ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING FOR WIRELESS CHANNELS

LEONARD J. CIMINI, JR.
YE (GEOFFREY) LI

AT&T LABS - RESEARCH

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING FOR WIRELESS CHANNELS

Leonard J. Cimini, Jr.
AT&T Labs – Research
100 Schulz Dr., Rm. 4-146
Red Bank, NJ 07701-7033, USA
Email: ljc@research.att.com
Tel/Fax: 1-732-345-3129/3039

Ye (Geoffrey) Li
AT&T Labs – Research
100 Schulz Dr., Rm. 4-152
Red Bank, NJ 07701-7033, USA
Email: ljye@research.att.com
Tel/Fax: 1-732-345-3132/3039

ABSTRACT

Orthogonal frequency division multiplexing (OFDM) has been shown to be an effective technique to combat multipath fading in wireless communications. It has been successfully used for HF radio applications and has been chosen as the standard for digital audio broadcasting and digital terrestrial TV broadcasting in Europe and high-speed wireless local areas networks. In this tutorial, we present the basic principles of OFDM and discuss the problems, and some of the potential solutions, in implementing an OFDM system. Techniques for peak-to-average power ratio reduction, time and frequency synchronization, and channel estimation will be discussed. We conclude with a brief overview of current application areas

BIOGRAPHIES OF PRESENTERS:

Leonard J. Cimini, Jr., received the B.S.E. (summa cum laude), M.S.E. and Ph.D. degrees in electrical engineering from the University of Pennsylvania in 1978, 1979, and 1982, respectively. During the graduate work he was supported by a National Science Foundation Fellowship. Since 1982, he has been employed at AT&T, where his research interests are in wireless communications systems. Dr. Cimini is a member of Tau Beta Pi and Eta Kappa Nu. He has been very active in the IEEE Communications Society and is *Editor-in-Chief* of the *IEEE J-SAC: Wireless Communications Series.* He is also an Adjunct Professor at the University of Pennsylvania.

Ye (Geoffrey) Li received the B.Eng and M.Eng degrees in 1983 and 1986, respectively, from the Department of Wireless Engineering, Nanjing Institute of Technology, Nanjing, China, and the Ph.D. degree in Electrical Engineering in 1994, Auburn University, Alabama. Since May 1996, he has been with AT&T Labs - Research. His current research interests are in statistical signal processing and wireless communications. He has served as a guest editor for a special issue on *Signal Processing for Wireless Communications* for the *IEEE J-SAC* and is an editor for Wireless Communication Theory for the *IEEE Transactions on Communications.*

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

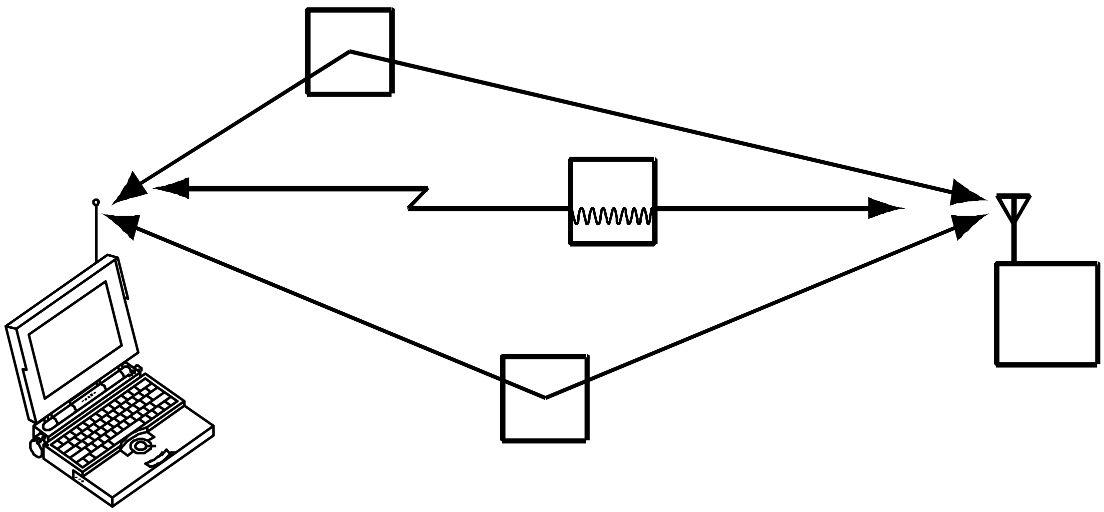
INTRODUCTION

- **Motivation**
- **Radio Environment**
- **Brief History**

MOTIVATION

- High-bit-rate wireless applications
- Limitations caused by the radio environment
- OFDM can overcome these inherent bit rate limitations

PATH LOSS MODEL



- Path Loss
- Shadow Fading
- Multipath
    - Flat fading
    - Doppler spread
    - Delay spread
- Interference

PATH LOSS MODEL

- Different, often complicated, models are used for different environments.

- A simple model for path loss, L, is

$$L = \frac{\overline{P_r}}{P_t} = K \frac{1}{d^{\alpha}}$$

where P_r is the local mean received signal power, P_t is the transmitted power, and d is the transmitter receiver distance.

The path loss exponent $\alpha = 2$ in free space; $2 \leq \alpha \leq 4$ in typical environments.

SHADOW FADING

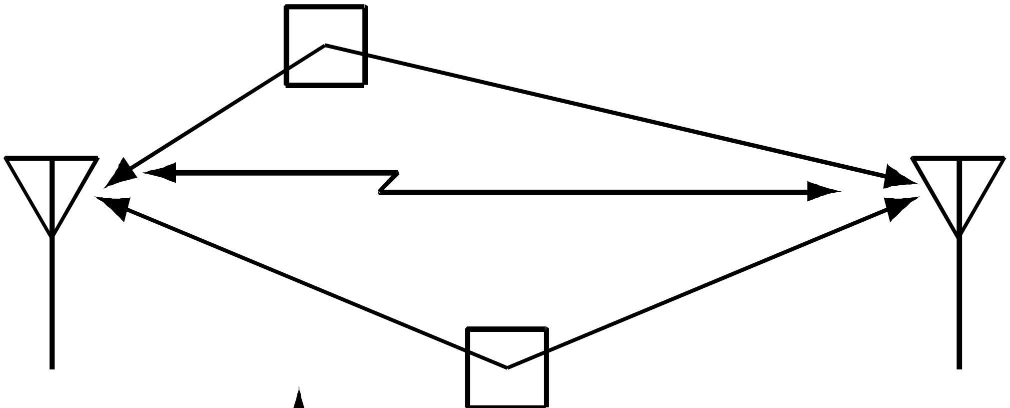
- The received signal is shadowed by obstructions such as hills and buildings.
- This results in variations in the local mean received signal power,

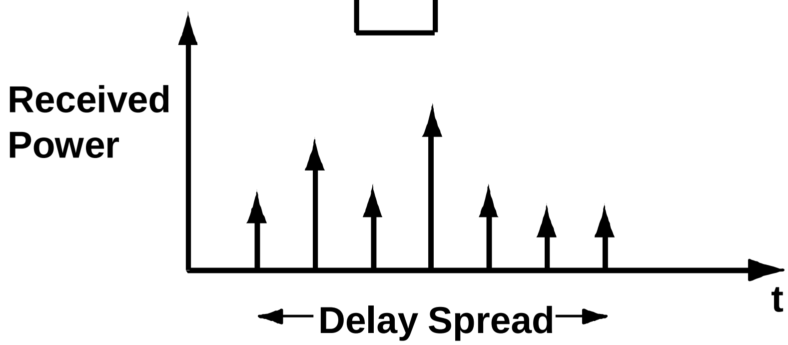
$$P_r(dB) = \overline{P_r}(dB) + G_s$$

$$\text{where } G_s \sim N\left(0, \sigma_s^2\right), 4 \leq \sigma_s \leq 10\, dB.$$

- Implications
  - nonuniform coverage
  - increases the required transmit power

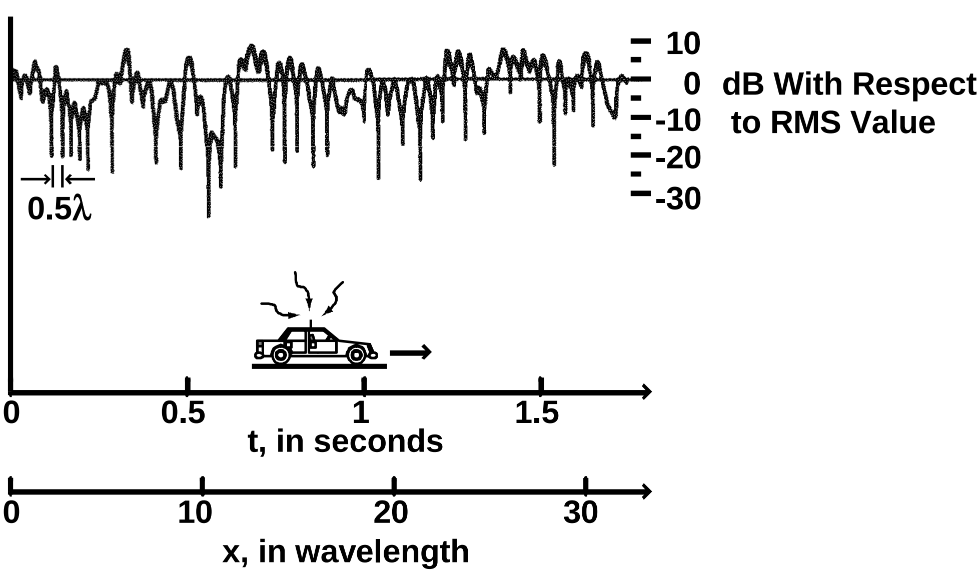
MULTIPATH





$$h(t) = \sum_i a_i e^{j\theta_i} \delta(t - t_i)$$

Constructive and destructive interference of arriving rays

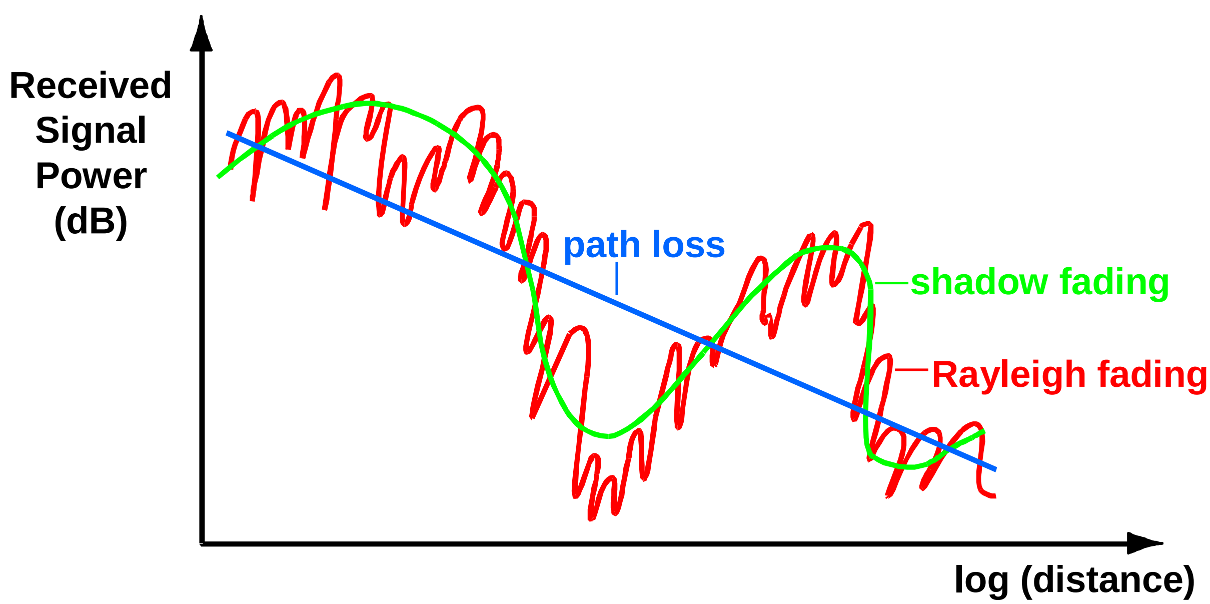


FLAT FADING

- The delay spread is small compared to the symbol period.

- The received signal envelope, r, follows a Rayleigh or Rician distribution.

$$P_r(dB) = \overline{P}_r(dB) + G_S + 20 \log r$$



- Implications
  - increases the required transmit power
  - causes bursts of errors

DOPPLER SPREAD

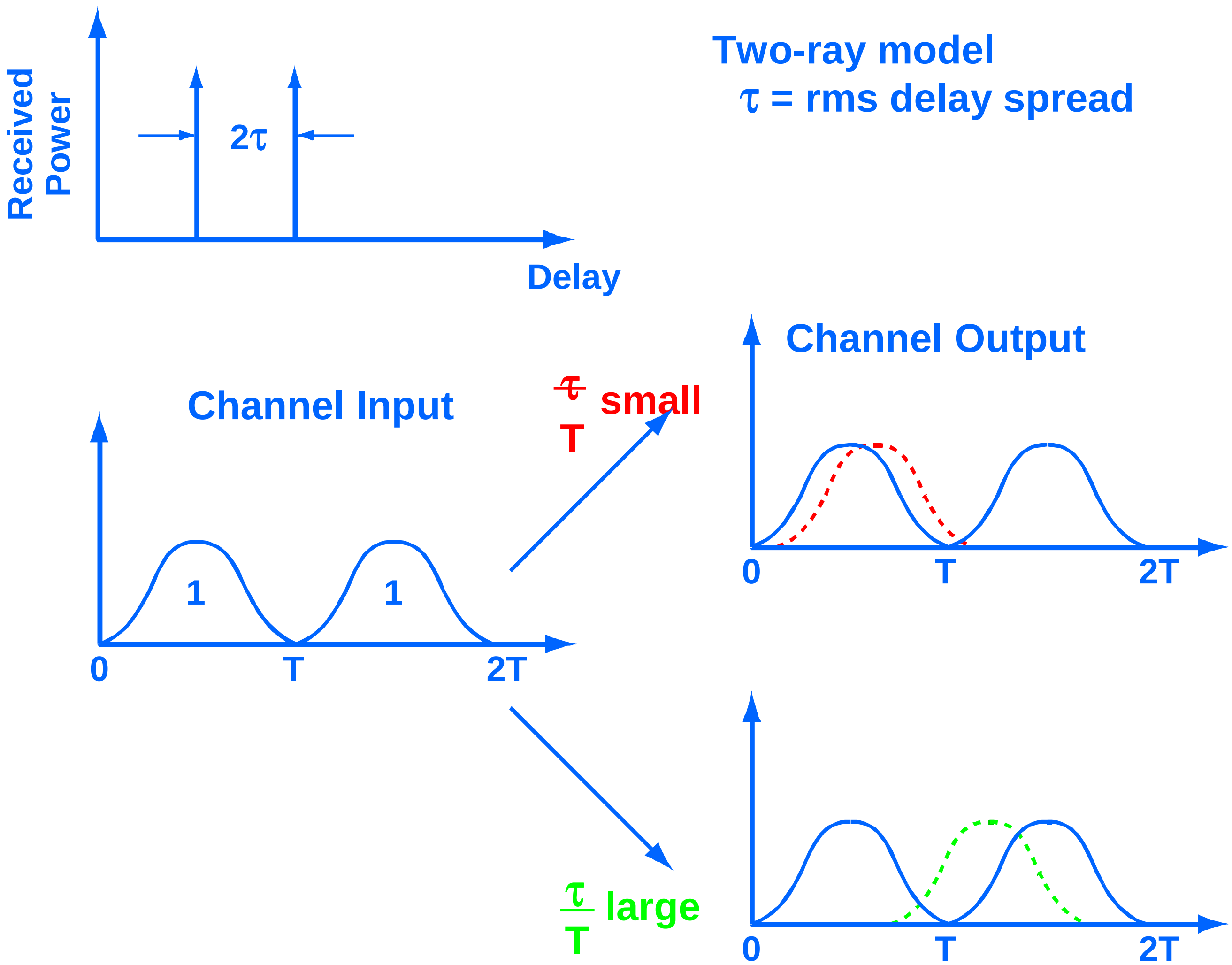
- A measure of the spectral broadening caused by the channel time variation.

$$f_D \leq \frac{v}{\lambda}$$

Example: 900 MHz, 60 mph, f_D = 80 Hz
5 GHz, 5 mph, f_D = 37 Hz

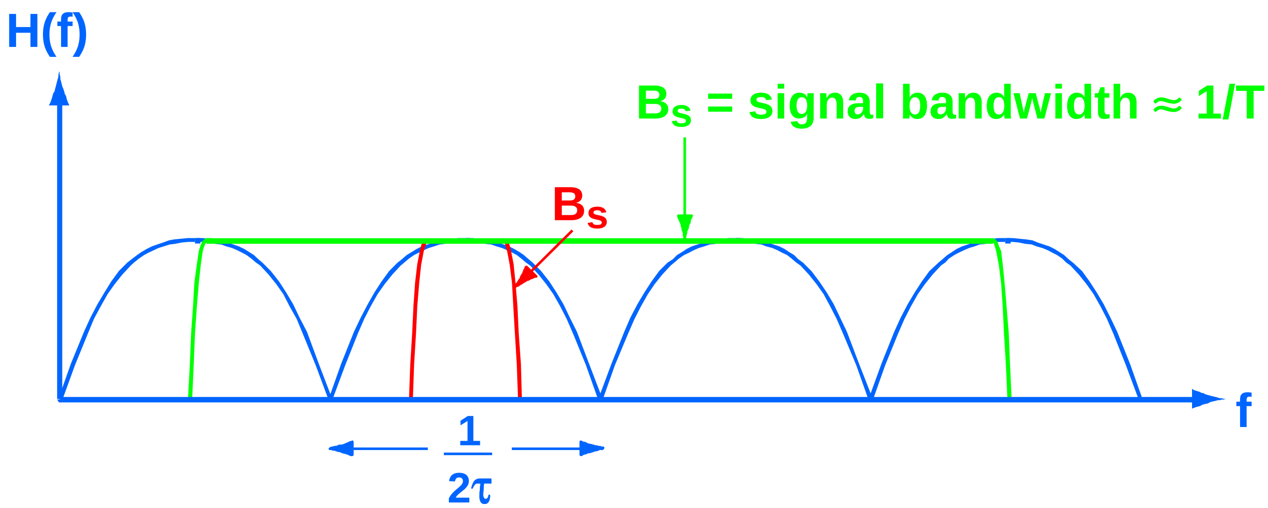
- Implications
  - signal amplitude and phase decorrelate after a time period ~ $1/f_D$

DELAY SPREAD
TIME DOMAIN INTERPRETATION



- $\frac{\tau}{T}$ small ⇒ negligible intersymbol interference
- $\frac{\tau}{T}$ large ⇒ significant intersymbol interference, which causes an irreducible error floor

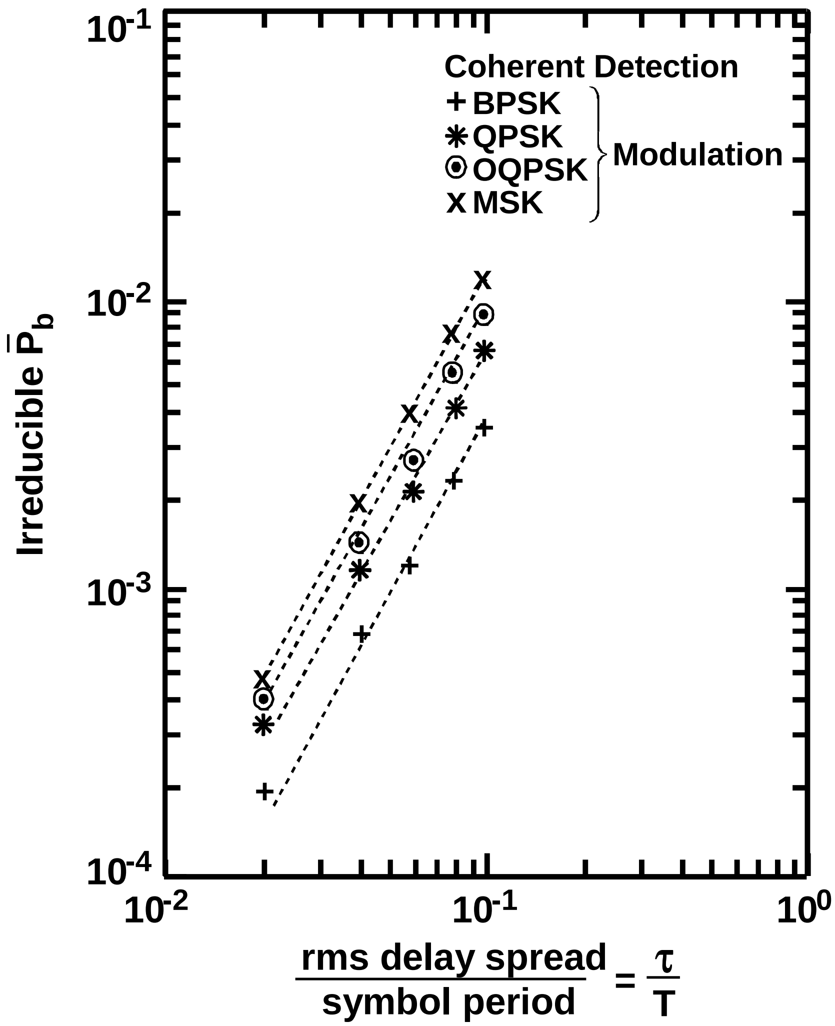
DELAY SPREAD
FREQUENCY DOMAIN INTERPRETATION



- $\frac{\tau}{T}$ small ⇒ flat fading
- $\frac{\tau}{T}$ large ⇒ frequency-selective fading

BIT RATE LIMITATIONS

- ISI causes an irreducible error floor.

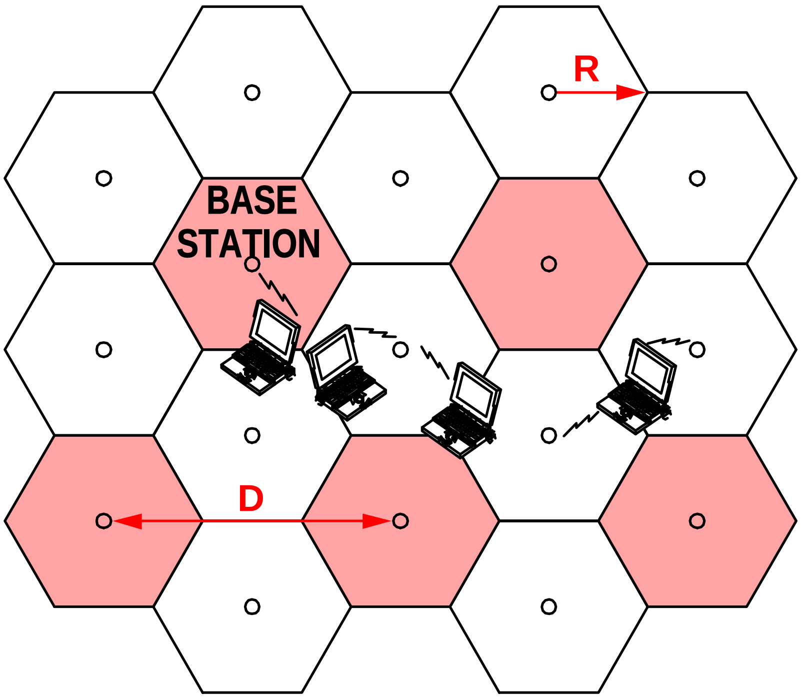


The rms delay spread imposes a limit on the maximum bit rate. For example, for QPSK

	τ	Maximum Bit Rate
Mobile (rural)	25 μsec	8 kbps
Mobile (city)	2.5 μsec	80 kbps
Microcells	500 nsec	400 kbps
Large Building	100 nsec	2 Mbps

INTERFRENCE

- Frequencies are reused often to maximize spectral efficiency.



- For interference-limited systems, the noise floor is dominated by co-channel interference.

$$\frac{S}{I+N} \approx \frac{S}{I} = \frac{1}{6}\left(\frac{D}{R}\right)^{\alpha}$$

- Implications
  - high reuse efficiency requires interference mitigation

HISTORY

- Military HF radio (1950's - 1960's)
  - Kineplex
  - Kathryn
- Wireline modem (Telebit, Gandalf)
- Cellular modem (Telebit)
- Digital audio and terrestrial TV broadcasting (Europe)
- Asymmetric digital subscriber line (DMT)
- Wireless LANs
  - IEEE802.11 - National Information Infrastructure
  - HIPERLAN TYPE II

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

BASIC CONCEPTS

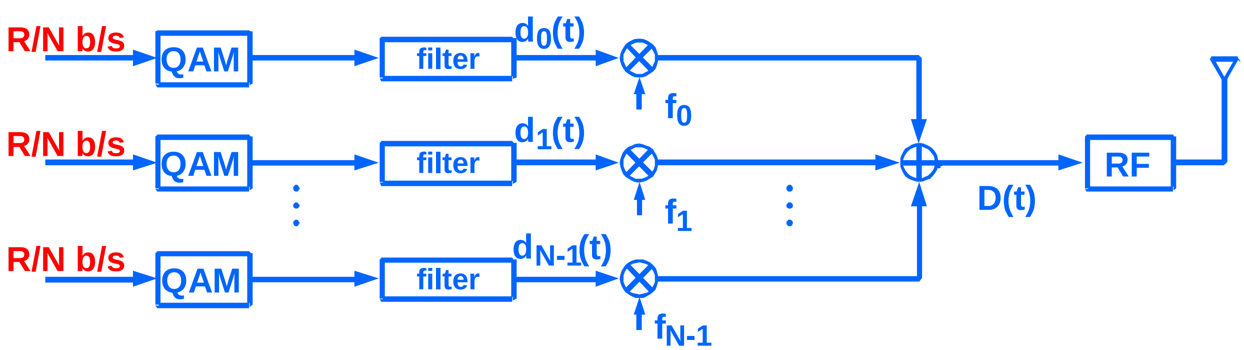
- Multicarrier
- Basic OFDM
- Impairments
- Alternative forms

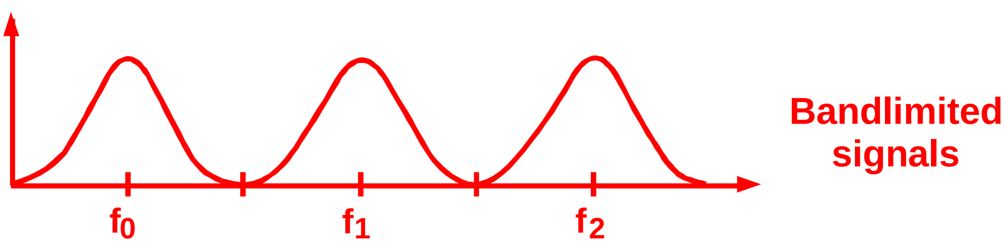
MULTICARRIER

- The transmission bandwidth is divided into many narrow subchannels which are transmitted in parallel.

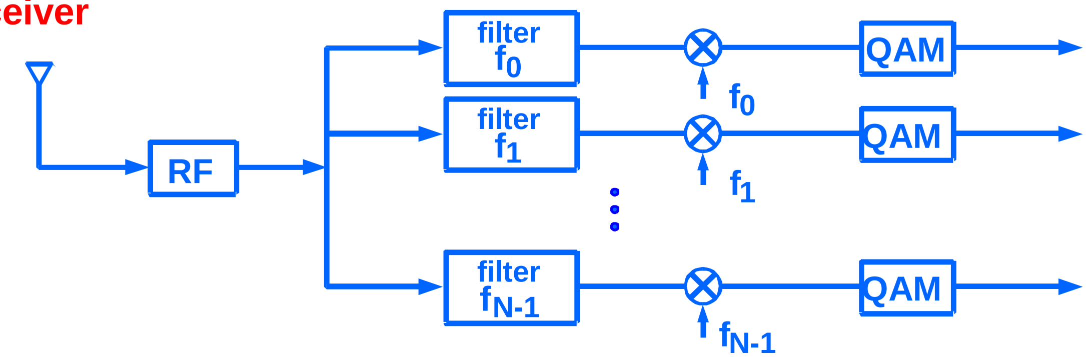
- Ideally, each subchannel is narrow enough so that the fading it experiences is flat $\Rightarrow$ no ISI.

Transmitter





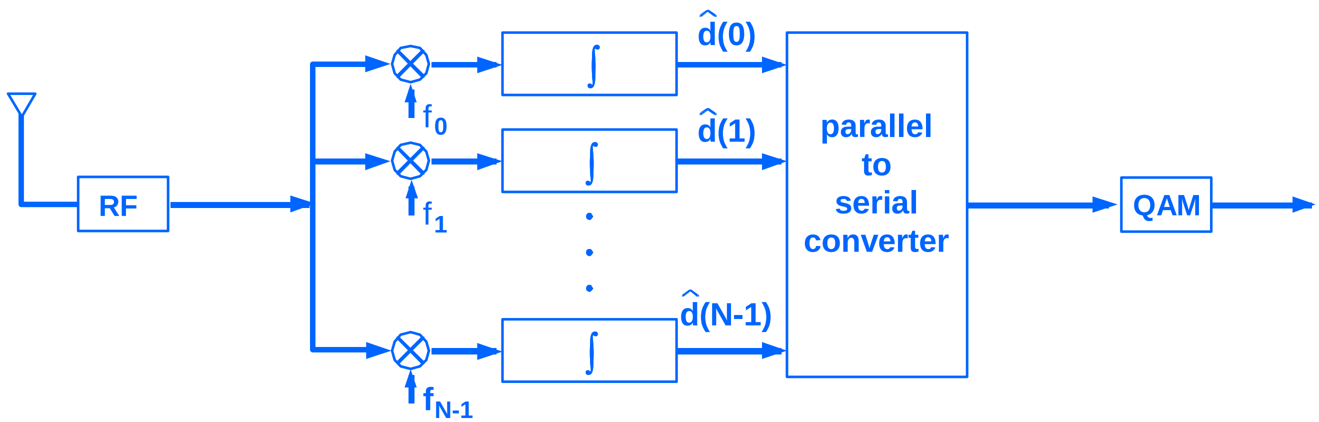
Receiver



- Disadvantage:
  - Requires filter bank at receiver
  - Spectrally inefficient

Horizontal slide here

BASIC OFDM RECEIVER



- Subchannel separation
  - choose $f_n = f_0 + n\Delta f$, with $\Delta f = \dfrac{1}{NT}$
  - integrate over NT, then $\hat{d}(m) = d(m)$
- A guard interval can virtually eliminate ISI (or, interblock interference) $\Rightarrow$ lower spectral or power efficiency.

PASSBAND VERSUS BASEBAND

- **Passband**

$$x_p(t) = \Re\left\{\sum_{k=0}^{N-1} a[k]e^{j2\pi(f_c+k\Delta f)t}\right\},\ 0 \le t \le T_s$$

- **Baseband**

$$x_b(t) = \sum_{k=0}^{N-1} a[k]e^{j2\pi k\Delta ft},\ 0 \le t \le T_s$$

DFT IMPLEMENTATION
TRANSMITTER

- Transmitted signal can be obtained using a Discrete Fourier Transform

$$x_b(t) = \sum_{k=0}^{N-1} a[k] e^{j2\pi k \Delta f t}, \; 0 \le t \le T_s$$

- If sampled at a rate of T_s /N,

$$x_b[n] = x_b\left(\frac{n}{N} T_S\right) = \sum_{k=0}^{N-1} a[k] e^{j2\pi n k \Delta f T_s / N}$$

- For orthogonality, $\Delta f T_s = 1$,

$$x_b[n] = \sum_{k=0}^{N-1} a[k] e^{j2\pi n k / N} = \mathrm{IDFT}\{a[k]\}$$

- Efficient FFT implementation

DFT IMPLEMENTATION
RECEIVER

$$
\begin{aligned}
\hat{a}[k] &= \mathrm{DFT}\{x_b[n]\} \\
&= \frac{1}{N}\sum_{n=0}^{N-1} x_b[n]\, e^{-j2\pi nk/N} \\
&= \frac{1}{N}\sum_{n=0}^{N-1}\sum_{m=0}^{N-1} a[m]\, e^{j2\pi n(m-k)/N} \\
&= \frac{1}{N}\sum_{m=0}^{N-1} a[m] \sum_{n=0}^{N-1} e^{j2\pi n(m-k)/N} \\
&= \frac{1}{N}\sum_{m=0}^{N-1} a[m]\, N\delta[m-k] \\
&= a[k]
\end{aligned}
$$

PERFORMANCE IMPROVEMENT

- Coding across subchannels $\Rightarrow$ works best with large delay spread
- Adaptive loading
  - More bits/symbol where SNR is sufficient
  - Could also adapt transmit power in each subchannel
  - Requires reliable feedback channel and accurate channel information
- Frequency equalization and coherent detection $\Rightarrow$ requires accurate channel estimation

SAMPLE DESIGN

- Goal
  - Transmit 1.2 Mbits/sec using QPSK with B=800 kHz bandwidth channel
  - Delay span up to 40 μsec (max 5 kbaud for single carrier)

- Design
  - Choose subchannel width so that there is no ISI in each subchannel ⇒ $\Delta f = 6.25$ kHz ⇒ $N = B/\Delta f = 128$ subchannels
  - OFDM symbol duration $T_s = 1/\Delta f = 160$ μsec
  - Guard interval $T_g = 40$ μsec
  - OFDM block length: $T_f = T_s + T_g = 200$ μsec
  - Assuming 4 guard channels on each end, there are 120 data subchannels, each transmitting 2 bits in 200 μsec

$$R_b = \frac{120 \text{ x } 2 \text{ bits}}{200 \ \mu\text{sec}} = 1.2 \text{ Mbits/sec}$$

IMPAIRMENTS

- **Time-varying fading, frequency offset, and timing mismatch impair the orthogonality of the subchannels.**

- **Large amplitude fluctuations can be a serious problem when transmitting through a nonlinearity.**

TIME-VARYING IMPAIRMENTS

- **General expression:**

$$\hat{a}[k] = \text{DFT}\{\chi_b[n]\} = \underbrace{a[k]K[k,k]}_{\text{attenuated \& rotated}} + \underbrace{\sum_{n \neq k} a[n]K[n,k]}_{\text{ICI}}$$

- **Frequency offset**
  - For a frequency offset between the transmitter and receiver,

$$x_b(t) = \sum_{k=0}^{N-1} a[k]\, e^{j2\pi(k\Delta f - \delta f)t},\ 0 \le t \le Ts$$

$$K[n,k] = \left[\frac{\sin\left[\pi\left(n-k-\frac{\delta f}{\Delta f}\right)\right]}{\pi\left(n-k-\frac{\delta f}{\Delta f}\right)} \right] e^{j\pi\left(n-k-\frac{\delta f}{\Delta f}\right)}$$

$$K[k,k] = \left[\frac{\sin\left(\pi\frac{\delta f}{\Delta f}\right)}{\pi\frac{\delta f}{\Delta f}} \right] e^{j\pi\frac{\delta f}{\Delta f}}$$

TIMING MISMATCH

- Timing offset smaller than the guard interval results in a phase shift.

$$\hat{a}_{\delta t}[k] = a[k]e^{j2\pi f_k \delta t}$$

$$\Downarrow$$

a phase shift

- Otherwise, additional interference is generated.

- Best solution is to choose sufficient guard interval.

DELAY SPREAD

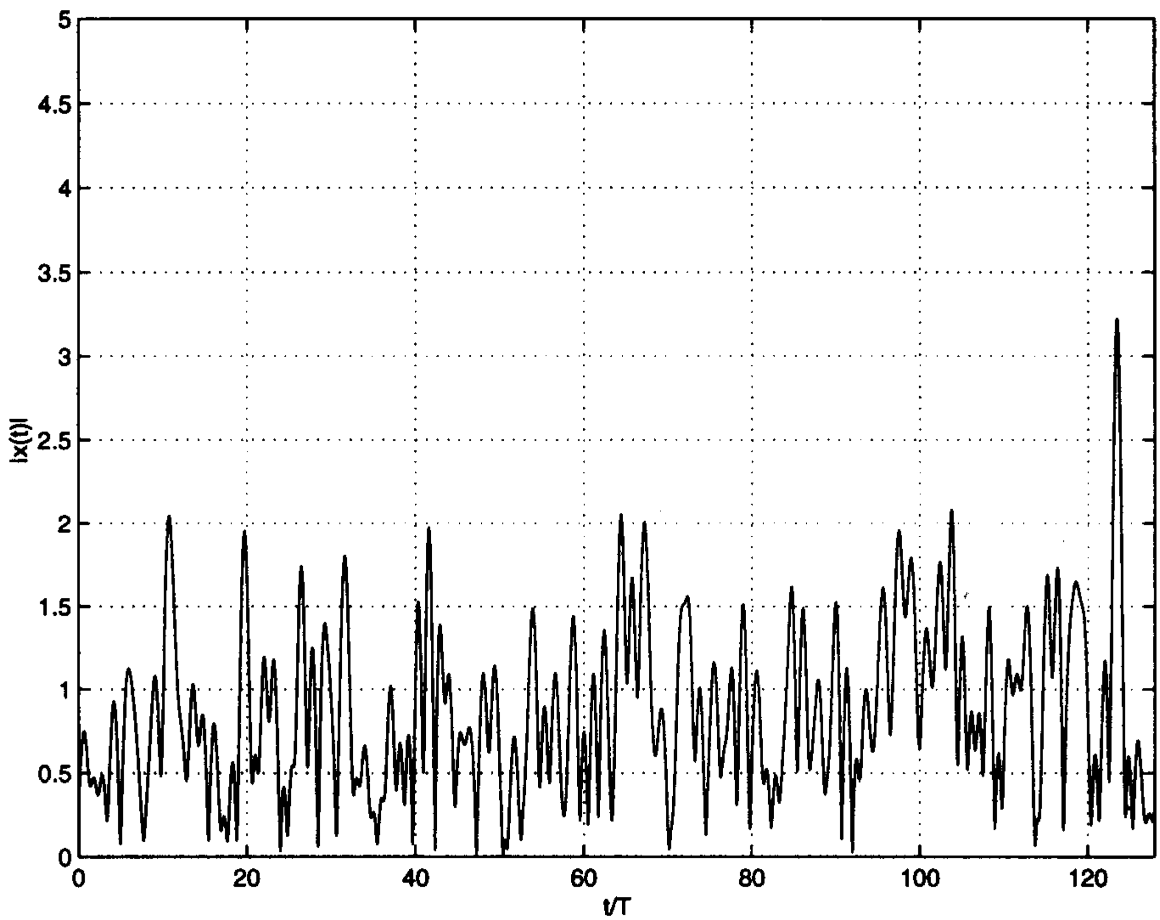
- Assuming time-invariance, the multipath channel results in a received signal at k-th subchannel

$$\hat{a}[k] = H[k]a[k] + w[k]$$

- Simple complex multiplicative distortion
- For coherent detection, channel parameter estimation and tracking are required.

NONLINEARITIES

- **Large peak-to-average power ratio (PAPR)**
- **PAPR ~ number of subcarriers**



- **Large PAPR $\Rightarrow$ inband distortion and spectral spreading**
- **PAPR reduction techniques required**

ALTERNATIVE FORMS

- **Bandlimited OFDM:**
  - **R.W. Chang (*BSTJ*, Dec. 1966)**
  - **B.R. Saltzberg (*IEEE Trans. on Comm. Tech*., Dec. 1967)**
  - **B. Hirosaki (*IEEE Trans. on Comm*., Jan. 1980)**

- **Wavelet-Based OFDM:**
  - **B. LeFloch (*Proc. IEEE*, June 1995)**

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

PAP RATIO REDUCTION

- PAPR properties
- Clipping and filtering
- Selective mapping
- Partial transmit sequences
- Coding
- Other techniques

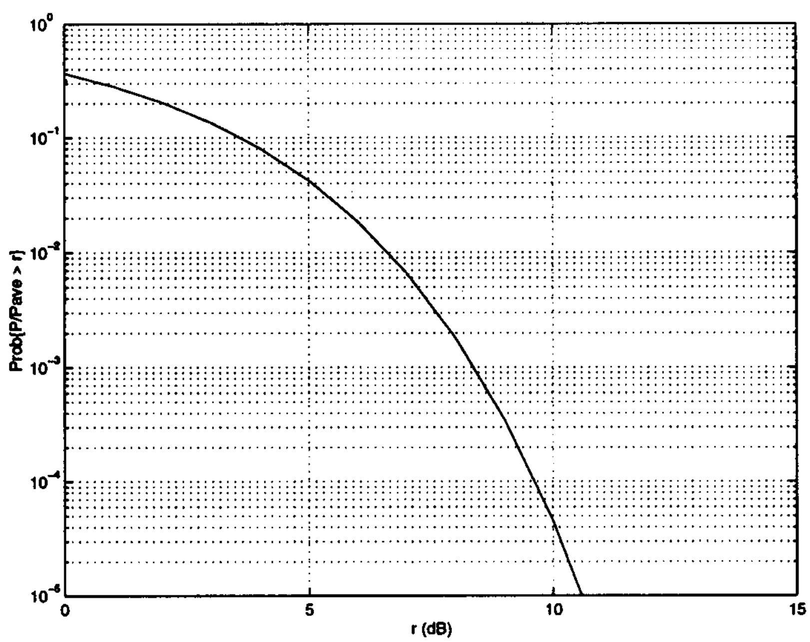
PAPR PROPERTIES

- Superposition of a large number of subcarrier signals results in a Rayleigh envelope.
- PAPR definition

$$\mathrm{PAPR} = \frac{\max_{0<t<Ts} |x_b(t)|^2}{P_{ave}} = N$$

For N=128, PAPR = 21 dB.

- However, these large peaks do not occur very often.



PAPR PROPERTIES

- Large PAPR
  - In band noise $\Rightarrow$ increases BER
  - Spectral spreading $\Rightarrow$ ACI

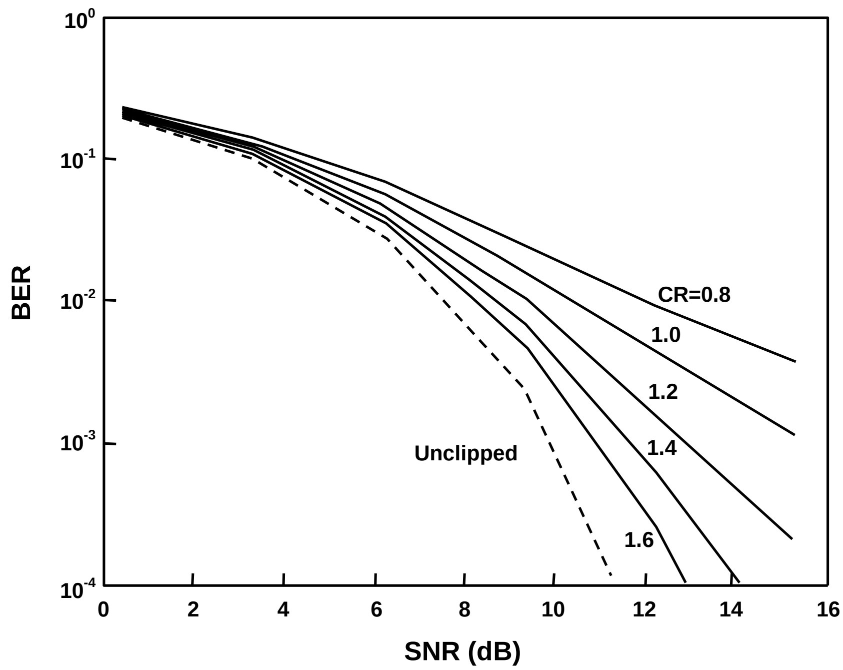
- Possible Solutions
  - Amplifier backoff
  - Reduce PAPR of OFDM signal

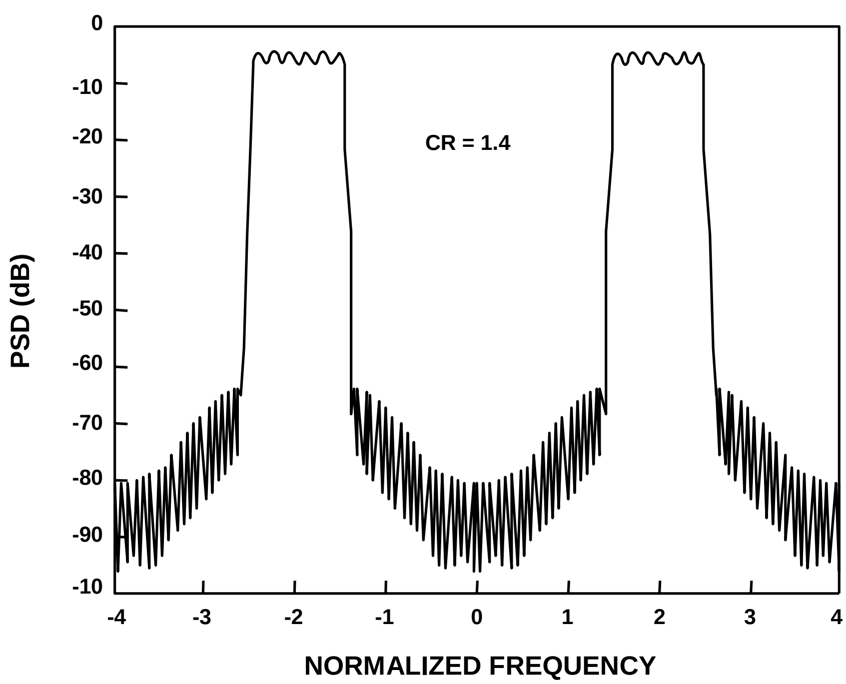
CLIPPING AND FILTERING

- Deliberate clipping will reduce peak value, but will result in spectral spreading (ACI) and in-band distortion (BER).

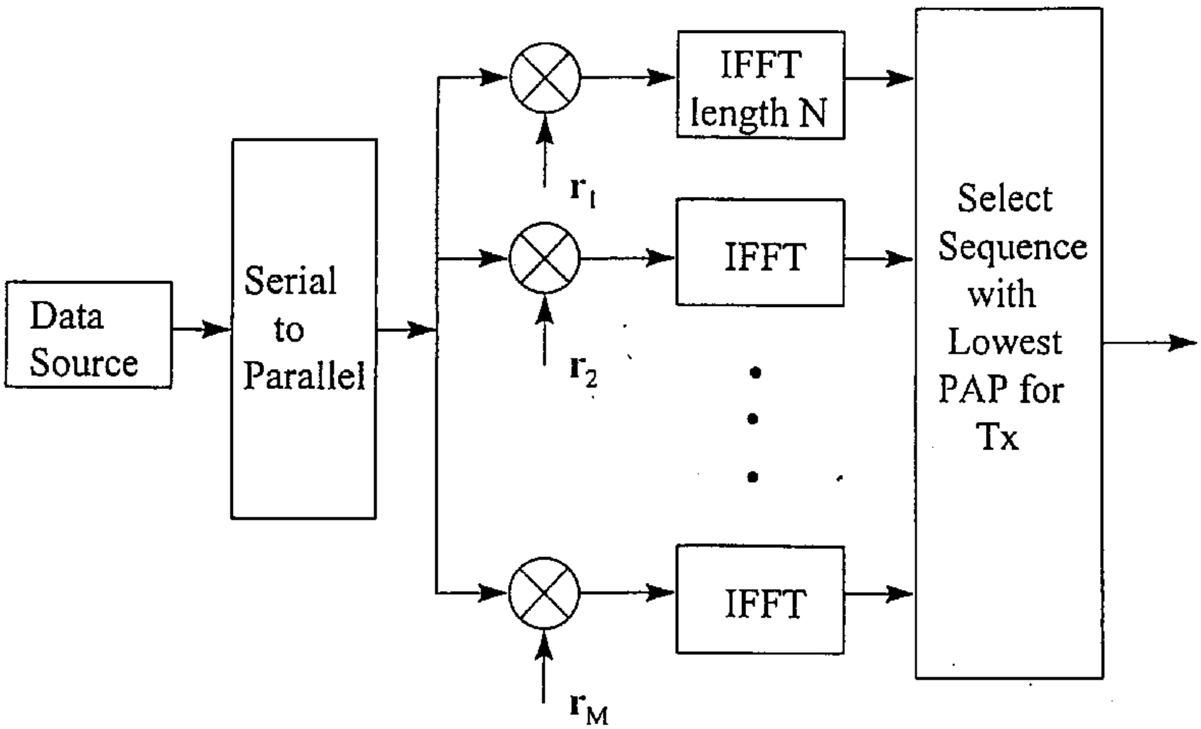
- Filtering is required to minimize spectral spreading. $\Rightarrow$ peak regrowth

CLIPPING AND FILTERING



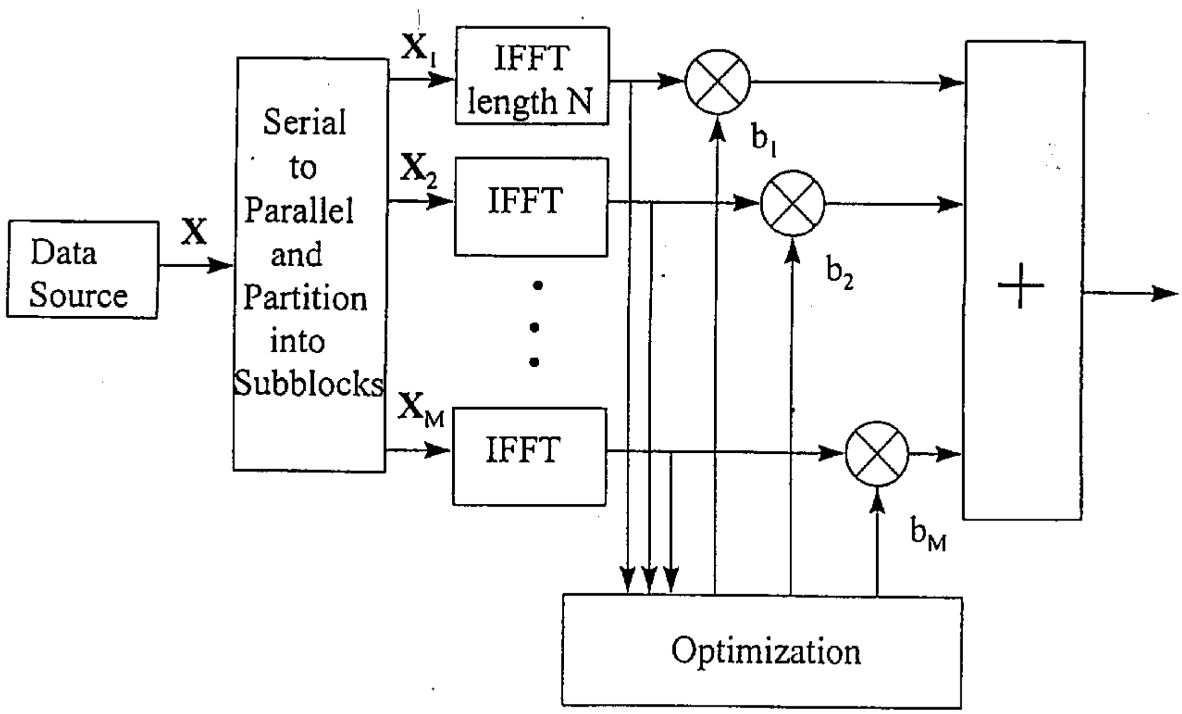


SELECTIVE MAPPING



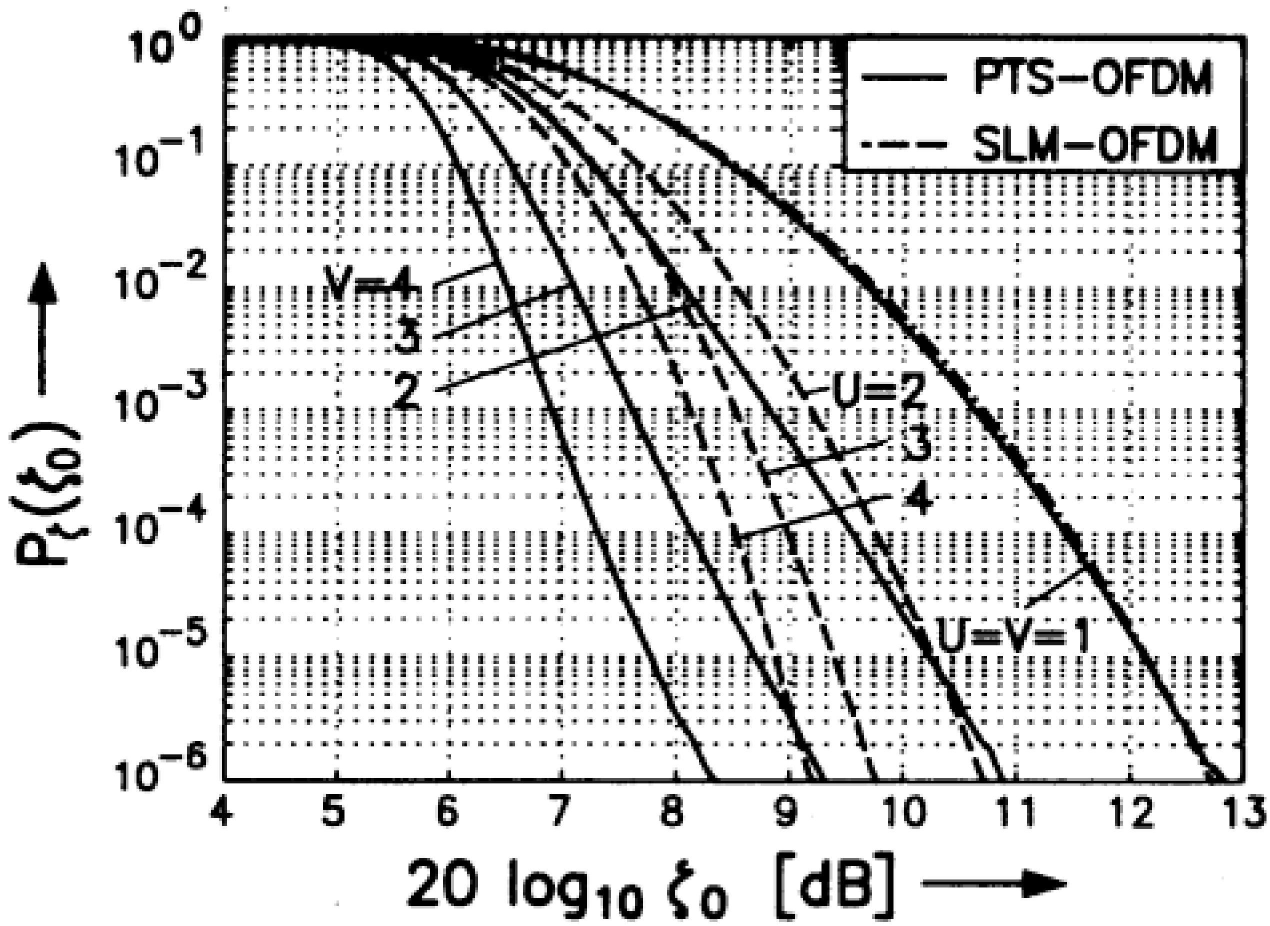
- Multiply data signal by M different sequences, $r_1, \ldots r_M$,
- Convert each data sequence into the time-domain with an N-point IFFT
- Select sequence for transmission with the smallest PAPR

PARTIAL TRANSMIT SEQUENCE



- Divide the OFDM tones into M clusters
- Convert each cluster into the time-domain using an N-point IFFT
- Combine the M output sequences to minimize the PAPR

PERFORMANCE



Using the same redundancy, PTS can achieve a lower PAPR at the expense of more complexity.

CODING

- Nonlinear
  - Map transmitted sequence into a larger sequence where high-peak sequences are not used
  - Good performance with little overhead
  - Requires table look-up $\Rightarrow$ only applicable for small number of subchannels
  - Error propagation

- Current work searching for systematic implementation with some error correction capability

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

TIME AND FREQUENCY SYNCHRONIZATION

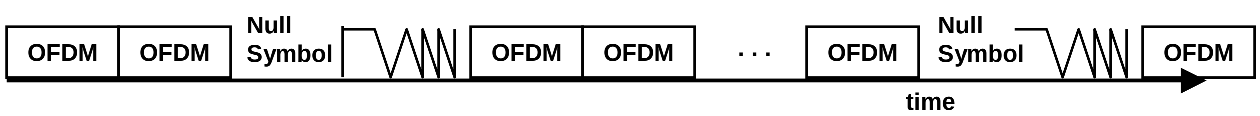
- Timing offset estimation
- Frequency offset estimation
- Joint offset estimation

TIMING OFFSET ESTIMATION

- Pilot-based methods
  - Non-OFDM-based pilot symbols
  - OFDM-based pilot symbols
- Non-pilot based methods

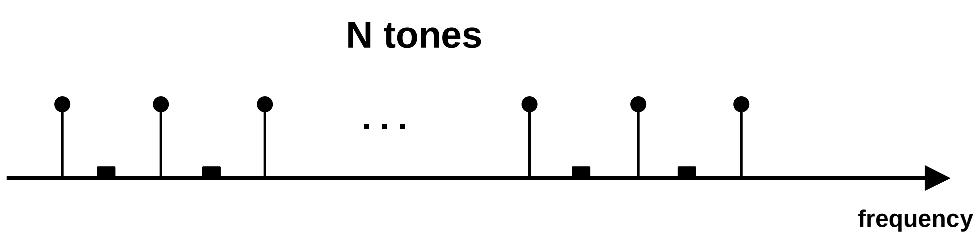
PILOT-BASED TIMING
Non-OFDM Pilot Symbols

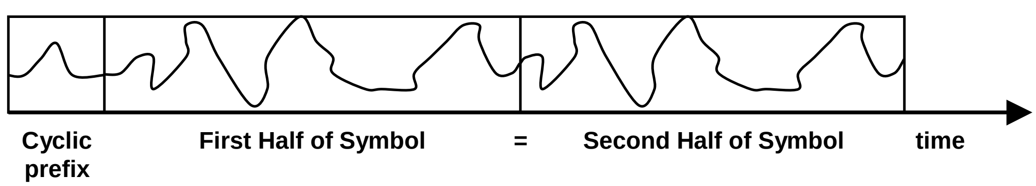
Use a null signal inserted at the start of each group of OFDM blocks



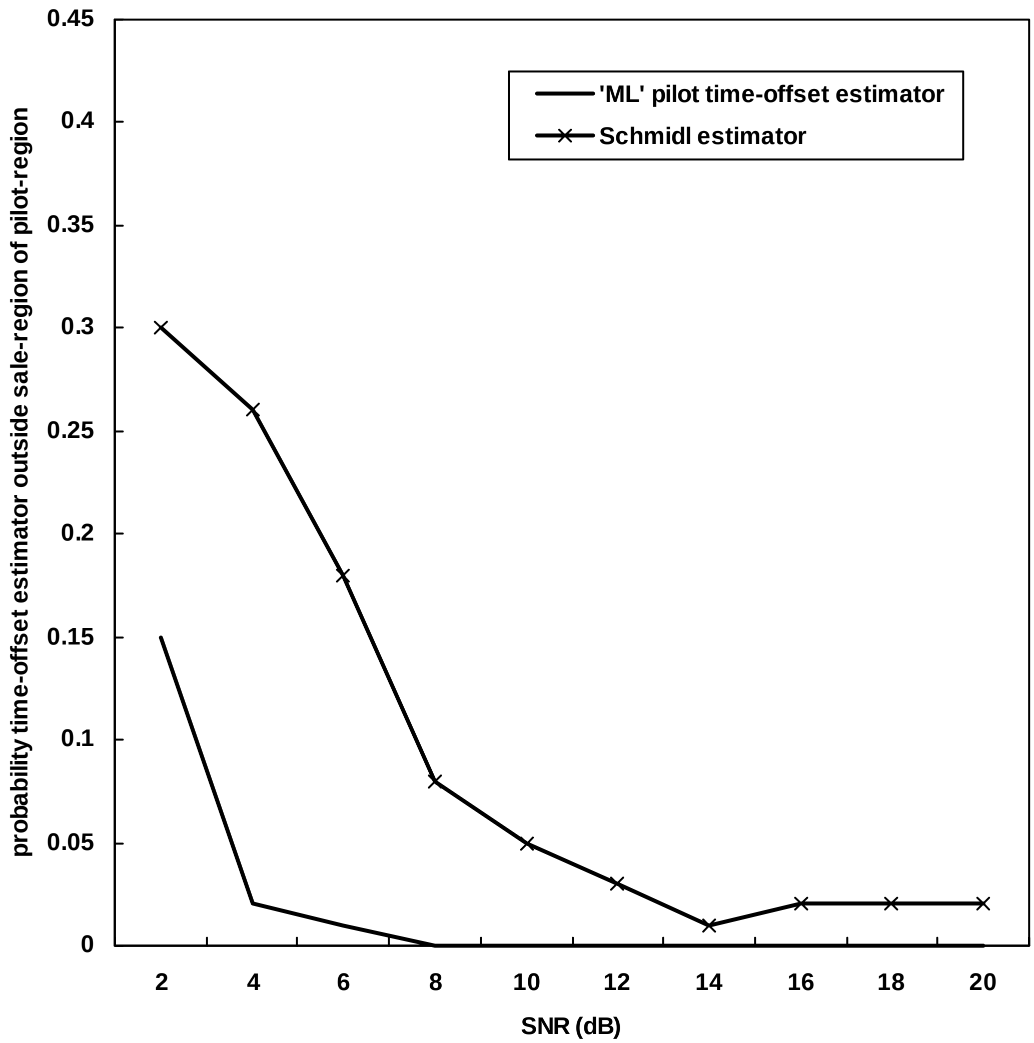
PILOT-BASED TIMING
OFDM Pilot Symbols

Design special OFDM block for estimation (Moose, Schmidl)



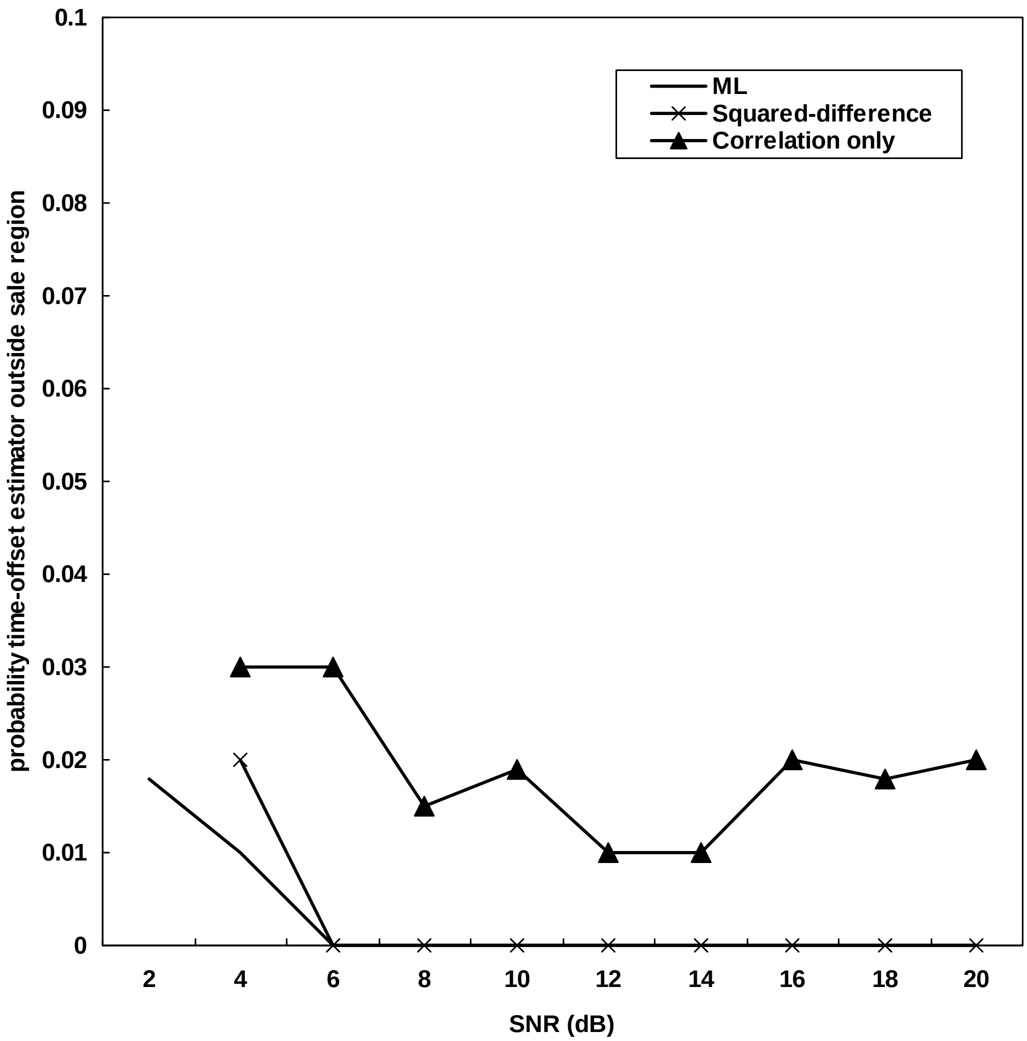


PILOT-BASED TIMING
Performance



NON-PILOT BASED TIMING

Use redundancy in the cyclic prefix to estimate the time offset



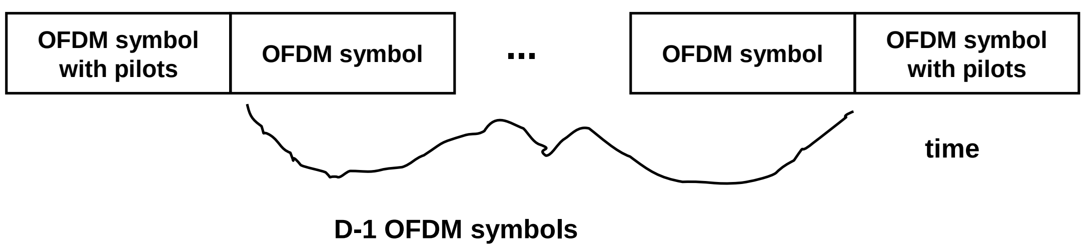
FREQUENCY OFFSET ESTIMATION

- Pilot-based methods
  - Non-OFDM-based pilot symbols
  - OFDM-based pilot symbols

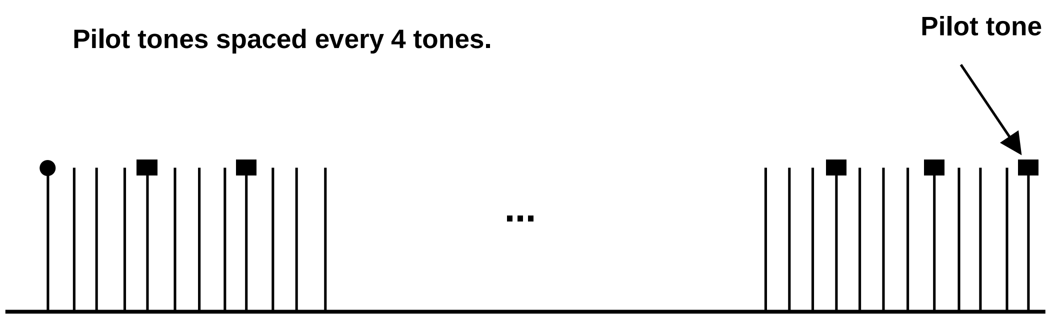
- Non-pilot based methods

FREQUENCY OFFSET ESTIMATION
Pilot-Based

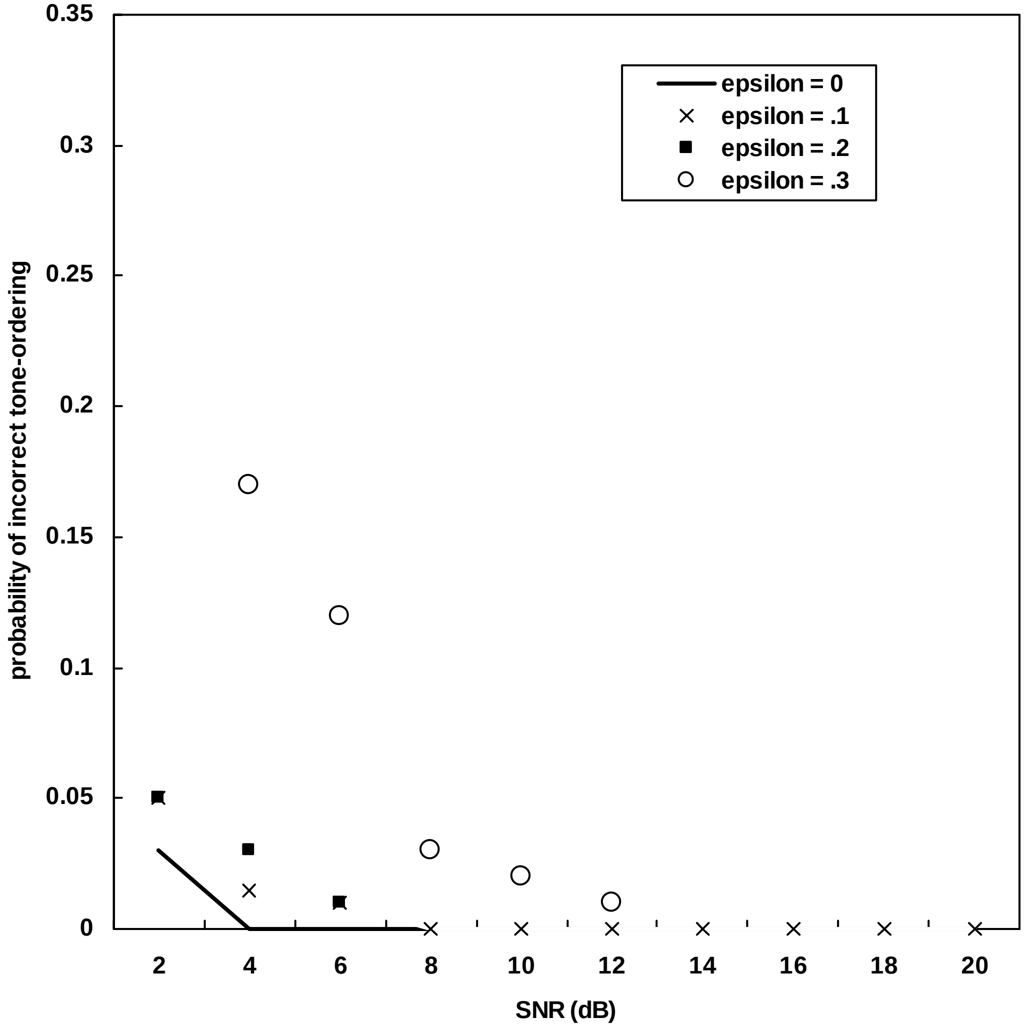
An OFDM-based pilot scheme for coarse and fine frequency synchronization



Frequency domain of an OFDM pilot symbol

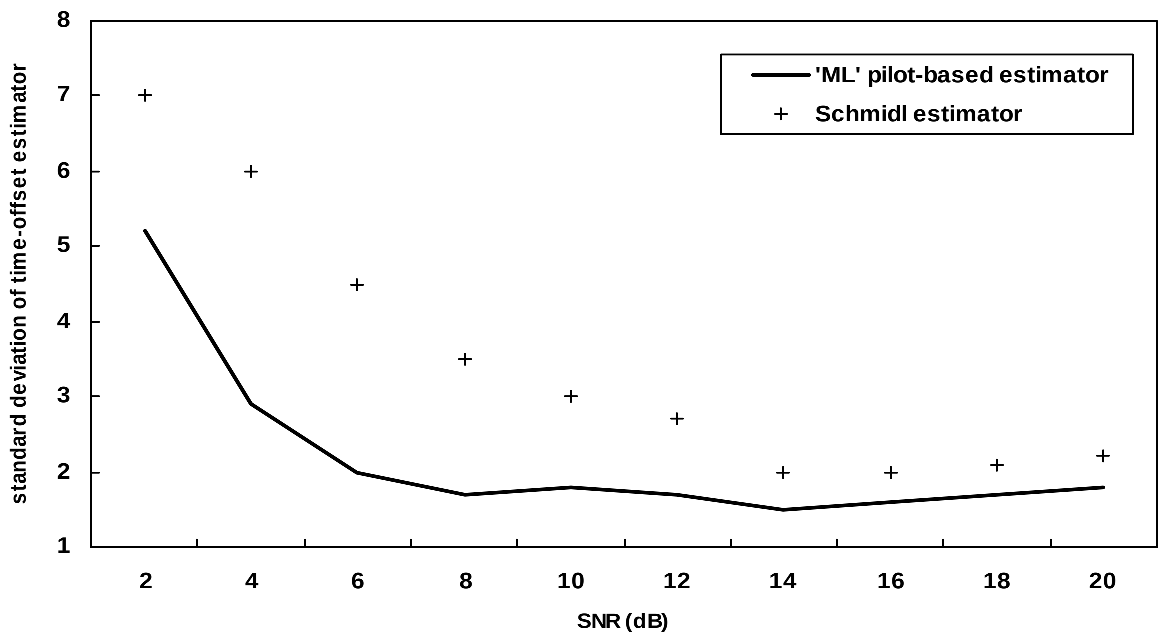


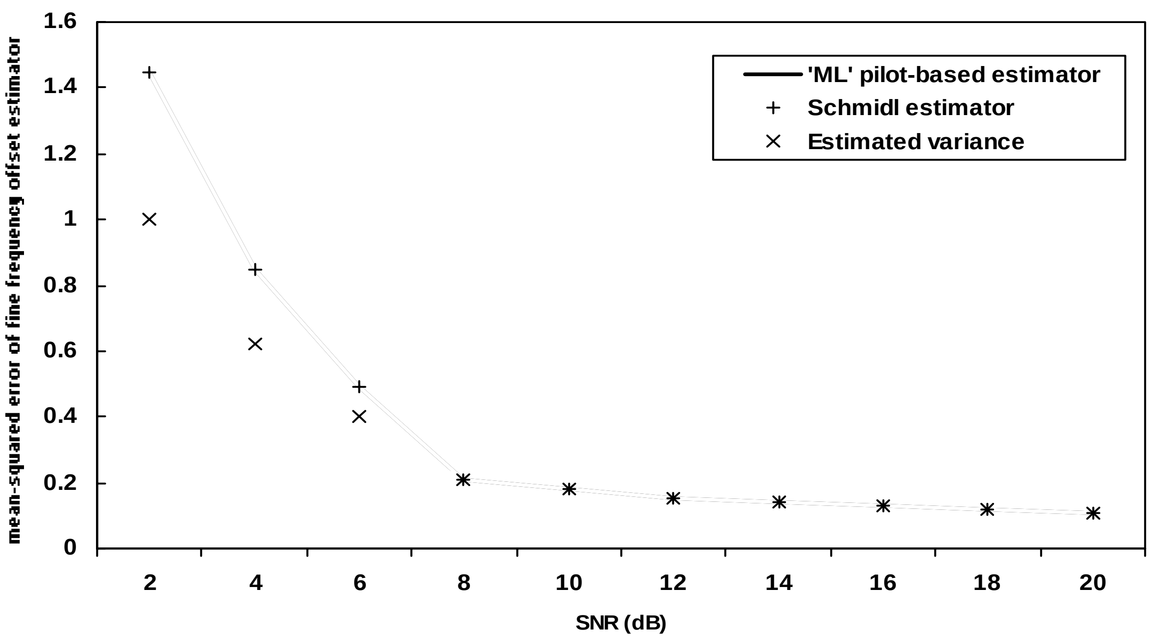
FREQUENCY OFFSET ESTIMATION
Performance



JOINT ESTIMATION

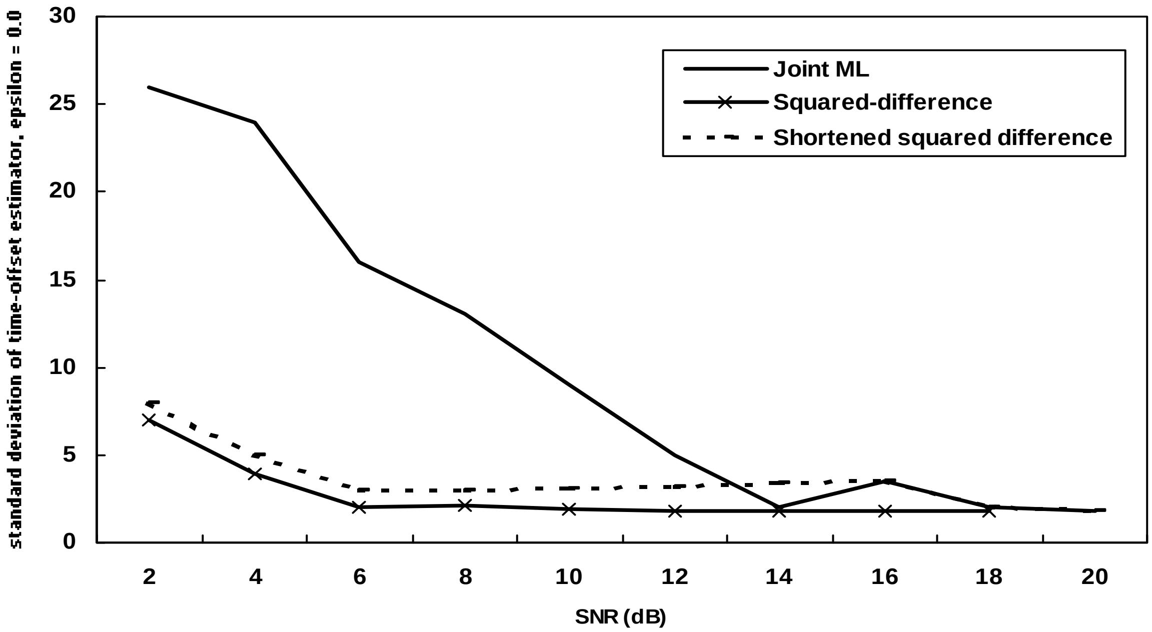
Based on shortened Moose pilot symbol

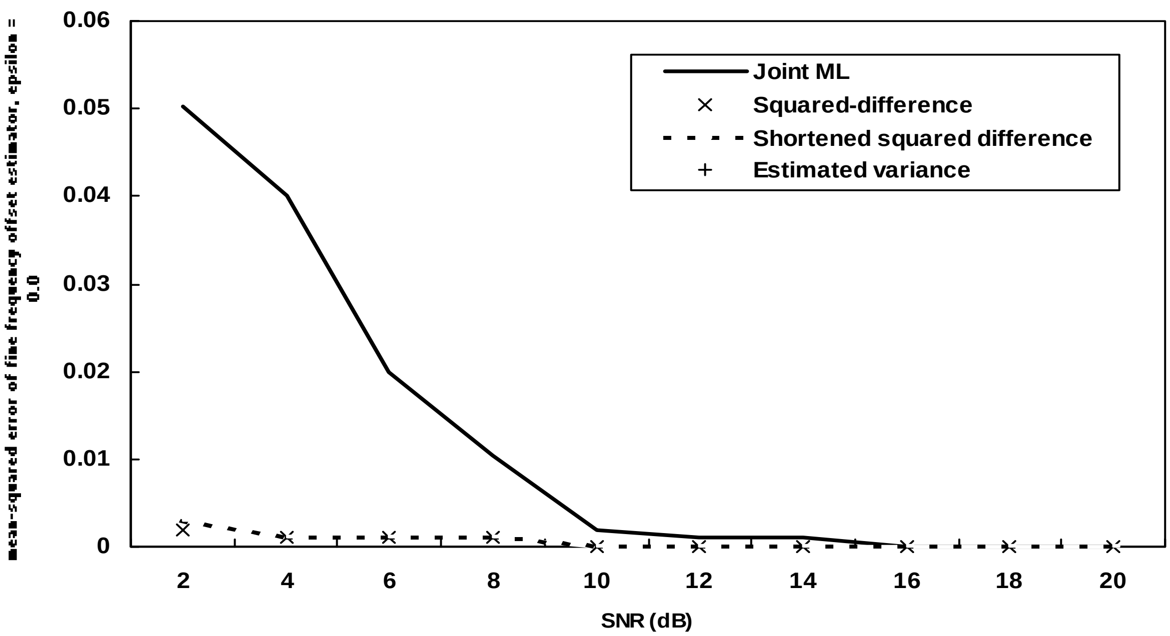




JOINT ESTIMATION

Based on a 16-sample cyclic prefix





OUTLINE

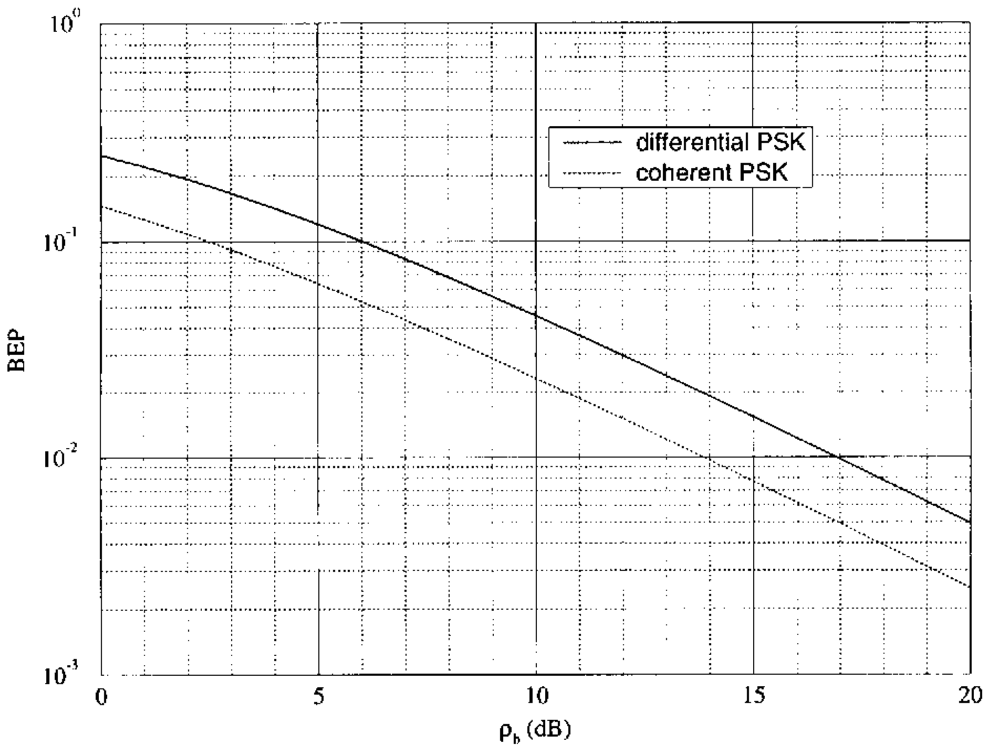
- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

CHANNEL ESTIMATION

- **Differential and coherent detection**
- **Decision-directed estimation**
- **Pilot-symbol-aided estimation**

DIFFERENTIAL AND COHERENT DETECTION

- 3-dB SNR degradation for differential detection



- Differential
  - in time ⇒ sensitive to Doppler shift
  - in frequency ⇒ sensitive to delay spread
- Coherent detection requires channel information

DECISION-DIRECTED ESTIMATION

- Use sliced data for estimating channel parameters

- Obtain an MMSE or robust estimator using the correlations of the channel parameters in time and/or frequency.

DECISION-DIRECTED ESTIMATION

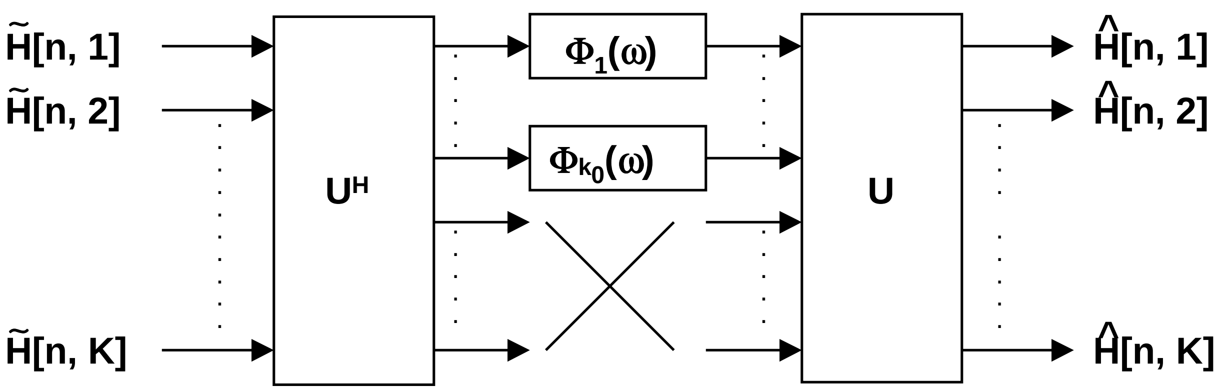
MMSE Estimator

- Using time and frequency correlations

- Estimator coefficients

$$C[n] = U\Phi[n]U^H$$
$$\Phi[n] = \mathrm{diag}\{\Phi_1[n], \ldots, \Phi_N[n]\}$$

- Estimator structure



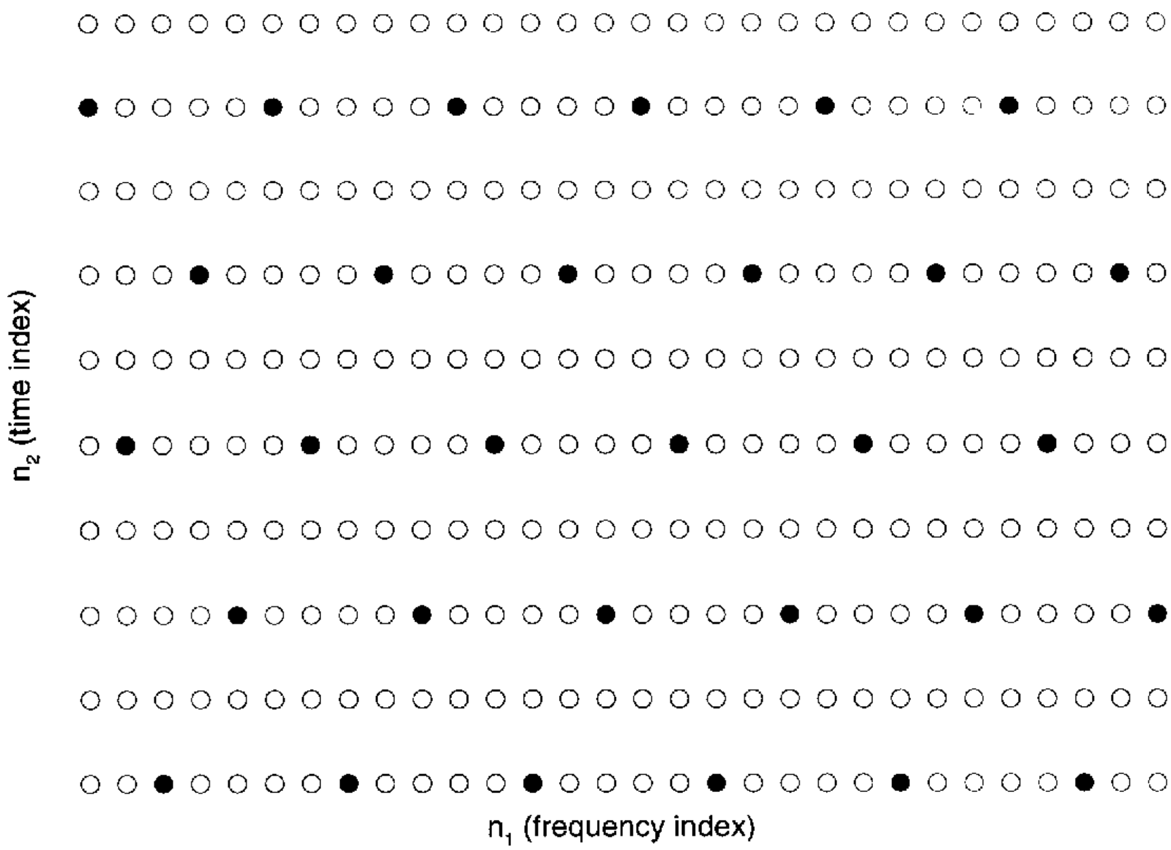
DECISION-DIRECTED ESTIMATION

Robust Estimator

- **Why robust estimation?**
  - **A large performance degradation is possible if MMSE estimator is not matched to the channel.**
- **Robust design**
  - **Match rectangular spectrum in time and frequency domains**
  - **Good performance for almost all channels**
  - **Relatively insensitive to Doppler and delay profiles**

PILOT-SYMBOL-AIDED ESTIMATION

- **Pilot symbol grid**

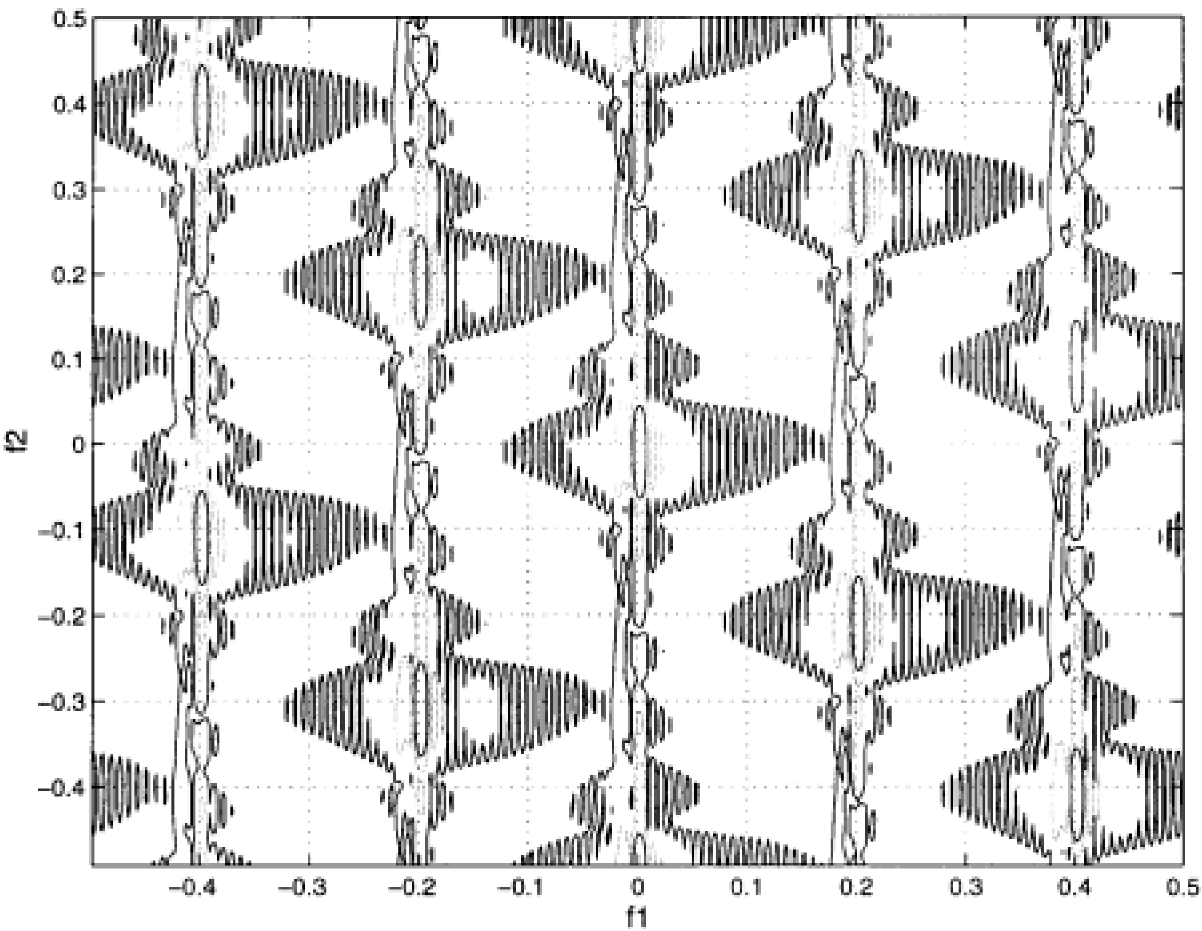


- **Obtain an estimate of the channel at the pilot symbol positions.**

- **Obtain estimates at other frequencies and times by interpolation.**

PILOT-SYMBOL-AIDED ESTIMATION
Grid Selection

- 2-D spectrum of channel parameters at pilot symbol positions



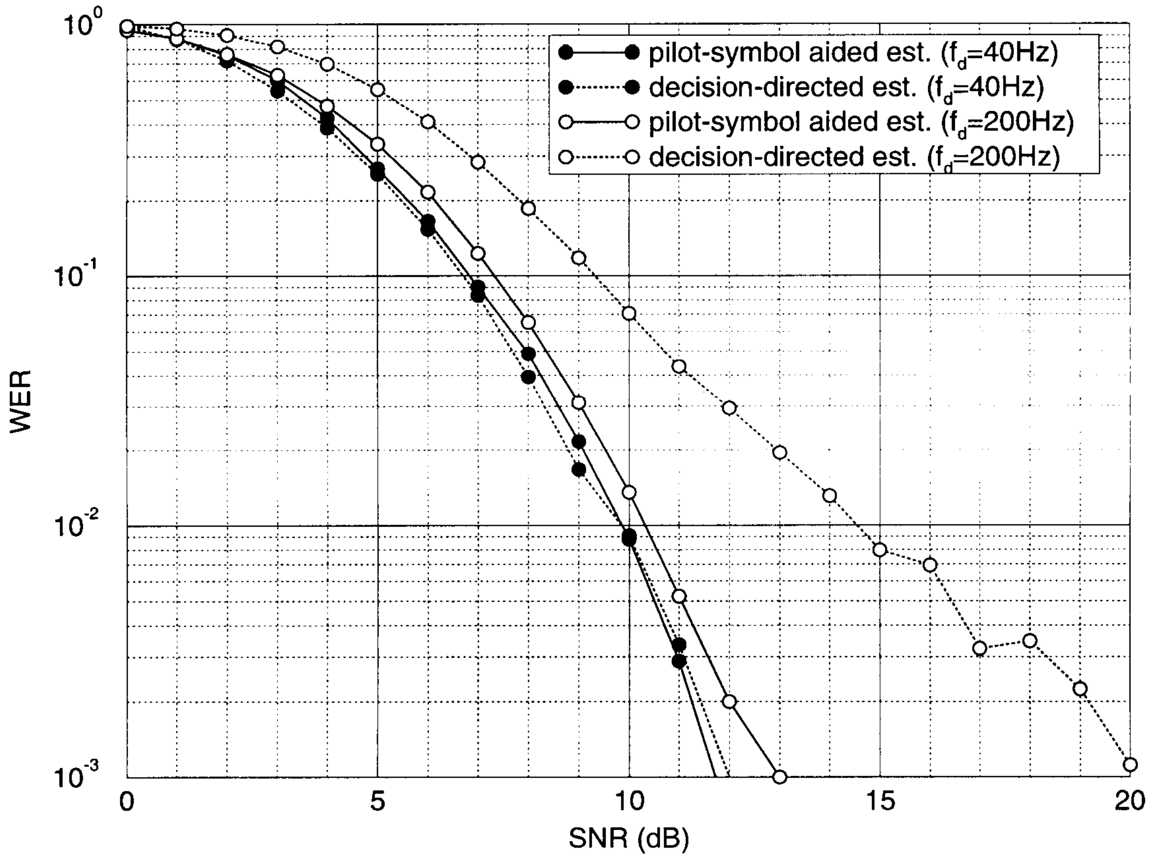
- Non-rectangular pilot symbol grids are better

SIMULATION PARAMETERS

- **800 kHz bandwidth**
- **Number of subchannels N = 128 subchannels (4 guard subchannels at each end)**
- **OFDM block duration T_f = 200 μsec (with 40-μsec guard interva)**
- **(40,20) R-S code, which corrects 10 erasures, based on signal strength, and correct 5 random errors**

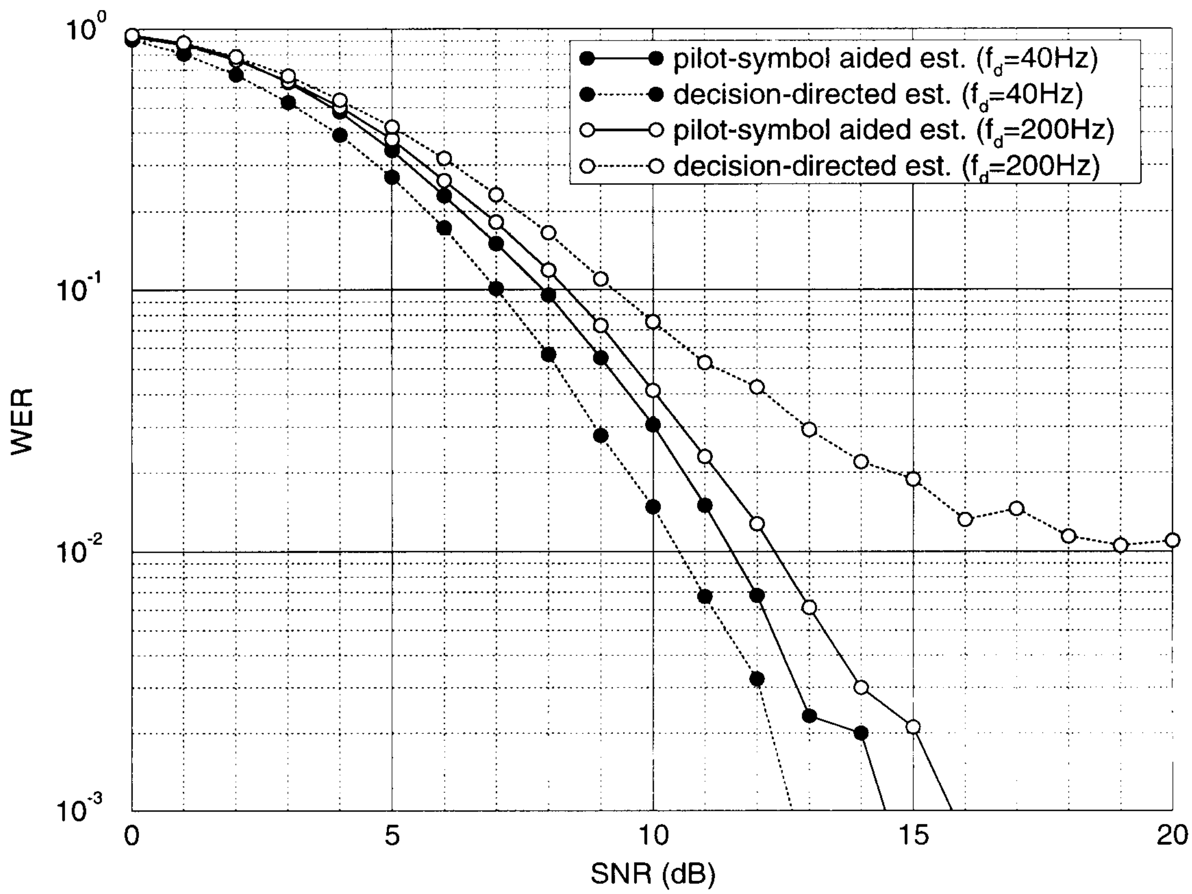
WORD ERROR RATE
Typical Urban Channel

(a)



WORD ERROR RATE
Hilly Terrain Channel

(b)



OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

APPLICATIONS

- Asymmetric digital subscriber line
- Digital audio and terrestrial TV broadcasting
- Wireless LAN’s
- High-speed cellular data

DIGITAL AUDIO BROADCASTING

- Broadcasting standard in Europe
- Single frequency network
- Bandwidth = 7 MHz
- Useful bit rate = 5.6 Mbits/sec
- N = 448 subchannels
- T_f = 80 μsec, T_f = 64 μsec, and T_g = 16 μsec
- Rate-1/4 conv. coding with constraint length 7
- Time interleaving: 16 X 24 msec
- Pilot symbols for channel estimation

WIRELESS LANS

- IEEE802.11(a)
  - New NII spectrum at about 5 GHz
  - Indoor applications

Modulation scheme	OFDM
Sub-carrier Modulation	DBPSK, 16 QAM in each subchannel
Number of subchannels	48 Subchannels out of 64
Coding	Convolution K=7, R=1/2 or R=3/4 inter-carrier interleave
Data rates	5 Mbps (BPSK, R=1/2)
	10 Mbps (QPSK, R=1/2)
	15 Mbps (QPSK, R=3/4))
	20 Mbps (16QAM, R=1/2)
	30 Mbps (16QAM, R=3/4)

WIRELESS LANS

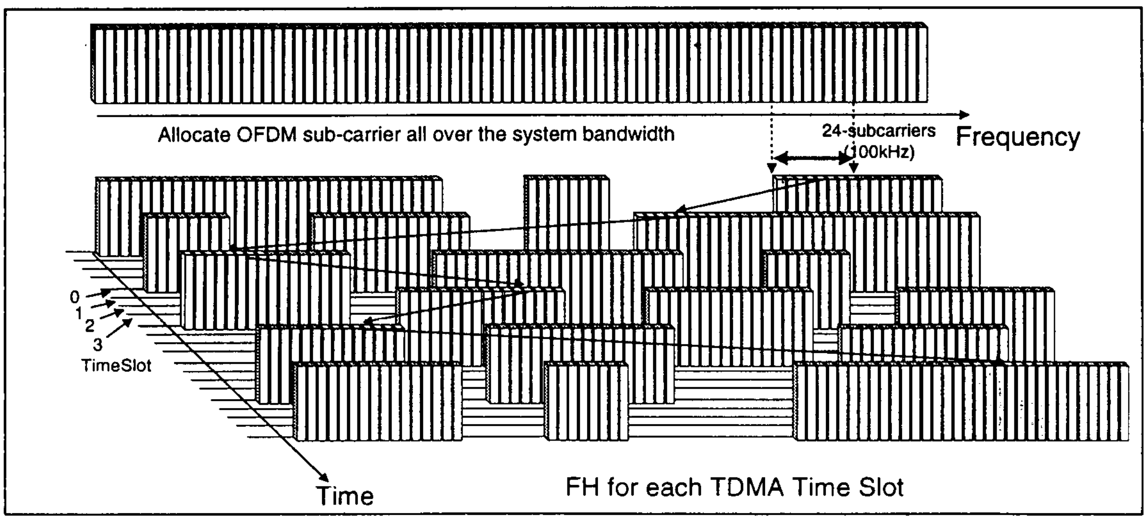
- HIPERLAN: High Performance Radio Local Area Network
  - Standard in Europe at 5.2 GHz
  - HIPERLAN Type I: single carrier GSMK with equalization
  - HIPERLAN Type II: COFDM

Information data rate	48, 32, 24, 16 and 8 Mbps
Modulation	OFDM with 16-QAM, QPSK or BPSK
Coding rate	Convolutional 3/4 or 1/2
Coding	48
OFDM symbol duration	3 μs
Guard interval	600 ns
T_{prefix}	600 ns
$T_{postfix}$	75 ns
Subchannel spacing	416.666 kHz
Roll-off factor	0.025
Channel Spacing	25 MHz
Occupied -3 dB Bandwidth	20 MHz

HIGH SPEED CELLULAR

Band Division Multiple Access (BDMA)

- Proposal by Sony, Japan
- Combination of TDMA, OFDM and cluster hopping



- Parameters
  - number of tones per cluster: $N_c = 24$
  - tone spacing: $\Delta f = 4.17$ kHz
  - symbol duration: $T_s = 1/\Delta f = 240$ μsec
  - guard interval: $T_g = 38.8$ μsec
  - ramp time: $T_r = 10$ μsec
  - block length: $T_f = T_s + T_r + T_g = 288.5$ μsec
  - cluster width: $B_c = N_c \Delta f = 100$ kHz

HIGH SPEED CELLULAR

Advanced Cellular Internet Service (ACIS)

- Goal to provide wide-area Internet service to mobile subscribers
- Combines OFDM with multiple transmitter and receiver antennas and coding
- Parameters
  - total bandwidth: $B = 800$ kHz
  - number of tones: $N = 192$
  - tone spacing: $\Delta f = B/N = 4.17$ kHz
  - symbol duration: $T_s = 1/\Delta f = 240\ \mu$sec
  - guard interval: $T_g = 48.5\ \mu$sec
  - block length: $T_f = T_s + T_g = 288.5\ \mu$sec
  - rate-1/2 R-S code across subchannels

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

SUMMARY

- High-bit-rate wireless data is desirable, but the radio environment puts an upper limit on the achievable bit rate.
- OFDM, by transmitting data over many narrow subchannels, can overcome the bit rate limit.
- However, to realize an OFDM system, several practical issues must be addressed, including PAPR, frequency offset and timing mismatch, and channel estimation.
- Several promising solutions have been proposed for all of these problems.
- OFDM is currently a very popular choice for future wireless applications, including wireless LANs, cellular and PCS data, and possibly Fourth Generation systems.

OUTLINE

- Introduction
- Basic Concepts
- Peak-to-Average Power Ratio Reduction
- Time and Frequency Synchronization
- Channel Estimation
- Applications
- Summary
- References

REFERENCES

• Basic Concepts

1. **M.L. Doelz, E.T. Heald, and D.L. Martin, "Binary data transmission techniques for linear systems," *Proc. IRE,* pp. 656-661, May 1957.**
2. **G.A. Franco and G. Lachs, "An orthogonal coding technique for communications," *1961 IRE International Convention Record,* pp. 126-130.**
3. **J. Holsinger, "Digital communication over fixed time-continuous channel with memory - with special application to telephone channels," *Ph.D. dissertation,* Massachusetts Institute of Technology, 1964.**
4. **P.A. Bello, "Selective fading limitations of the Kathryn modem and some system design considerations," *IEEE Trans. on Comm. Tech.,* pp. 320-333, Sept. 1965.**
5. **R.W. Chang, "Synthesis of band-limited orthogonal signals for multichannel data," pp. 1775-1797, *BSTJ,* Dec. 1966.**
6. **R.W. Chang, "Orthogonal frequency division multiplexing." *U.S. Patent 3,488,445,* filed Nov. 4 1966, issued Jan. 1970.**
7. **M.S. Zimmerman and A.L. Kirsh, "The AN/GSC-10 (KATHRYN) variable rate data modem for HF radio," *IEEE Trans. on Comm. Tech.,* pp. 197-205, April 1967.**
8. **B.R. Saltzberg, Performance of an efficient parallel data transmission systems," *IEEE Trans. on Comm. Tech.* pp. 805-811, Dec. 1967.**
9. **G.C. Porter, "Error distribution and diversity performance of a frequency-differential PSK HF modem," *IEEE Trans. on Comm. Tech.,* pp. 567-575, Aug. 1968.**

REFERENCES

- **Basic Concepts (cont'd)**

10. R.W. Chang and R.A. Gibby, "A theoretical study of performance of an orthogonal multiplexing data transmission scheme," *IEEE Trans. on Comm. Tech.,* pp. 529-541, Aug. 1968.
11. S.B. Weinstein and P.M. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," *IEEE Trans. on Comm. Tech.,* pp. 628-634, October 1971.
12. B. Hirosaki, "An analysis of automatic equalizers for orthogonally multiplexed QAM systems," *IEEE Trans. on Comm. Tech.,* pp. 73-83, Jan. 1980.
13. A. Peled and A. Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms," *Proc. of ICASSP '80,* pp. 964-967.
14. W.E. Keasler, Jr., "Reliable data communications over the voice bandwidth telephone using orthogonal frequency division multiplexing." *Ph.D. dissertation,* Univ. of Illinois, Urbana-Champaign, 1982.
15. L.J. Cimini, Jr., "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," *IEEE Trans. on Comm.,* pp. 665-675, July 1985.
16. B. Hirosaki, S. Hasegawa, and A. Sabato, "Advanced groupband data modem using orthogonally multiplexed QAM techniques," *IEEE Trans. on Comm.,* pp. 587-592, June 1986.
17. I. Kalet, "The multitone channel," *IEEE Trans. on Comm.,* pp. 119-124, Feb. 1989.

REFERENCES

• Basic Concepts (cont'd)

18. J.A.C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Comm. Mag.,* pp. 5-14, May 1990.
19. E.F. Casas and C. Leung, "OFDM for data communication over mobile radio FM channels," *IEEE Trans. on Comm.,* pp. 783-793, May 1991.
20. Special Issue on Multi-Carrier Modulation, *Kluwer Wireless Pers. Comm.,* January 1996.
21. L.J. Cimini, Jr., and N.R. Sollenberger, "OFDM with diversity and coding for high-bit-rate mobile data applications," *Proc. of the 3rd International Workshop on Mobile Multimedia Comm.,* Sept. 1996.
22. L.J. Cimini, Jr., B. Daneshrad, and N.R. Sollenberger, "Clustered OFDM with transmitter diversity and coding," *Proc. of Globecom '96,* pp. 703-707.

• Radio Environment

1. R.S. Kennedy, *Fading Dispersive Communication Channels,* Wiley, 1969.
2. W.C. Jakes, Jr., Ed., *Microwave Mobile Communications,* Wiley, 1974.
3. J.D. Parsons, *The Mobile Radio Propagation Channel,* Wiley, 1992.
4. J.B. Anderson, T.S. Rappaport, and S. Yoshida, "Propagation measurements and models for wireless communications channels," *IEEE Comm. Mag.,* pp. 42-49, January 1995.

REFERENCES

• Radio Environment (cont'd)

5. R. Steele, *Mobile Radio Communications,* IEEE Press, 1995.
6. T.S. Rappaport, *Wireless Communications,* IEEE Press/ Prentice-Hall, 1996.

• Peak-to-Average Power Reduction

1. A.E. Jones, T.A. Wilkinson, and S.K. Barton, "Block coding scheme for reduction of peak to mean envelope power ratio of multicarrier transmission schemes," *Elect. Lett.,* pp. 2098-2099, Dec. 1994.
2. R. O'Neil and L.B. Lopes, "Envelope variations and spectral splatter in clipped multicarrier signals," *Proc. of PIMRC '95,* pp. 71-75.
3. P. Van Eetvelt, G. Wade, and M. Tomlinson, "Peak to average power reduction for OFDM schemes by selective scrambling," *Elect. Lett.,* pp. 1963-1964, Oct. 1996.
4. R.W. Bäuml, R.F.H. Fischer, and J.B. Huber, "Reducing peak-to-average power ratio of multicarrier modulation by selected mapping." *Elect. Lett.,* pp. 2056-2057, Oct. 1996.
5. R.D.J. van Nee, "OFDM codes for peak-to-average power reduction and error correction," *Proc. of Globecom '96,* pp. 740-744.
6. S.H. Müller and J.B. Huber, "OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences," *Elect. Lett.,* pp. 368-369, Feb. 1997.
7. X. Li and L.J. Cimini, Jr., "Effects of clipping and filtering on the performance of OFDM," *IEEE Comm. Letts.,,* pp. 131-133, May 1998.

REFERENCES

• Peak-to-Average Power Reduction (cont'd)

8. S.H. Müller and J.B. Huber, "A novel peak power reduction scheme for OFDM," *Proc. of PIMRC '97,* pp. 1090-1094.
9. M. Friese, "Multitone signals with low crest-factor," *IEEE Trans. on Comm.,* pp. 1338-1344, Oct. 1997.
10. J. Tellado and J.M. Cioffi, "PAR reduction in multicarrier transmission systems," *ANSI T1E1.4 committee contribution,* number 97-367, Dec. 1997.

• Time and Frequency Synchronization

1. P.H. Moose, "A technique for orthogonal frequency-division multiplexing frequency offset correction," *IEEE Trans., on Comm.,* pp. 2908-2914, Oct. 1994.
2. T. Pollet, P. Spruyt, and M. Moeneclaey, The BER performance of OFDM systems using non-synchronized sampling," *Proc. of Globecom '94,* pp. 253-257.
3. K.W. Kang, J. Ann, and H.S. Lee, "Decision-directed maximum-likelihood estimation of OFDM frame synchronization offset," *Elect Lett.,* pp. 2153-2154, Dec. 1994.
4. J.S. Oh, Y.M. Chung, and S.U. Lee, "A carrier synchronization technique for OFDM on the frequency-selective fading environment," *Proc. of VTC '96,* pp. 1574-1578.
5. F. Daffara and O. Adami, "A novel carrier recovery technique for orthogonal multicarrier systems," *European Trans. on Telecomm.,* pp. 323-334, July-Aug. 1996.

REFERENCES

• Time and Frequency Synchronization (cont'd)

6. **H. Nogami and T. Nagashima, "A frequency and timing period acquisition technique for OFDM systems,"** ***IEICE Trans. on Comm.,*** **pp. 1135-1146, Aug. 1996.**
7. **M. Luise and R. Reggiannini, "Carrier frequency acquisition and tracking for OFDM systems,"** ***IEEE Trans. on Comm.,*** **pp. 1590-1598, Nov. 1996.**
8. **M. Speth, F. Classen, and H. Meyr, "Frame synchronization OFDM systems in frequency selective fading channels,"** ***Proc. of VTC '97,*** **pp. 1807-1881.**
9. **L. Hazy and M. El-Tanany, "Synchronization of OFDM systems over frequency selective fading channels,"** ***Proc. of VTC '97,*** **pp. 2094-2098.**
10. **J.J. van de Beek, M. Sandell, and P.-O. Börjesson, "ML estimation of timing and frequency offset in OFDM systems,"** ***IEEE Trans. of Sig. Proc.,*** **pp. 1800-1805, July 1997.**
11. **D. Lee and K. Cheun, "A new symbol timing recovery algorithm for OFDM systems,"** ***IEEE Trans. on Consum. Elect.,*** **pp. 767-775, Aug. 1997.**
12. **T. Schmidl and D. Cox, "Robust frequency and timing synchronization for OFDM,"** ***IEEE Trans. on Comm.,*** **pp. 1613-1621, Dec. 1997.**

• Channel Estimation

1. **J.J. van de Beek, O. Edfors, M. Sandell, S.K. Wilson, and P.O. Börjesson, "On channel estimation in OFDM systems,"** ***Proc. of VTC '95,*** **pp. 815-819.**

REFERENCES

• Channel Estimation (cont'd)

2. V. Mignone and A. Morello, "CD3-OFDM: a novel demodulation scheme for fixed and mobile receivers," *IEEE Trans. of Comm.,* pp. 1144-1151, Sept. 1996.
3. P. Hoeher, S. Kaiser, and P. Robertson, "Two-dimentional pilot-symbol-aided channel estimation by Wiener filtering," *Proc. of ICASSP '97,* pp. 1845-1848.
4. H.H. H'mimy, "Channel estimation based on coded pilot for OFDM," *Proc. of VTC '97,* pp. 1375-1379.
5. F. Tufvesson and T. Maseng, "Pilot assisted channel estimation for OFDM in mobile cellular systems," *Proc. of VTC '97,* pp. 1639-1643.
6. P. Hoeher, S. Kaiser, and P. Robertson, "Pilot-symbol-aided channel estimation in time and frequency," *Proc. of Globecom '97,* pp. 90-96.
7. Y.(G.) Li, L.J. Cimini, Jr., and N.R. Sollenberger, "Robust channel estimation for OFDM systems with rapid dispersive fading channels," *IEEE Trans. on Comm.,* pp. 902-915, July 1998.
8. O. Edfors, M. Sandell, J.J. van de Beek, S.K. Wilson, and P.O. Börjesson, "OFDM channel estimation by singular value decomposition," *IEEE Trans. on Comm.,* pp. 931-939, July 1998.
9. Y.(G.) Li and N. Sollenberger, "Interference suppression in OFDM systems using adaptive antenna arrays," *IEEE Trans. on Comm.,* pp. 217-229, Feb. 1999.
10. Y.(G.) Li, N. Seshadri, and S. Ariyavisitakul, Transmitter diversity of OFDM systems with dispersive fading channels," *IEEE J-SAC,* pp.461-471, March 1999.

REFERENCES

• Applications

1. **M. Alard and R. Lassalle, "Principles of modulation and channel coding for digital broadcasting for mobile receivers,"** ***EBU Review - Technical,*** **Aug. 1987.**
2. **B. Le Floch, R. Halbert-Lassalle, and D. Castelain, "Digital sound broadcasting to mobile receivers,"** ***IEEE Trans. of Broad.,*** **pp. 493-503, Aug. 1989.**
3. **D. Raychaudhuri and N.D. Wilson, "ATM-based transport architecture for multi-services wireless personal communication networks,"** ***IEEE J-SAC,*** **pp. 1401-1413, Oct. 1992.**
4. **"Radio broadcasting systems: Digital audio broadcasting (DAB) to mobile, portable and fixed receivers,"** ***ETS 300 401, ETSI -*** **European Telecommunications Standards Institute, Valbonne, France, Feb. 1995.**
5. **IEEE P802.11D3,** ***Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,*** **IEEE Standard Department, Jan. 1996.**
6. **K.M. Aldinger, "A Multi-carrier scheme for HIPERLAN."** ***Wireless Personal Comm., Kluwer Acad. Pub.,*** **Jan. 1997.**
7. **L.J. Cimini, Jr., J.C. Chaung, and N.R. Sollenberger, "Advanced Cellular Internet Service (ACIS),"** ***IEEE Comm. Mag.,*** **pp. 150-159, Oct. 1998.**