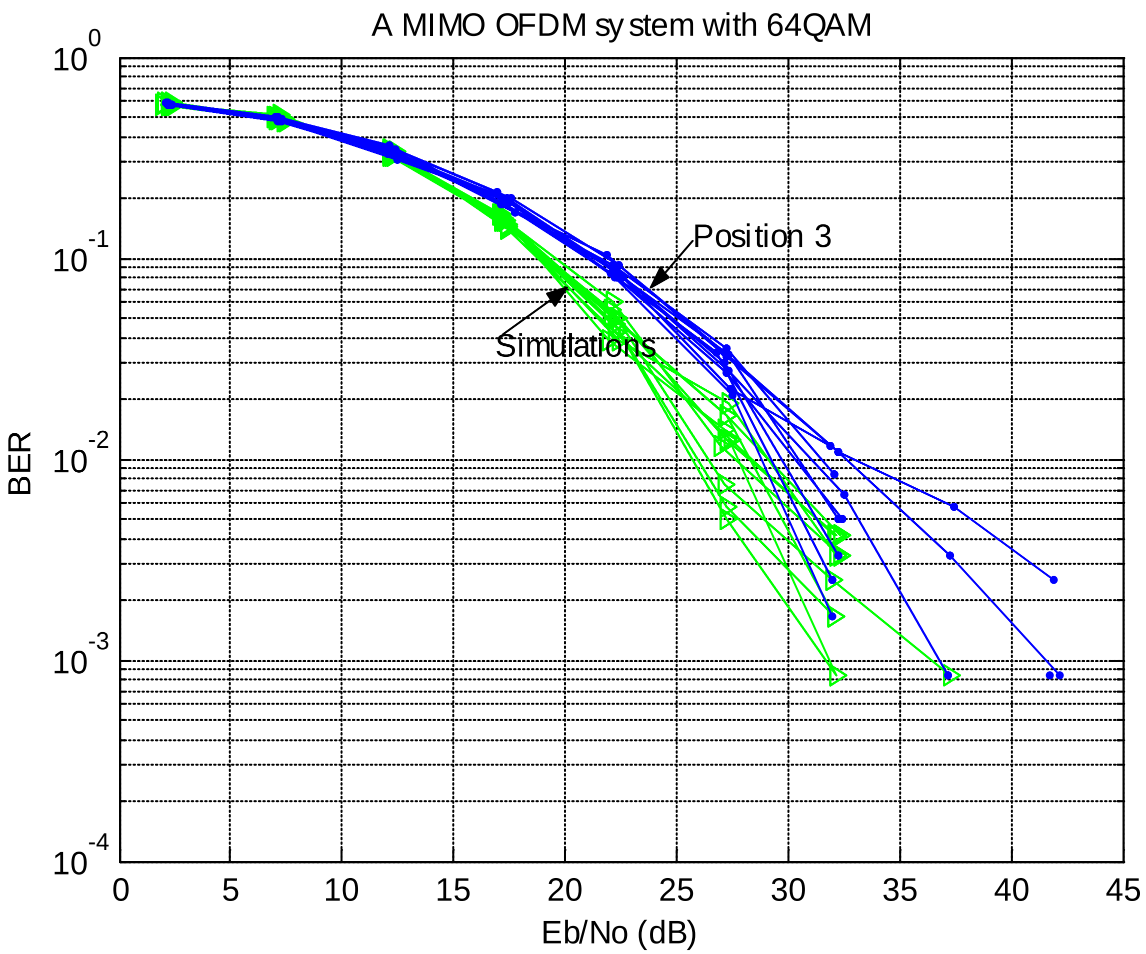
Variations of Channel Condition Number Measured at Three Different Positions



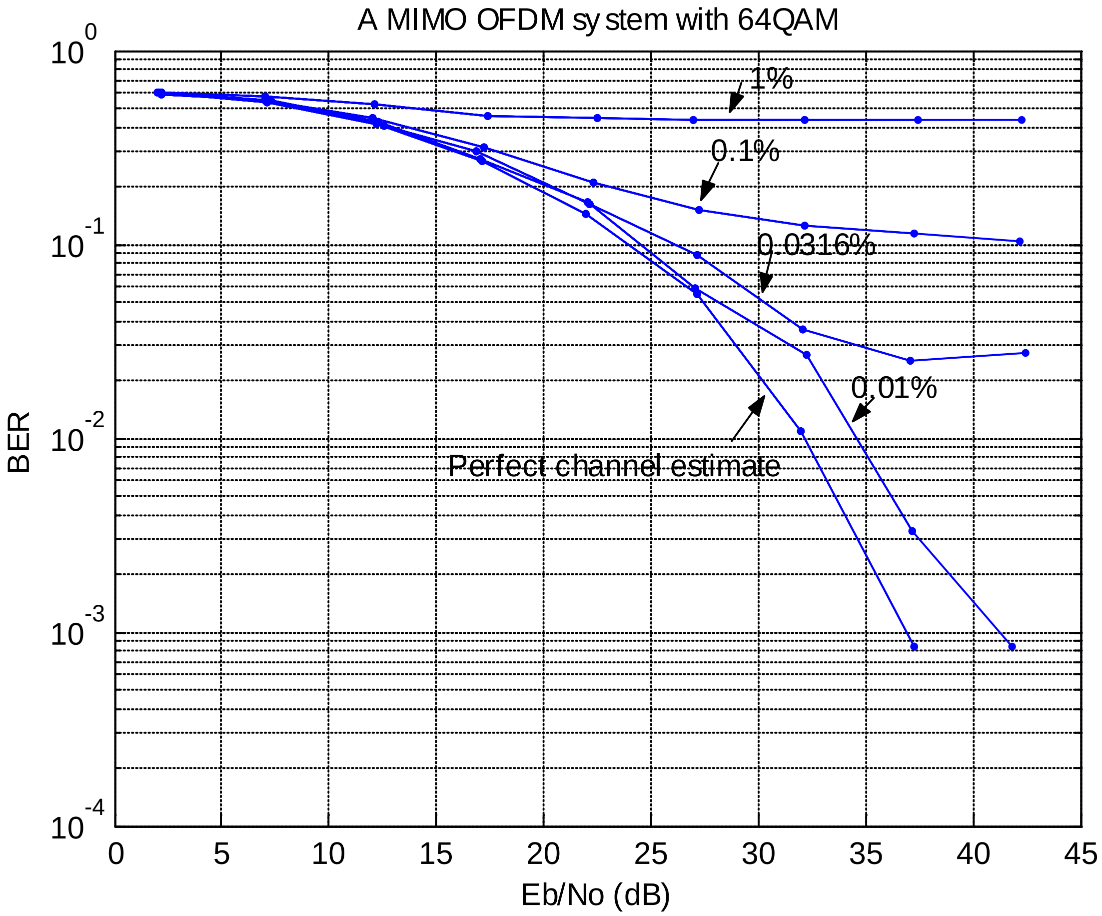
BER-SNR Curves Measured at the Three Positions



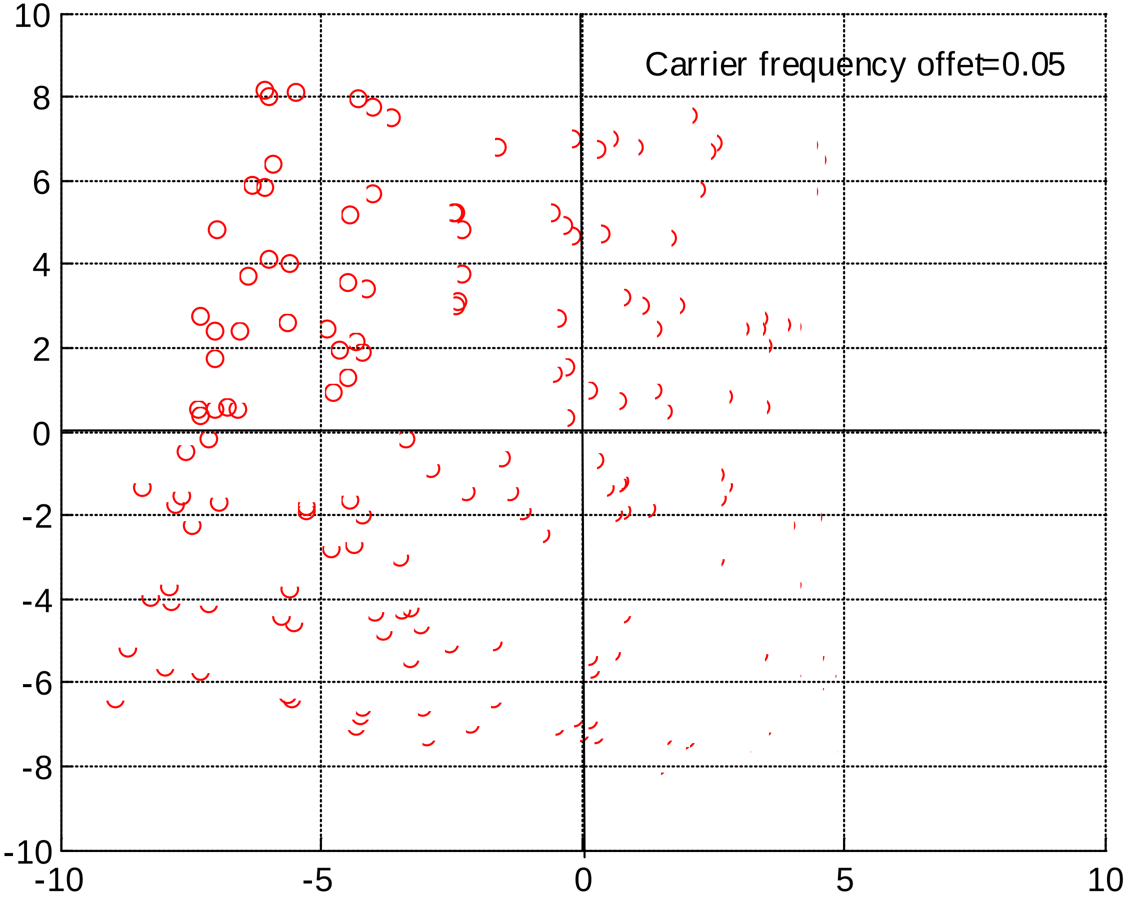
Comparison of BER-SNR Curves From Measurements and Simulations



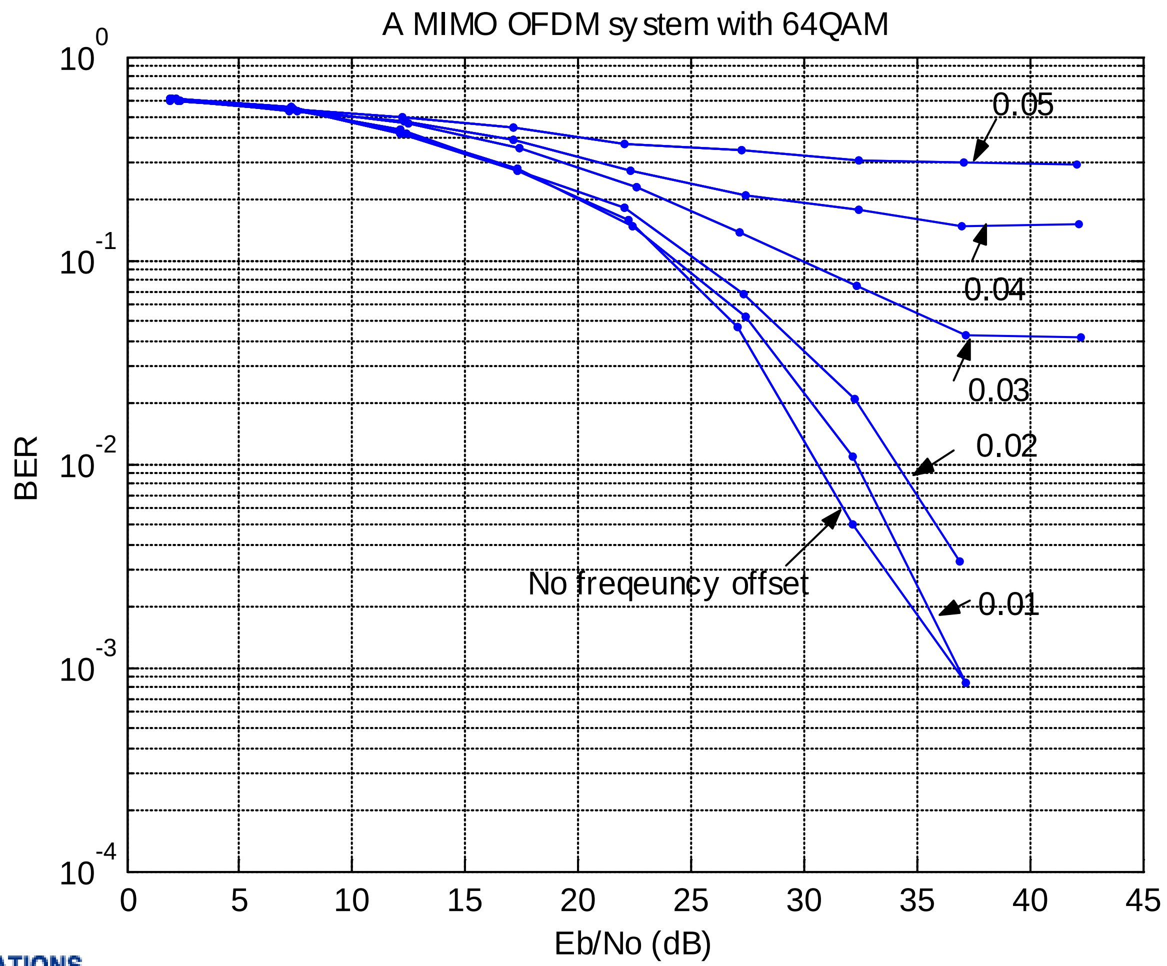
Requirements of the Accuracy of the Channel Estimate



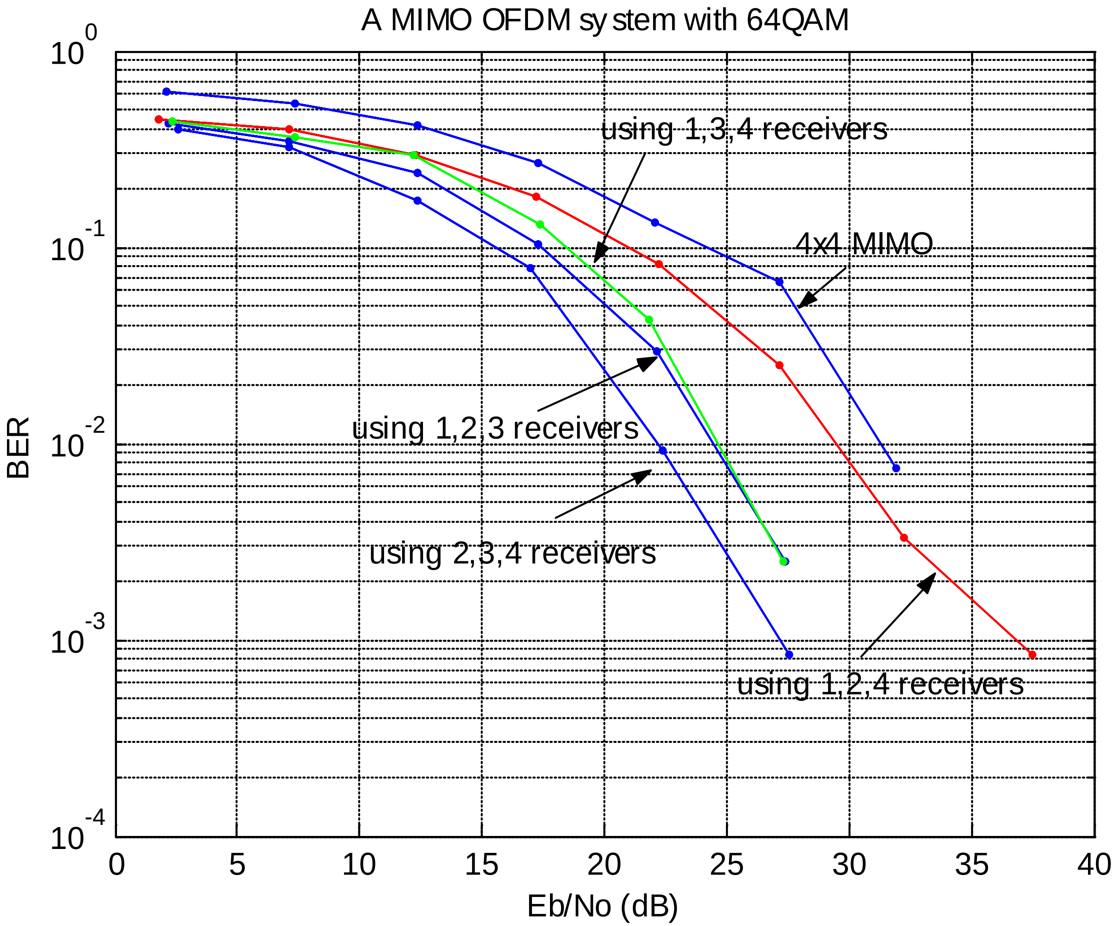
The Impacts on Constellations for 64 QAM Systems when a Carrier Frequency Offset of 0.05 is Presented



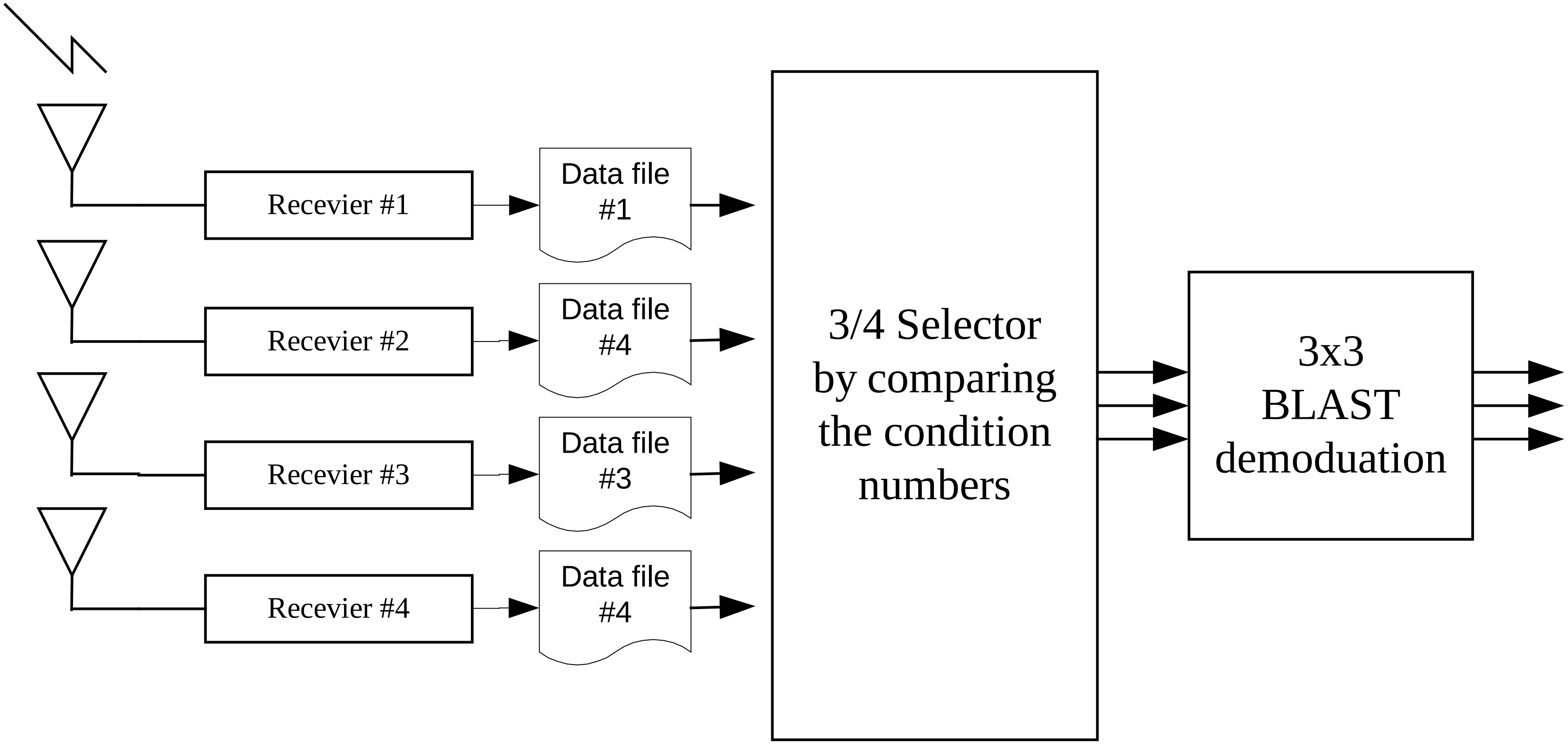
The Impacts on the BER-SNR Curves Due to Carrier Frequency Offsets at Position 1



The BER-SNR Curves of the Suggested 3×4 Asymmetric MIMO OFDM Systems



3×4 Asymmetric MIMO OFDM Systems



Recevier #1

Recevier #2

Recevier #3

Recevier #4

Data file #1

Data file #4

Data file #3

Data file #4

3/4 Selector by comparing the condition numbers

3x3 BLAST demoduation

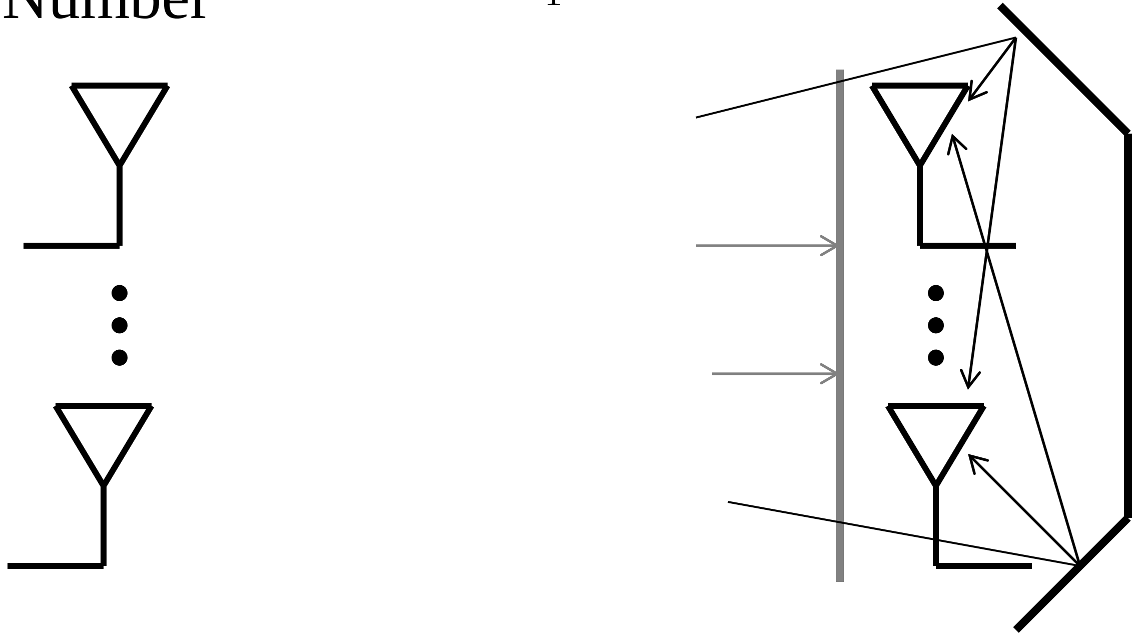
Four Combinations and Related Condition Numbers

Selection	Condition number
1,2,3 receivers	6.2
1,2,4 receivers	9.3
1,3,4 receivers	7.1
2,3,4 receivers	4.5

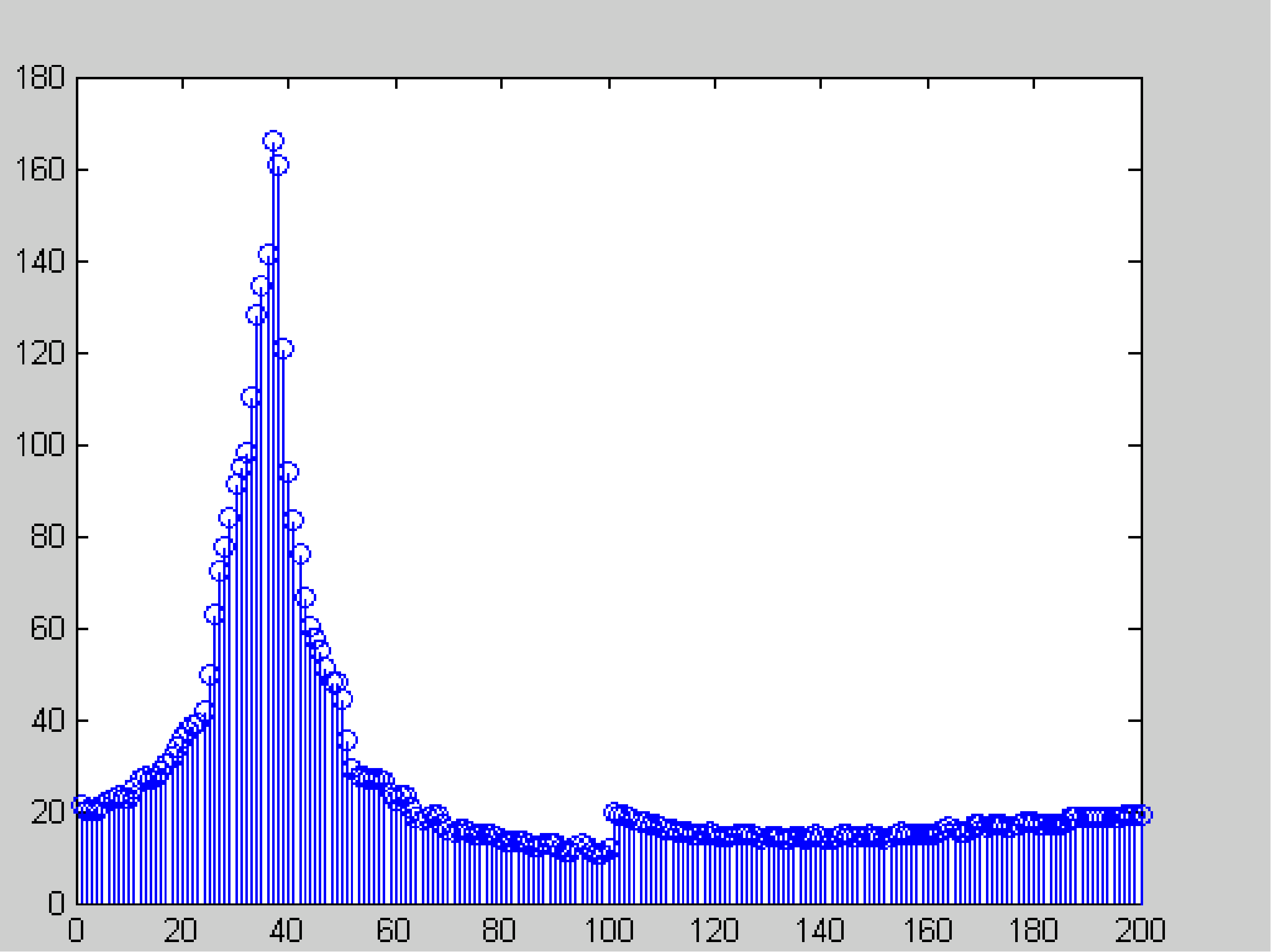
Enhance the Scattering

- MIMO shows highly sensitive to the positions in a LOS environment.
- Reflector Antenna
- Condition Number

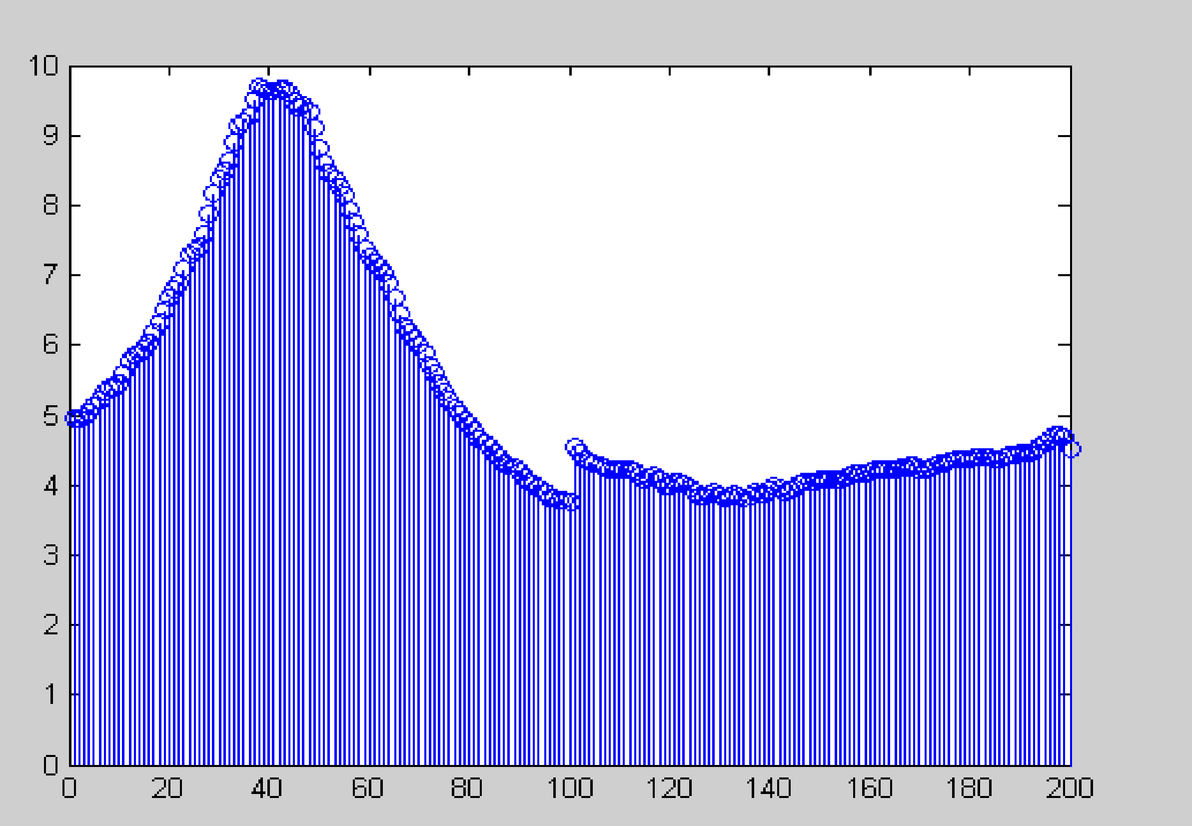
$$K = \frac{\lambda_3}{\lambda_1}$$



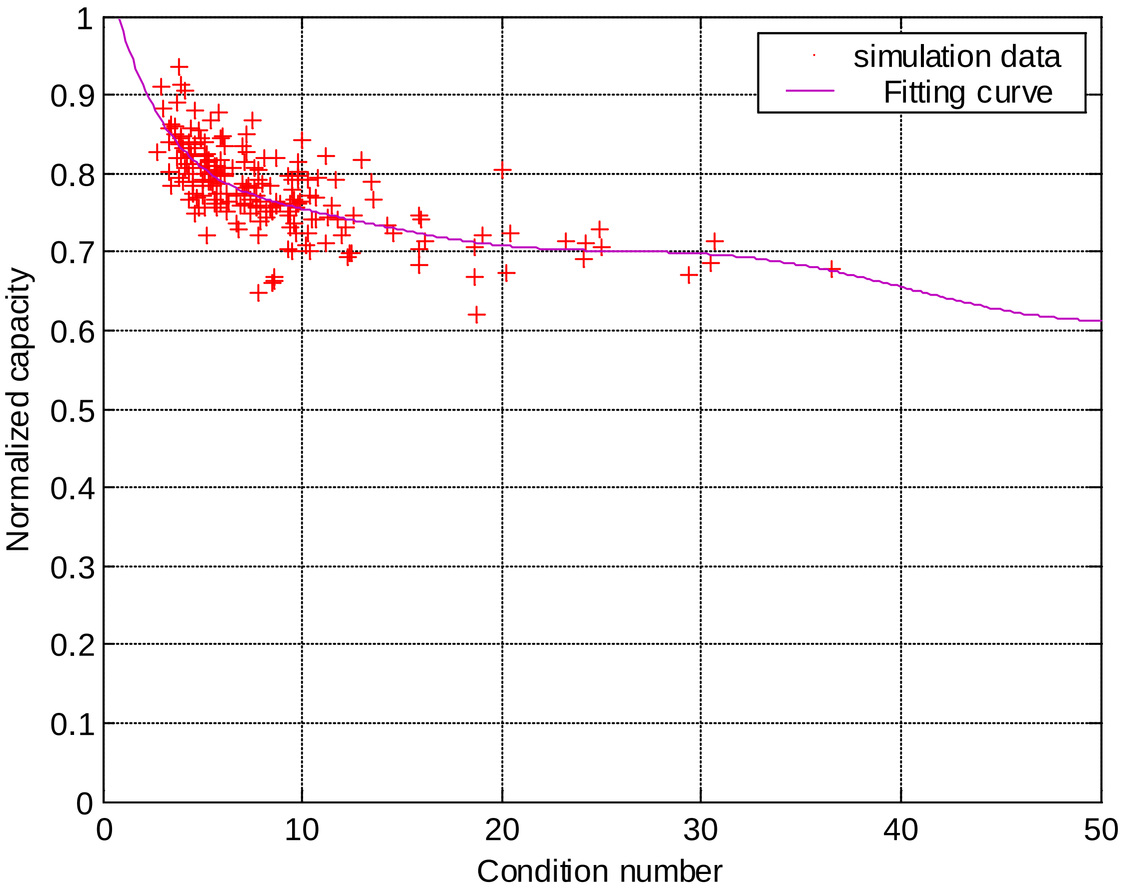
Condition Number of LOS



Condition Number of NLOS with Reflector



Capacities vs. Channel Condition Number



The Comparisons of Recently Reported MIMO Testbeds

Name	MIMO configuration	Data rate	Frequency/bandwidth	Spectral efficiency	Modulation	Completed year
Georgia Tech Testbed	4×4	525Mbits/s	2.435GHz/27.3MHz	19.2bits/Hz/s	64QAM/OFDM	2004
Georgia Tech testbed *(Real-time mode)*	2×2	30Mbits/s	2.435GHz/6.25MHz	4.8bits/Hz/s	64QAM/OFDM	2002
Bell Laboratory testbed	8×12	777.6Kbits/s	1.9GHz/30KHz	25.92bits/Hz/s	16QAM	1999
Iospan wireless testbed	2×3	13.6Mbits/s	2.5-2.6GHz/2MHz	6.8bits/Hz/s	64QAM/OFDM	2002
University of Bristol testbed	4×6	96Mbits/s	5GHz/12MHz	8bits/Hz/s	QPSK/OFDM	2001
Motorola testbed	2×2	180Mbits/s	3.65GHz/20MHz	9bits/Hz/s	64QAM/OFDM	2001
BYU testbed *(Real-time mode)*	4×4	2Mbits/s	2.45GHz/250KHz	8bits/Hz/s	QPSK	2001

Publications

1. Weidong Xiang and Thomas Pratt, “A software radio testbed for two-transmitter two-receiver space-time coding OFDM wireless LAN”, *IEEE Comm. Magazine*, June 2004.
2. Weidong Xiang, Deric Waters, Thomas Pratt and John Barry, "Implementation and experimental results of a Three-transmitter Three-receiver (3×3) OFDM/BLAST testbed,” *IEEE Comm. Magazine*, December 2004
3. Weidong Xiang, Paul Richardson, Brett Walkenhorst, Xudong Wang and Thomas Pratt “A High-Speed Four-Transmitter Four-Receiver MIMO OFDM Testbed: Experiment Results and Analyses,” to appear in *EURASIP*, December 2004

Summary

- The software radio concept has been validated by the real-time 2x2 wireless LAN prototype

- The 4x4 OFDM/BLAST prototype has demonstrated the capacity to achieve a data rate up to 525Mbs/s with a spectrum efficiency of 19.2b/Hz/s.

- Software radio testbed significantly benefits the research, teaching, product development and deployment.

Thanks and Any Questions ?

xwd@umich.edu