

Seminar Outline

- **Communications for the new Economy**
- **Wireless Technology Evolution**
- **Broadband Wireless Tutorial**
- **BLAST Overview: The next dimension**
- **BLAST Tutorial:**

BROADBAND WIRELESS TUTORIAL

OUTLINE:

- **Introduction**
- **Radio Environment**
- **Physical Layer Issues**
- **Channel Access Issues**
- **Network Issues**
- **Standards and Future Systems**
- **Summary**
- **References**

HIGH-SPEED WIRELESS DATA AND INTERNET ACEESS

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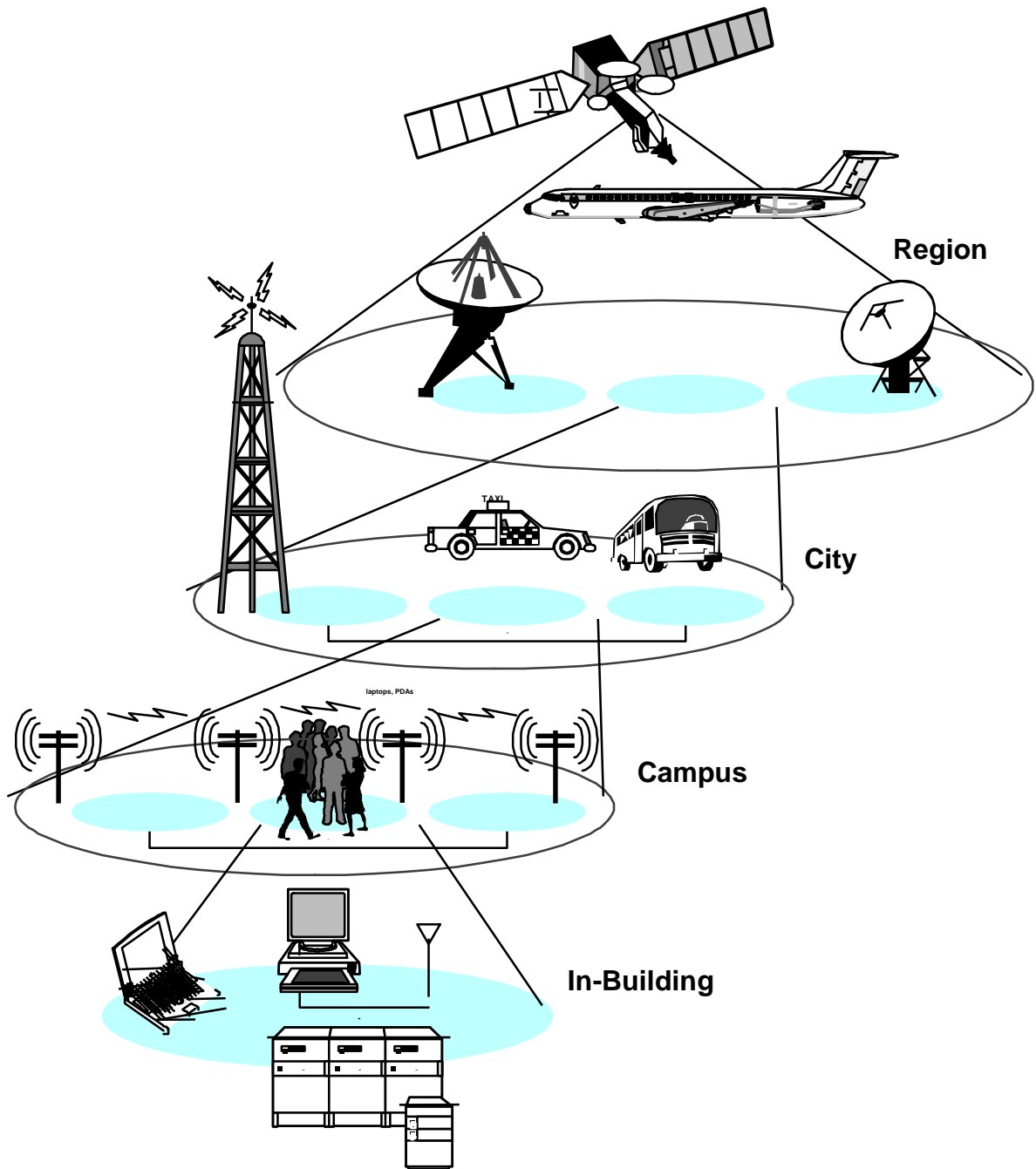
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INTRODUCTION

- **Wireless Data Vision**
- **Current Wireless Data Options**
- **Is There a Future for Wireless Data?**
- **The Issue is Performance**
- **Technical Challenges**

WIRELESS DATA VISION



**Seamless Multimedia Networks
with Mobility and Freedom from Tethers**

[R. Katz, "Does Wireless Data Have a Future?", Plenary Talk, INFOCOM '96]

WHAT IS WIRELESS DATA?

- **Paging/Short Messaging**
- **Vehicle Tracking and Dispatch**
- **Transaction Processing**
- **Warehouse Inventory**
- **Subscriber Information Services**
- **Wireless Remote Access to Host**
- **File Transfer to/from Laptop**
- **Wireless Internet Access**
- **Video Teleconferencing**

VOICE VERSUS DATA VERSUS VIDEO

	Voice	Data	Video
Delay	< 100 ms	–	< 100 ms
Packet Loss	< 1%	0	<1%
BER	$10^{-2} - 10^{-3}$	$< 10^{-5}$	$< 10^{-7}$
Data Rate	8-32 kbps	1-100 Mbps	1-20 Mbps
Traffic	Continuous	Bursty	Continuous



**Wired Networks Trying to Integrate
(ATM, SONET, Multimedia Services)**

WIRELESS DATA REQUIREMENTS

Services	Throughput (kbps)	Target Bit Error Rate
Telephony	8-32	10^{-3}
Teleconference	32	10^{-3}
Voice mail	32	10^{-3}
Program sound	128	10^{-6}
Video telephony	64	10^{-7}
Video conference	384-768	10^{-7}
Remote terminal	1.2-9.6	10^{-6}
User profile editing	1.2-9.6	10^{-6}
Telefax (Group 4)	64	10^{-6}
Voiceband data	64	10^{-6}
Database access	2.4-768.0	10^{-6}
Message broadcast	2.4	10^{-6}
Unrestricted digital information	64-1,920	10^{-6}
Navigation	2.4-64.0	10^{-6}
Location	2.4-64.0	10^{-6}

[V. K. Garg and J. E. Wilkes, *Wireless and Personal Communications Systems*, Prentice Hall, 1996]

CURRENT WIRELESS DATA OPTIONS

- **High-Bit-Rate Local Area Networks**
- **Low-Bit-Rate Wide Area Networks**

WIRELESS LOCAL AREA NETWORKS

- LAN Replacement, Inventory, E-mail, Internet Access
- Link Rates: Tens of Mbps
- Data Rates: A Few Mbps
- Designed for Local Indoor, Less Than 100 m Range
- Most Operate in ISM Band (902-928 MHz, 2.4 GHz)
- Most Uses Spread-Spectrum to Satisfy ISM-Band Rules
- Most Provide Ethernet Connectivity
- Examples: WaveLAN, Freeport, RangeLAN2, ArLAN
- Standards Activities: IEEE 802.11, HIPERLAN, WINForum, Wireless ATM Forum

"... the world's wireless LAN market remains a small one. For radio links, it hovers at around \$200 million,... Why? The technology is new, so components are expensive and data rates are low".

IEEE Spectrum, September 1996

PARTIAL LIST OF WLAN PRODUCTS

Product Company Location	Frequency	Link Rate	User Rate	Protocol	Access	Range	Power	Network Topology
WaveLAN Lucent Tech. Dayton, OH	902-928 MHz 2.4 GHz	2 Mb/s	1.6 Mb/s	Ethernet-like	DS SS	200-800 ft	250 mW	Peer-to-peer
Freeport Windata Inc. Northboro, MA	902-928 MHz	16 Mb/s	5.7 Mb/s	Ethernet	DS SS	260 ft	650 mW	Hub
ArLAN 1200 Aironet Wireless Comm. (Telxon) Fairlawn, OH.	902-928 MHz 2.4 GHz	2 Mbps	1.35 Mb/s	Ethernet	DS SS	500 ft	1 W	PCs with ant.; radio to hub
Range LAN	902-928 MHz		242 kb/s	Ethernet, token ring	DS SS	500 ft	100 mW	
Range LAN2 Range LAN 802 Proxim, Inc. Mountain View, CA	2.4 GHz	1.6 Mb/s	50 kb/s max.	Ethernet, token ring	FH SS		100 mW	Peer-to-peer bridge

[D. C. Cox, "Wireless Personal Communications: What Is It?," *IEEE Personal Communications Magazine*, April 1995]

[M. Edwards, "Wireless LANs: Their Time Has Come," *Communications News*, May 1997]

WIRELESS LAN MARKETS

- **Not a mass-market product**
- **Obstacles to Widespread Acceptance**
 - **Cost**
 - **Performance**
 - **Mostly niche market acceptance such as inventory**
 - **RF engineering**
 - **Limited coverage and mobility**
- **Future Directions**
 - **WLANs will continue as adjuncts for foreseeable future**
 - **Higher bit rates and wireless ATM**
 - **Multimode operation with widespread wireless data systems may be a good long-term opportunity**

WIDE-AREA WIRELESS DATA SERVICES

- **Paging and Messaging, FAX, E-mail, Dispatch**
- **Link Rates and Data Rates: Less Than 100 kbps**
- **Designed for Metropolitan Area Coverage**
- **Most Operate in Cellular or SMR Bands**
- **Most Provide Gateways to the Internet**
- **Packet Systems Have Significant Latency**
- **Examples**
 - Existing: ARDIS (AMS), RAM Mobile Data (Bell South), CDPD, Metricom
 - Upcoming: Digital Cellular

EXISTING WIDE-AREA WIRELESS DATA

System	ARDIS	RAM Mobile Mobitex	CDPD	Metricom Ricochet
Frequency Band Base to Mobile (MHz) Mobile to Base (MHz)	(800 Band) (45 kHz sep.)	935-940 896-901	869-894 824-849	902-928
RF Channel Spacing	25 kHz (U.S.)	12.5 kHz	30 kHz	160 kHz
Channel Access/ Multiuser Access	FDMA/ DSMA	FDMA/ Dynamic- S-ALOHA	FDMA/ DSMA	FHSS
Modulation Method	FSK, 4-FSK	GMSK	GMSK	GMSK
Bit Rate (kbps)	19.2	8.0	19.2	75
Packet Length	Up to 256 Bytes (HDLC)	Up to 512 Bytes	24 to 928 Bits	
Private or Public Carrier	Private	Private	Public	
Service Coverage	400 Metro. Areas in U.S.	50 Metro. Areas in U.S.	All AMPS Areas	A Few Metro. Areas in U.S.
Type of Coverage	In-building & Mobile	In-building & Mobile	Mobile	Mobile

[D. C. Cox, "Wireless Personal Communications: What Is It?," *IEEE Personal Communications Magazine*, April 1995]

CDPD VOICE/DATA TERMINALS

**CDPD Handset
with HDML**



**Sierra PCMCIA Type II
CDPD Modem**



WIDE-AREA WIRELESS DATA MARKETS FOR USA

YEAR 1996

- ~ 1 million data users: mostly FAX
- ~ 100k packet users: ARDIS, RAM, CDPD
- ~ 200k units per year

YEAR 2000

- 10 million data users: FAX, Internet, Intranet
- 1 to 3 million units per year

CHALLENGES

Standards

High Performance

SATELLITE-BASED MOBILE SYSTEMS

- **Link Rates: Less Than 20 kbps**
- **Very Widespread, Often Global, Coverage**
- **Orbits: LEOs Versus MEOs Versus GEOs**
- **Examples: Inmarsat, Iridium, Globalstar, Teledesic, VITAsat**

GEOS

System	MSAT	Inmarsat-3	Mobilesat	EMS	LLM
Organization	AMSC, TMI	Inmarsat	Optus Comm.	ESA	ESA
No. of satellites	2	5	2	1	1
Satellite lifetime [yrs]	12	13	9	8	5
Satellite weight [kg]	1650	1900			
Coverage	North America, Caribbean	Global	Australia	Europe, N. Africa	Europe, Asia
User link freq. [MHz]	1646.5-1660.5 [↑] 1545-1559 [↓]	L-band	1646.5-1660.5 [↑] 1545-1559 [↓]	1631.5-1660.5 [↑] 1530-1559 [↓]	L-band
Feeder link freq. [GHz]	K _u -band	C-band	K _u -band	K _u -band	K _a -band
Repeater type	Bent-pipe	Bent-pipe	Bent-pipe	Bent-pipe	Bent-pipe
Access method	FDMA	FDMA	FDMA	CDMA/FDMA	CDMA/FDMA
Max. data rate [kbps]	4.8	2.4	2.4	10.0	10.0
Service date	1995	1996	1994	1996	1997/1998

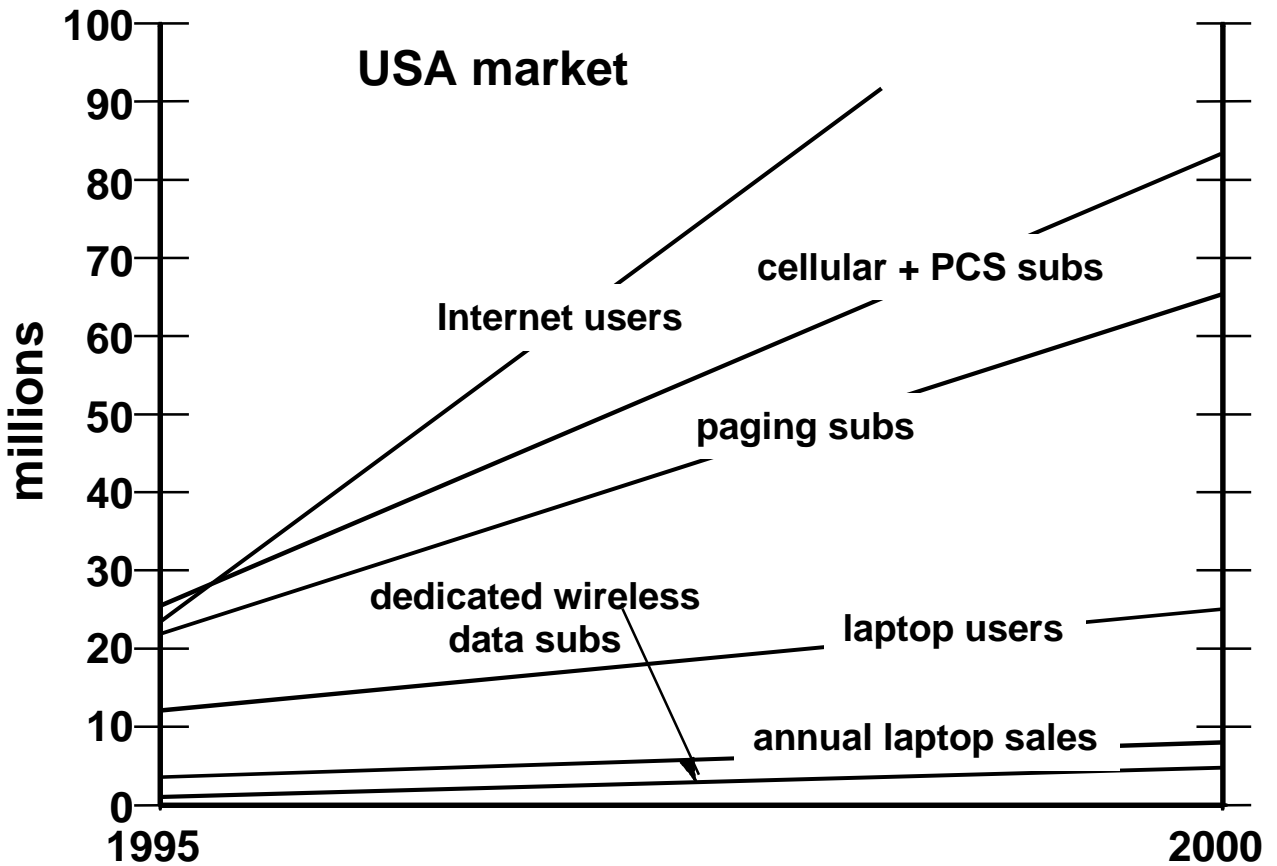
[F. Abrishamkar and Z. Siveski, "PCS Global Mobile Satellites," *IEEE Communications Magazine*, September 1996]

"LITTLE" LEOS

System	Orbcomm	Starsys	VITAsat	GEMnet
Organization	Orbital Comm.	Starsys Global Pos.	VITA/ Final Analysis	CTA Commerc. Systems
Orbital type	LEO	LEO	LEO	LEO
No. of orbital planes	6	6	1	5
No. of satellites	28	24	2	38
Orbit altitude [km]	775	1000	1000	1000
Satellite lifetime [yrs]	4	5	3-5	5-7
Satellite weight [kg]	43	85	90	45
Coverage	Global	Global	Global	Global
User link frequency [MHz]	148.905-149.9↑ 137-138↓	148-148.905↑ 137-138↓ 400.15-401↓	148-149.9↑ 400-400.1↓	148-149.9↑ 137-138↓
Feeder link frequency [GHz]	149.61↑ 137.56↓	148-.9↑ 137.5↓	149.9↑ 400.0↓	148-149.9↑ 400.15-401↓
Access method	FDMA	CDMA	FDMA	FDMA
Max. data rate [kbps]	2.4 ↑ 4.8↓	0.6 ↑ 2.4↓	19.2 ↑ 38.4↓	4.8 ↑ 19.2↓
Service date	1998	2001	1996	1997

[F. Abrishamkar and Z. Siveski, "PCS Global Mobile Satellites," *IEEE Communications Magazine*, September 1996]

WHAT IS THE FUTURE OF WIRELESS DATA?



*Estimates as of 1996

DOES WIRELESS DATA HAVE A FUTURE?

"Although it's been the pot of gold just around the corner for the last five years, we still don't have a hugely profitable business case for wireless data."

Dr. David Roddy, Chief Telecom Economist, Deloitte & Touche, 4/98

"Up to now, the wireless data party has been more flop than fete, with precious few subscribers showing even a hint of interest in using unwired services for anything more than voice calls. This year may finally see wireless data make its long-expected splash"

Meg McGinity, Wireless Editor, 4/98

"Wireless data service operators believe that wireless Internet access holds the key to growth that has largely eluded the market to date."

Arthur P. Little, Wireless Business and Finance, 7/17/96

"Wireless LANs finally appear poised for the growth and popularity long expected of them. The wireless LAN market in the U.S. will enjoy a sixfold expansion by the year 2000, reaching more than 1 billion in revenue."

Morris Edwards, Communications News, May, 1997.

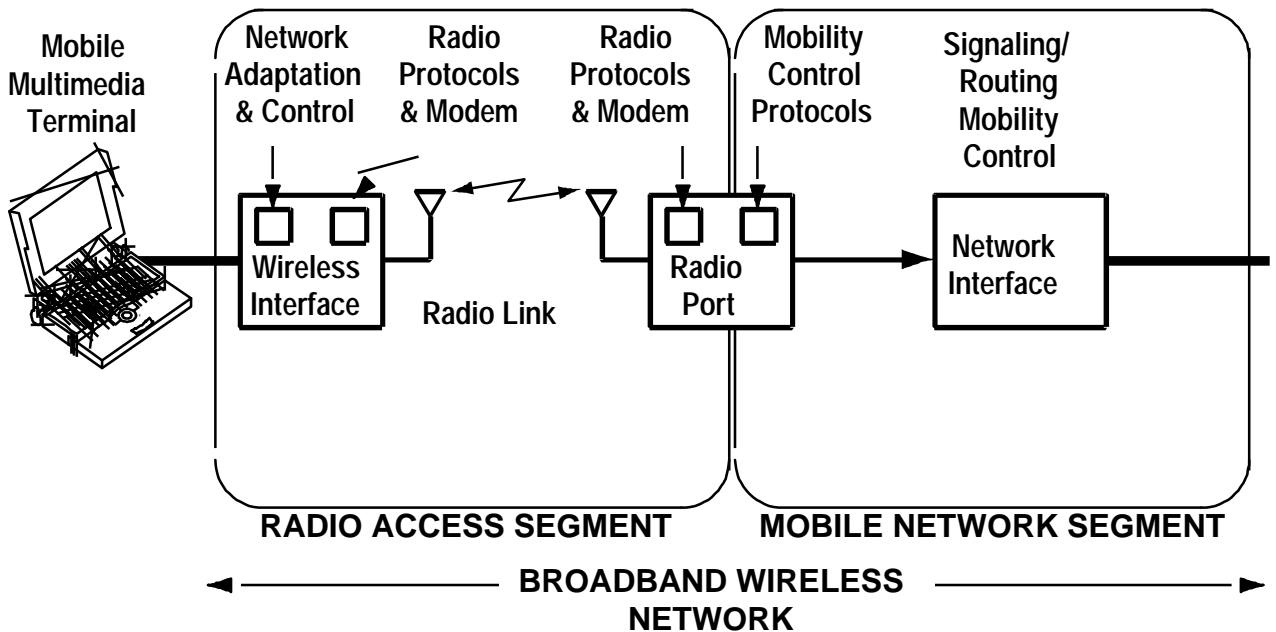
DRIVERS FOR WIRELESS DATA

- **Huge Success of Cellular and Paging Services**
- **Proliferation of Laptop and Notebook Computers**
- **Explosive Demand for Internet Access (e.g., World Wide Web, E-mail)**

THE ISSUE IS PERFORMANCE

"The mobile data market has been slow to take off, but progress is being made. The most formidable obstacle to user acceptance remains performance."

I. Brodsky, "Countdown to Mobile Blast Off",
Network World, February 19, 1996



- **Link Performance: Data Rate and Quality**
- **Network Performance: Access, Coverage, Reliability, QoS, and Internetworking**

TECHNICAL CHALLENGES

- **Low-Power/Low-Cost Implementations**
- **Scarce Radio Spectrum**
- **Radio Channel Characteristics**
 - **Limits on Signal Coverage**
 - **Limits on Data Rates**
- **Efficient Network Architectures and Protocols**
- **Seamless Internetworking**
- **Authentication and Security**

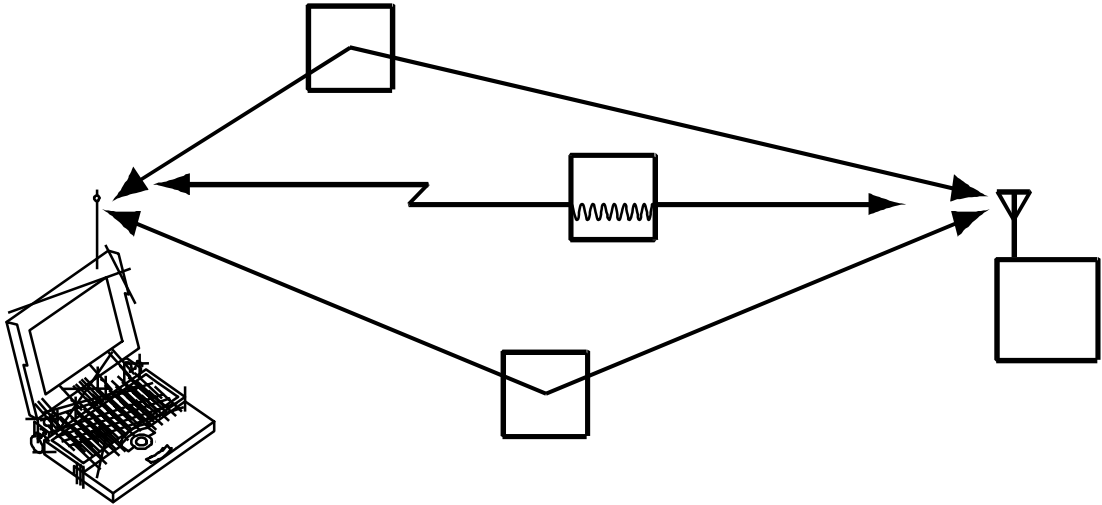
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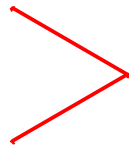
RADIO ENVIRONMENT

- **Path Loss**
- **Shadow Fading**
- **Multipath**
- **Interference**
- **Infrared Versus Radio**

RADIO ENVIRONMENT



- Path Loss
- Shadow Fading
- Multipath



**Limit the Bit Rate
and/or Coverage**

PATH LOSS MODEL

- Different, often complicated, models are used for different environments.
- A simple model for path loss, L , is

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

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.

PATH LOSS LIMITATIONS

- The received signal-to-noise power ratio, SNR, is

$$\text{SNR} = \frac{\bar{P}_r}{P_n} = \frac{KP_t}{d^\alpha} \cdot \frac{1}{N_o B}$$

where N_o is the one-sided noise power spectral density and B is the signal bandwidth.

- Given the performance requirement $\text{SNR} \geq \text{SNR}_o$, the path loss imposes limits on the bit rate and the signal coverage.

$$B \leq \frac{KP_t}{d^\alpha N_o \text{SNR}_o} \quad \text{or} \quad d \leq \left(\frac{KP_t}{N_o B \text{SNR}_o} \right)^{1/\alpha}$$

EXAMPLE – OUTDOOR

$$\text{SNR}_o = 8 \text{ dB}$$

$$K = -38 \text{ dB}$$

$$N_o = -204 \text{ dB/Hz}$$

$$\alpha = 4$$

$$P_t = 0 \text{ dB (1 Watt)}$$

Suppose it is desired to provide coverage for cells with 1 km radius

$$B \leq 6.3 \text{ kHz}$$

Alternatively, suppose $B = 200 \text{ kHz}$,

$$d \leq 420 \text{ meters}$$

EXAMPLE – INDOOR

$$\text{SNR}_o = 12 \text{ dB}$$

$$K = -45 \text{ dB}$$

$$N_o = -204 \text{ dB/Hz}$$

$$\alpha = 3.5$$

$$B = 100 \text{ MHz}$$

$$d = 100 \text{ meters}$$

$$P_t = \frac{N_o B \text{ SNR}}{K} d^\alpha$$

$$= 200 \text{ mW}$$

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,

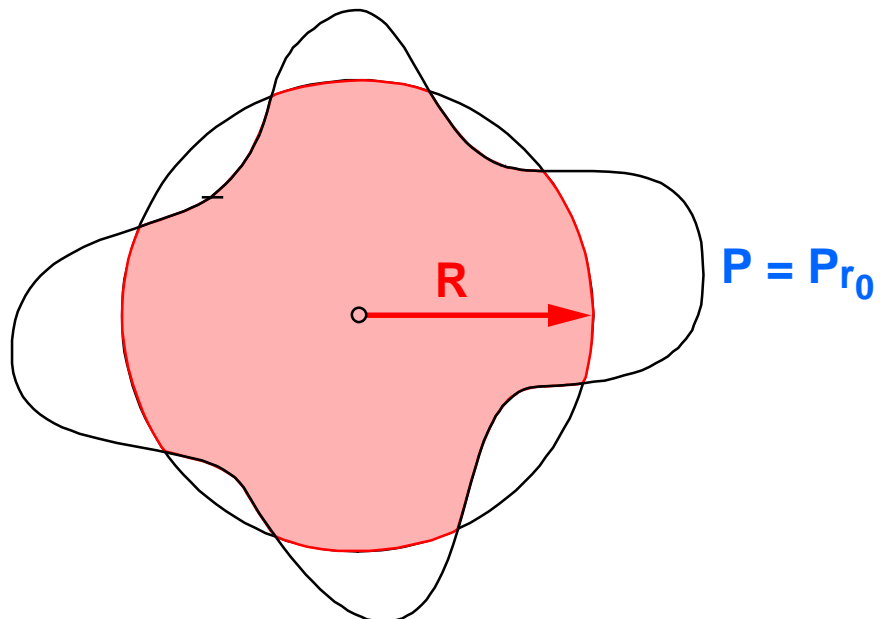
$$P_r \text{ (dB)} = \bar{P}_r \text{ (dB)} + G_s$$

where $G_s \sim N(0, \sigma_s^2)$, $4 \leq \sigma_s \leq 10$ dB.

- Implications
 - nonuniform coverage
 - increases the required transmit power

COVERAGE AREA

- For a desired received power P_{r_0} the coverage area C defines the percentage of the cell with received power $P \geq P_{r_0}$.

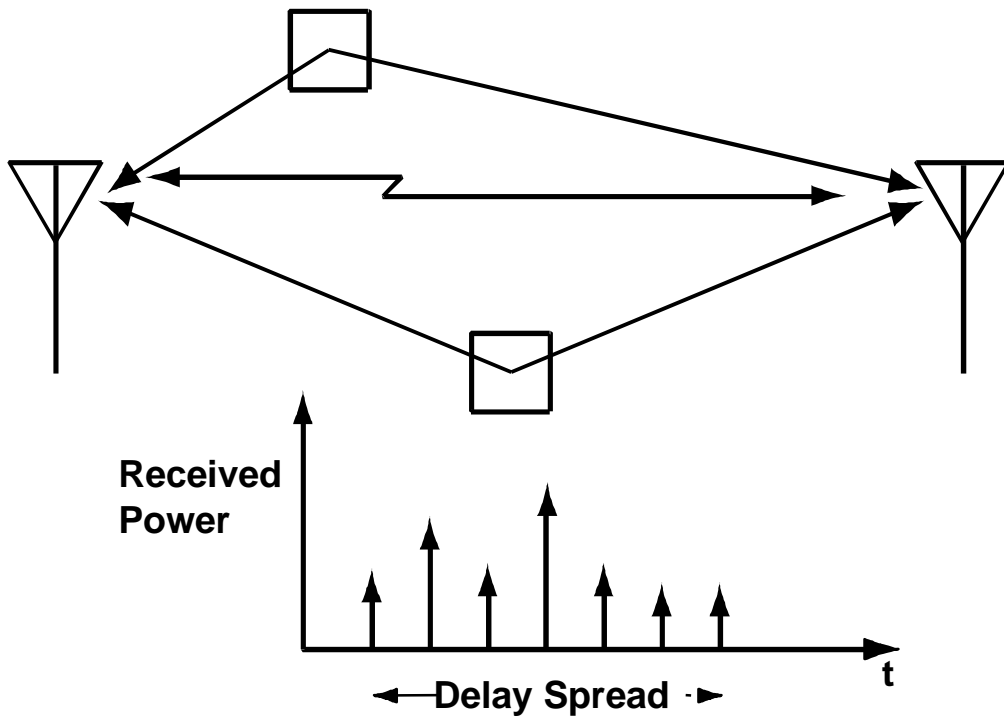


For $P(R) = P_{r_0}$

$$C = \frac{1}{2} \left[1 + \exp \left(-\frac{1}{2} \right) \left(1 - \operatorname{erf} \left(\frac{1}{b} \right) \right) \right], \quad b = \frac{10\alpha \log e}{\sigma_s \sqrt{2}}$$

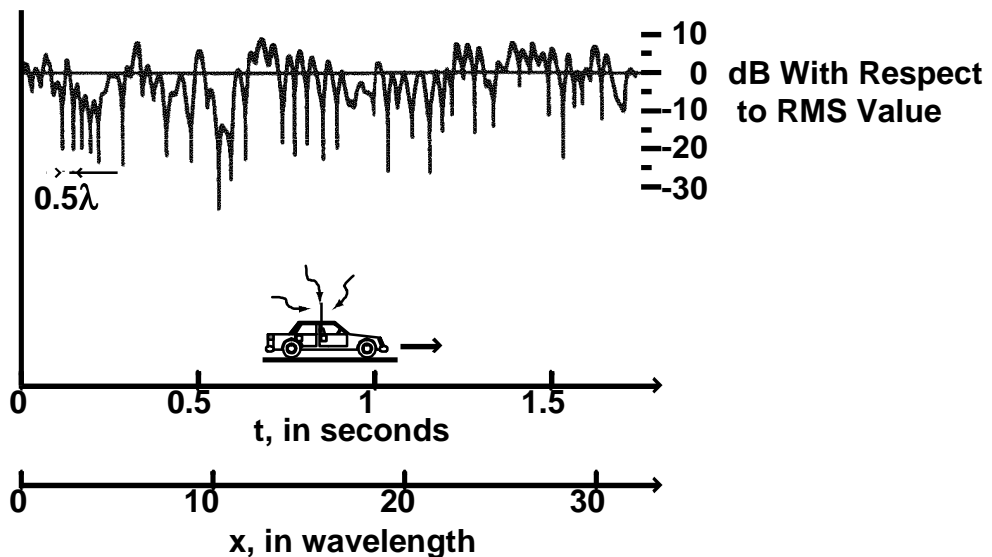
$\alpha \backslash \sigma_s$	4	8	12
2	77%	67%	63%
4	85%	77%	71%
6	90%	83%	77%

MULTIPATH



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

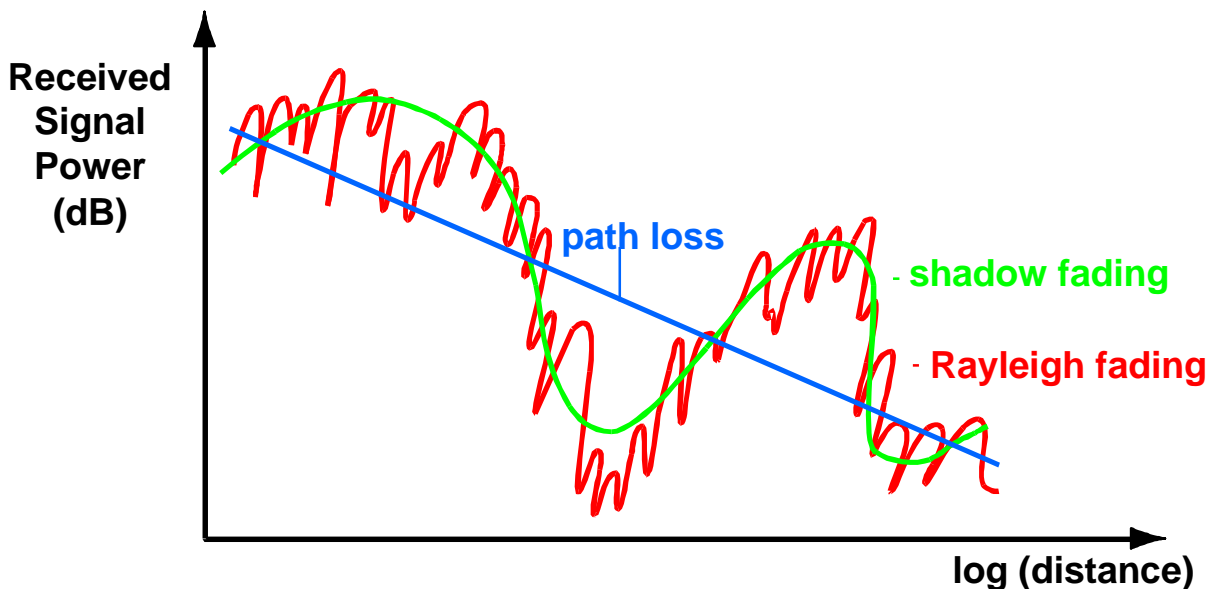
- Constructive and Destructive Interference of Arriving Rays



FLAT FADING

- The delay spread is small compared to the symbol period.
- The received signal envelope, r , follows a Rayleigh or Rician distribution.

$$P_r \text{ (dB)} = P_t \text{ (dB)} + G_s + 20 \log r$$



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

DOPPLER SPREAD

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

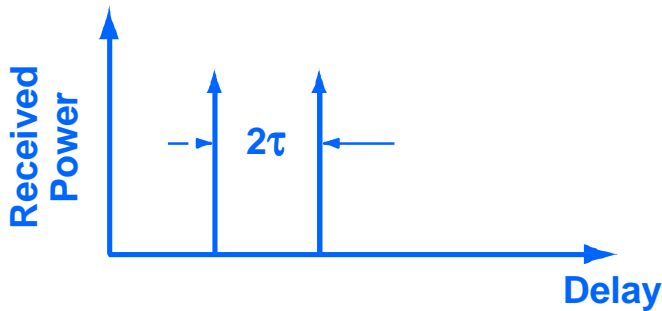
$$f_D \leq \frac{v}{\lambda}$$

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

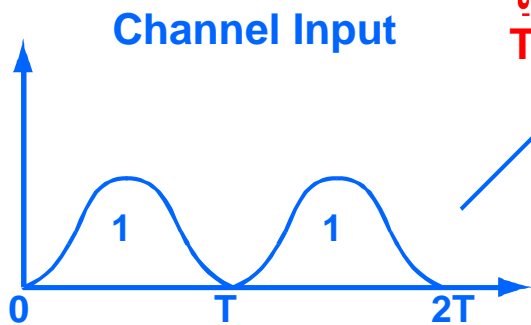
- Implications
 - signal amplitude and phase decorrelate after a time period $\sim 1/f_D$

DELAY SPREAD

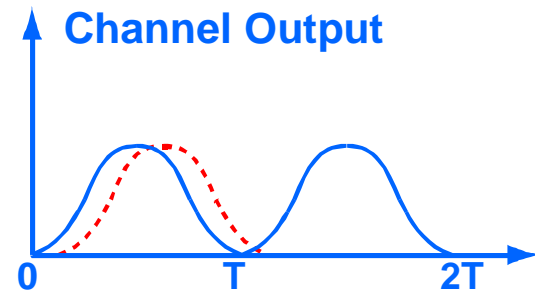
TIME DOMAIN INTERPRETATION



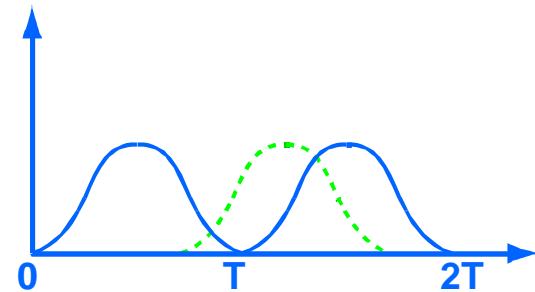
Two-ray model
 $\tau = \text{rms delay spread}$



$\frac{\tau}{T}$ small



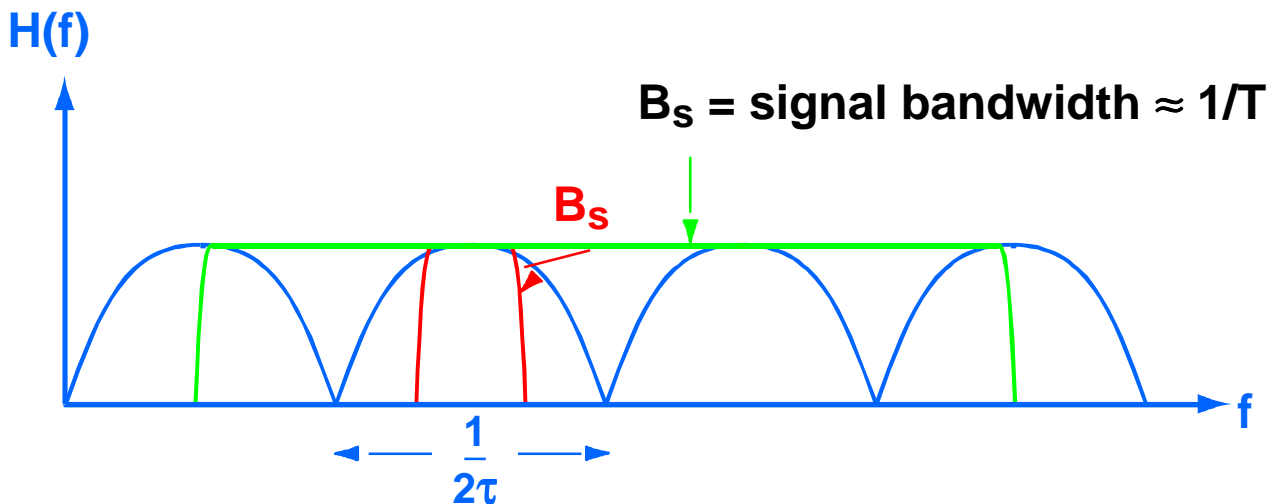
$\frac{\tau}{T}$ large



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

DELAY SPREAD

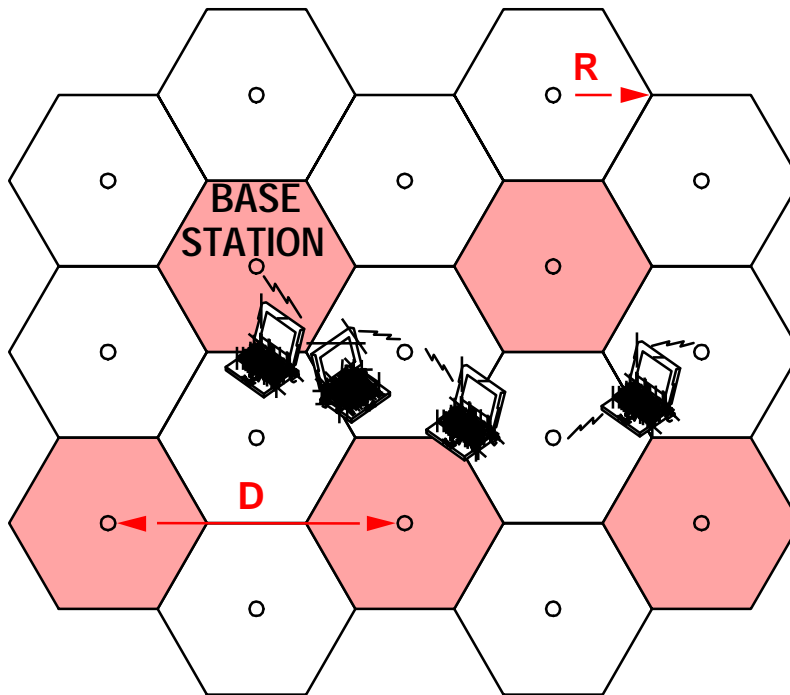
FREQUENCY DOMAIN INTERPRETATION



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

INTERFERENCE

- 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

INFRARED VERSUS RADIO

Channel Property	Non-Directive IR	Radio
Carrier Frequency	100 THz	1-20 GHz
Path Loss	High	Moderate
Multipath Fading	No	Yes
Multipath Dispersion	Yes	Yes
BW Limitation	Photodiode Capacitance	FCC
Dominant Noise	Background Light	Receiver

- **Infrared: limited coverage, low bit rates, sensitive to natural light**

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PHYSICAL LAYER ISSUES

- **Link Performance Measures**
- **Modulation Tradeoffs**
- **Flat Fading Countermeasures**
- **Delay Spread Countermeasures**

LINK PERFORMANCE MEASURES

PROBABILITY OF BIT ERROR

- The probability of bit error, P_b , in a radio environment is a random variable.
 - average P_b , \bar{P}_b
 - $P_r [P_b > P_{b\text{target}}] \triangleq$ outage, P_{out}
- Typically only one of these measures is useful, depending on the Doppler frequency and the bit rate.

LINK PERFORMANCE MEASURES

EFFICIENCY

- **Spectral Efficiency**
 - a measure of the data rate per unit bandwidth for a given bit error probability and transmitted power
- **Power Efficiency**
 - a measure of the required received power to achieve a given data rate for a given bit error probability and bandwidth
- **Throughput/Delay**

GOALS OF MODULATION TECHNIQUES

- **High Bit Rate**
- **High Spectral Efficiency**
- **High Power Efficiency**
- **Low-Cost/Low-Power Implementation**
- **Robustness to Impairments**

DIGITAL MODULATION

- Any modulated signal can be represented as

$$s(t) = A(t) \cos [\omega_c t + \phi(t)]$$

↑
amplitude

↑
phase or frequency

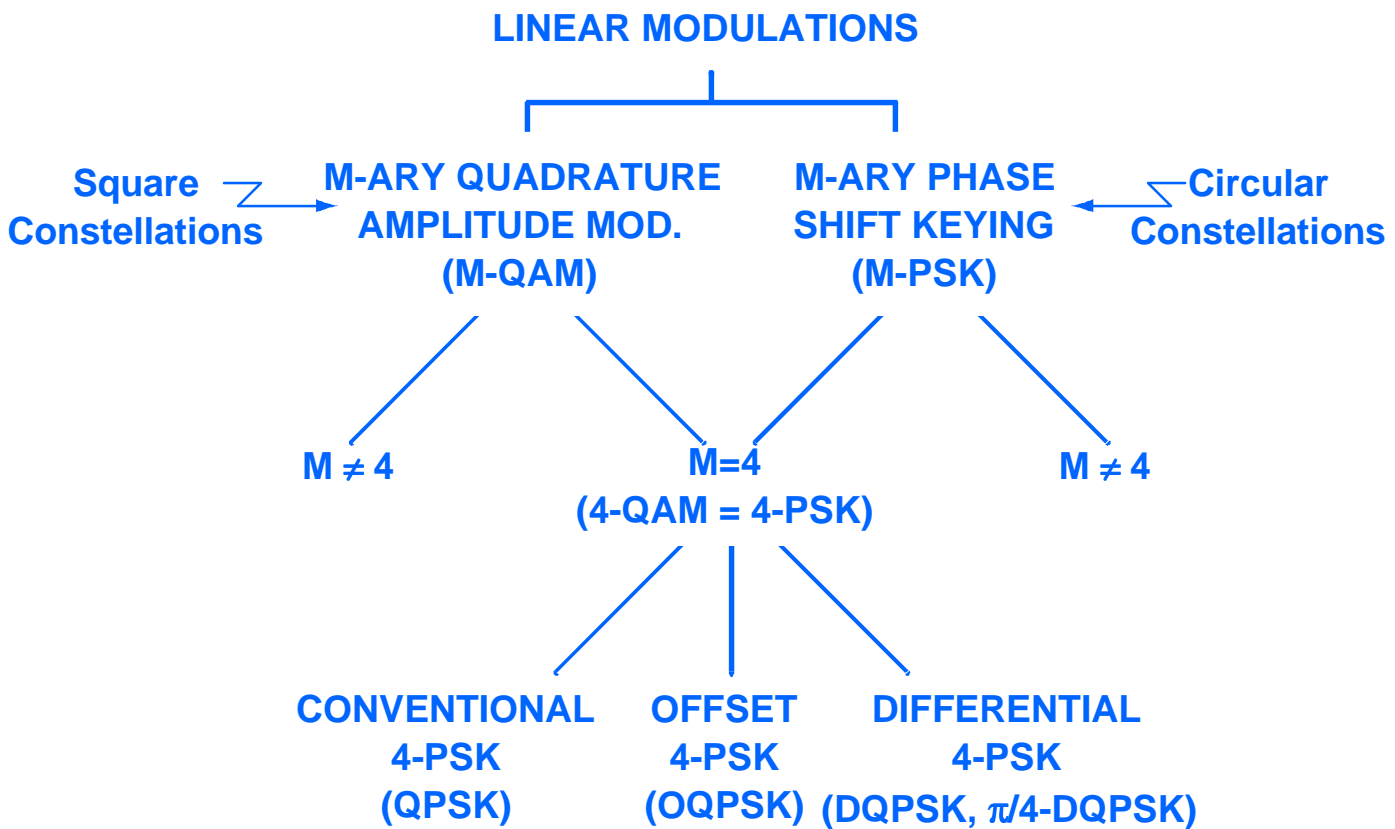
$$= \underbrace{A(t) \cos \phi(t)}_{\text{in-phase}} \cos \omega_c t$$

$$- \underbrace{A(t) \sin \phi(t)}_{\text{quadrature}} \sin \omega_c t$$

- Linear versus nonlinear modulation \Rightarrow impact on spectral efficiency
- Constant envelope versus non-constant envelope \Rightarrow hardware implications with impact on power efficiency

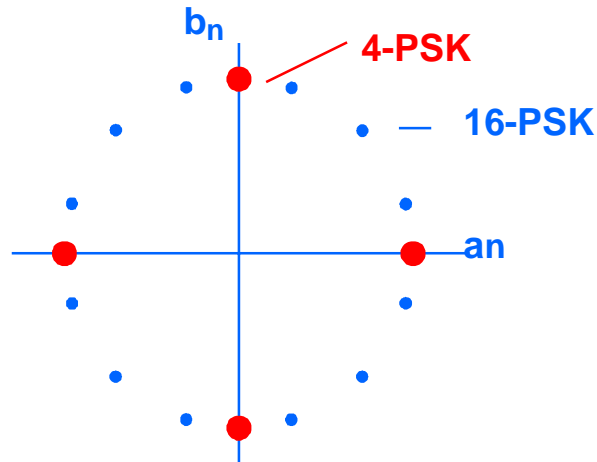
LINEAR MODULATION TECHNIQUES

$$s(t) = \underbrace{\left[\sum_n a_n g(t-nT) \right]}_{I(t), \text{ in-phase}} \cos \omega_c t - \underbrace{\left[\sum_n b_n g(t-nT) \right]}_{Q(t), \text{ quadrature}} \sin \omega_c t$$

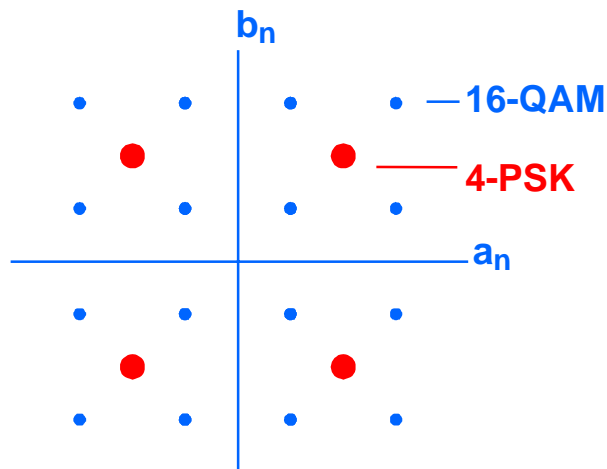


SIGNAL CONSTELLATIONS

M-PSK (Circular Constellations)



M-QAM (Square Constellations)



Tradeoffs

- Higher-order modulations (M large) are more spectrally efficient but less power efficient.
- M-QAM is more spectrally efficient than M-PSK but also more sensitive to system nonlinearities.

PULSE SHAPING

Rectangular pulses are spectrally inefficient



pulse shaping



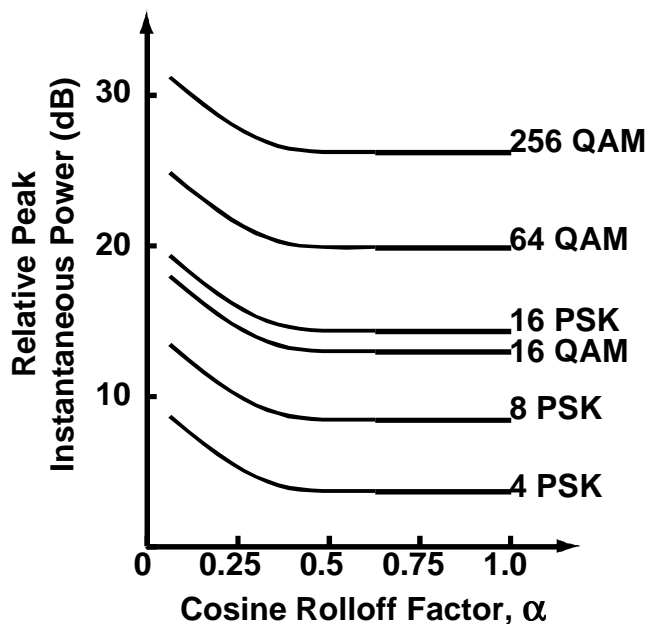
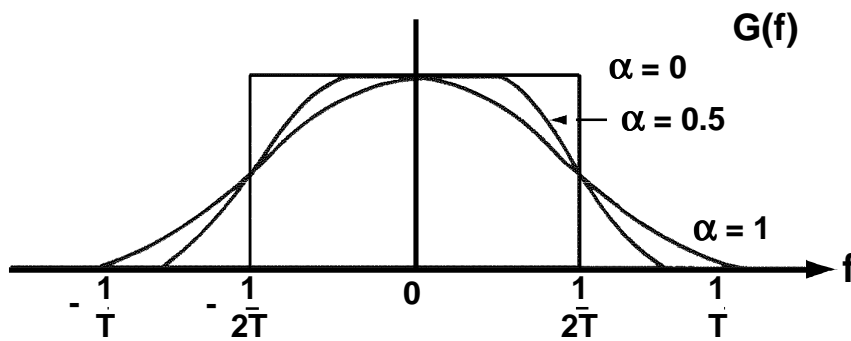
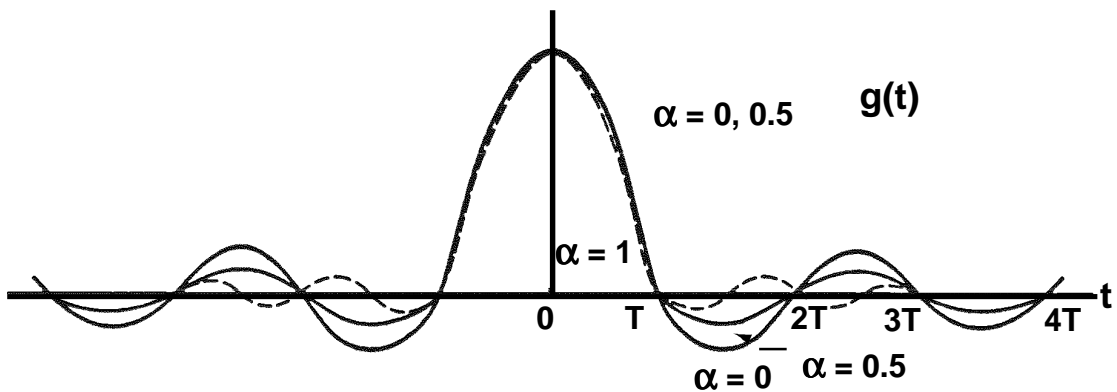
intersymbol interference (ISI)

non-constant envelope



Nyquist pulses

RAISED COSINE PULSE SHAPING



DEMODULATION

- **Coherent detection requires a coherent phase reference.**
 - difficult to obtain in a rapidly fading environment
 - increases receiver complexity
- **Differential detection uses the previous symbol for the reference signal.**
 - eliminates need for coherent reference
 - entails loss in power efficiency (up to 3 dB)
 - Doppler causes irreducible error floor, typically small for high bit rates

FREQUENCY SHIFT KEYING

- **Continuous Phase FSK (CPFSK)**

- digital data encoded in the frequency shift
- typically implemented with frequency modulator to maintain continuous phase

$$s(t) = A \cos \left[\omega_c t + 2 \pi k_f \int_{-\infty}^t d(\tau) d\tau \right]$$

- nonlinear modulation but constant-envelope

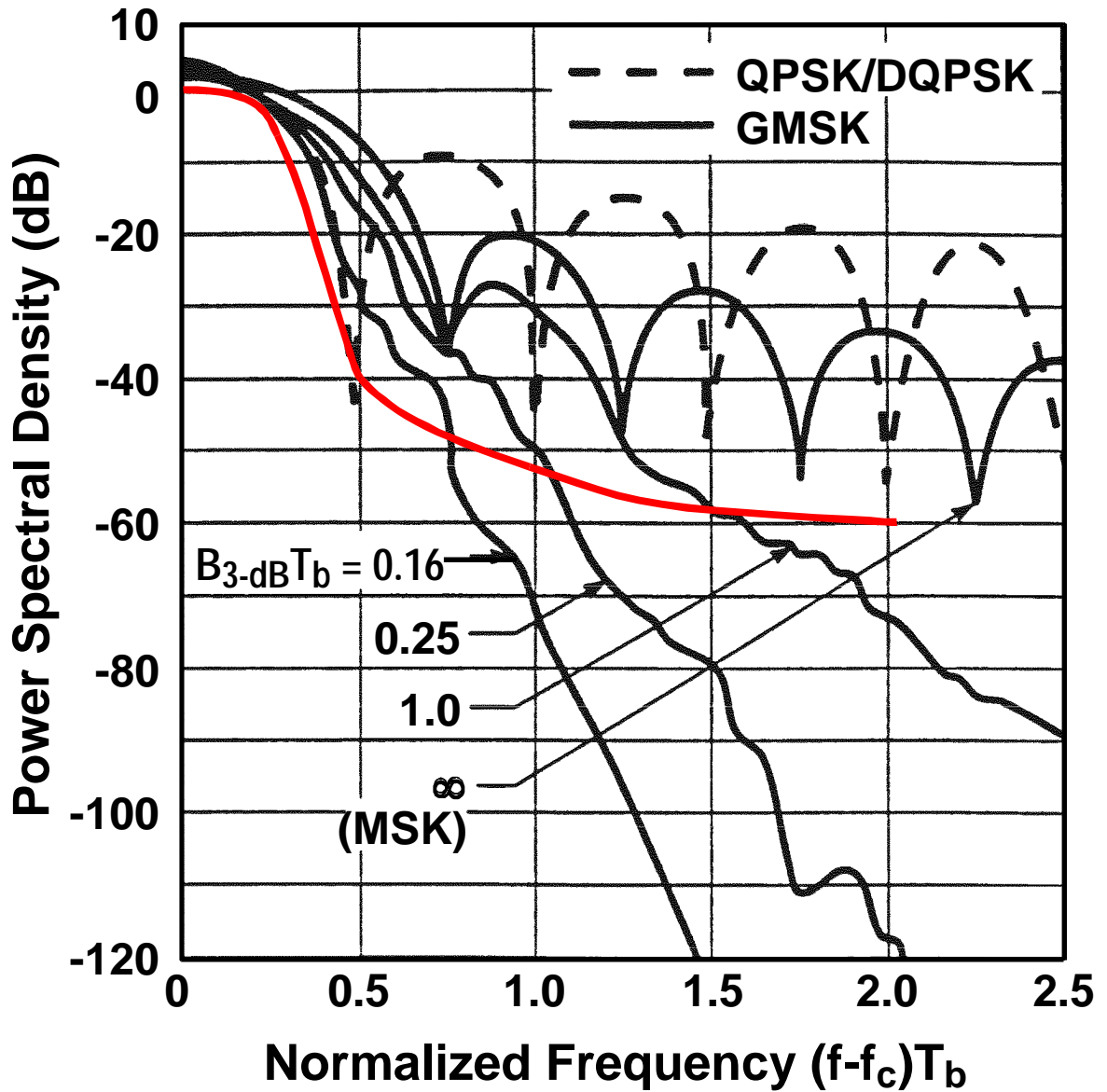
- **Minimum Shift Keying (MSK)**

- minimum bandwidth, sidelobes large
- can be implemented using I-Q receiver

- **Gaussian Minimum Shift Keying (GMSK)**

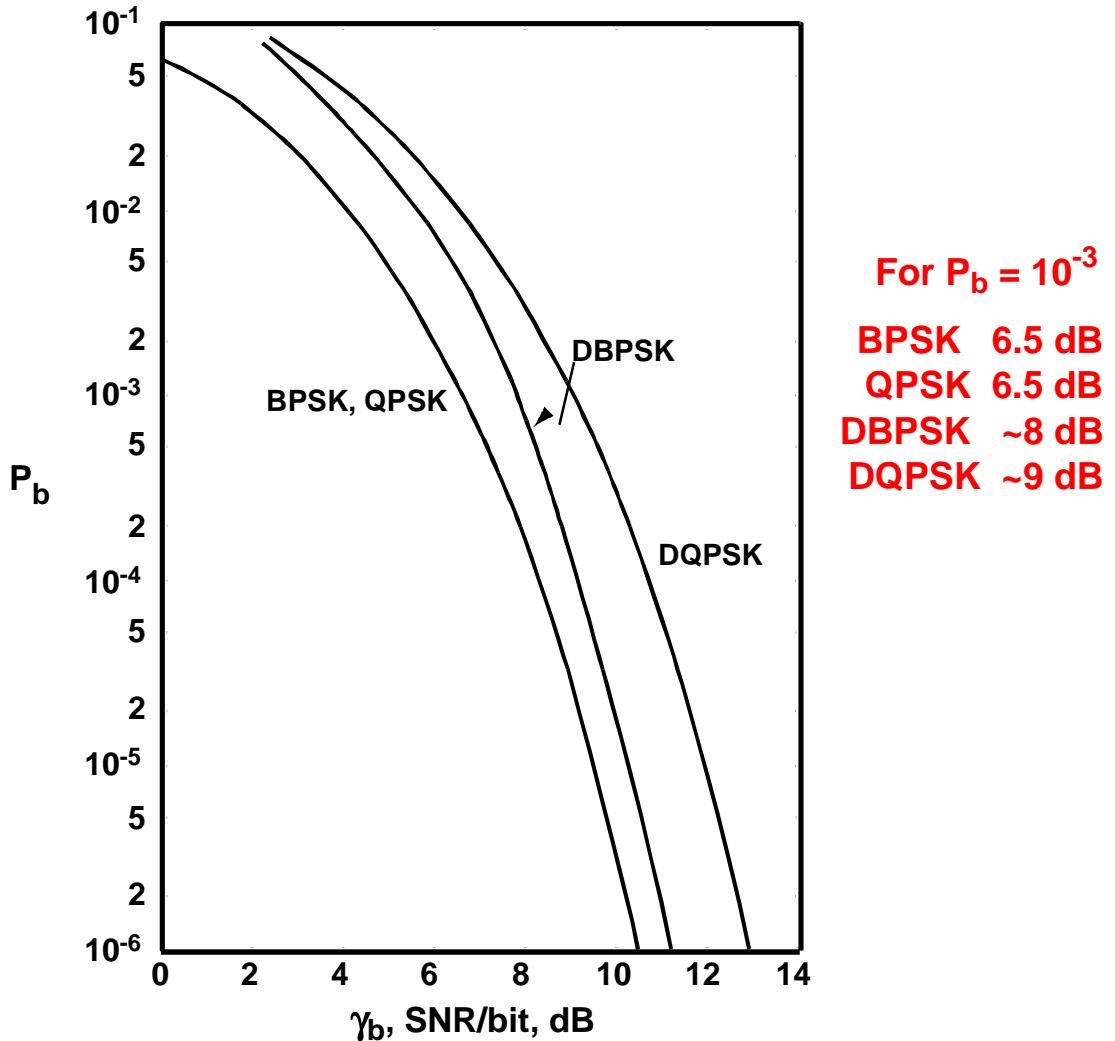
- reduces sidelobes of MSK using a premodulation filter
- used by RAM Mobile Data, CDPD, and HIPERLAN

SPECTRAL CHARACTERISTICS



BIT ERROR PROBABILITY

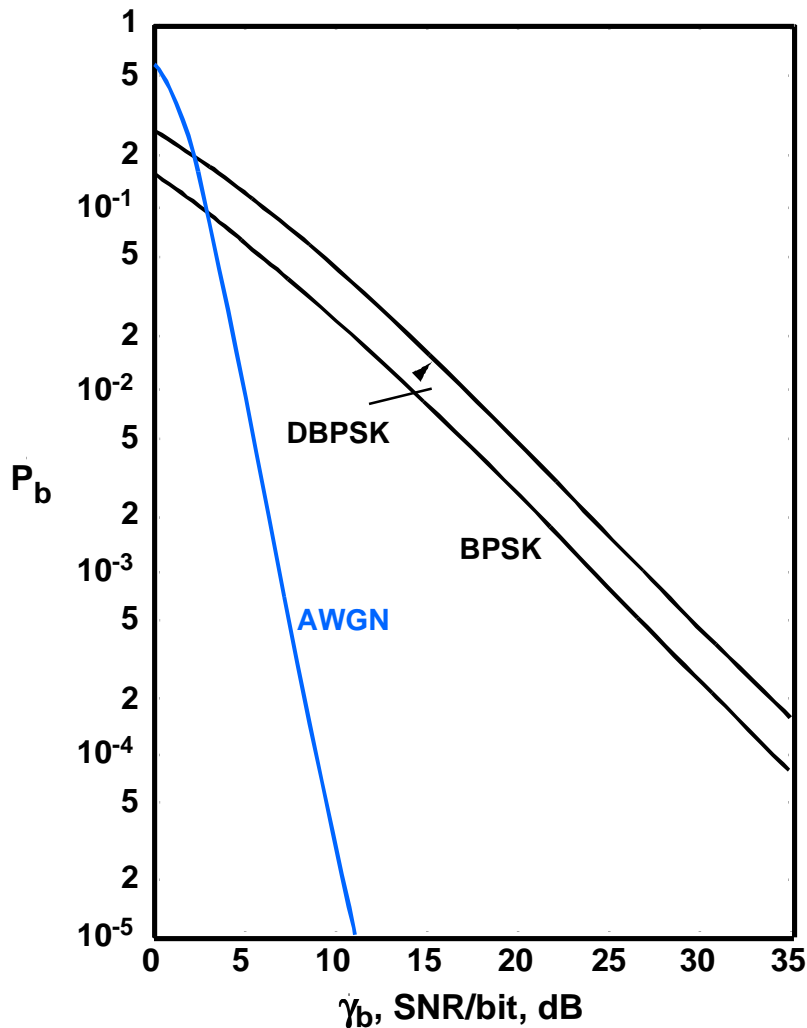
AWGN CHANNEL



- QPSK is more spectrally efficient than BPSK with the same performance.
- M-PSK, for $M > 4$, is more spectrally efficient but requires more SNR per bit.
- There is ~3 dB power penalty for differential detection.

BIT ERROR PROBABILITY

FADING CHANNEL

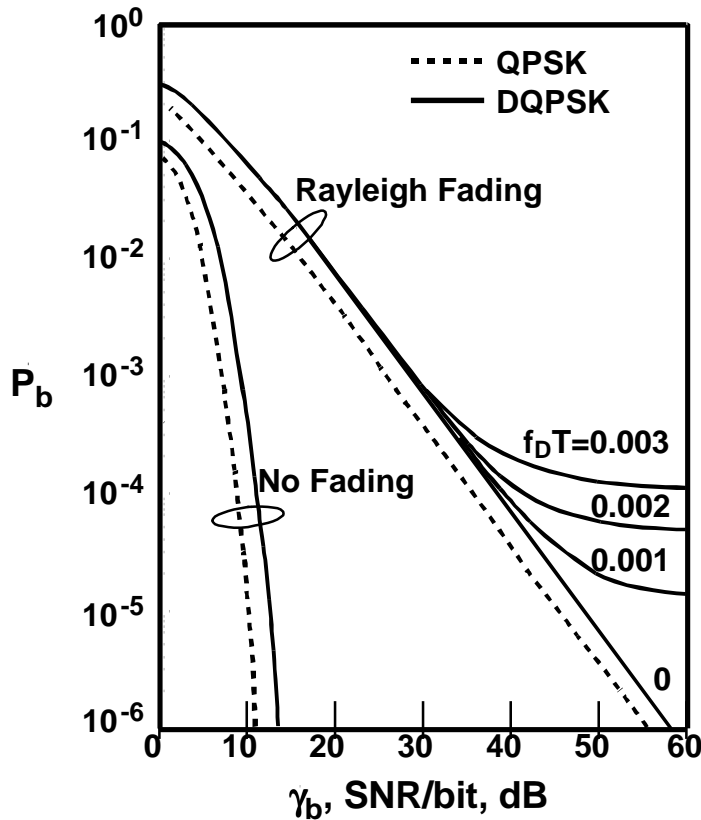


- P_b is inversely proportion to the average SNR per bit.
- Transmission in a fading environment requires about 18 dB more power for $P_b = 10^{-3}$.

BIT ERROR PROBABILITY

EFFECTS OF DOPPLER SPREAD

- Doppler causes an irreducible error floor when differential detection is used \Rightarrow decorrelation of reference signal.



- The irreducible P_b depends on the data rate and the Doppler.
For $f_D = 80$ Hz,

data rate	T	$P_{b_{\text{floor}}}$
10 kbps	10^{-4} s	3×10^{-4}
100 kbps	10^{-5} s	3×10^{-6}
1 Mbps	10^{-6} s	3×10^{-8}

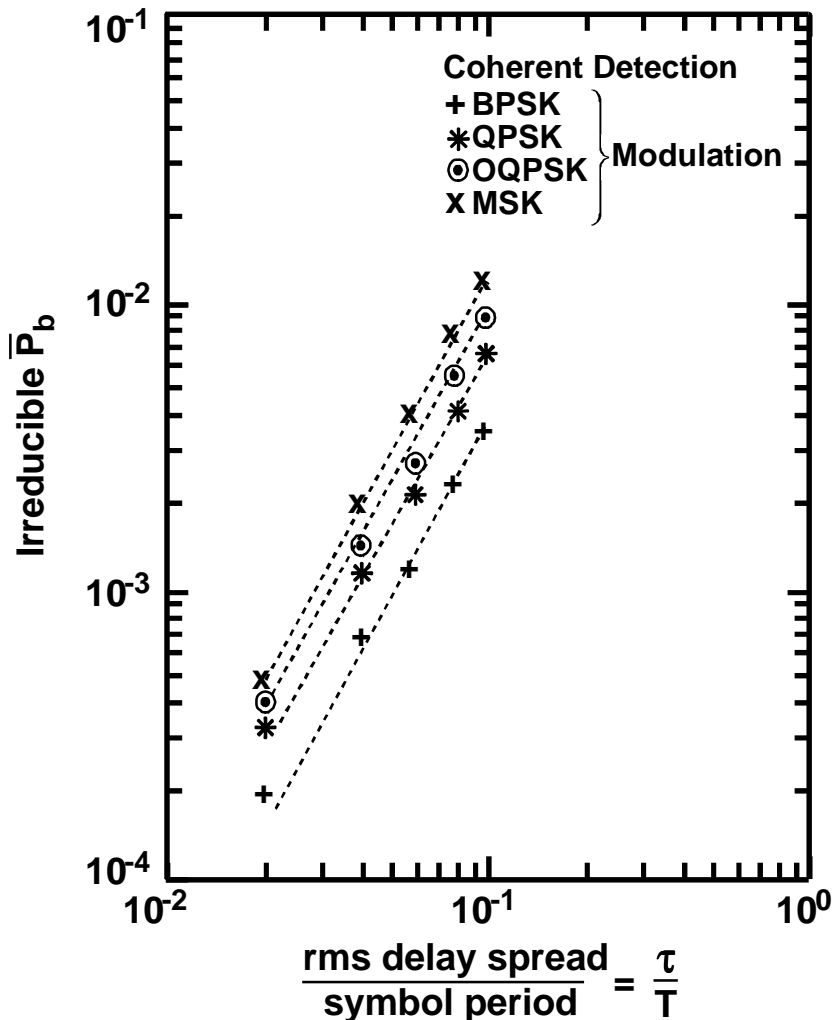
The implication is that Doppler is not an issue for high-speed wireless data.

[M. D. Yacoub, *Foundations of Mobile Radio Engineering*, CRC Press, 1993]

BIT ERROR PROBABILITY

EFFECTS OF DELAY SPREAD

- ISI causes an irreducible error floor.



- The rms delay spread imposes a limit on the maximum bit rate in a multipath environment.

For example, for QPSK,

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

[J. C.-I. Chuang, "The Effects of Time Delay Spread on Portable Radio Communications Channels with Digital Modulation," *IEEE JSAC*, June 1987]

SUMMARY OF MODULATION ISSUES

- **Tradeoffs**

- linear versus nonlinear modulation
- constant envelope versus non-constant envelope
- coherent versus differential detection
- power efficiency versus spectral efficiency

- **Limitations**

- flat fading
- doppler

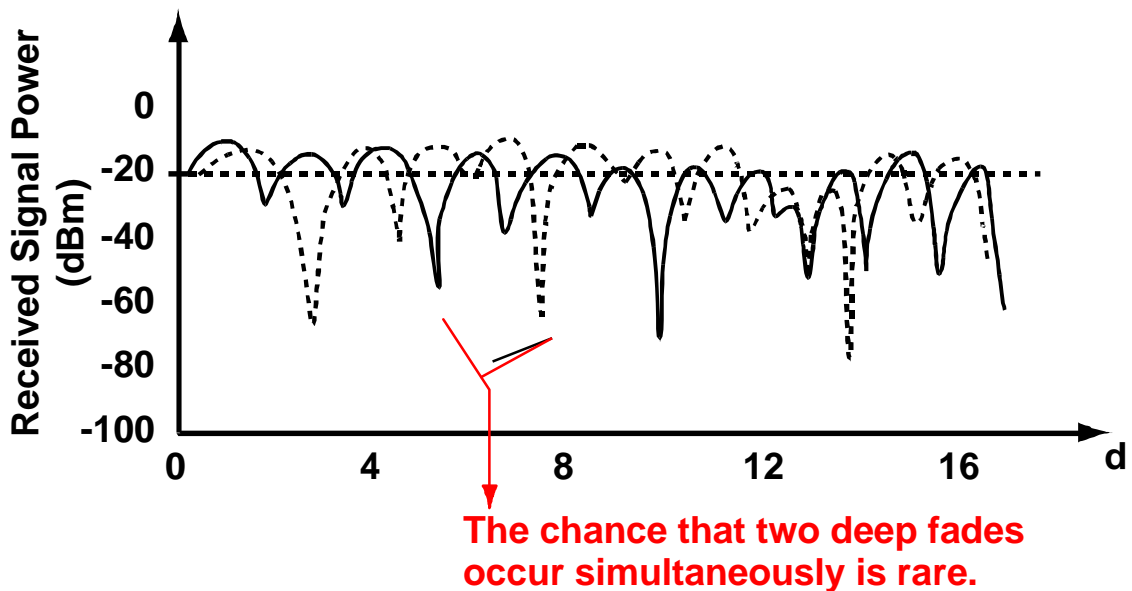
HOW DO WE OVERCOME THE LIMITATIONS IMPOSED BY THE RADIO CHANNEL?

- **Flat Fading Countermeasures**
 - **Fade Margin**
 - **Diversity**
 - **Coding and Interleaving**
 - **Adaptive Techniques**

- **Delay Spread Countermeasures**
 - **Equalization**
 - **Multicarrier**
 - **Spread Spectrum**
 - **Antenna Solutions**

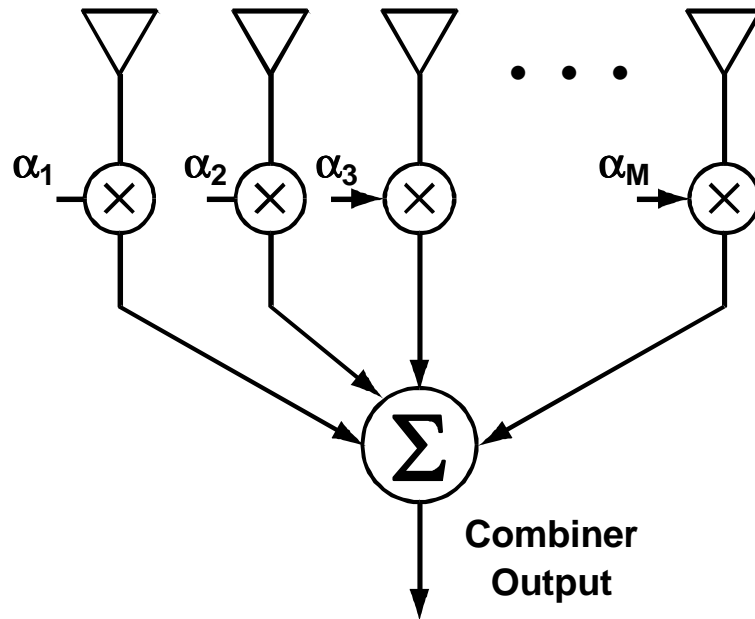
DIVERSITY

- Independent signal paths have a low probability of experiencing deep fades simultaneously.



- The basic concept is to send the same information over independently fading radio
- Independent fading paths can be achieved by separating the signal in time, frequency, space, polarization, etc.

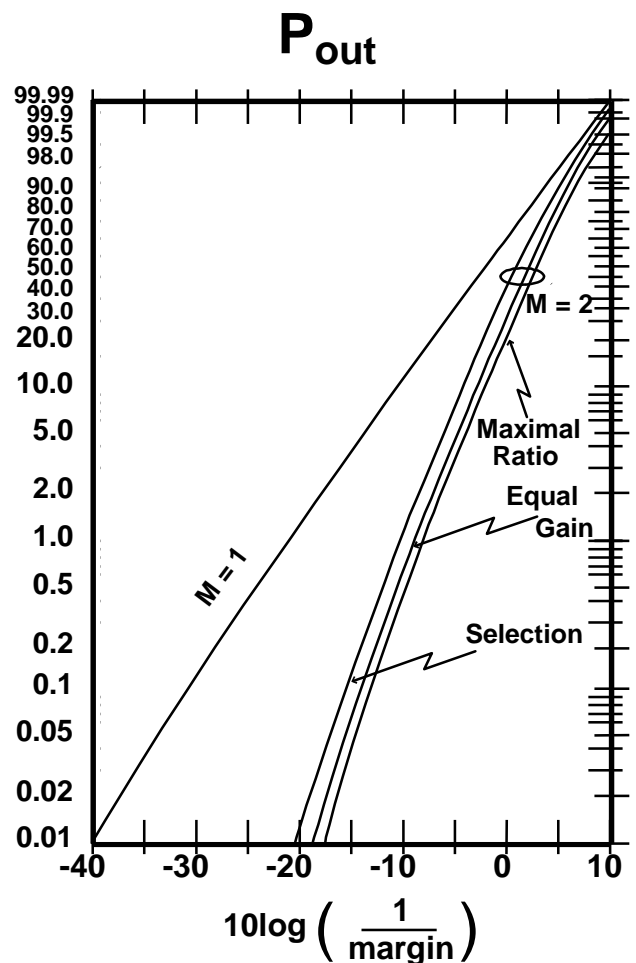
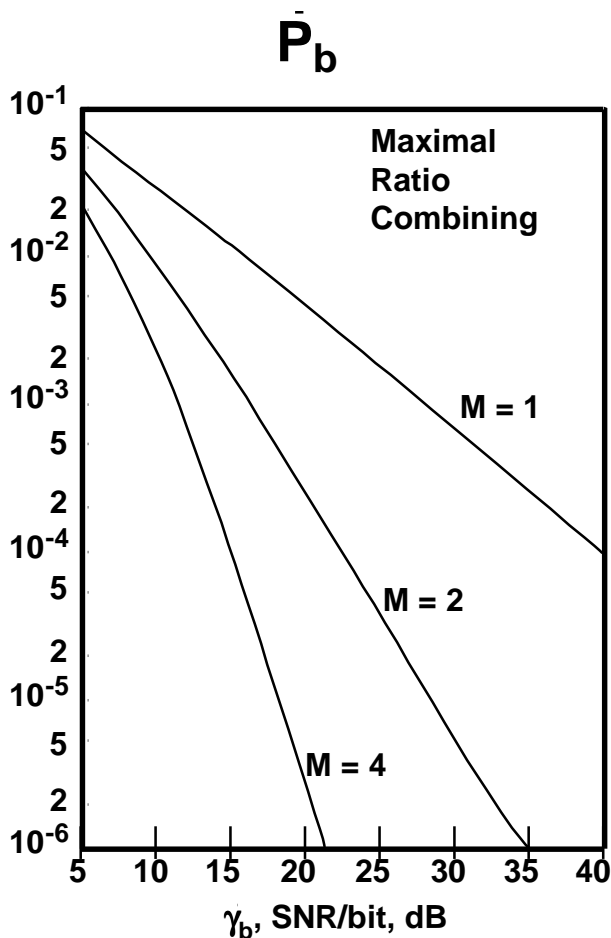
DIVERSITY COMBINING TECHNIQUES



- **Selection Combining:** picks the branch with the highest SNR.
- **Equal-Gain Combining:** all branches are coherently combined with equal weights.
- **Maximal-Ratio Combining:** all branches are coherently combined with weights which depend on the branch SNR.

DIVERSITY PERFORMANCE

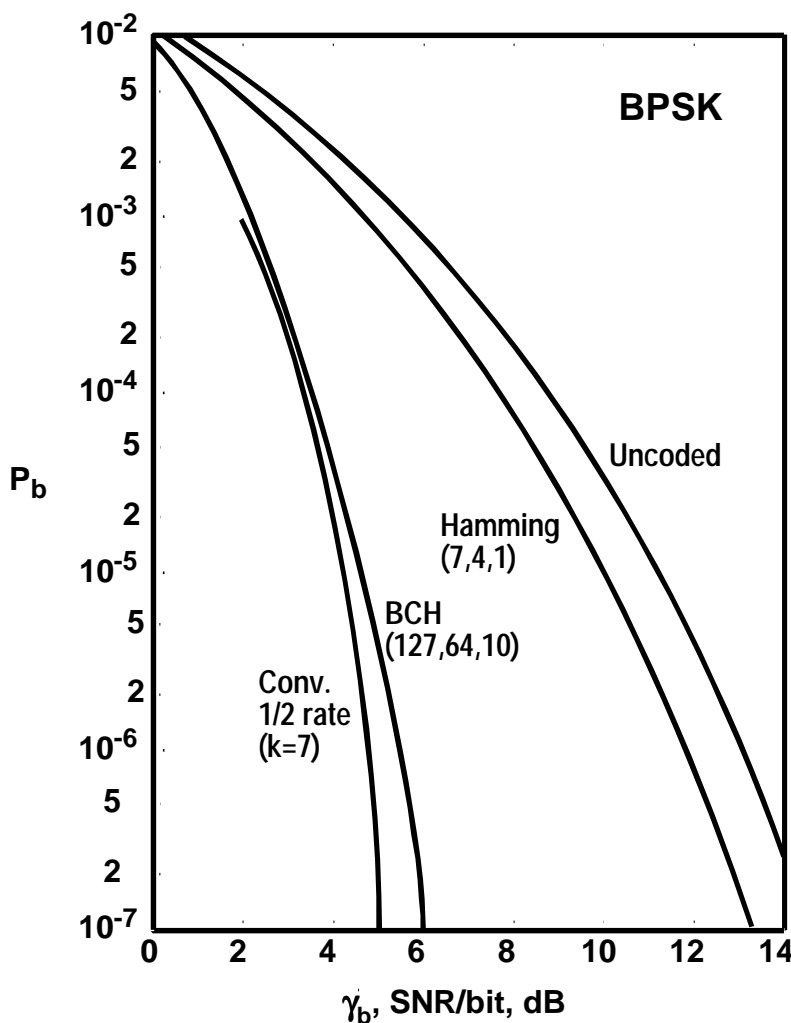
- There is dramatic improvement even with two-branch selection combining.
 - 10 dB reduction in required SNR for 1% outage \Rightarrow less transmitted power or higher bit rates or larger coverage area



- The output SNR with Maximal-Ratio Combining improves linearly with the number of diversity branches, $M \Rightarrow$ the complexity becomes prohibitive.

CHANNEL CODING

- Channel coding reduces P_b by introducing redundancy in the transmitted bit stream.
- Block and convolutional codes achieve this improvement at the expense of increased signal bandwidth or a lower data rate.
- Bit error probability–AWGN channel

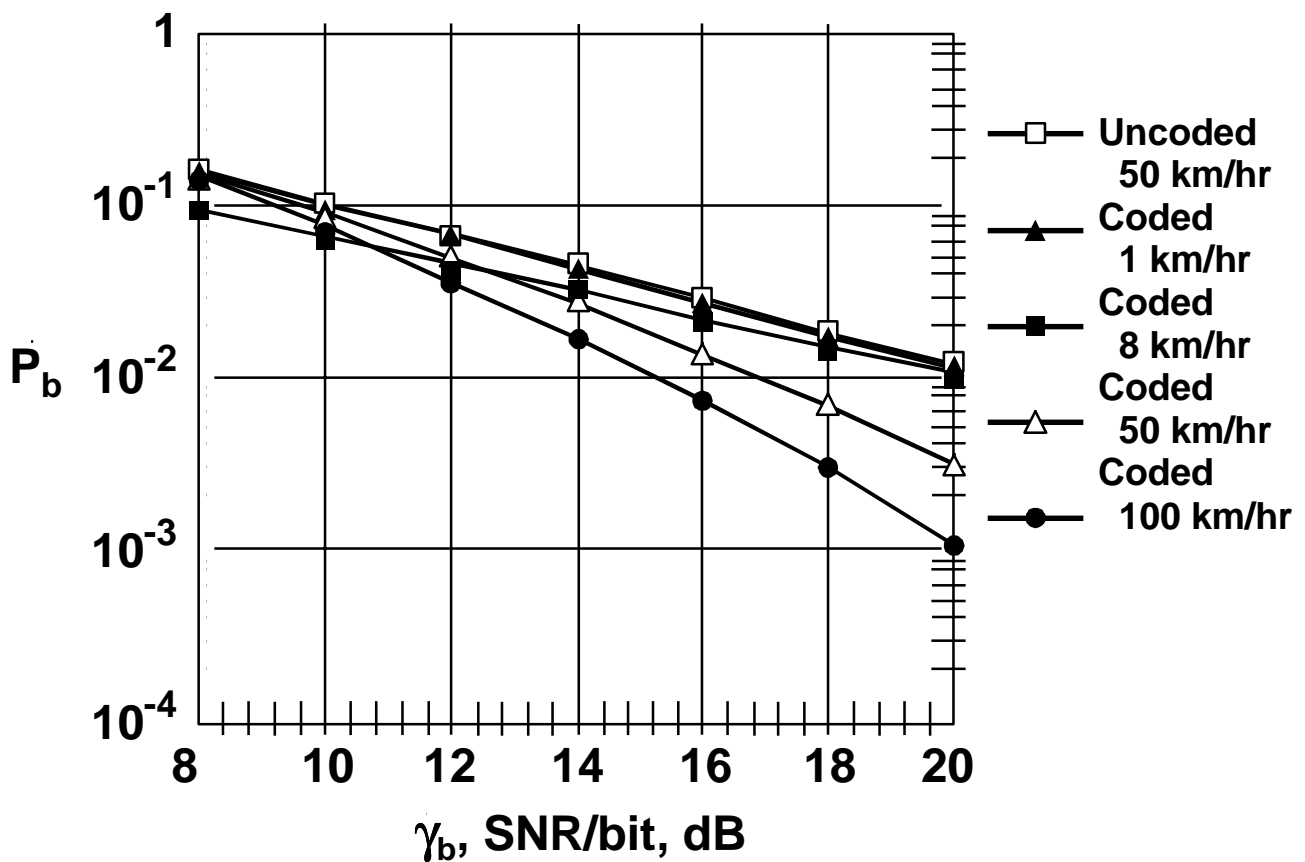


For $P_b = 10^{-6}$
Uncoded 10.5 dB
Hamming 10.0 dB
BCH 6.5 dB
Conv. 5.0 dB

- Fading causes burst errors. If the fading is slow enough relative to the symbol rate, coding will not be effective.

CODING PERFORMANCE FADING CHANNEL

- P_b performance for the IS-136 rate-1/2 convolutional code on a simulated mobile radio channel (hard-decision decoding).

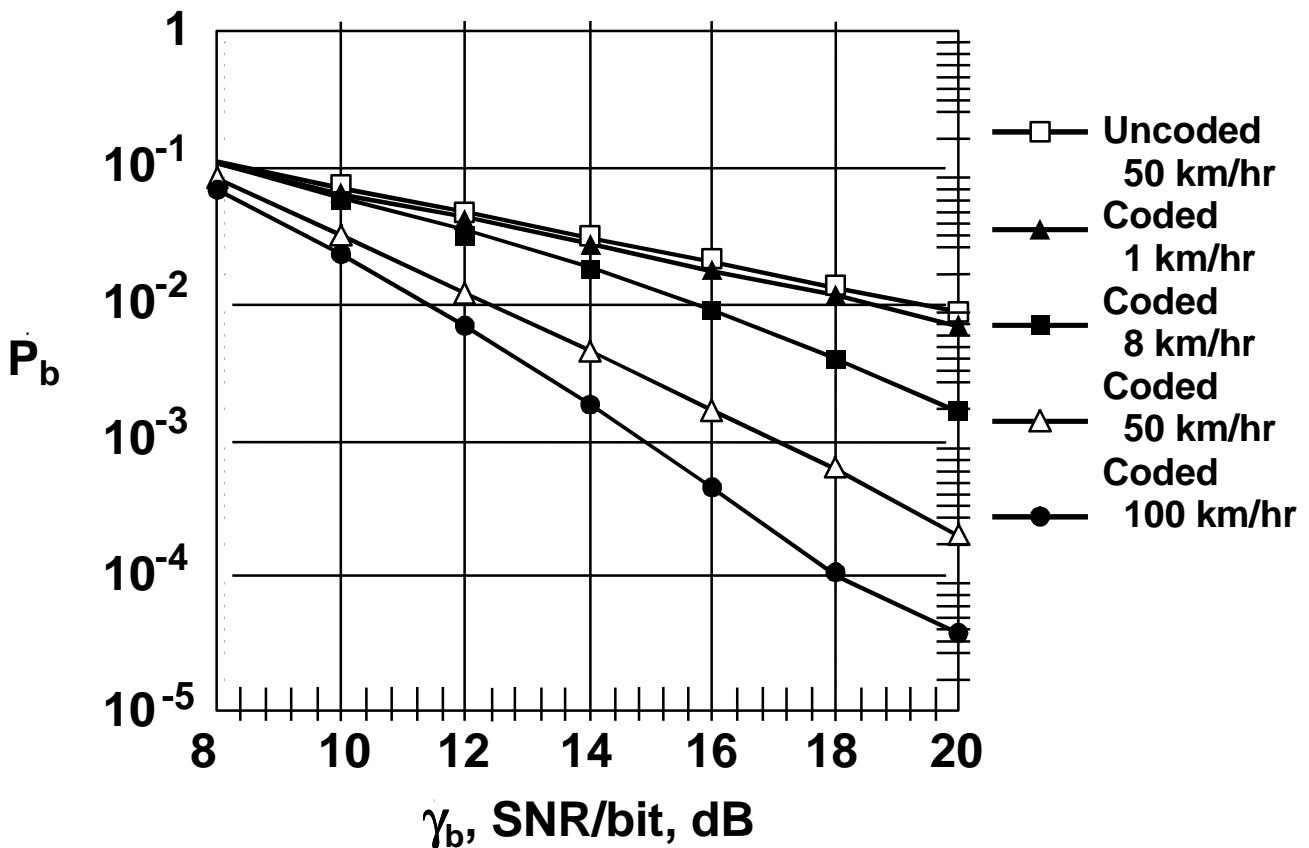


- Negligible coding gain if fading is slow compared to bit rate \Rightarrow interleaving

[V. Iyengar and J. Michaelides, "Performance Evaluations of RLPs (Radio Link Protocols) for TDMA Data Services," *ITIA Contribution TR45.3.2.5/93.03.30.10*, Chicago, March 30, 1993]

CODING PERFORMANCE FADING CHANNEL

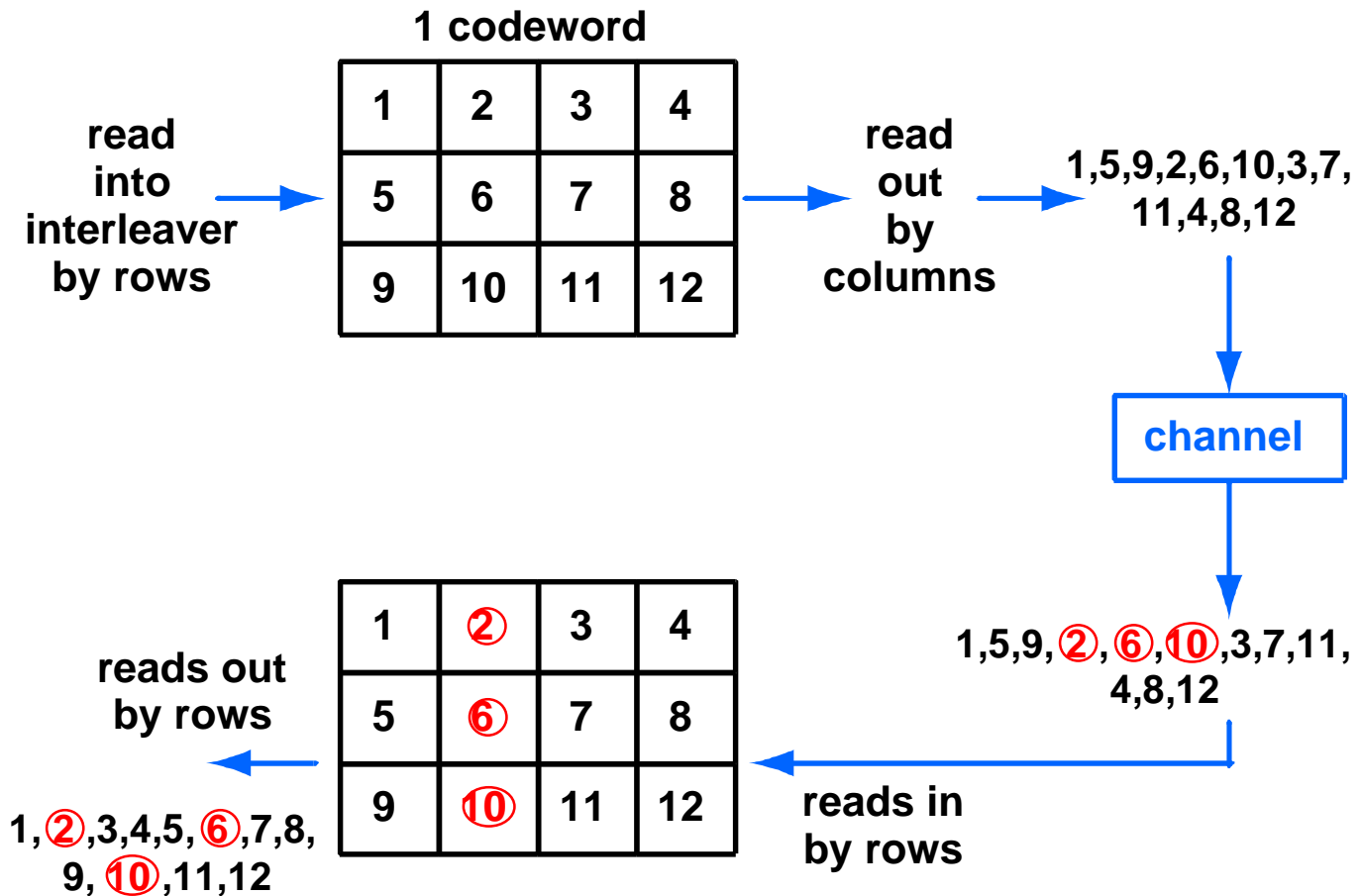
- P_b performance for the IS-136 rate-1/2 convolutional code on a simulated mobile radio channel (soft decision decoding).



[V. Iyengar and J. Michaelides, "Performance Evaluations of RLPs (Radio Link Protocols) for TDMA Data Services," *ITIA Contribution TR45.3.2.5/93.03.30.10*, Chicago, March 30, 1993]

CODING AND INTERLEAVING

- The basic principle is to spread the burst errors over many code words.



- The required interleaver size can be large if the relative fading rate is slow, as is usually the case for high-speed data. For example, $f_D = 10$ Hz, bit rate = 10 Mb/s, error burst = 330,000 bits.



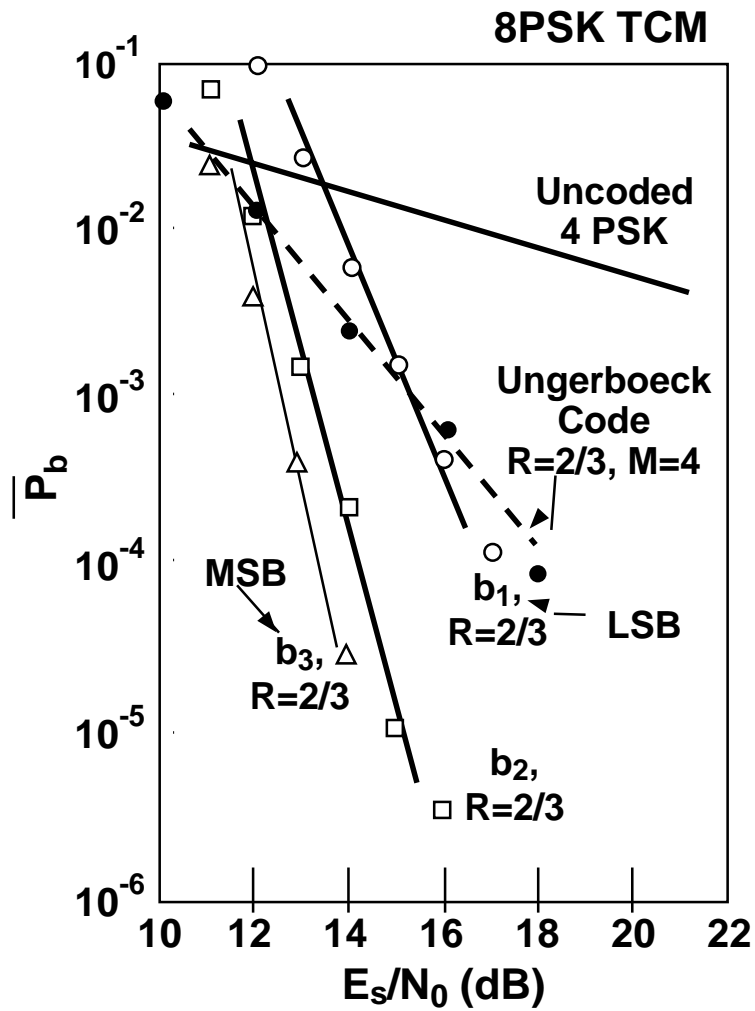
delay and complexity

ADVANCED CODING TECHNIQUES

- **Trellis Codes**
 - reduce P_b without bandwidth expansion through joint design of the channel code and signal constellation
 - can be designed with “built-in” time diversity

- **Turbo Codes**
 - exhibit enormous coding gains
 - interleaving inherent to code design
 - very complex with large delays
 - not well-understood for fading channels

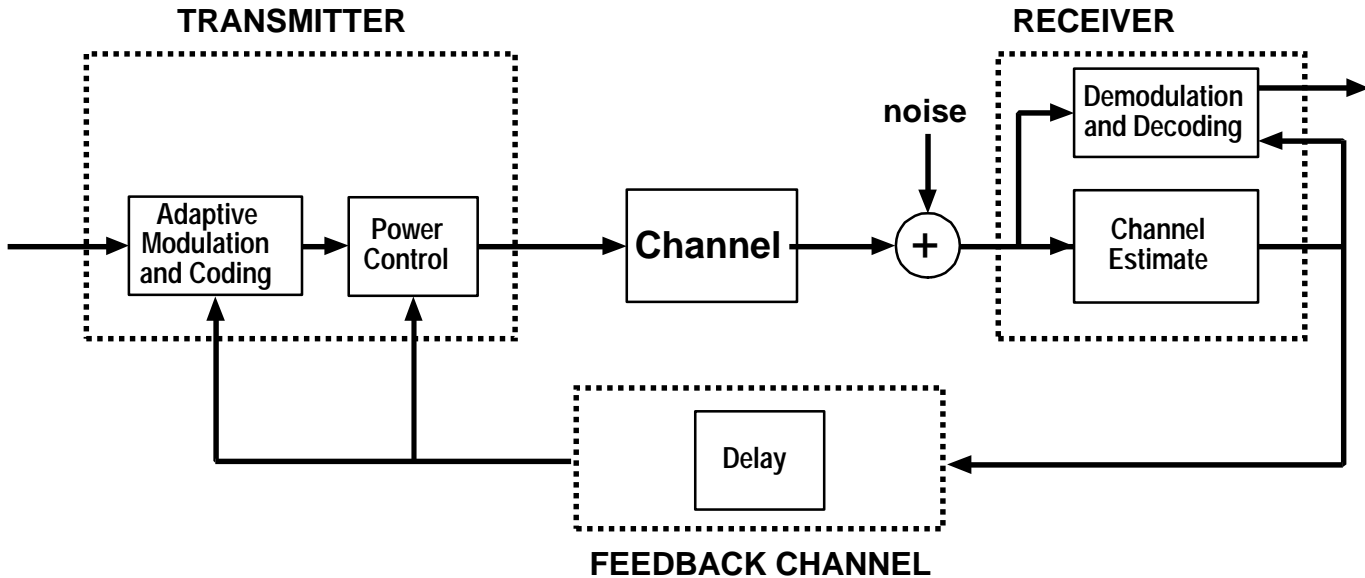
CODING PERFORMANCE TCM



ADAPTIVE TECHNIQUES

- **Adaptive Modulation**
- **Automatic Repeat Request**

ADAPTIVE MODULATION



- Power and/or data rate adapted at transmitter to channel conditions
- Potential for large increase in spectral efficiency
- Can be combined with adaptive compression



- requires reliable feedback channel and accurate channel estimation
- increases transmitter and receiver complexity

AUTOMATIC REPEAT REQUEST (ARQ)

- Method of "self-adapting" the data rate to the channel conditions
- Used in combination with error-detecting code
- Variations of ARQ used in Mobitex and CDPD
- Types: Stop-and-Wait, Go-Back-N, Selective-Repeat



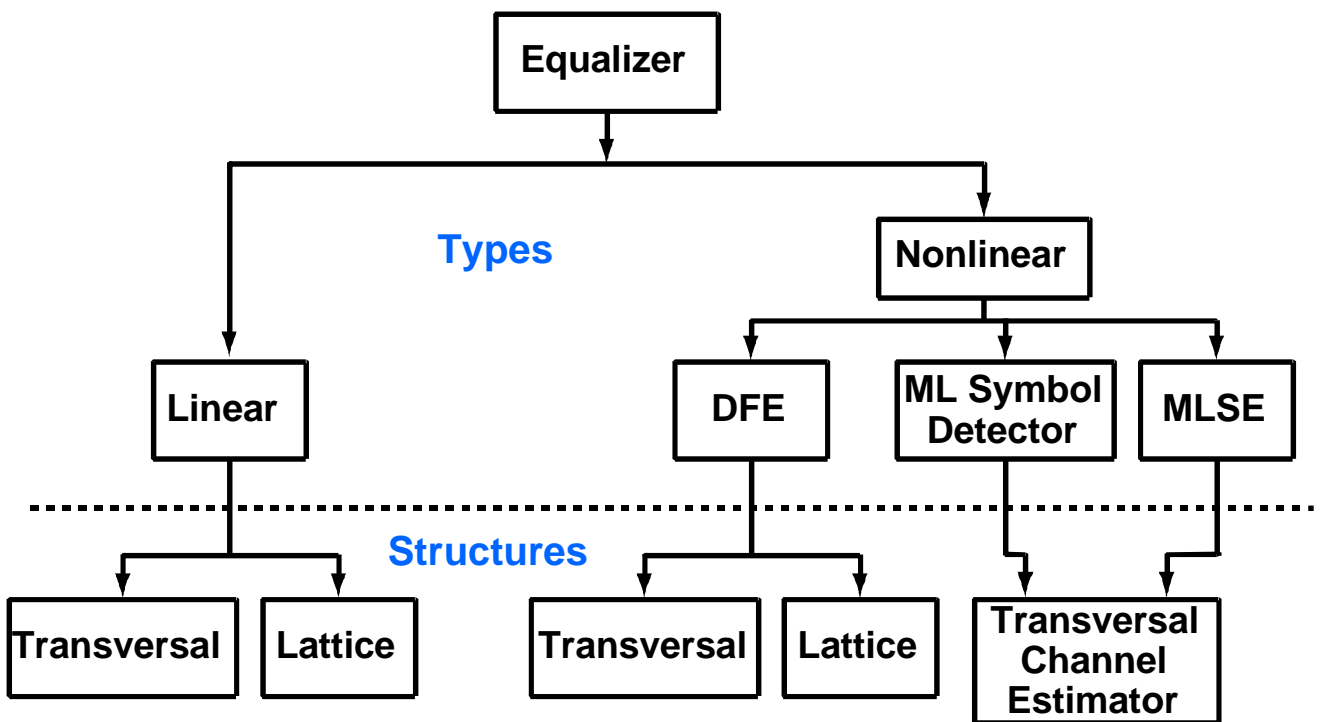
- power and spectrally inefficient
- impacts higher layer protocols
- necessary for meeting stringent P_b requirements or data

DELAY SPREAD COUNTERMEASURES

- **Signal Processing**
 - at the receiver, to alleviate the problems caused by delay spread (**equalization**)
 - at the transmitter, to make the signal less sensitive to delay spread (**multicarrier, spread spectrum**)
- **Antenna Solutions**
 - change the environment to reduce, or eliminate, the delay spread (**distributed antenna system, small cells, directive antennas**)

EQUALIZER TYPES AND STRUCTURES

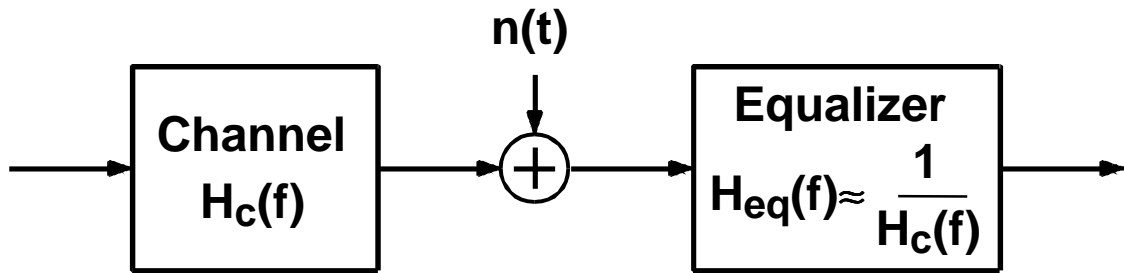
The goal of equalization is to cancel the ISI or, equivalently, to flatten the frequency response.



[J. G. Proakis, "Adaptive Equalization for TDMA Digital Mobile Radio," *IEEE Trans. on Veh. Tech.*, May 1991]

LINEAR EQUALIZER

- A linear equalizer effectively inverts the channel.

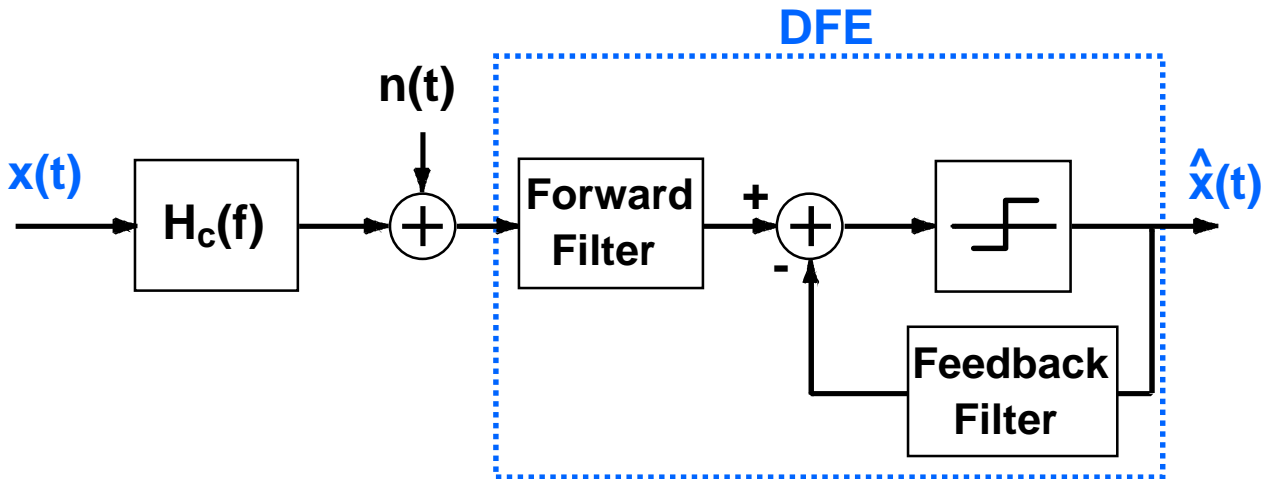


- The linear equalizer is usually implemented as a tapped delay line.
- On a channel with deep spectral nulls, this equalizer enhances the noise.



poor performance on frequency-selective fading channels

DECISION FEEDBACK EQUALIZER



- The DFE determines the ISI from the previously detected symbols and subtracts it from the incoming symbols.
- This equalizer does not suffer from noise enhancement because it estimates the channel rather than inverting it.
⇒ The DFE has better performance than the linear equalizer in a frequency-selective fading channel.
- The DFE is subject to error propagation if decisions are made incorrectly.
- Decisions are made on coded symbols. ⇒ no coding gain

MAXIMUM LIKELIHOOD SEQUENCE ESTIMATION

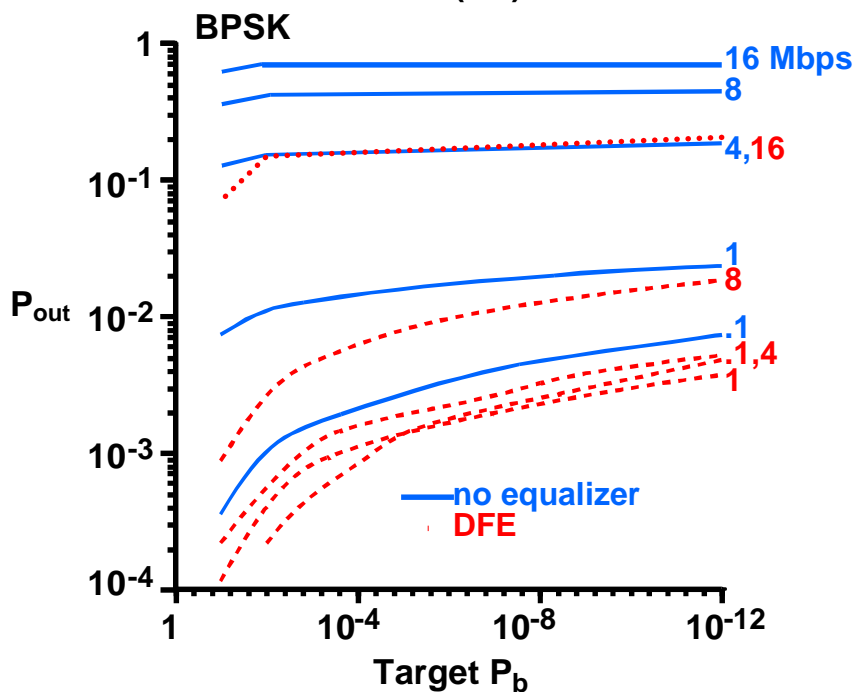
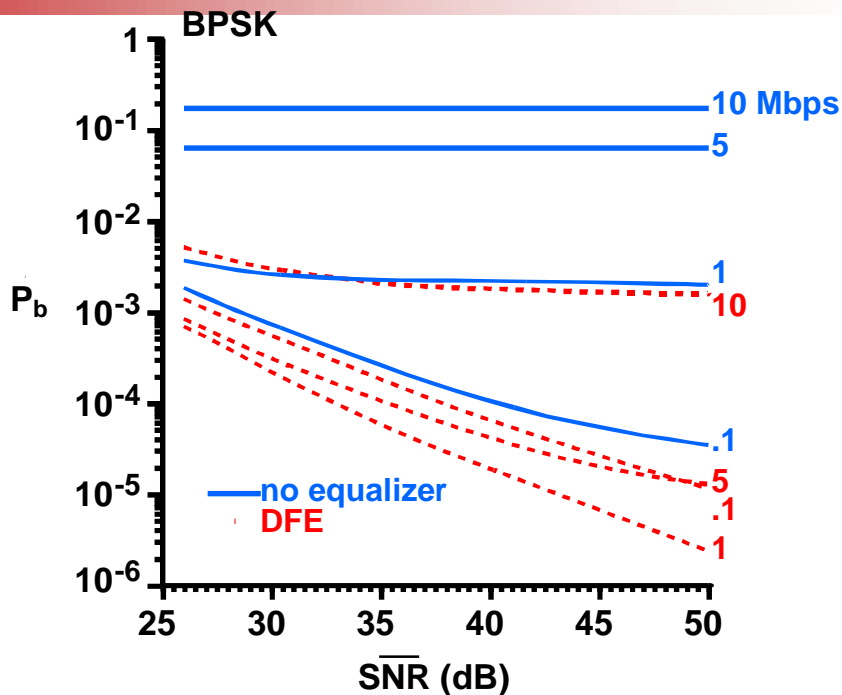
- **MLSE has theoretically optimum performance.**
- **It requires knowledge of the channel parameters and the noise distribution.**
- **The implementation complexity grows exponentially with the length of the channel impulse response ⇒ not practical for high bit rates.**

EQUALIZER ISSUES FOR HIGH-SPEED WIRELESS DATA

- The number of required equalizer taps, N , is proportional to the delay spread.
- The equalizer taps must be adapted at the highest Doppler rate.
 - The length and periodicity of the training sequence impacts the spectral efficiency.
 - There is a tradeoff between speed of convergence and complexity.

Algorithms (for DFE)	Number of Multiply Operations	Convergence	Advantages	Disadvantages
Least Mean Square (LMS)	$2N + 1$	$\sim 10-100N$	Low computational complexity	Slow convergence, depends on channel
Kalman Recursive Least Squares (RLS)	$2.5N^2 + 4.5N$	$\sim N$	Fast convergence, good tracking ability	High computational complexity
Square Root	$1.5N^2 + 6.5N$	$\sim N$	Better stability than Kalman	High computational complexity
Fast Kalman	$20N + 5$	$\sim N$	Fast convergence and good tracking	Could be unstable

EQUALIZER PERFORMANCE



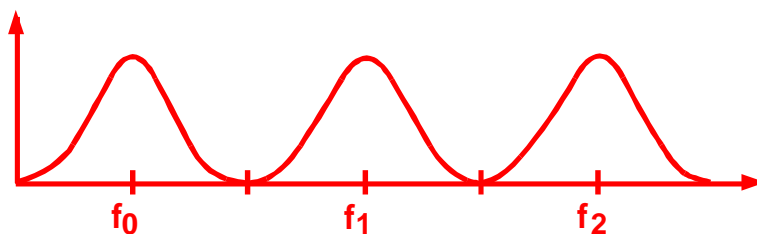
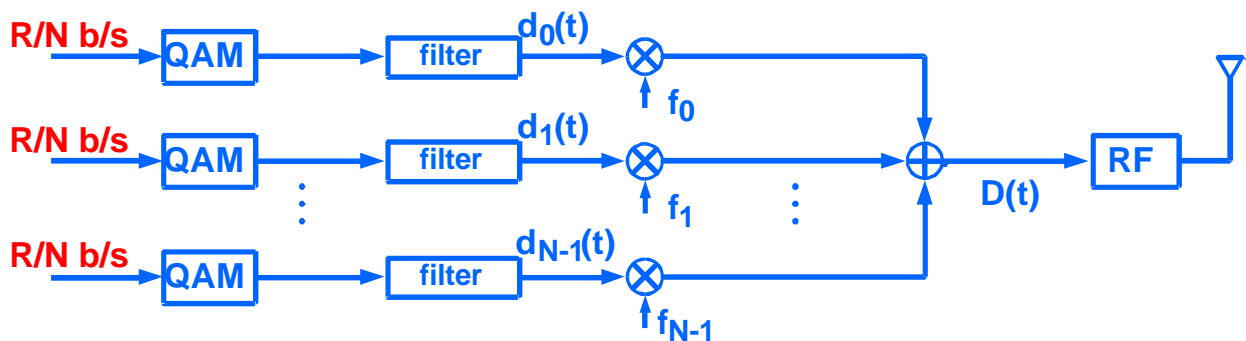
- Pahlavan has shown that, for 30-meter cells ($\tau = 50$ ns), 20 Mb/s can be achieved using a DFE with 3 forward taps and 3 feedback taps.

[K. Pahlavan, S. J. Howard, and T. A. Sexton, "Decision Feedback Equalization of the Indoor Radio Channel," *IEEE Trans. on Commun.*, January 1993]

MULTICARRIER MODULATION

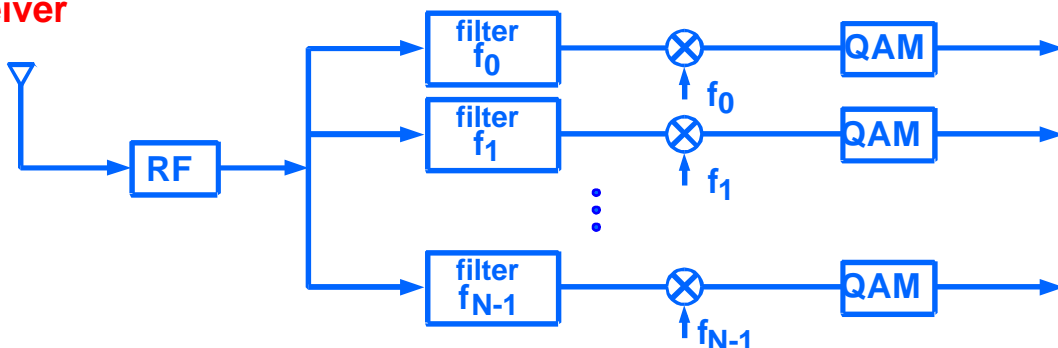
- The transmission bandwidth is divided into many narrow subchannels which are transmitted in parallel.
- Ideally, each subchannel is narrow enough so that the fading it experiences is flat \Rightarrow **no ISI**.

Transmitter

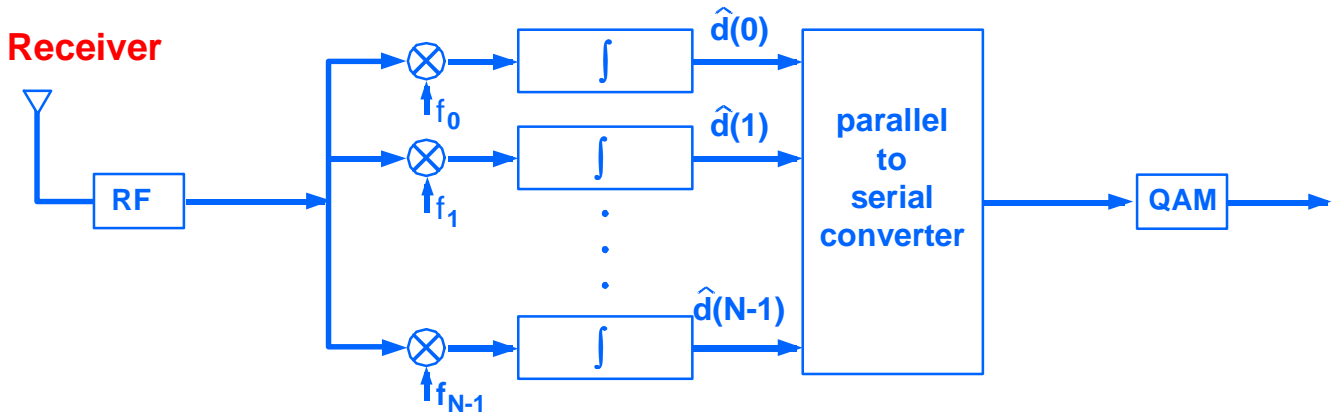


Bandlimited signals

Receiver



OFDM RECEIVER STRUCTURE



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

WHAT TO DO WITH BAD SUBCHANNELS?

- **Coding Across Subchannels** \Rightarrow **works best with large delay spread**
- **Frequency Equalization** \Rightarrow **requires accurate channel estimation**
- **Adaptive Loading** \Rightarrow **requires reliable feedback channel and accurate channel estimation**

MULTICARRIER MODULATION ISSUES FOR HIGH-SPEED WIRELESS DATA

- Minimal training is required.
- Time-varying fading, frequency offset, and timing mismatch impair the orthogonality of the subchannels.
- Large peak-to-average power ratio is a serious problem when transmitting through a nonlinearity.
 - possible solutions: nonlinear coding, clipping and filtering

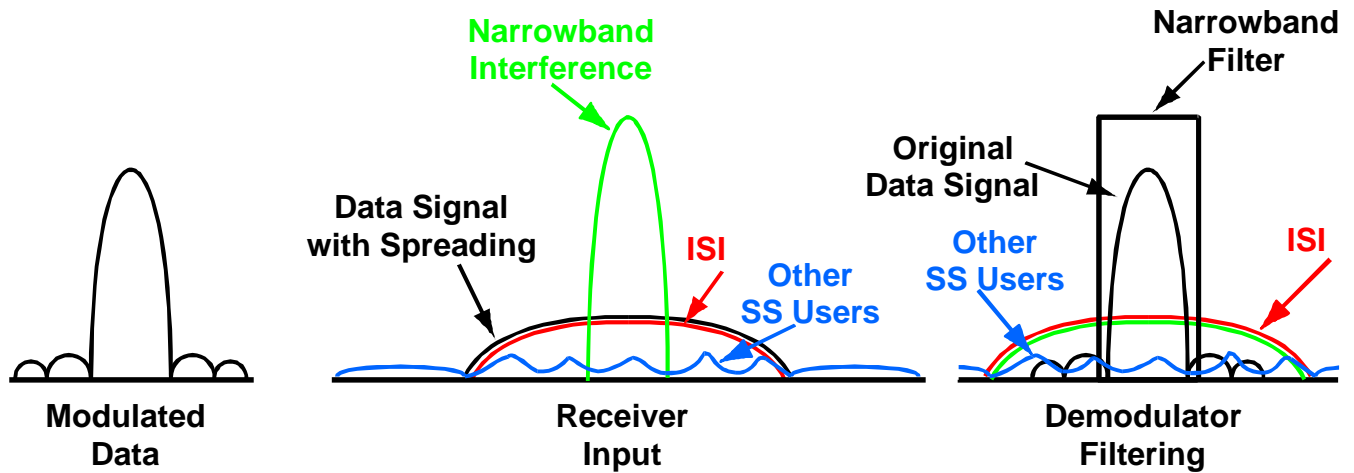
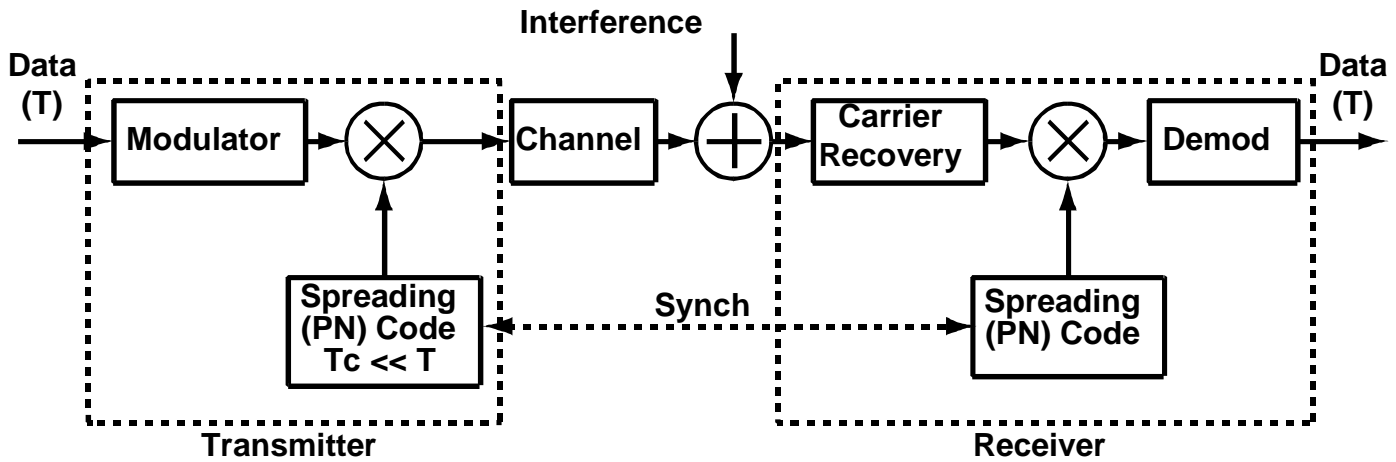
CURRENT AND PROPOSED APPLICATIONS OF OFDM

- **Asymmetric Digital Subscriber Line**
- **Digital Audio Broadcasting**
- **Wireless LAN**
- **Digital Terrestrial Television**
- **High Speed Cellular**

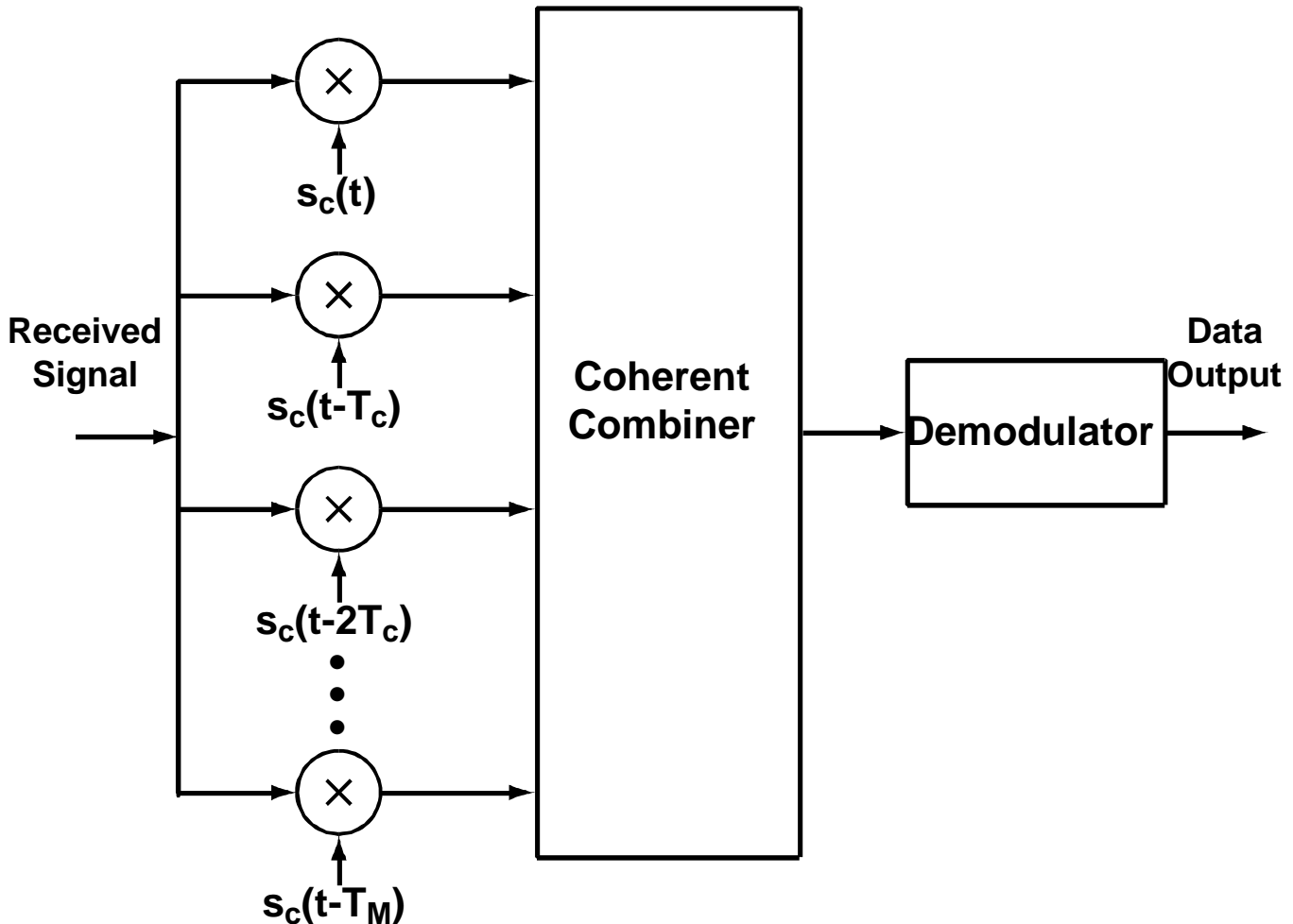
SPREAD SPECTRUM

- Spread spectrum increases the transmit signal bandwidth to reduce the effects of flat fading, ISI and interference.
- SS is used in all wireless LAN products in the ISM band
 - required for operation with reasonable power levels
 - minimal performance impact on other systems
 - IEEE 802.11 standard
- There are two SS methods: direct sequence and frequency hopping.
 - Direct sequence multiplies the data sequence by a faster chip sequence.
 - Frequency hopping varies the carrier frequency by the same chip sequence.

DIRECT SEQUENCE SPREAD SPECTRUM

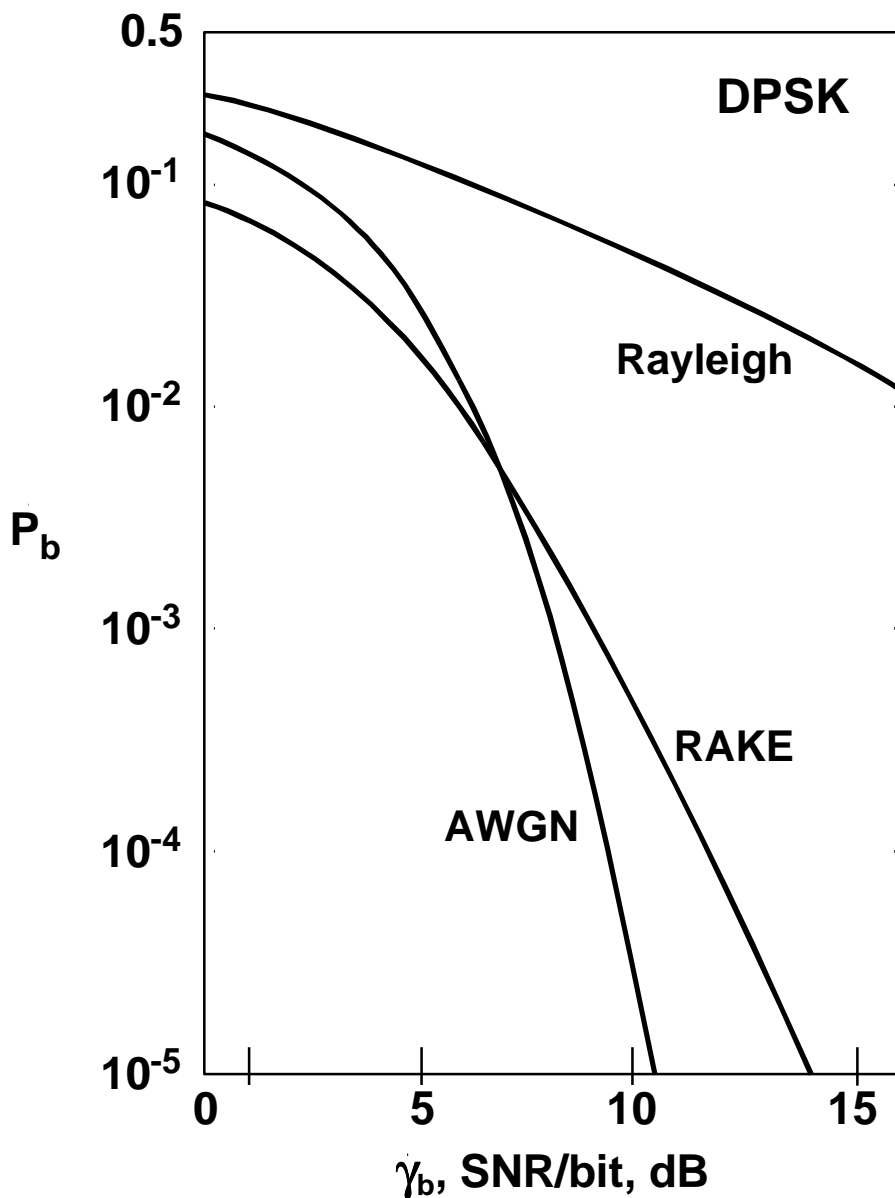


RAKE RECEIVER



- When the chip time is much less than the rms delay spread, each branch has independent fading \Rightarrow **equivalent to diversity combining.**
- When the chip time is greater than the rms delay spread, the paths cannot be resolved \Rightarrow **no diversity gain.**

PERFORMANCE OF RAKE RECEIVER FADING CHANNEL



SPREAD SPECTRUM ISSUES FOR HIGH-SPEED WIRELESS DATA

- **Hardware Complexity**
 - **synchronization**
 - **high processing speeds for high bit rates**
 - **RAKE receiver**
- **High Required Bandwidth to Accommodate Spreading**



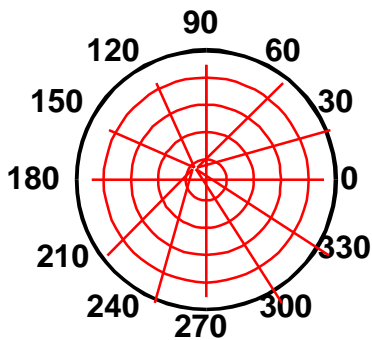
Spread spectrum is difficult at high bit rates and not really needed.

ANTENNA SOLUTIONS

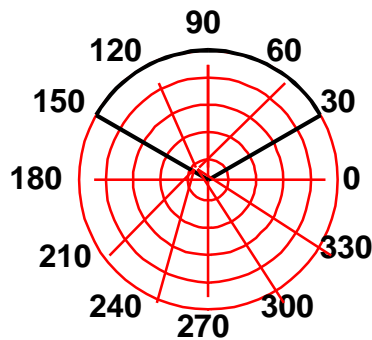
Goal: Reduce (or eliminate) delay spread

- **Distributed Antenna System**
- **Very Small Cells \Rightarrow antenna in every room**
- **Sectorization**
- **Directive Antennas/Beam Steering**

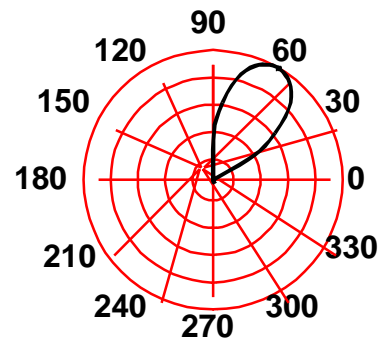
Omnidirectional



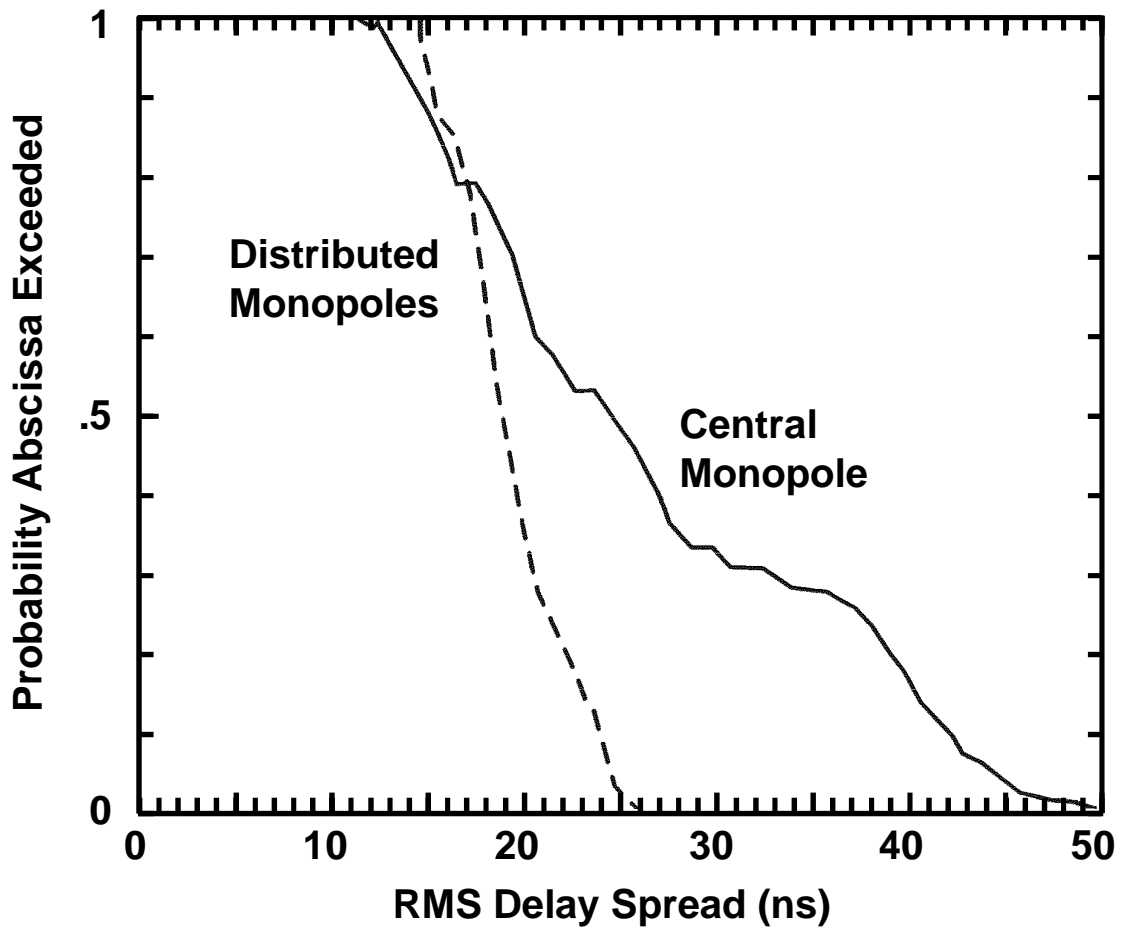
Sectorized



Directive



DISTRIBUTED ANTENNA SYSTEM

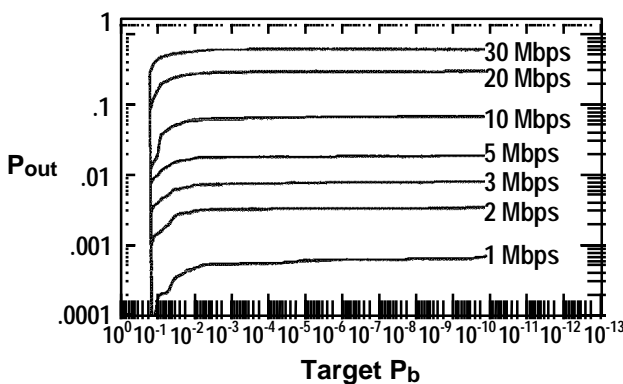


[A. A. M. Saleh, A. J. Rustako, Jr., and R. S. Roman, "Distributed Antennas for Indoor Radio Communications," *IEEE Trans. on Commun.*, December 1987]

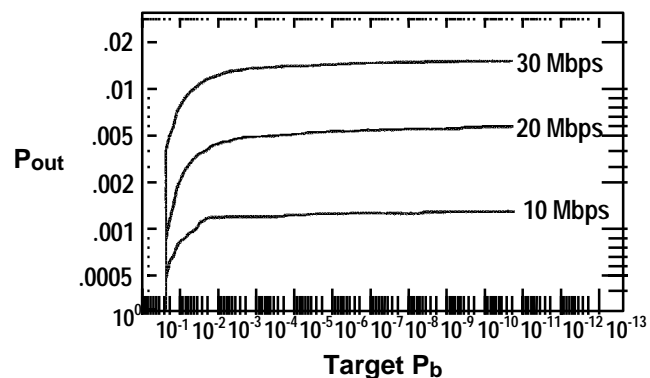
EXAMPLES OF PERFORMANCE IMPROVEMENTS

- High-Speed Narrowbeam Antenna Experiment [P. F. Driessen "Gigabit/s Indoor Wireless Systems with Directional Antennas," *IEEE Trans. on Comm.*, August 1996]
 - directional antennas (15° beamwidth) at both ends of LOS link
 - no equalization
 - 622 Mbps BPSK transmission without errors
- Sectored Antennas [G. Yang and K. Pahlavan, "Comparative Performance Evaluation of Sector Antenna and DFE Systems in Indoor Radio Channels," *Proc. of ICC '92*]
 - 6 sectors at base and mobile
 - best combination chosen
 - for $P_{out} = 0.01$, 5 Mbps with omni, 25 Mbps with sectored antenna

Omnidirectional Antennas



Six Sector Antennas



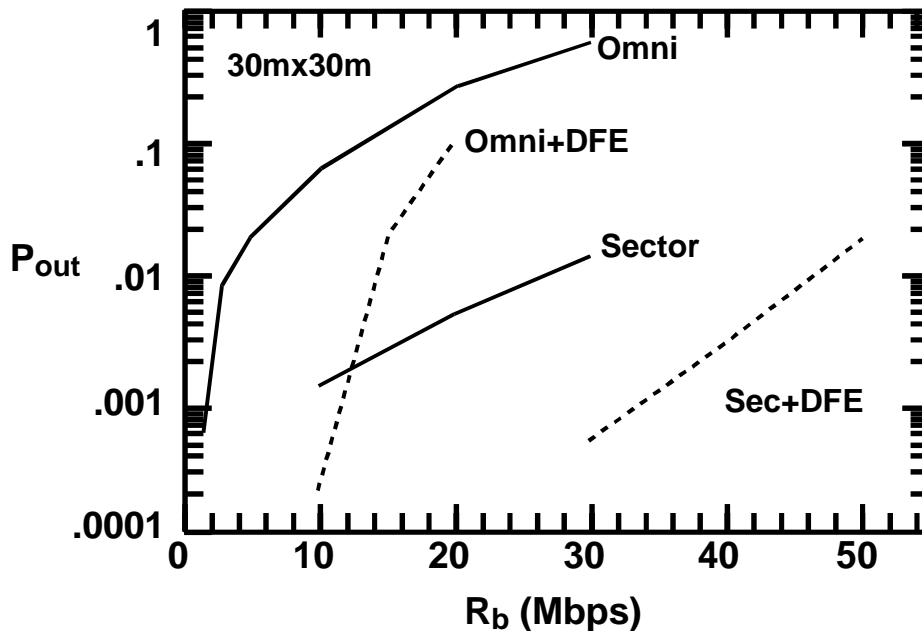
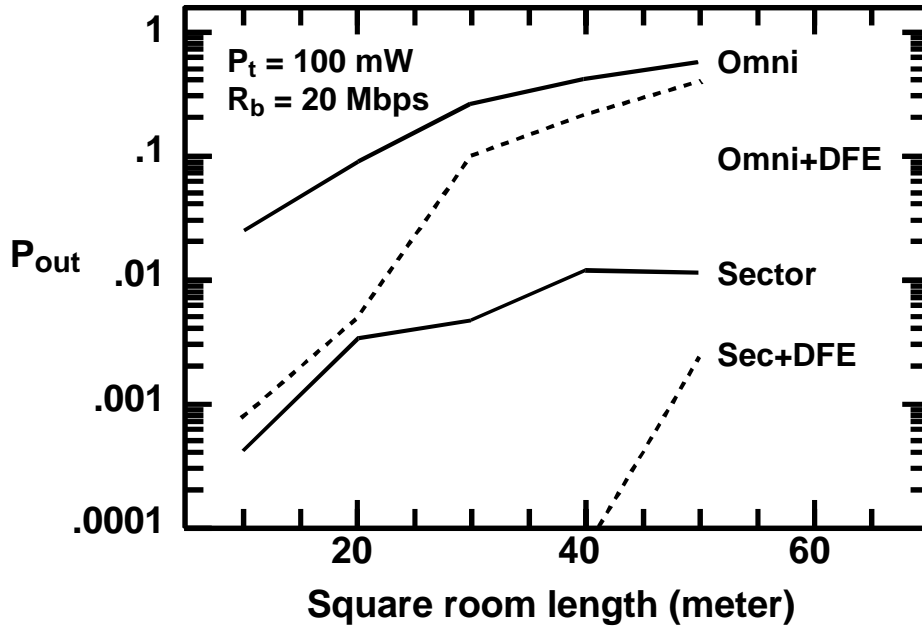
SUMMARY OF COUNTERMEASURES

- Diversity
- Coding and Interleaving
- Adaptive Techniques
- Equalization
- Multicarrier
- Spread Spectrum
- Antenna Solutions



These techniques can be combined.

COMBINED EQUALIZATION AND SECTORED ANTENNAS



[G. Yang and K. Pahlavan, "Comparative Performance Evaluation of Sector Antenna and DFE Systems in Indoor Radio Channels," *Proc. of ICC '92*]

HIGH-SPEED WIRELESS DATA AND INTERNET ACCESS

Reinaldo A. Valenzuela
Director, Wireless Communications
Research Department

BELL LABORATORIES
LUCENT TECHNOLOGIES

ABSTRACT

This course introduces the technology to provide high-speed wireless data communication in both indoor and outdoor environments. The main impediment here is multipath. The course outlines two approaches to overcome this impairment: signal processing techniques such as microdiversity, equalization, and multicarrier modulation, and architectural techniques such as directed beams, smart antennas, and macrodiversity. In addition, channel access strategies and their relative performance are outlined along with a discussion of next generation system and network issues. There is also an overview of current systems and standards, and the course concludes with the state of the art in commercial and research data systems.

BIOGRAPHY OF PRESENTER:

Reinaldo A. Valenzuela obtained his Bachelor of Science from University of Chile and his Ph.D. from the Imperial College of Science and Technology of the University of London, UK. His doctoral work introduced novel digital filter architectures for Transmultiplexer design. At Bell Laboratories, he has studied indoor microwave propagation and modeling, packet reservation multiple access techniques for indoor wireless systems and optical WDM networks. During 1988 and 1989 he was Manager, Voice Research Dept., at Motorola Codex, involved in the real time implementation of low bit rate voice coding for integrated voice and data packet systems.. He is now with Bell Laboratories, where he is engaged in research on wireless systems for personal communication networks. His interests include wireless system design, propagation measurements and site-specific propagation models for indoor and microcellular systems. He has led a multi-disciplinary team effort to create a software tool for Wireless System Engineering (WiSE), now in widespread use in Lucent Technologies. He has recently received the Bell Laboratories Distinguished Member of Technical Staff award. He is currently Head of the Wireless Communications Research Department. He has published over sixty papers and has several patents. He is a Fellow of the IEEE.