MODERN DIGITAL MODULATION TECHNIQUES

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Columbia University
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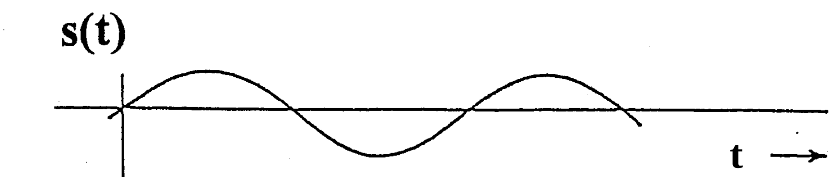
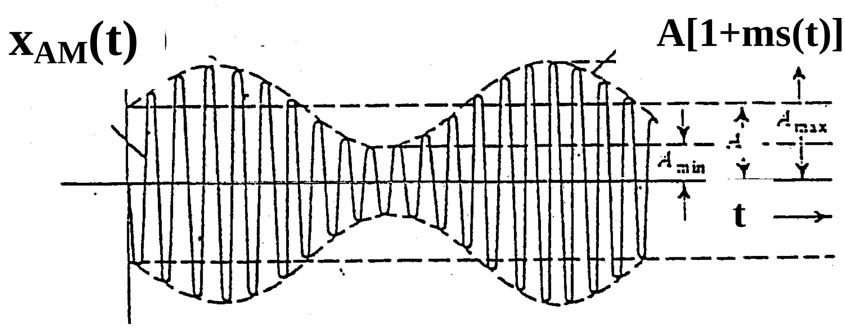
FIGURES FOR THE COURSE

AMPLITUDE MODULATION

Not a Constant Envelope (or Amplitude) Modulation



(a) Sinusoidal Modulating Wave

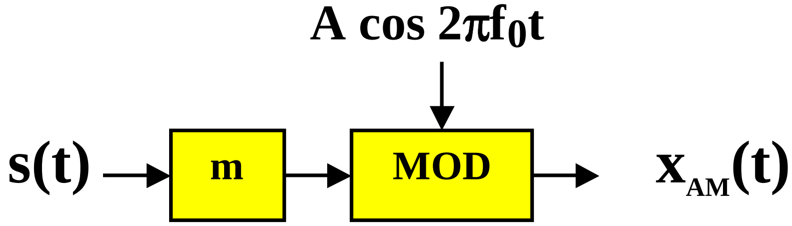


(b) Resulting AM Signal

$$\boxed{x_{AM}(t) = A\,[1 + m\,s(t)]\cos 2\pi f_0 t}$$

$$|s(t)|_{max} = 1$$

$0 \leq m \leq 1$ m=index of modulation

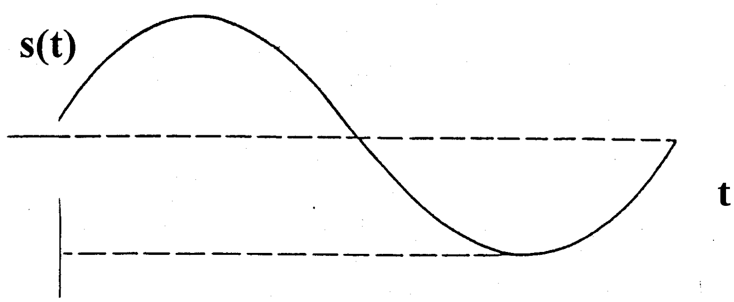


FREQUENCY MODULATION

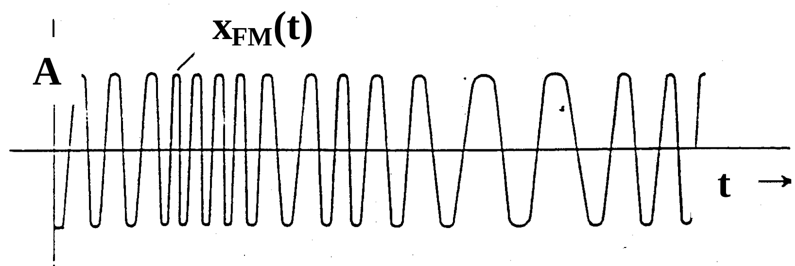
(Continuous Phase Modulation)

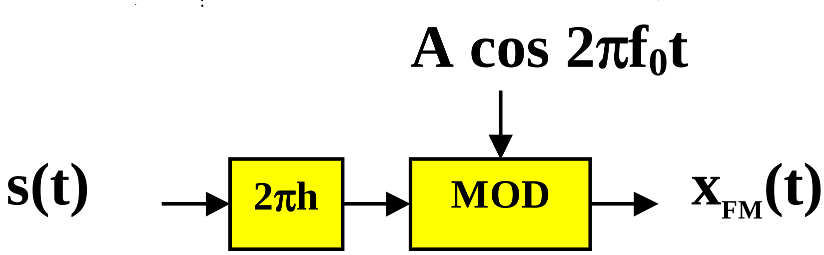
Constant Envelope

Edwin Armstrong, "A method of reducing disturbances in radio signaling by a system of frequency modulation", New York Section of IRE, November 6, 1935.



Transmitted FM Signal, $x_{FM}(t)$

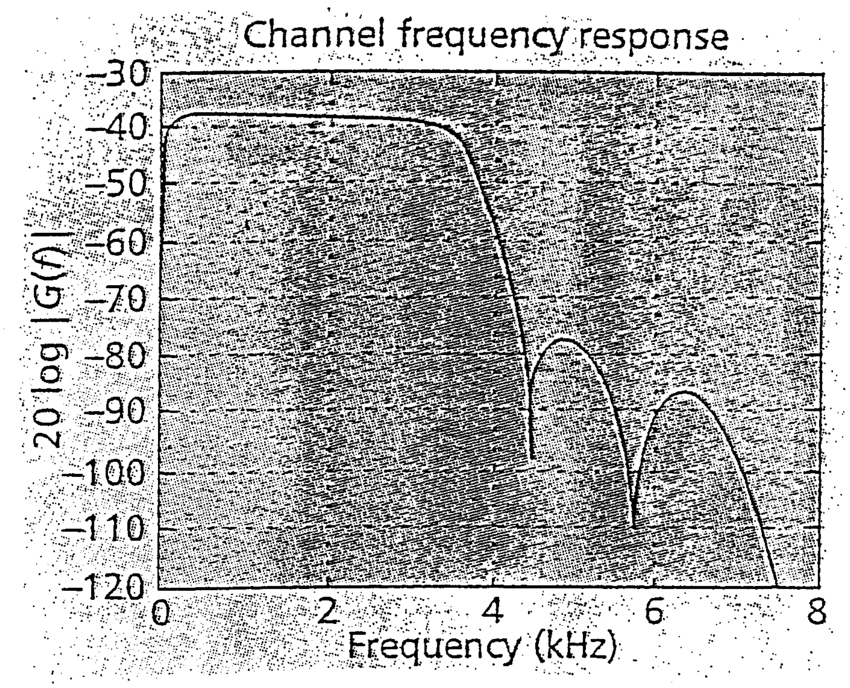




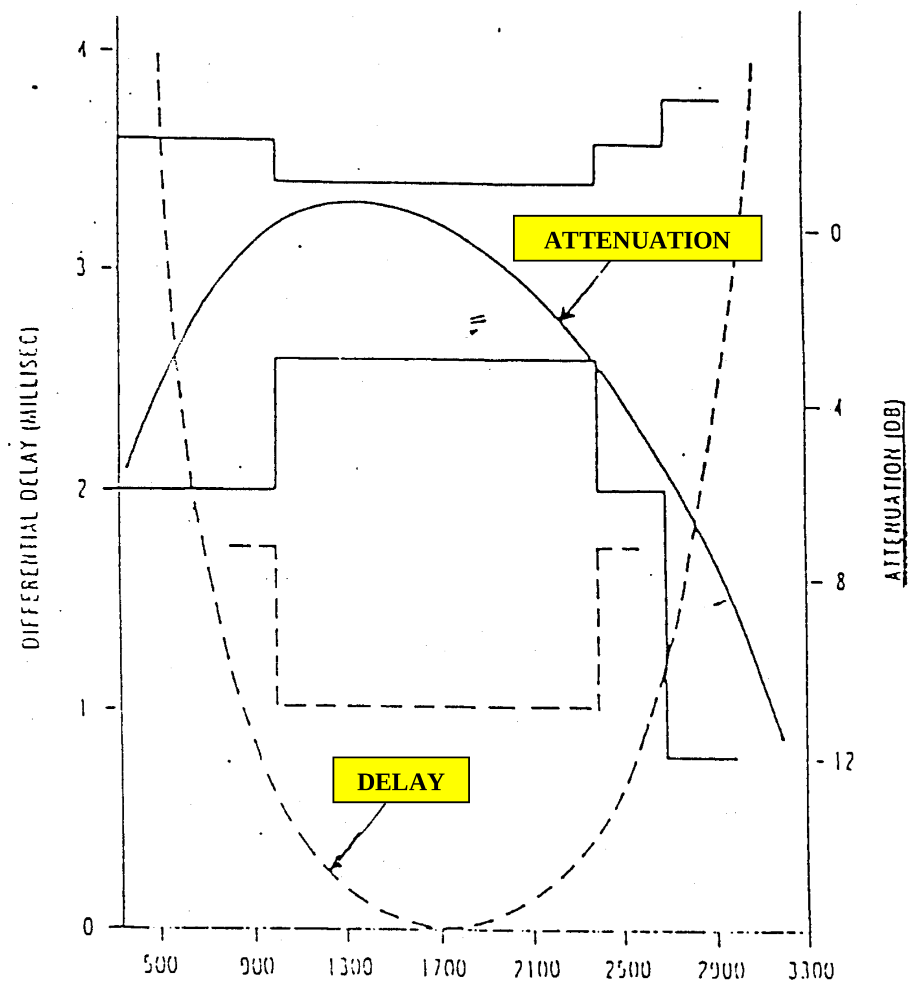
$$x_{FM}(t) = A \cos \left\{ 2\pi f_0 t + 2\pi h \int_0^t s(\tau)\, d\tau \right\}$$

The constant, h, is similar to what is normally called the "maximum frequency deviation" in analog modulation techniques.

Baseband Filter
(used in PCM)



Telephone Channel
(C1 Conditioning)
Bandwidth is about 3000 Hz



Frequency (Hz)

TWISTED-PAIR CHANNEL

- **HDSL-High-Speed Digital Subscriber Lines**
- **ADSL-Asymmetric Digital Subscriber Lines**
- **VDSL-Very High Rate Digital Subscriber Lines**
- **g.lite-An ADSL system operating at relatively low bit rates, i.e., less than or equal to about 1.5 Mbps**

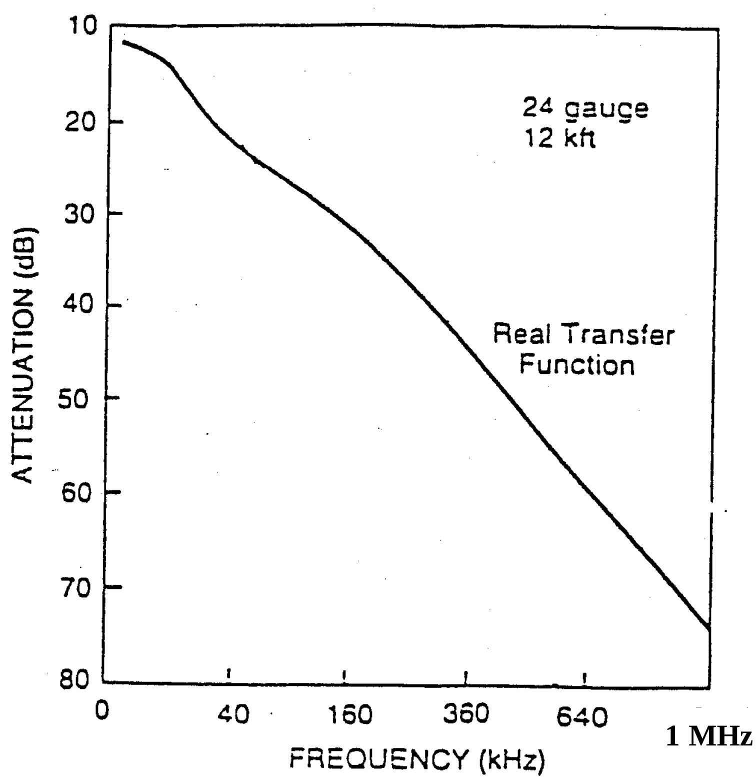
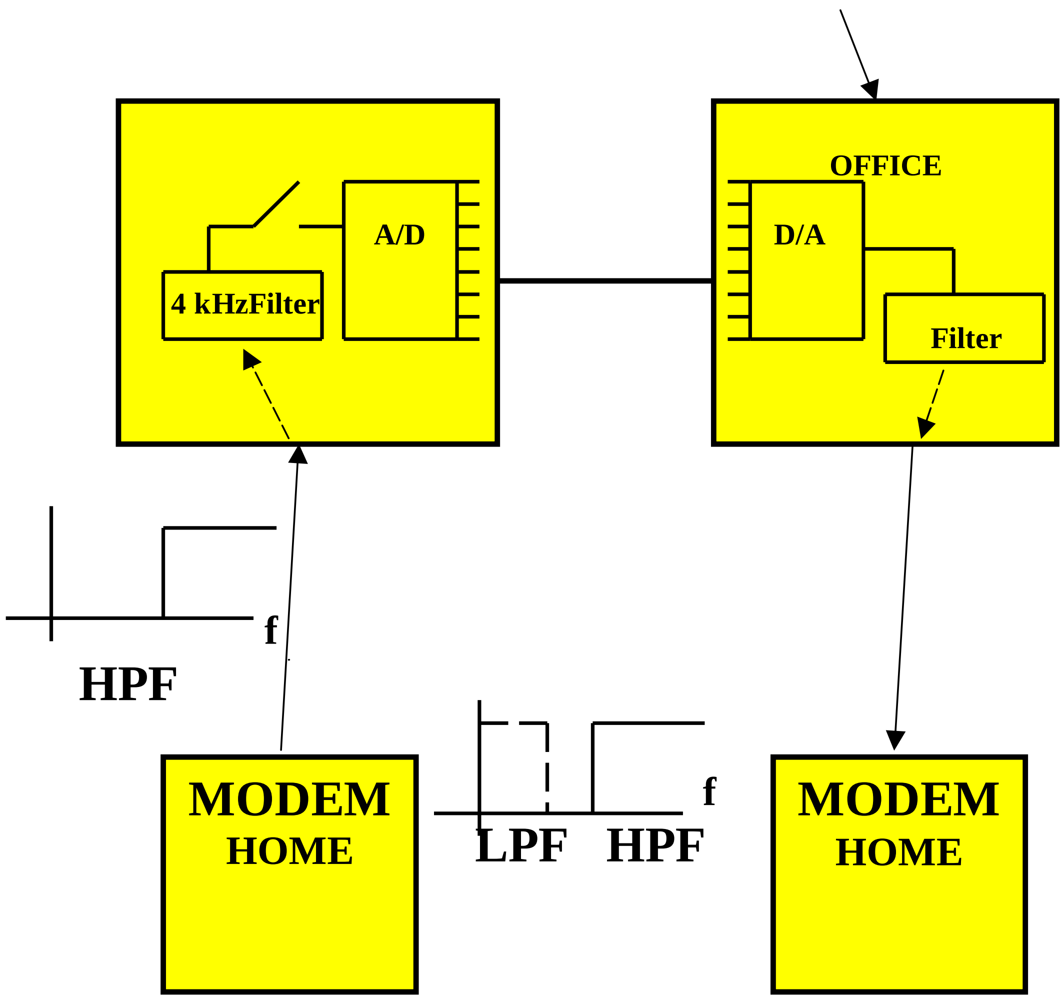
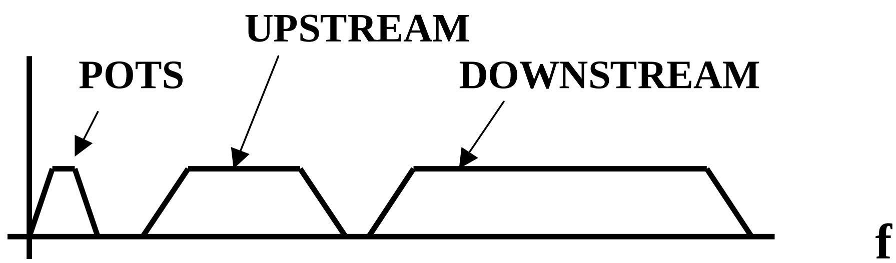


Fig. 4. Attenuation characteristic of a 24-gauge 12-kft PIC loop.

Twisted-Pair- ADSL Example



SPECTRAL OCCUPANCY TWISTED-PAIR CHANNEL



ADSL 0 5 25 128 kHz 1.1 MHz

System	Band	Bit Rates
POTS	300-3.5 kHz	56 Kbps (48 Kbps)
ISDN-2B1Q	10-50 kHz	144 kbps
ADSL (POTS)	25.875-1.104 kHz	UP-640 kbps DOWN-8 Mbps
HDSL-2B1Q 3 pairs	.1-196 kHz	2 Mbps
HDSL-2B1Q 2 pairs	.1-292 kHz	2 Mbps
HDSL-CAP 1 pair	.1-485 kHz	2 Mbps
SDSL	10-500 kHz	192-2.3 Mbps
VDSL	300 kHz-10/20/30 MHz	ASYMMETRIC UP 4 Mbps DOWN 24 Mbps SYMMETRIC 36 Mbps

Modern Digital Modulation Techniques

CLASSIC MODULATION TECHNIQUES

NYQUIST SIGNALING (PAM)
BPSK
QPSK
π/4-QPSK
SQPSK
MPSK
8PSK-
LINEAR GMSK SHAPING
QAM-NYQUIST SHAPING
BFSK, MFSK

CPM SIGNALS

GMSK
MSK
SFSK
FQPSK
TFM-GTFM

CODING TECHNIQUES

VITERBI ALGORITHM
TRELLIS CODING
TURBO-CODING
ITERATIVE DECODING
LDPC CODES

DIVERSITY TECHNIQUES

MIMO, BLAST
SPACE OR ANTENNA DIVERSITY
SMART ANTENNAS
TIME DIVERSITY-CODING
FREQUENCY DIVERSITY
CDMA
OFDM, OFDMA
FREQUENCY HOPPING
MIMO-OFDM-CODING
SPACE-TIME (-FREQUENCY) CODING
ALAMOUTI CODING

MULTITONE SIGNALS

DMT
OFDM
UWB-OFDM

EQUALIZATION TECHNIQUES

VITERBI EQUALIZATION
RAKE RECEIVER
DECISION FEEDBACK EQUALIZATION
LINEAR EQUALIZATION
TURBO-EQUALIZATION

MULTIPLE ACCESS TECHNIQUES

FDMA
TDMA
CDMA
WCDMA
OFDMA
FDD
TDD
FREQUENCY HOPPING
UWB-OFDM (Impulse UWB Radio)

ADAPTIVE MODULATION AND CODING TECHNIQUES

NEW TOPICS

- **Adaptive Modulation and Coding**
- **Antenna Diversity**
- **BLAST**
- **MIMO**
- **OFDM and OFDMA**
- **MIMO-OFDM-CODING**
- **Turbo-Coding and LDPC Codes**
- **Multi-user Communications**
- **Multi-user Diversity Gain**
- **Iterative Decoding Techniques**
- **Capacity of Rayleigh Fading Channels**
- **Space-Time Coding (Alamouti)**
- **Time-Space-Frequency Diversity**
  - **Combinations of above**
- **ACI Cancellation in CPM**
- **UWB-OFDM**
- **Cooperative Diversity**

Cellular land-mobile radio: Why spread spectrum-1979

G.R. Cooper, R. W. Nettleton and D. P. Grybos, "Cellular land-mobile radio: Why spread spectrum", IEEE Communications Magazine, Vo. 17, No.2, March 1979, pp.17-23.

Editor's Note

By proposing a land mobile radio system which employs spread spectrum, the authors have stimulated considerable interest and controversy. The theoretical capacity of their scheme is uncertain because some aspects of system performance are still the subject of debate. For example, one study argues that the authors should reduce their system capacity estimate by a factor of two because their calculation of the signal-to-noise ratio required to achieve a given bit error-rate is in error by 3 dB. Another question is the improvement obtainable by using sectoral (instead of omnidirectional) base station antennas. There is concern that some regions near the cell boundaries in a multicell system will be exposed to interference from a large number of sectors, and that this increased interference may negate some of the apparent advantage of sectoral illumination. One analysis of this spread spectrum system which predicts somewhat poorer performance than claimed here will be presented by P. S. Henry at the 29th IEEE Vehicular Technology Conference in March 1979.

Other critics, including reviewers of this paper, are concerned that readers may give undue credence to the authors' conclusions and infer that a workable and economically feasible solution is being proposed. However, the authors acknowledge the existence of controversy and the fact that they do not know whether or not their scheme is economically viable. Their work is certainly of conceptual interest, at least because it is the first spread spectrum approach to land mobile radio. Even if it should not turn out to be a workable scheme, their proposal may stimulate further exploration of alternative spread spectrum systems for mobile communication.

——A.G.

Two New Standards For Wireless in Duel

Battle Over Next-Generation Service

By SETH SCHIESEL

At a cellular telecommunications convention this spring in Dallas, the head of **Primeco Personal Communications** made a bold prediction for his company's introduction of the new type of wireless telephone service known as P.C.S.

"We'll have all 11 markets ready for the Christmas season," said Ben Scott, Primeco's chief executive.

Nicholas Kauser, chief technology officer for **AT&T Wireless Services**, a Primeco competitor who attended the convention, was quick to respond. "I'll bet a month's wages that it won't happen," Mr. Kauser was quoted as saying in Wireless Week, a trade publication.

Mr. Kauser better get out his checkbook. Primeco, which takes a fundamentally different technological approach to P.C.S. than AT&T, introduced its service last week in 15 metropolitan markets including Chicago and Miami.

There is much more at stake than a gentlemen's bet between corporate rivals, for the Primeco rollout was the first United States market test in a raging financial and technical battle between two rival standards for personal communications services, or P.C.S. On one side is a time-tested technology that only AT&T Wireless plans to deploy on a nationwide basis. On the other is a newer, less-proven format — but one upon which Primeco, **Sprint Spectrum** and most of the nation's other P.C.S. providers are staking their futures.

For customers, the technical debate will come down mainly to which format — if either — offers better voice and data services. But for makers of P.C.S. handsets and network equipment, billions of dollars hang in the balance, as companies like **Qualcomm, Ericsson, Lucent Technologies, Motorola** and **Northern Telecom** angle for business.

Mr. Kauser's wager reflected widespread skepticism about the type of P.C.S. technology adopted by Primeco: code division multiple access, or C.D.M.A.

And while it is too early to tell how well the technology will work as thousands of subscribers move onto these new wireless systems, the fact that Primeco's networks appeared to be operating without major incident last week was an early vindication of the chosen format.

"If your argument was that C.D.M.A. was a hoax, well it's here," said Gregory S. Geiling, an analyst at J. P. Morgan. "The debate over whether C.D.M.A. is a viable technology has been put to rest."

Both C.D.M.A. and its main alternative in this country — time division multiple access, or T.D.M.A., chosen by AT&T Wireless — process calls digitally. That enables more subscribers to use a network, which should translate to lower costs for operators and lower prices for consumers. Digital transmission can also offer better voice quality than traditional analog cellular systems.

Both technologies support data communications. (A T.D.M.A. variant known as G.S.M., dominates Europe's wireless market and is used by some smaller American operators including **Omnipoint Communications**, which introduced service in New York last week.)

But the two technologies accomplish those goals in radically different ways, and their partisans see radically different results.

T.D.M.A., championed by Ericsson, the Swedish maker of handsets and wireless network systems, allows three users to share a single radio-frequency channel by dividing each user's voice or data conversations into tiny time segments, interspersing the segments and and reassembling the traffic at the receiver's end.

AT&T Wireless is the sole national proponent of T.D.M.A., which is the format for the Digital P.C.S. system the company introduced as updated cellular phone service in September and plans to roll out at higher P.C.S. frequencies next year.

Instead of using time division, C.D.M.A. scatters the contents of voice and data conversation over many channels, giving each snatch of information a unique identification code to allow reassembly on the receiving end.

Though the San Diego-based Qualcomm Corporation introduced the basic technology in the late 1980's, providers have faced daunting technical challenges in getting C.D.M.A. from the laboratory to the marketplace. But last week, its supporters were reveling.

"If you go back and look at what we claimed for this technology, we've delivered," said Harvey P. White, Qualcomm's president.

Not quite. Originally projected to offer up to 40 times the capacity of analog systems, most analysts now say the technology will offer at most a ninefold improvement over analog.

That is still more of an upgrade than the three-for-one expansion of T.D.M.A. And it is why many industry figures say C.D.M.A. offers long-term financial benefits — though T.D.M.A. advocates like AT&T Wireless and Ericsson dispute this.

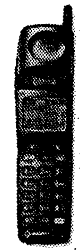
Scott K. Erickson is a marketing vice president at Lucent, which makes both systems and counts as clients both AT&T Wireless and Primeco — a joint venture of **Nynex, Bell Atlantic, U S West** and **Airtouch Communications**. Even Mr. Erickson describes C.D.M.A. as "a much more economical system to deploy."

But, like Mr. Kauser, T.D.M.A.'s defenders continue to bet that the rival technology will fall on its face.

"We're not experimenting on our customers, which is what is going to happen with some of these new technologies," said Roderick D. Nelson, an AT&T Wireless vice president.

Over time, many industry experts expect the relative advantages of the two formats to blur, as the providers with the best marketing plans prevail. "The consumer is the one who's going to win," said Matthew J. Desch, president of Northern Telecom's wireless networks group.

Competing Standards

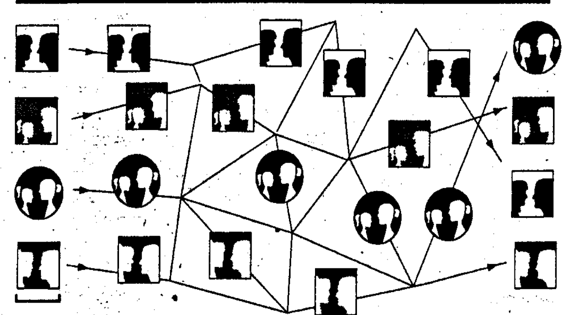


There are two main United States standards for digital wireless phone service: Time Division Multiple Access (T.D.M.A.) and Code Division Multiple Access (C.D.M.A.). Both process calls by compressing more conversations into a given amount of radio space than an analog signal can. The result is a clearer signal and better voice quality. The two technologies accomplish this goal in radically different ways.

T.D.M.A.

1. One to three users share each available radio frequency.
2. The conversations are divided into tiny bits of sound.
3. When the bits are reassembled, the ear hears a continuous sound much as the eye sees a continuous image at the movies.

C.D.M.A.



1. Multiple users share available radio frequencies.
2. Each conversation is broken into segments and coded.
3. The conversations travel along different paths.
4. And then using the codes, the segments are reassembled on the receiving end.

Sources: Qualcomm, AT&T Wireless

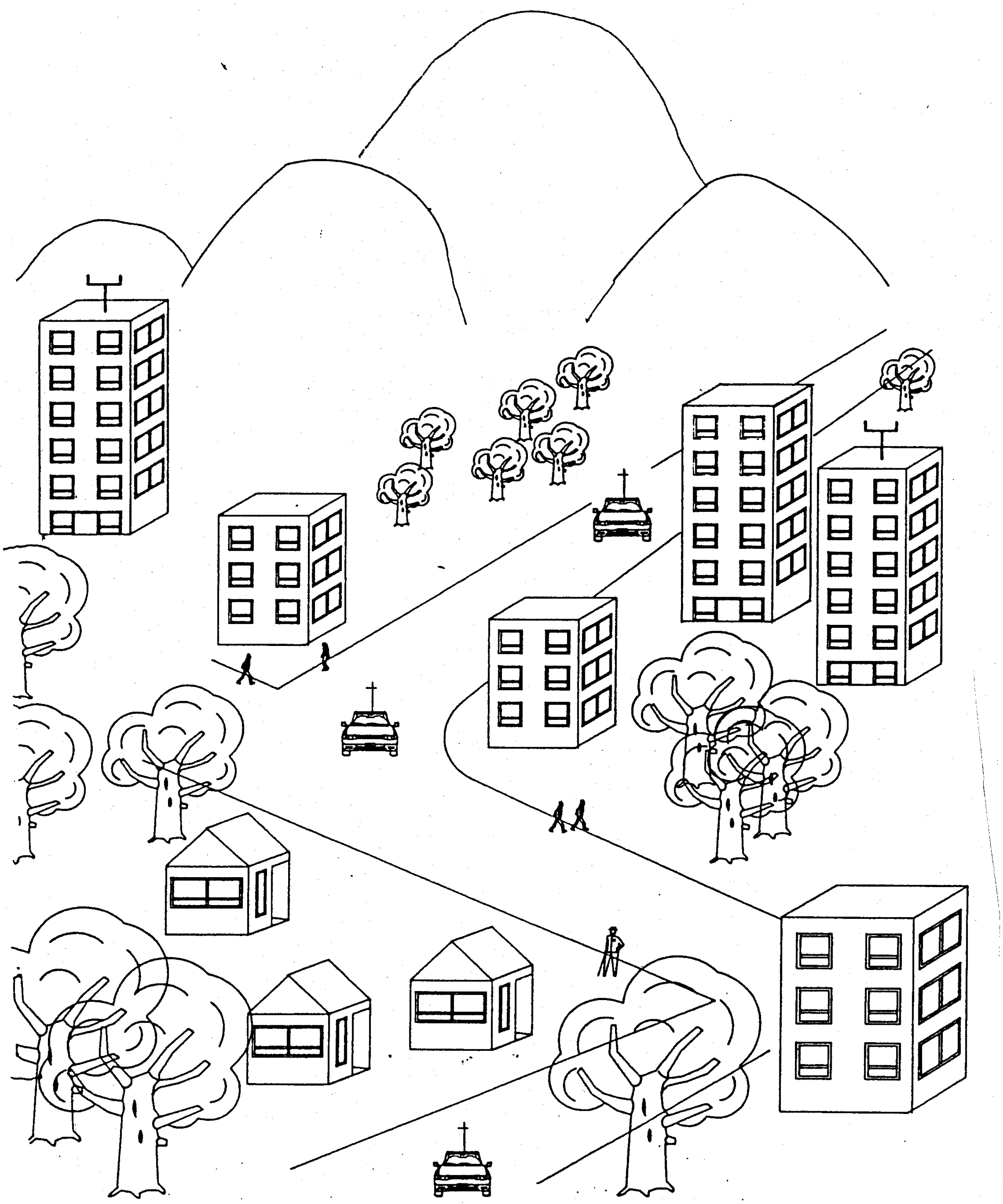
The New York Times

IMT-2000 RADIO INTERFACE SPECIFICATIONS

Approved –ITU Helsinki
October 25-November 5, 1999

- **IMT-DS-Wideband CDMA-UTRA-FDD (3.84Mch/sec)**
- **IMT-MC-cdma2000-1x and 3x (1.2288Mch/sec)**
- **IMT-TC-UTRA TDD (3.84Mch/sec)**
- **IMT-SC-UWC-136 or EDGE-Upgraded TDMA**
- **IMT-FT-DECT based**
- **China-1.3542 Mchips/sec-1.36 MHz (May 2000) (TD-SCDMA)**

Typical Small City



Path loss versus distance measured in several German cities

B. Sklar, "Rayleigh fading channels in mobile digital communication systems – Part I: Characterization, and Part II: Mitigation", IEEE Comm. Magazine., September 1997, pp. 136-146.

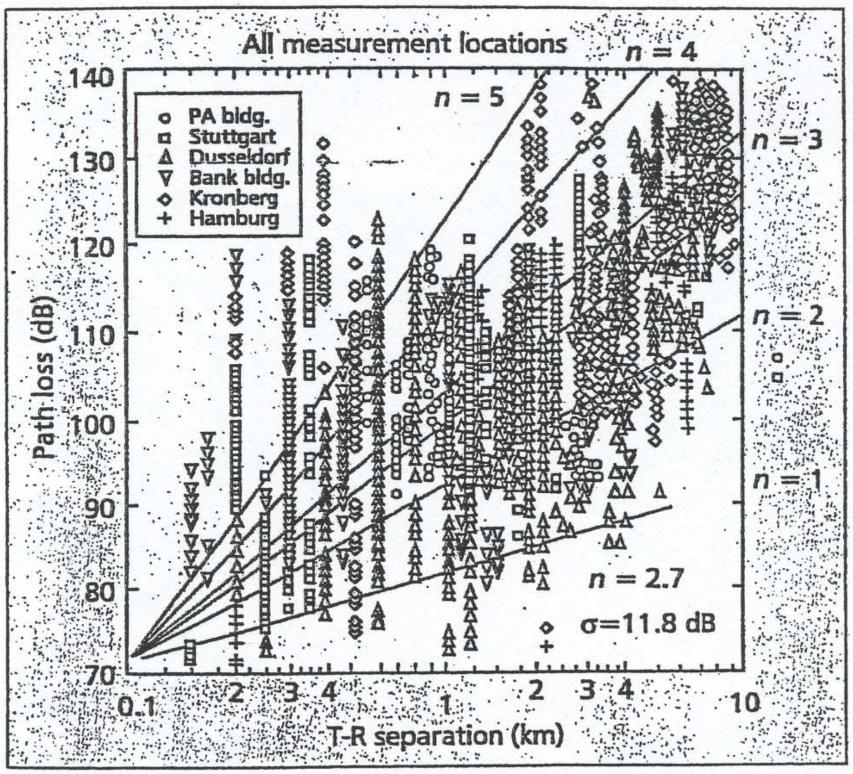


Figure 4. *Path loss versus distance measured in serveral German cities.*

*<u>Rayleigh Distribution</u>

$$f(r) = (r/\sigma^2)\, e^{-r^2/2\sigma^2} \quad ; r \geq 0$$

*<u>Rician Distribution</u>

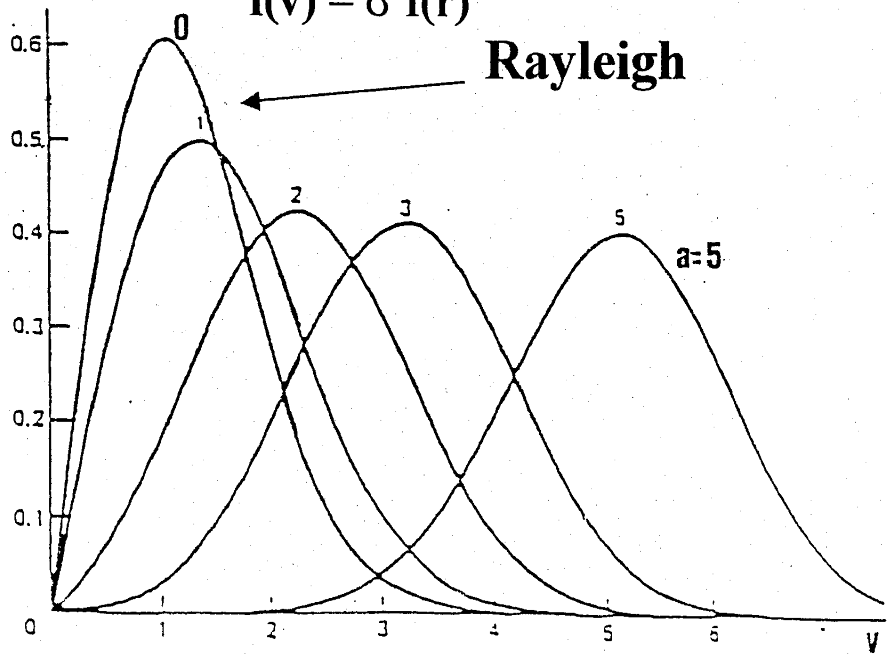
$$f(r) = (r/\sigma^2)\, e^{-(r^2+A^2)/2\sigma^2}\, I_0[r(A/\sigma^2)] \quad ; r \geq 0$$

$$I_0[x] = (1/2\pi) \int_{-\pi}^{\pi} e^{x\cos\theta}\, d\theta$$

***The plot below is a plot of f(v), where**

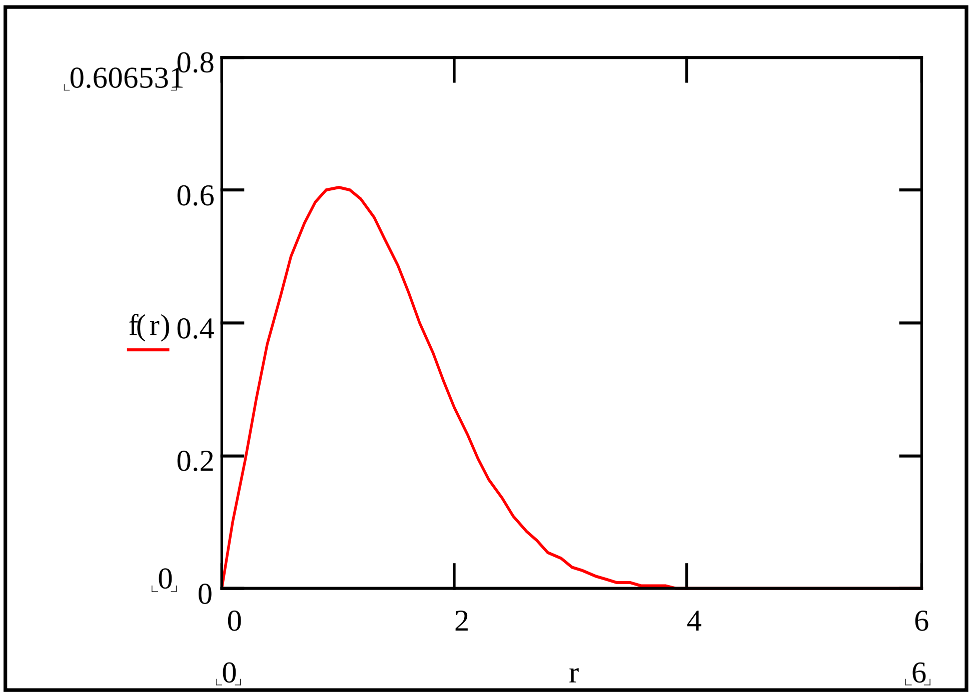
$$v = r/\sigma \quad \text{and} \quad a = A/\sigma$$

$$f(v) = \sigma\, f(r)$$



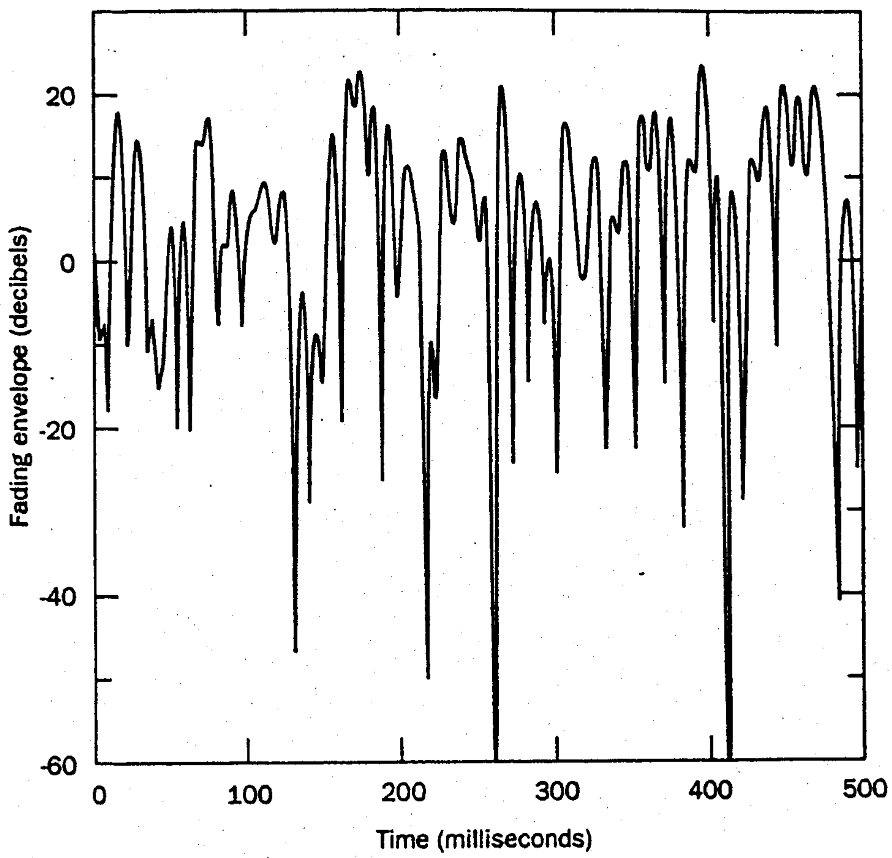
Rayleigh Probability Density Function

$$f(r)=(r/\sigma^2)e^{-r^2/2\sigma^2};\ r\geq 0$$



Rayleigh Fading Amplitude as a function of time

-Carrier frequency=900 Mhz
-Velocity=50 Mph (80 Km/h)



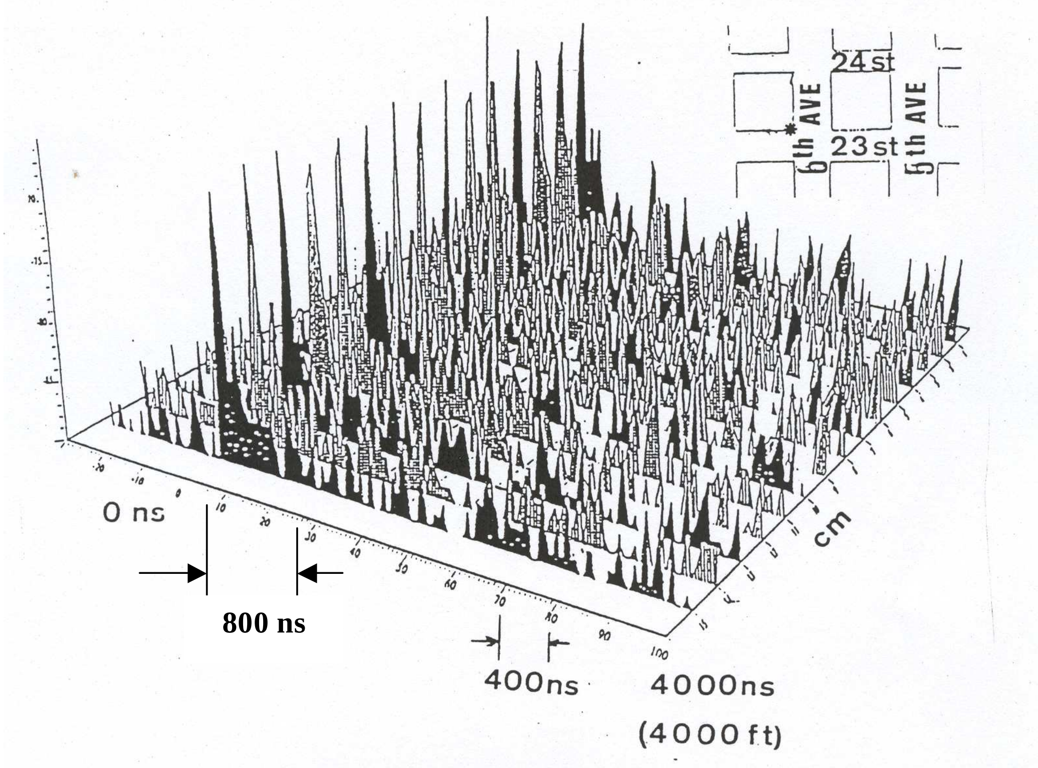
AT&T Technical Journal
July/August 1993

Delay Spread Measurements

- New York City
- Sixth Ave. and 23 rd St.

-Carrier Frequency-2 GHz (BPSK)
-Chip Rate-24 Mchips/sec
-$T_{ch}=1/R_{ch}=40$ ns

InterDigital (D. Schilling)

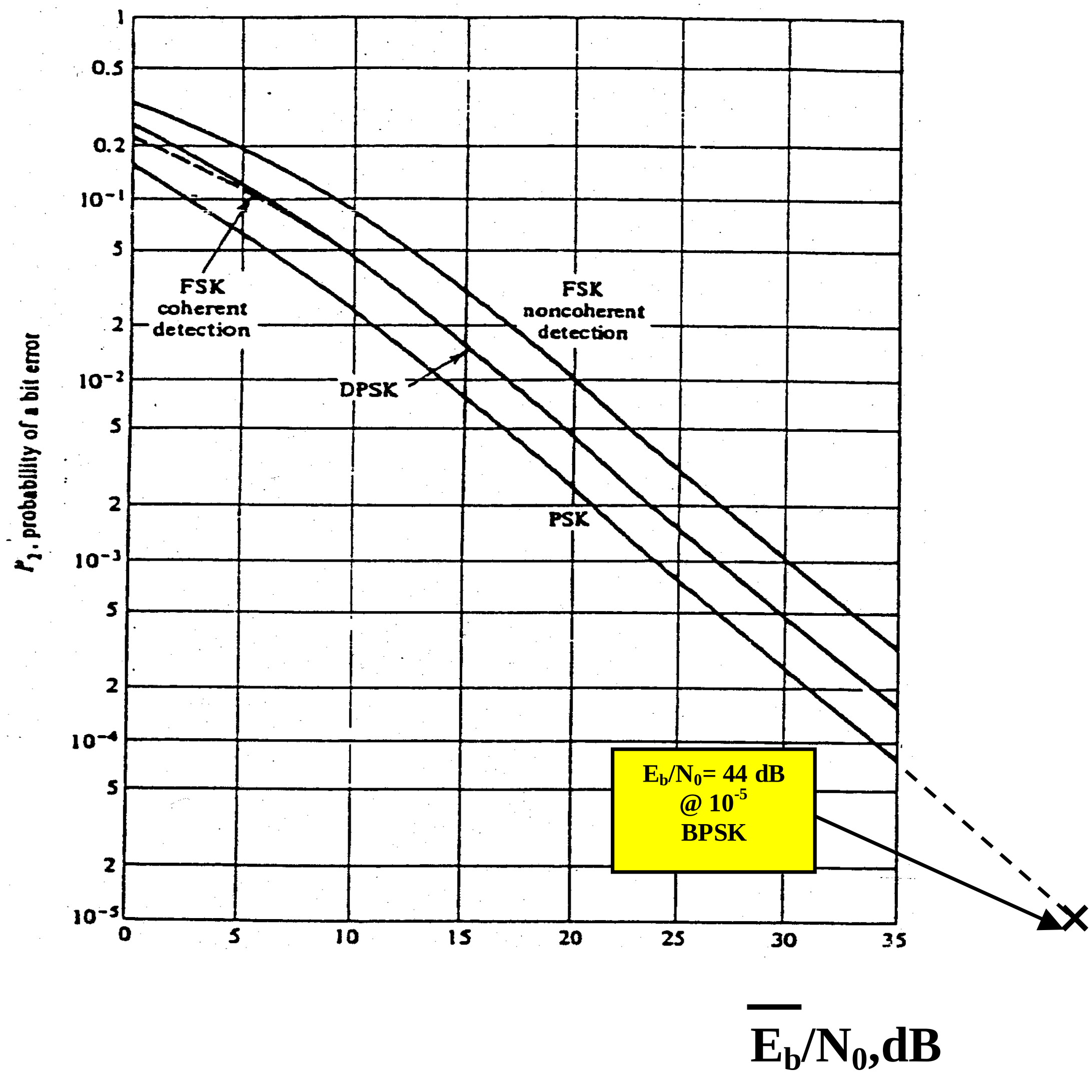


· 6th Ave. and 23rd St.

Fading Channel and Diversity

Figures

Slow Flat Rayleigh Fading Channel-SISO



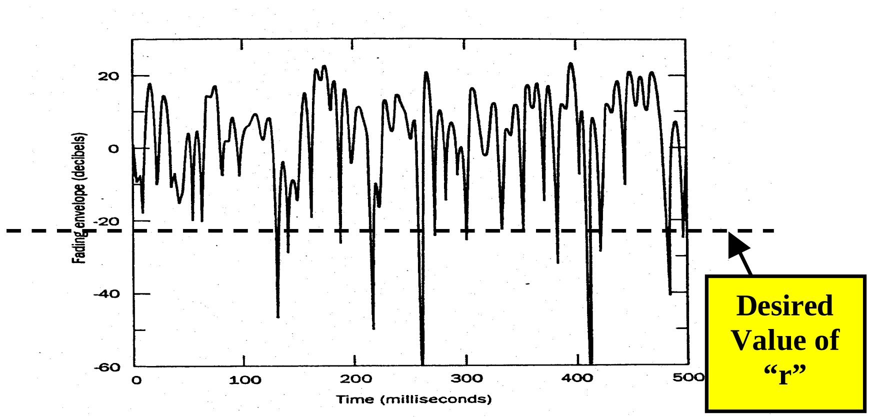
“Digital Communications”-Fourth Edition, 2000, by John G. Proakis, McGraw-Hill Co.

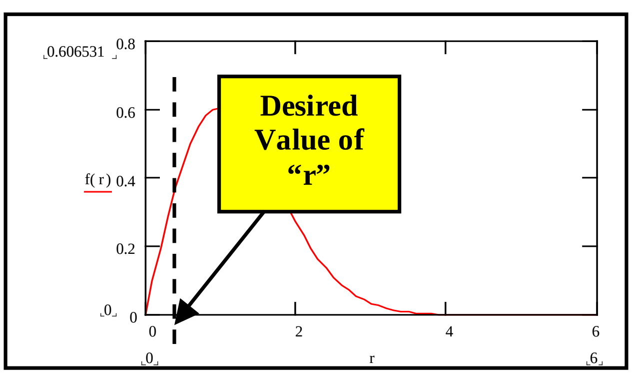
PROBABILITY OF OUTAGE
Pr{outage}

In many cases we may also look at the performance of fading channels by considering the so-called outage probability, Pr{outage}.

The outage probability, Pr{outage}, is defined as the probability that a certain desired "instantaneous" probability of error is not attained.

For example, let's consider the Rayleigh fading channel shown previously and redrawn below.





Suppose we would like the "instantaneous" error probability to be less than some desired threshold value, $Pr_{threshold}\{\varepsilon\}$, e.g., 10^{-5}. In other words we require that the received instantaneous value of $E_{b,instant}/N_0$,dB be greater than some required threshold value, e.g., for the case of 10^{-5}, the required value would be $E_{b,instant}/N_0=r^2\ E_b/N_0$,dB equal to 9.6 dB.

The instantaneous received value of $E_{b,instant}/N_0=r^2\ E_b/N_0$.

Therefore, we would have to find that value of "r" which guarantees that

$$E_{b,instant}/N_0=r_{threshold}^2\ E_b/N_0 > E_{b,threshold}/N_0\ .$$

The probability that "r" <u>is not greater</u> than the required $r_{threshold}$ is the outage probability, Pr{outage}.

$$\boxed{Pr\{outage\}=Pr\{\ E_{b,instant}/N_0\ < E_{b,threshold}/N_0\ \}}$$

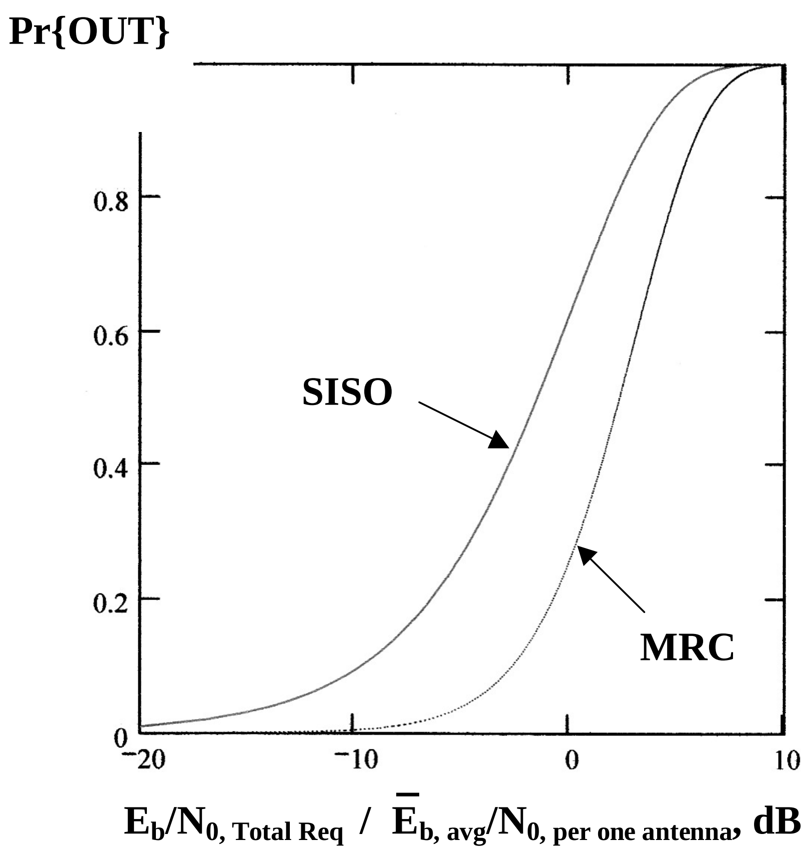
Probability of Outage

Single Diversity (SISO)

$$\Pr\{\text{outage}\}=1-\exp\{-[E_{b,\text{required}}/N_0]\ /[E_{b,\text{average}}/N_0\ ]\}$$

Dual Diversity (MRC-SIMO)

$$\Pr\{\text{outage}\}=1-\left[1+\frac{E_{b,\text{required}}/N_0}{E_{b,\text{avg, one ant}}/N_0}\right]\exp\left[-\frac{E_{b,\text{required}}/N_0}{E_{b,\text{avg,one ant}}/N_0}\right]$$



Probability of Outage

Single Diversity (SISO)

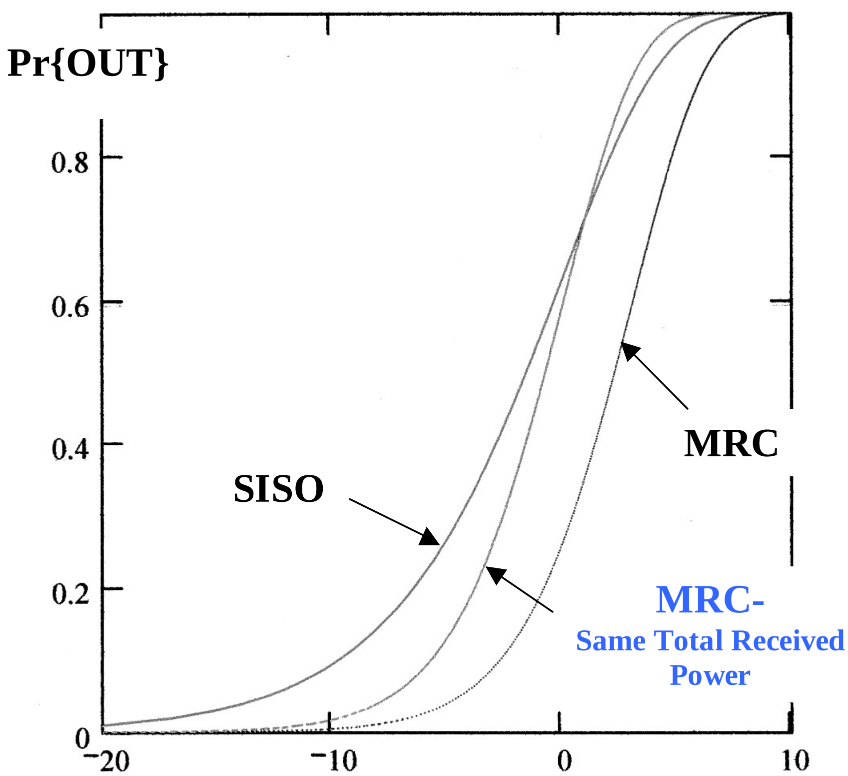
$$\Pr\{outage\}=1-\exp\{-[E_{b,required}/N_0]\ /[E_{b,average}/N_0\ ]\}$$

Dual Diversity (MRC-SIMO)

$$\Pr\{outage\}=1-\ 1+\left[\frac{E_{b,required}/N_0}{E_{b,avg,\ one\ ant}/N_0}\right]\exp\left[-\frac{E_{b,required}/N_0}{E_{b,avg,one\ ant}/N_0}\right]$$

Dual Diversity (MRC-SIMO-Received Power Remains the Same)

$$\Pr\{outage\}=1-\ 1+\left[\frac{E_{b,required}/N_0}{E_{b,avg,\ total}/N_0}\right]\exp\left[-\frac{E_{b,required}/N_0}{E_{b,avg,total}/N_0}\right]$$

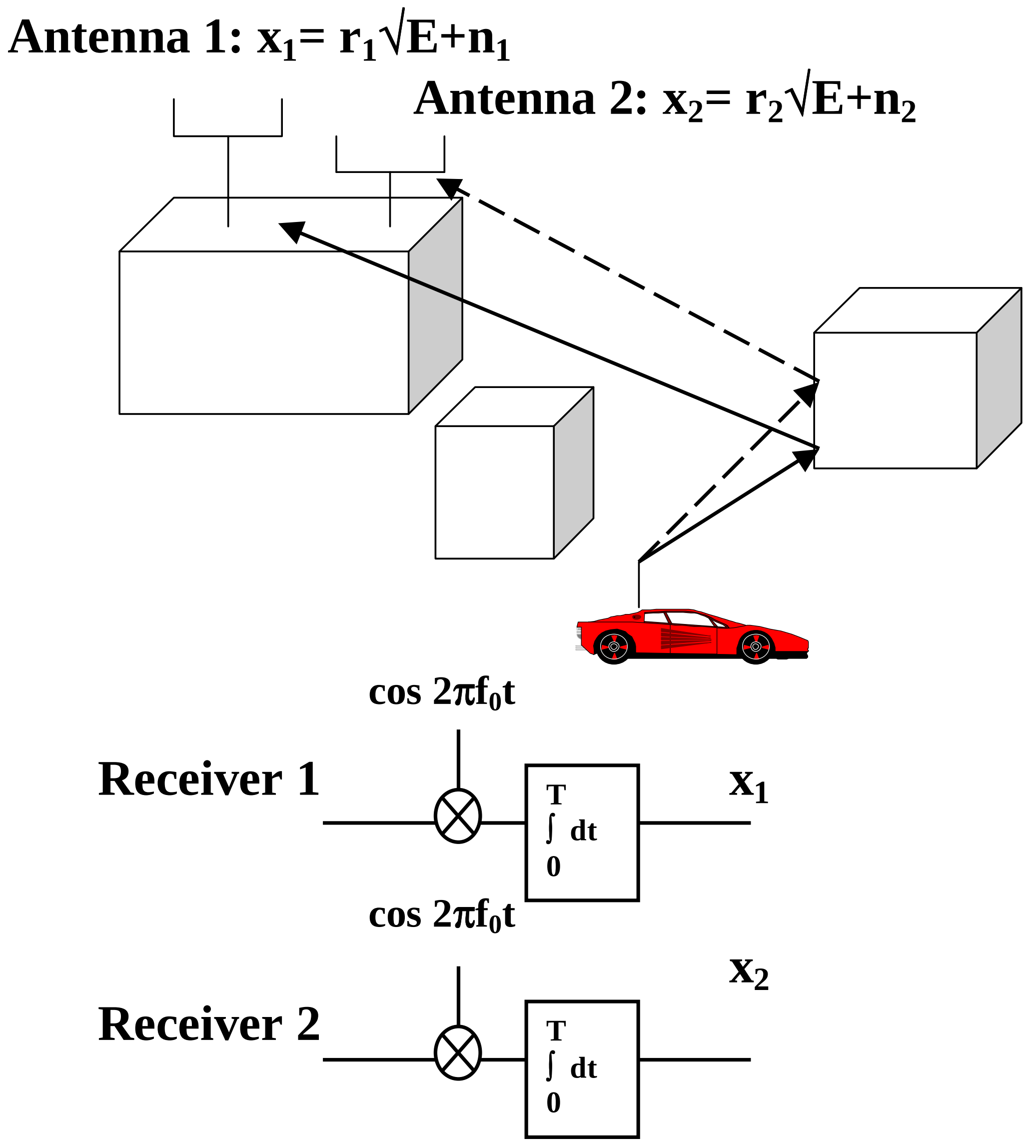


$E_b/N_{0,\text{ Total Req}}\ /\ E_{b,\text{ avg}}/N_{0,\text{ per one antenna}}$, dB

($E_b/N_{0,\text{ Total Req}}\ /\ E_{b,\text{ avg}}/N_{0,\text{ total received power}}$, dB- for the case in which total received power remains the same)

Slow Flat Rayleigh Fading Channel
• Antenna Diversity

-Selection Combining
-Equal Gain Combining
-Maximal Ratio Combining-MRC



Probability Density Functions, f(x)

The variable "x" represents total instantaneous received energy

-One Receiving Antenna (SISO)

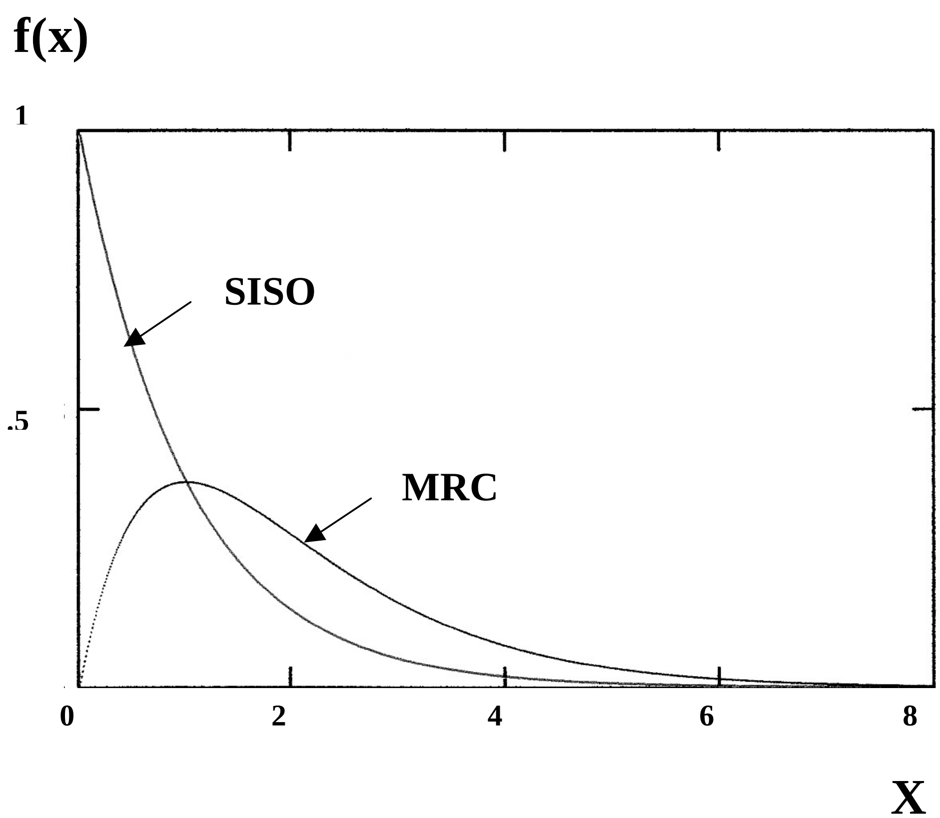
$$f(x)=(1/2\sigma^2)\exp(-x/2\sigma^2)$$

$$(x=r^2)$$

-Two Receiving Antennas –MRC

$$f(x)=[(1/2\sigma^2)]^2\, x\, [\exp(-x/2\sigma^2)]$$

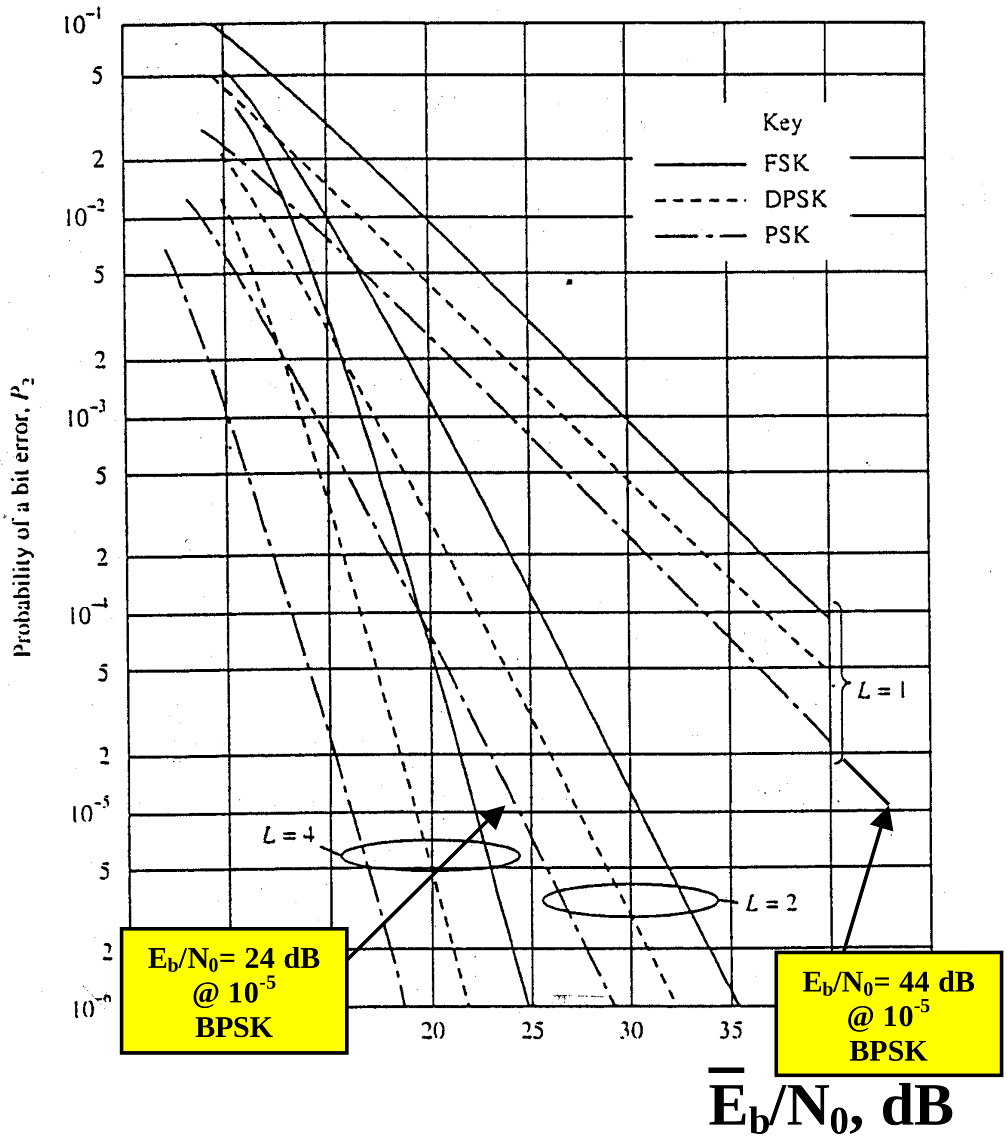
$$(r^2=r_1^{\ 2}+r_2^{\ 2} \Rightarrow x=x_1+x_2)$$



Slow Flat Rayleigh Fading Channel

Antenna Diversity-SIMO

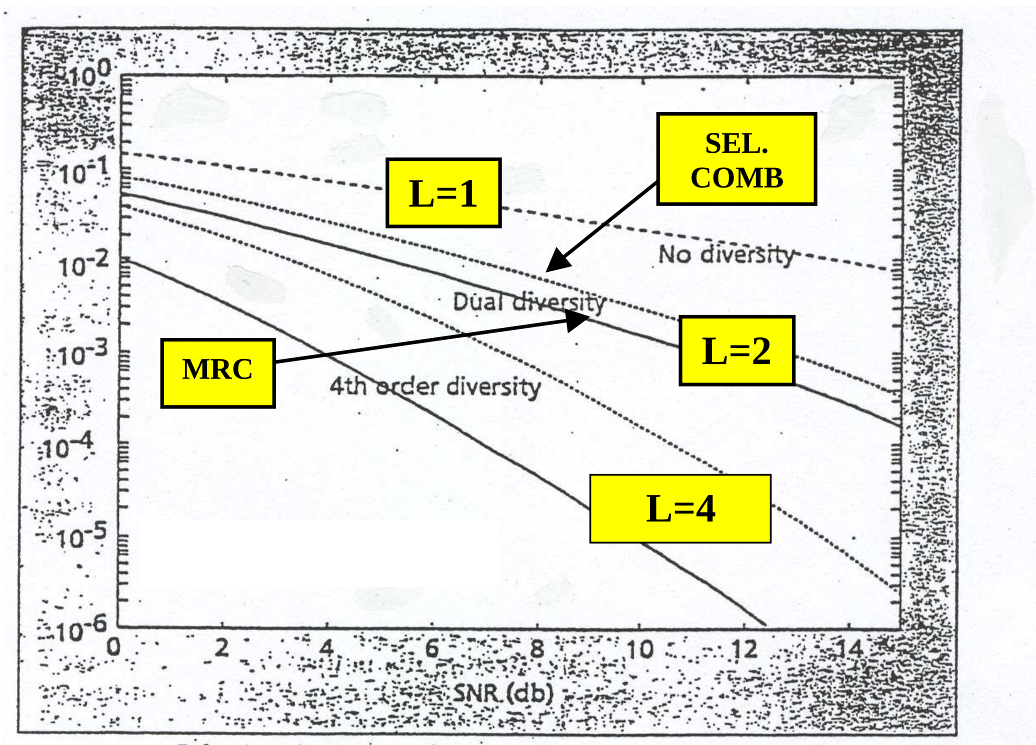
Maximal Ratio Combining



DIVERSITY COMBINING

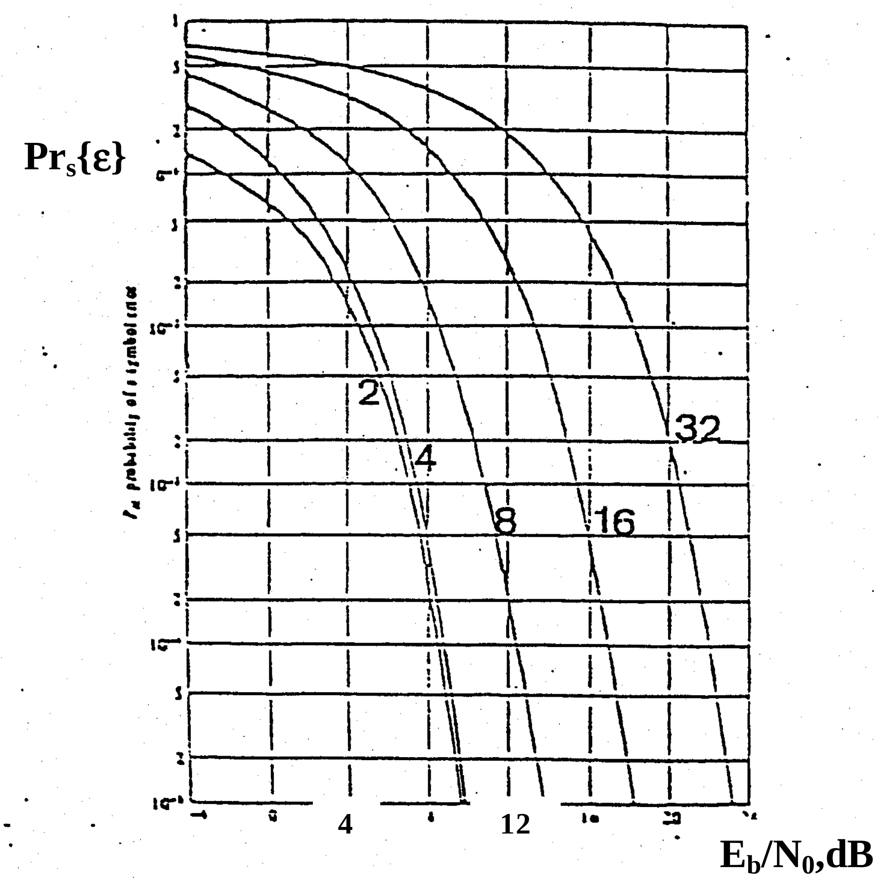
G. Pottie, "System Design Choices in Personal Communications", IEEE Communications Magazine, October 1995

- **Selection Combining**
- **Maximal Ratio Combining-MRC**



. *Selection diversity and maximal ratio combining for coherent PSK.*

MPSK
Probability of Symbol Error



- R_b is the same for all the modulations.
- The bandwidth, W, decreases as M increases.

QAM AND MPSK SIGNALS

Probability of Symbol Error, $Pr_s\{\varepsilon\}$

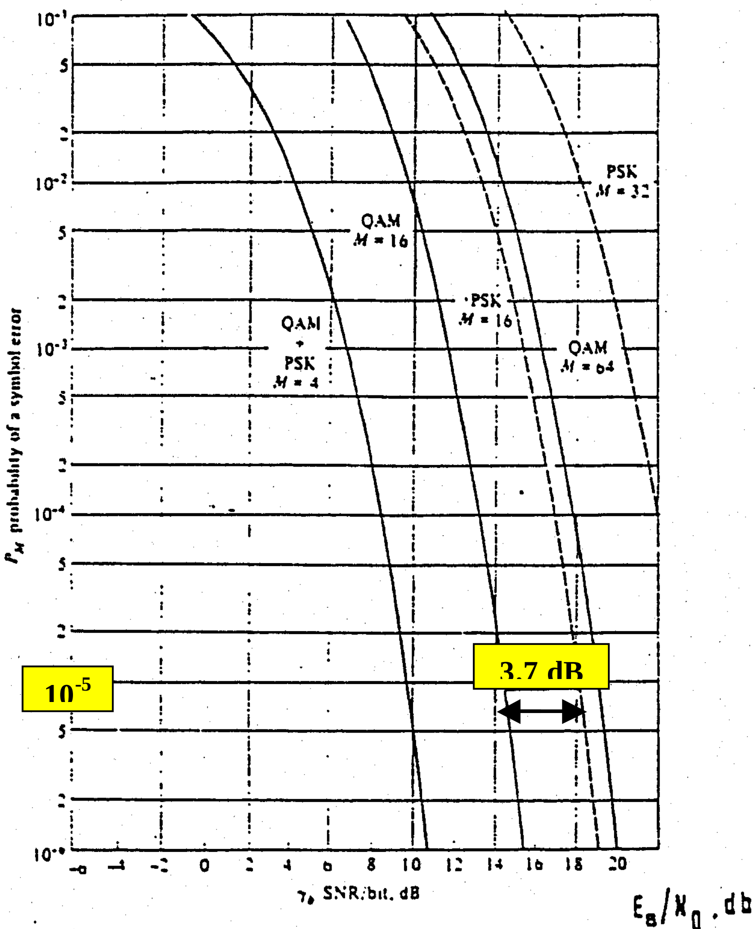
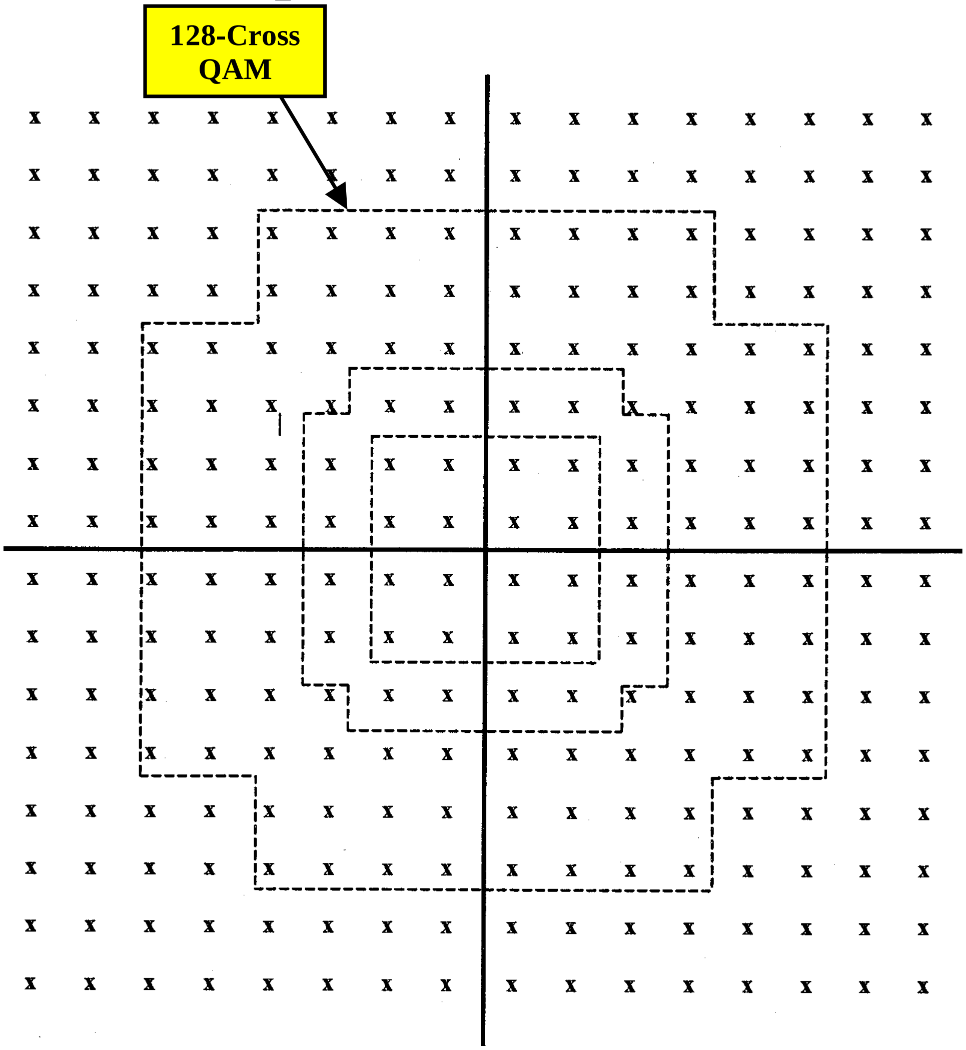


FIGURE 4.2.28
Probability of a symbol error for QAM and PSK.

- **16-QAM is about 3.7 dB better than 16-PSK (at 10^{-5})**

<u>SQUARE (AND CROSS) CONSTELLATIONS</u>
- up to 256 POINTS



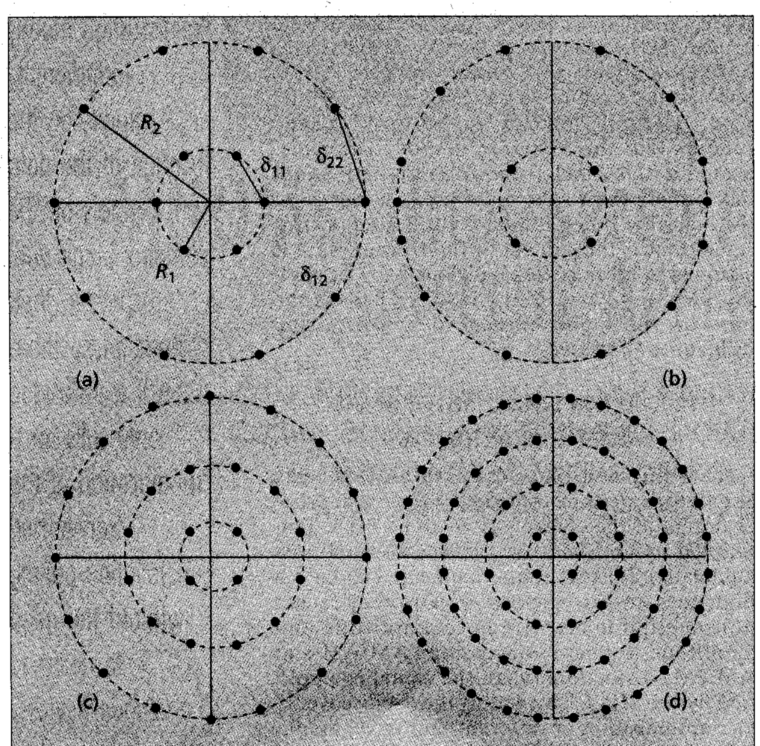
Notice that the minimum distance "d" is the same for all the constellations.

The "price" for increasing the <u>number of bits per sec/Hz</u> for Square QAM Constellations is about 6 dB/ 2 bits per symbol!

Multi-ring Amplitude Phase Shift Keying Constellations

S. Benedetto, R. Garello, G. Montorsi, C. Berrou, C. Douillard, D. Giancristofaro. A. Ginesi, L. Giugno and M.Luise, "MHOMS: High-speed ACM modem for satellite applications", IEEE Wireless Communications Magazine, Vol. 12, No.2, April 2005, pp. 66-77.

An example of a non-square QAM constellation, for use in deep space communications.

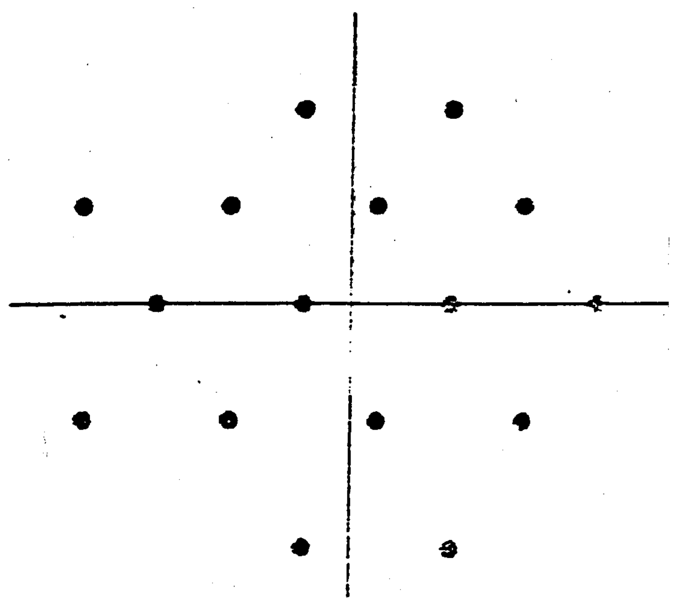


■ **Figure 1.** *Multi-ring APSK constellations: a) Euclidean distances; b) 16-point 4-12-APSK; c) 32-point 4-12-16-APSK; d) 64-point 4-12-20-28-APSK.*

OPTIMUM CONSTELLATION 16 QAM

About a .5 dB improvement over a Square- 16-QAM Constellation

G.J. Foschini, R. D. Gitlin, and S. B. Weinstein, "Optimization of two-dimensional signal constellations in the presence of gaussian noise", IEEE Trans. on Communications, Vol. 22, No. 1, January 1974, pp. 28-38.



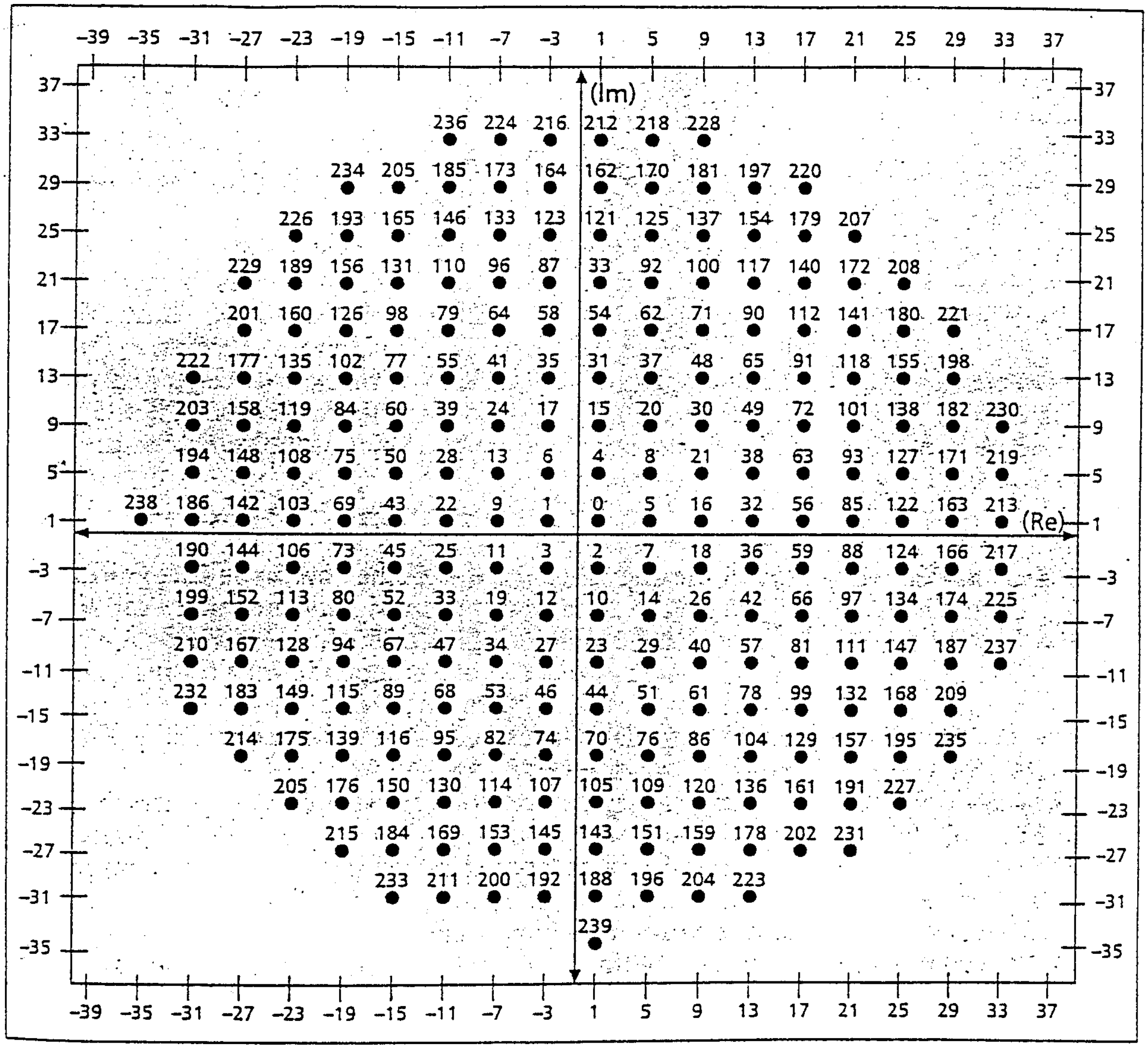
Notice the asymmetric constellation and the use of triangular spacing between points.

V.34 CONSTELLATIONS

*960 Points

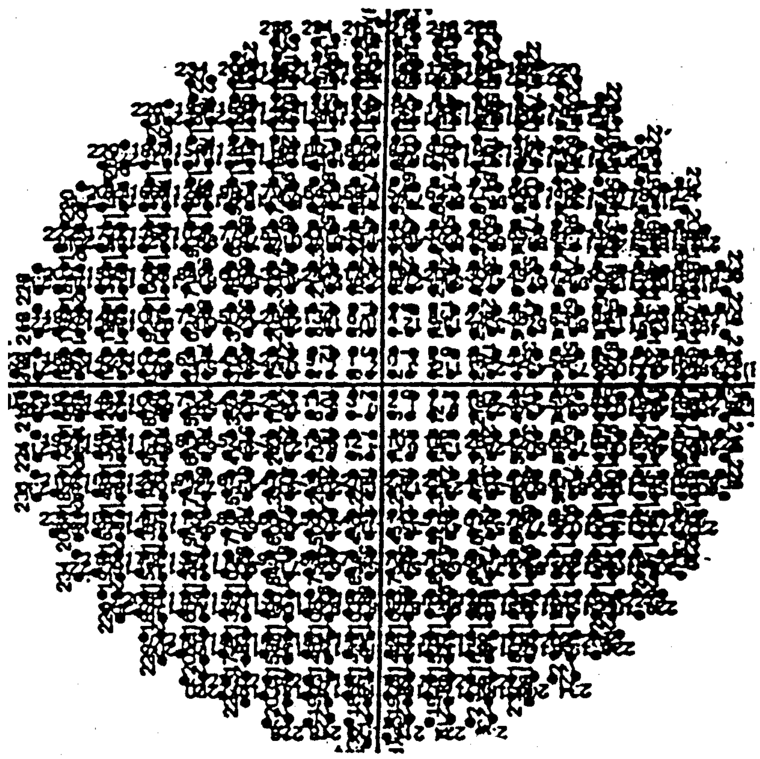
*1664 Points

This is one-quarter (240) of the total number of points, in the 960 point QAM constellation, used in the V.34 modem.



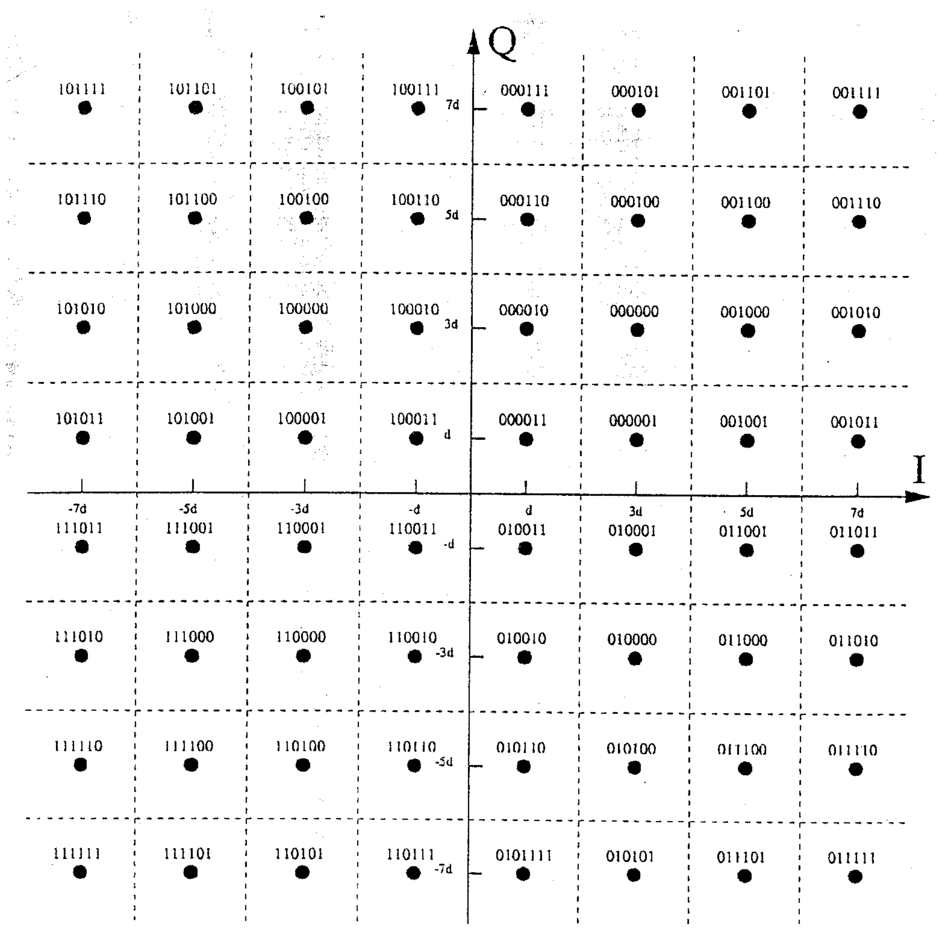
■ Figure 1. *V.34 quarter-superconstellation with 240 signal points. The full superconstellation is obtained by rotating these points by 0°, 90°, 180°, and 270°.*

THE FULL 960 POINT CONSTELLATION- OF THE V.34 MODEM



QAM CONSTELLATION (64-QAM)

GRAY CODING



ORTHOGONAL MFSK

$(f_i - f_j)\, T = n(1/2)$; n=1, 2,.....

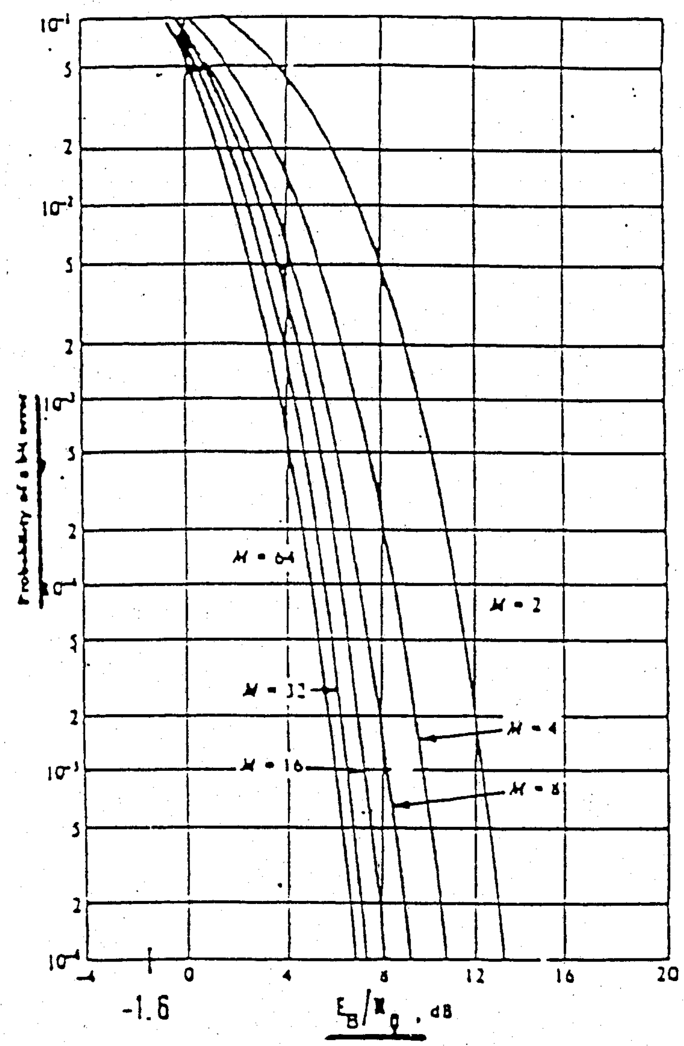


Figure 4.2.3 Probability of bit error for coherent detection of orthogonal signals.

PROBABILITY OF ERROR- M-ARY MODULATIONS

PAM

$$\Pr_s \varepsilon\} = 2[1 - (1/M)]\, Q\{d/\sqrt{2N_0}\}$$

where $E_s = [(M^2-1)/12]d^2$

and $E_s = nE_b = (\log_2 M)\, E_b$.

QAM

$$\Pr_s\{\varepsilon\} = 4[1 - (1/\sqrt{M})]\, Q\{d/\sqrt{2N_0}\} - 4[1 - (1/\sqrt{M})]^2\, Q^2\{d/\sqrt{2N_0}\}$$

where $E_s = [(M-1)/6]\, d^2$
and $E_s = nE_b$.

ORTHOGONAL MFSK

$$\Pr_s\{\varepsilon\} = 1 - \int_0^\infty (1/\sqrt{2\pi}) \exp\{-(y - \sqrt{2E_s/N_0})^2/2\}\, [1 - Q(y)]^{M-1}\, dy$$

MPSK

$$\Pr_s\{\varepsilon\} = 1 - \int_{-\pi/M}^{\pi/M} f(\theta)\, d\theta$$

$$f(\theta) = (1/2\pi) \exp\{-E_s/N_0 \sin^2\theta\} \int_0^\infty V \exp\{-(V - \sqrt{2E_s/N_0} \cos\theta)^2/2\}\, dV$$

SOME GOOD UPPER BOUNDS

MPSK

Simple upper (and lower) bounds

$$Q(d_{min} / \sqrt{2N_0}) \leq Pr\{\varepsilon\} \leq 2Q(d_{min} / \sqrt{2N_0})$$

$$d_{min}^2 = 2 \sqrt{E_s \sin^2 \pi/M}$$

$$E_s = E_b (\log_2 M) = nE_b$$

QAM

$$Pr_s\{\varepsilon\} \leq 4\, Q[d_{min}/\sqrt{2N_0}]$$

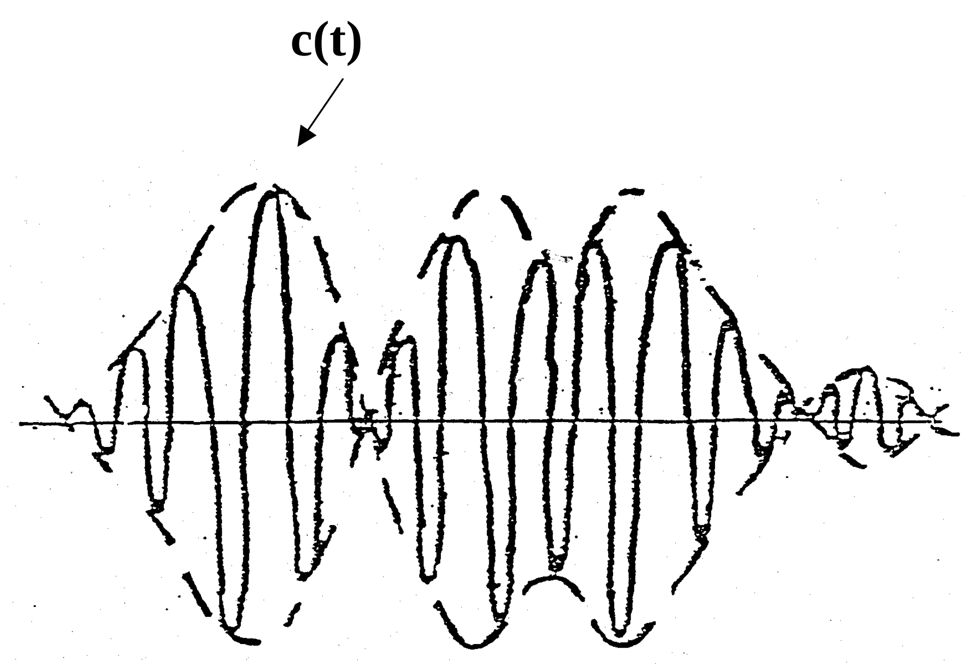
For Square- Constellations

$$d_{min}^2 = 6\, E_s / (2^n - 1)$$

ORTHOGONAL MFSK

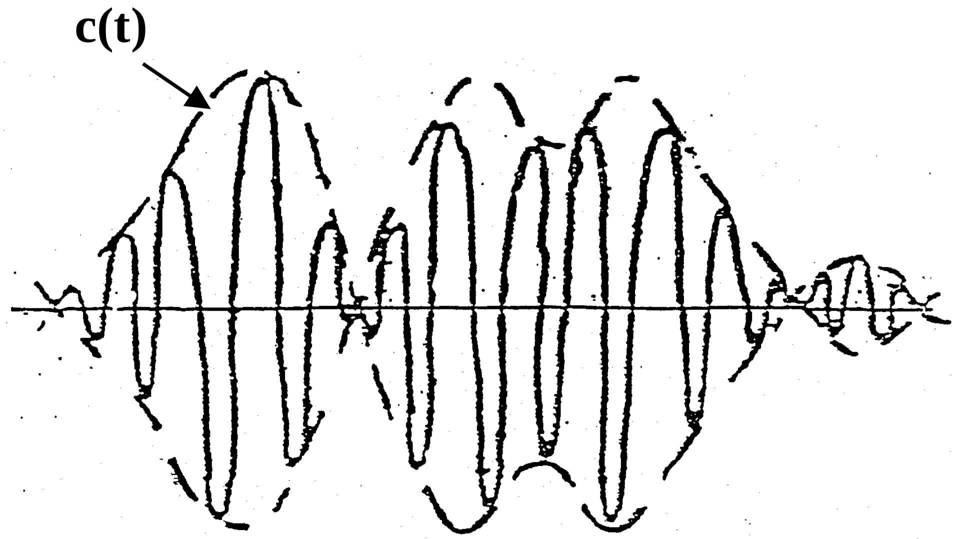
$$Pr_s\{\varepsilon\} \leq (M-1)\, Q[\sqrt{E_s / N_0}]$$

<u>BPSK</u>
-No longer Constant Envelope



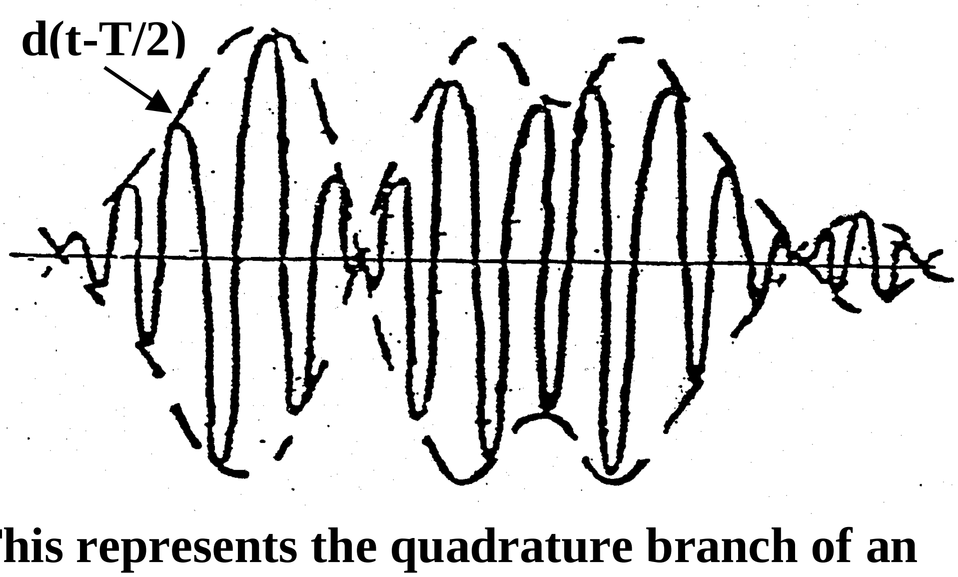
BPSK

-No longer Constant Envelope



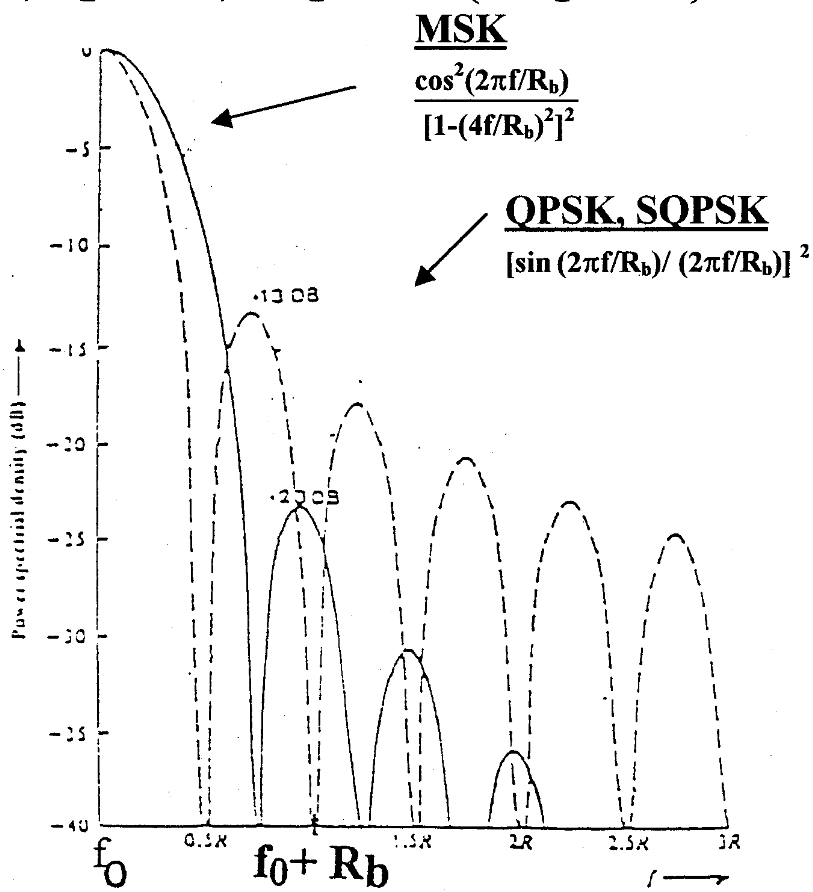
SQPSK

-Not Constant Envelope -BUT envelope never completely closes



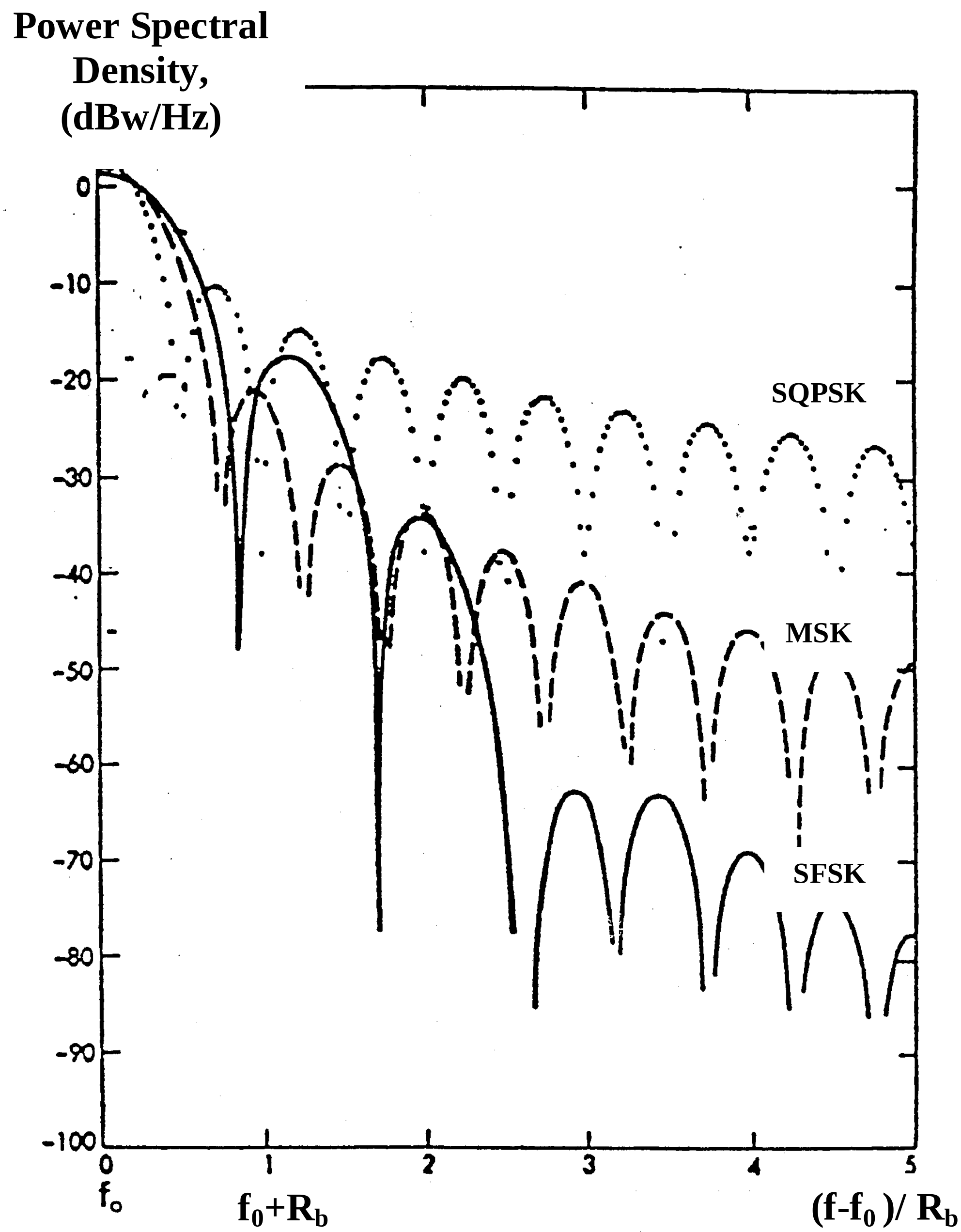
This represents the quadrature branch of an SQPSK transmitter.

POWER SPECTRAL DENSITY
MSK, QPSK, SQPSK (OQPSK)



	BPSK	QPSK SQPSK	MSK
$B_{90\%}$			
$B_{99\%}$			

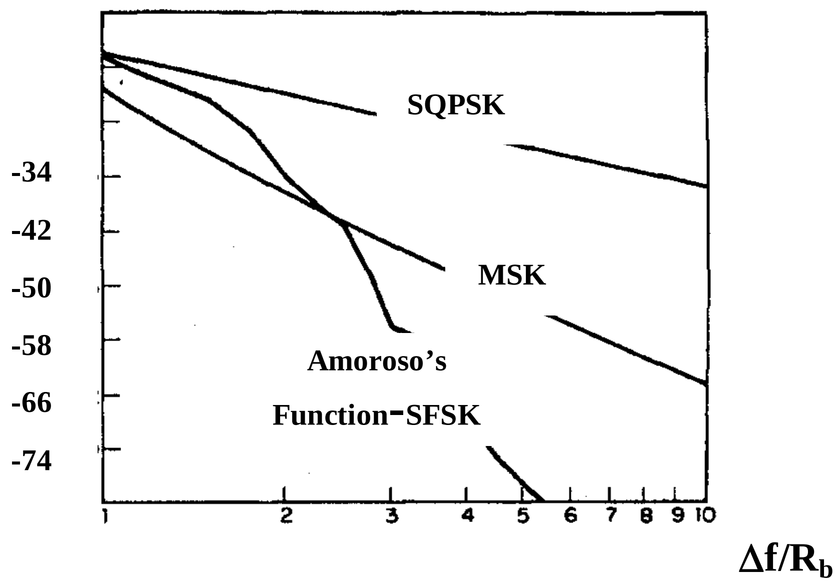
Power Spectral Densities
SQPSK, MSK, SFSK



MEAN-SQUARE CROSSTALK

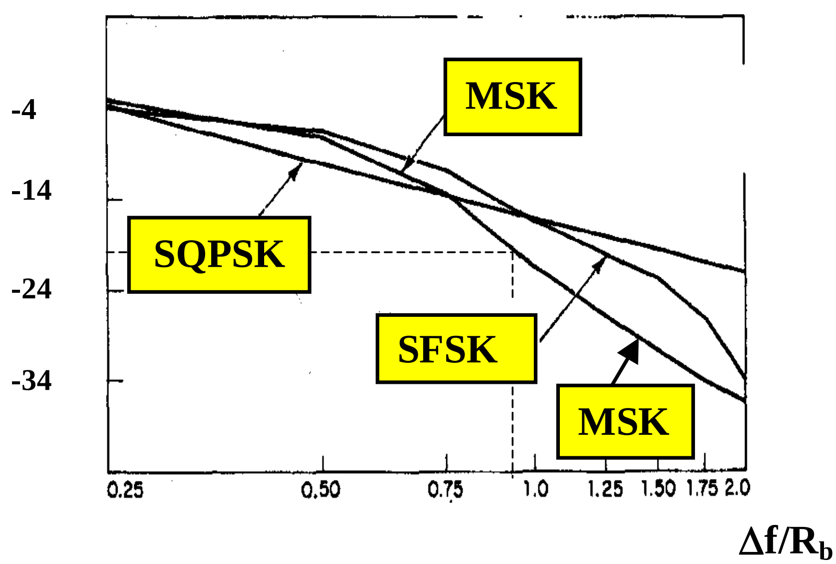
2 ACI Users

C/S, dB **(0dB) (30 dB)**



A=1(0 dB) means interfering user is at same power level as desired signal

C/S, dB



Claude Shannon, Mathematician, Dies at 84

By GEORGE JOHNSON

Dr. Claude Elwood Shannon, the American mathematician and computer scientist whose theories laid the groundwork for the electronic communications networks that now lace the earth, died on Saturday in Medford, Mass., after a long fight with Alzheimer's disease. He was 84.

Understanding, before almost anyone, the power that springs from encoding information in a simple language of 1's and 0's, Dr. Shannon as a young man wrote two papers that remain monuments in the fields of computer science and information theory.

"Shannon was the person who saw that the binary digit was the fundamental element in all of communication," said Dr. Robert G. Gallager, a professor of electrical engineering who worked with Dr. Shannon at the Massachusetts Institute of Technology. "That was really his discovery, and from it the whole communications revolution has sprung."

Dr. Shannon's later work on chess-playing machines and an electronic mouse that could run a maze helped create the field of artificial intelligence, the effort to make machines that think. And his ability to combine abstract thinking with a practical approach — he had a penchant for building machines — inspired a generation of computer scientists.

Dr. Marvin Minsky of M.I.T., who as a young theorist worked closely with Dr. Shannon, was struck by his enthusiasm and enterprise. "Whatever came up, he engaged it with joy, and he attacked it with some surprising resource — which might be some new kind of technical concept or a hammer and saw with some scraps of wood," Dr. Minsky said. "For him, the harder a problem might seem, the better the chance to find something new."

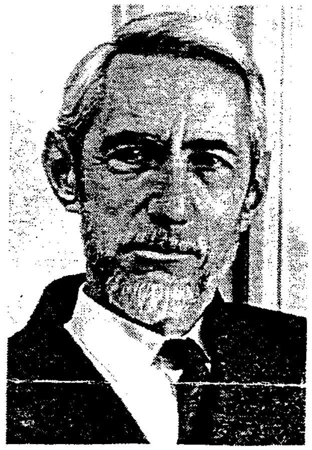
Born in Petoskey, Mich., on April 30, 1916, Claude Elwood Shannon got a bachelor's degree in mathematics and electrical engineering from the University of Michigan in 1936. He got both a master's degree in electrical engineering and his Ph.D. in mathematics from M.I.T. in 1940.

While at M.I.T., he worked with Dr. Vannevar Bush on one of the early calculating machines, the "differential analyzer," which used a precisely honed system of shafts, gears, wheels and disks to solve equations in calculus.

Though analog computers like this turned out to be little more than footnotes in the history of the computer, Dr. Shannon quickly made his mark with digital electronics, a considerably more influential idea.

In what has been described as one of the most important master's theses ever written, he showed how Boolean logic, in which problems can be solved by manipulating just two symbols, 1 and 0, could be carried out automatically with electrical switching circuits. The symbol 1 could be represented by a switch that was turned on; 0 would be a switch that was turned off.

The thesis, "A Symbolic Analysis of Relay and Switching Circuits,"



Dr. Claude E. Shannon in 1972.

was largely motivated by the telephone industry's need to find a mathematical language to describe the behavior of the increasingly complex switching circuits that were replacing human operators. But the implications of the paper were far more broad, laying out a basic idea on which all modern computers are built.

George Boole, the 19th-century British mathematician who invented the two-symbol logic, grandiosely called his system "The Laws of Thought." The idea was not lost on Dr. Shannon, who realized early on that, as he once put it, a computer is

A scientist who saw the potential of a series of 1's and 0's.

"a lot more than an adding machine." The binary digits could be used to represent words, sounds, images — perhaps even ideas.

The year after graduating from M.I.T., Dr. Shannon took a job at AT&T Bell Laboratories in New Jersey, where he became known for keeping to himself by day and riding his unicycle down the halls at night.

"Many of us brought our lunches to work and played mathematical blackboard games," said a former colleague, Dr. David Slepian. "Claude rarely came. He worked with his door closed, mostly. But if you went in, he would be very patient and help you along. He could grasp a problem in zero time. He really was quite a genius. He's the only person I know whom I'd apply that word to."

In 1948, Dr. Shannon published his masterpiece, "A Mathematical Theory of Communication," giving birth to the science called information theory. The motivation again was practical: how to transmit messages while keeping them from becoming garbled by noise.

To analyze this problem properly, he realized, he had to come up with a precise definition of information, a dauntingly slippery concept. The information content of a message, he proposed, has nothing to do with its content but simply with the number of 1's and 0's that it takes to transmit it.

This was a jarring notion to a generation of engineers who were accustomed to thinking of communication in terms of sending electromagnetic waveforms down a wire. "Nobody had come close to this idea before," Dr. Gallager said. "This was not something somebody else would have done for a very long time."

The overarching lesson was that the nature of the message did not matter — it could be numbers, words, music, video. Ultimately it was all just 1's and 0's.

Today, when gigabytes of movie trailers, Napster files and e-mail messages course through the same wires as telephone calls, the idea seems almost elemental. But it has its roots in Dr. Shannon's paper, which may contain the first published occurrence of the word "bit."

Dr. Shannon also showed that if enough extra bits were added to a message, to help correct for errors, it could tunnel through the noisiest channel, arriving unscathed at the end. This insight has been developed over the decades into sophisticated error-correction codes that ensure the integrity of the data on which society interacts.

In later years, his ideas spread beyond the fields of communications engineering and computer science, taking root in cryptography, the mathematics of probability and even investment theory. In biology, it has become second nature to think of DNA replication and hormonal signaling in terms of information.

And more than one English graduate student has written papers trying to apply information theory to literature — the kind of phenomenon that later caused Dr. Shannon to complain of what he called a "bandwagon effect."

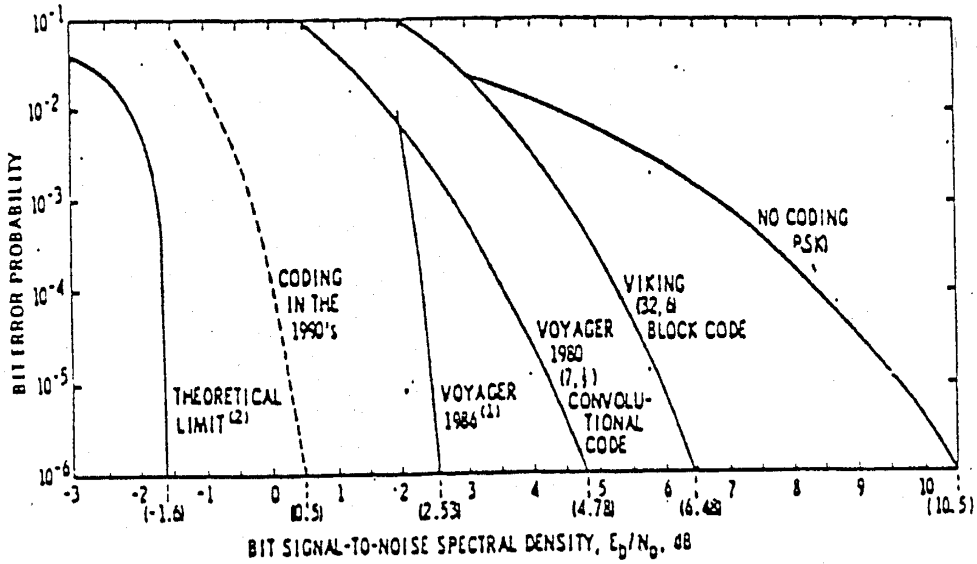
"Information theory has perhaps ballooned to an importance beyond its actual accomplishments," he lamented.

After he moved to M.I.T. in 1958, and beyond his retirement two decades later, he pursued a diversity of interests — a mathematical theory of juggling, an analog computer programmed to beat roulette, a system for playing the stock market using probability theory.

He is survived by his wife, Mary Elizabeth Moore Shannon; a son, Andrew Moore Shannon; a daughter, Margarita Shannon; a sister, Catherine S. Kay; and two granddaughters.

In the last years of his life, Alzheimer's disease began to set in. "Something inside him was getting lost," Dr. Minsky said. "Yet none of us miss him the way you'd expect — for the image of that great stream of ideas still persists in everyone his mind ever touched."

CODING RESULTS



(1) (7, ½) CONVOLUTIONAL CODE (VITERBI DECODING) CONCOTENATED WITH A REED-SOLOMON (255, 223) OUTER CODE

(2) INFINITE BANDWIDTH EXPANSION

Fig. 8. The progress of coded telemetry.

Voyager

1977-Launch
1986-Uranus-29.9 Kbps
1989-Neptune-21.6 Kbps

$$\Pr\{\varepsilon\}=10^{-6},\ E_b/N_0 \approx 2.5\text{-}3.0 \text{ dB}$$

E.C. Posner, " Deep Space Communications-Past, Present and Future", IEEE Communications Magazine, Vol. 22, No. 5,-May 1984, pp.8-21

The Most Beautiful Woman in The World

Yediot Aharonot-Israel
21 January 2000

מותה של „האישה היפה בעולם"

הדי לאמר, כוכבת הקולנוע של שנות ה־30 וה־40, מתה שלשום בגיל 86

מאת **אמיר קמינר**, כתב „ידיעות אחרונות"

כוכבת הקולנוע הדי לאמר, שזכתה לתואר „האישה היפה ביותר בעולם", מתה שלשום בביתה שבפלורידה בגיל 86. גופתה נמצאה על־ידי חברים שבאו לבקרה.

לדברי השריף המקומי, מתה לאמר מוות טבעי, כנראה בשנתה. פרקליטה של הכוכבת מסר כי היא לא סבלה ממחלות כלשהן והיתה צלולה עד רגעיה האחרונים.

לאמר הזוהרת, בעלת היופי האקזוטי האפל, כיכבה בסרטים רבים בשנות ה־30 וה־40, ובהם „אלג'יר" ו„נערת זיגפילד". במחד הרטיטה לבבות כשגילמה ב־1949 את דמותה של דלילה המפתה בסרט „שמשון ודלילה" של ססיל ב' דה־מיל.

הקריירה שלה היתה רצופה בסקנדלים. היא חוללה סערה גדולה כששחתה בעירום ורצה מעורטלת בסרט „אקסטזה", והיתה בכך לאחת הנשים הראשונות שהעזו להופיע בעירום בקולנוע. בעלה הראשון, פריץ מנדל, טייקון התחמושת האוסטרי שתמך בנאצים, ניסה בהמשך לרכוש את כל עותקי הסרט, אך ללא הצלחה.

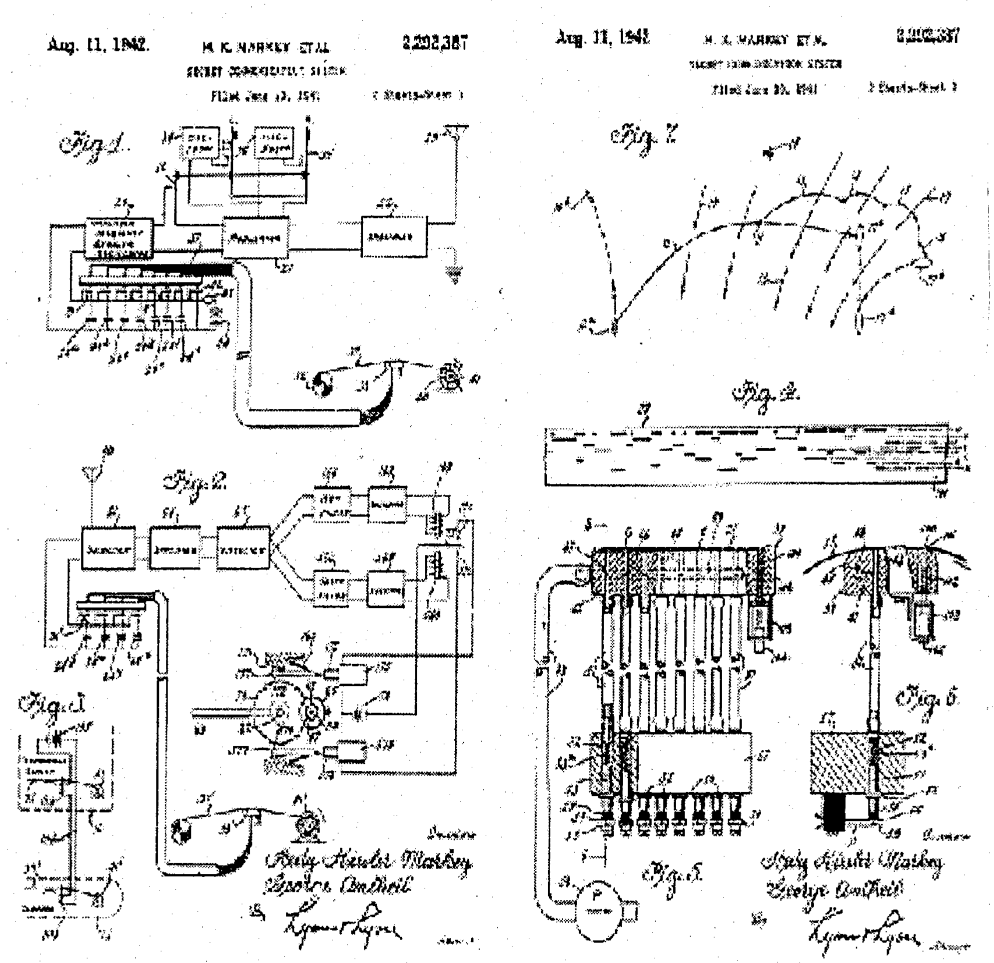
בעקבות השערורייה הגיעה לאמר להוליווד, שם המשיכה להשתתף בסרטים עד שלהי שנות ה־50. הטעות הגדולה ביותר שלה היתה כשסירבה לככב בסרט הנודע „קזבלנקה" ב־1943. לא פעם טענה כי הקריירה שלה דעכה מאחר „שסירבתי לשכב עם המפיקים".

לאמר מעוררת שערורייה בהופעה בעירום

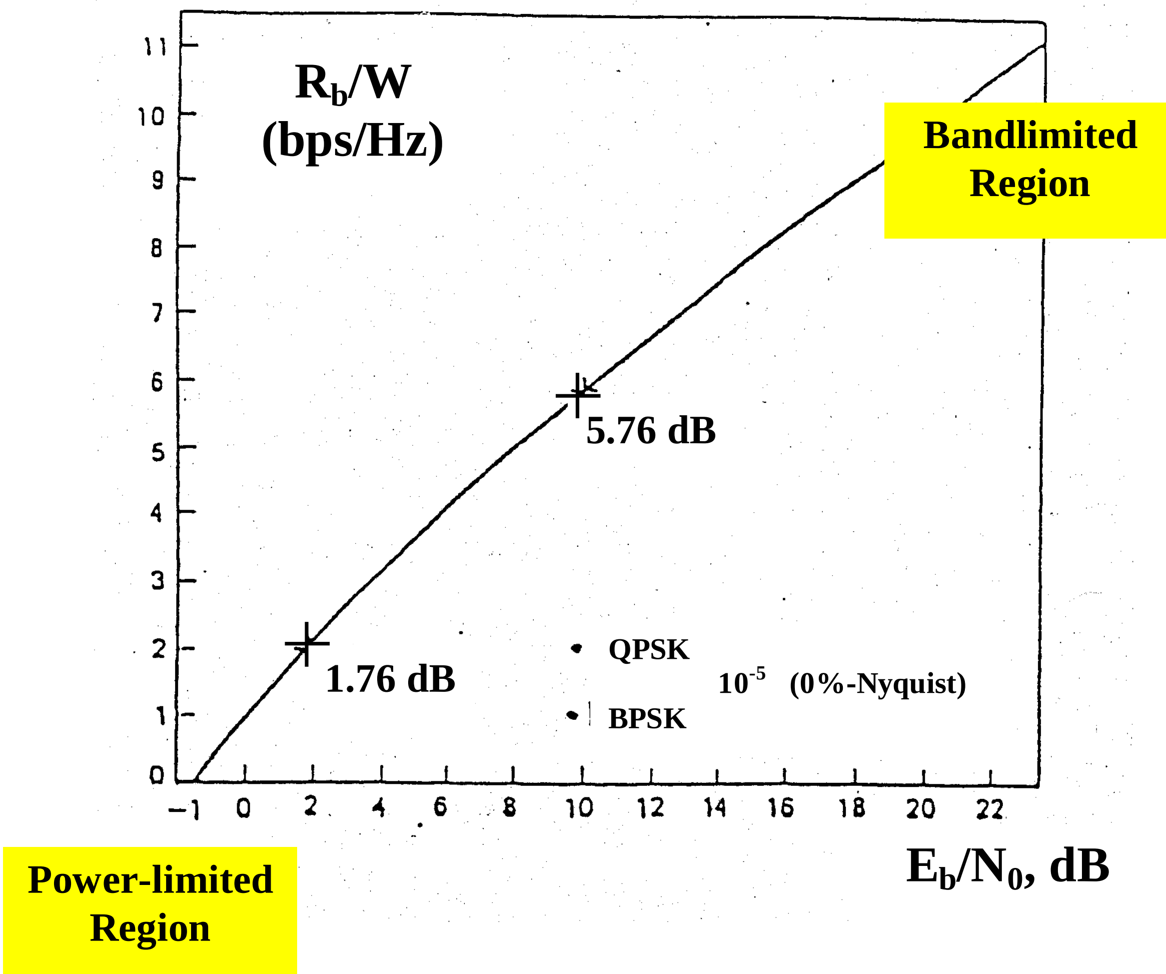
לאמר נולדה בווינה בשם הדוויג אווה מריה קיזלר. היא התחתנה והתגרשה שש פעמים, ילדה שני ילדים ואימצה ילד נוסף. היא נאסרה לא פעם בשל גניבה מחנויות והופיעה בבתי־משפט גם בתביעות שהגישה נגד סופר הצללים שלה, בטענה שעיוות את סיפוריה, ונגד חברת המחשבים ויקב קליפורני, בטענה שהשתמשו בתמונתה ללא רשות. הכוכבת הזוהרת התפרסמה גם כממציאה פורה, ולא מעט פטנטים בתעשייה, במחשבים ובתקשורת נרשמו על שמה.

לאמר כדלילה המפתה בסרט „שמשון ודלילה". (צילום: רויטרס)

HAND–DRAWN FIGURES FROM THE ORIGINAL HEDY LAMARR-GEORGE ANTHEIL PATENT



CAPACITY



R_b/W as a function of E_b/N_0, dB

IEEE 802.11a-1999

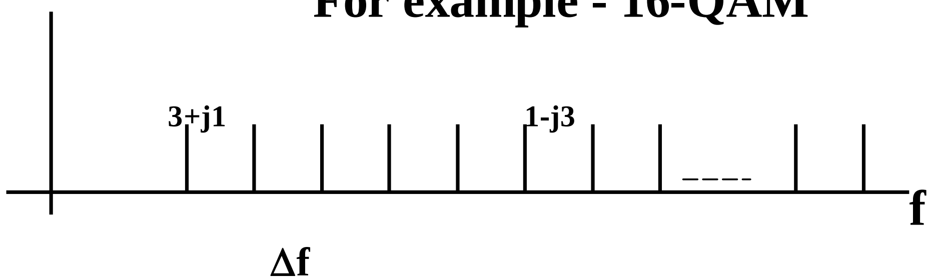
OFDM STANDARD

Part 11:Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHZ Band

Operating Bands	Maximum Power
5.15 GHz-5.25 GHz	40 mw
5.25 GHz-5.35 GHz	200 mw
5.725 GHz-5.875 GHz	800 mw

IEEE 802.11a
Frequency Domain

For example - 16-QAM



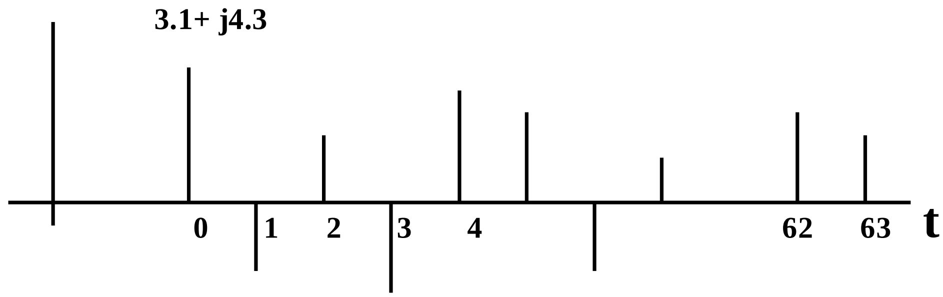
- **Channel spacing (Δf)=.3125 MHz**
  - **Spacing between two outermost frequecies =.3125 MHz x 52=<u>16.25 MHz</u>**

  - **64 frequencies (only 52 are used)**
    - **48 frequencies for data**
    - **4 frequencies for pilot tones**
    - **Modulations-BPSK, QPSK, 16-QAM or 64-QAM**
    - **<u>1 to 6 bits/symbol</u>**

    - **<u>6 to 54 information Mbps</u>**

Time Domain

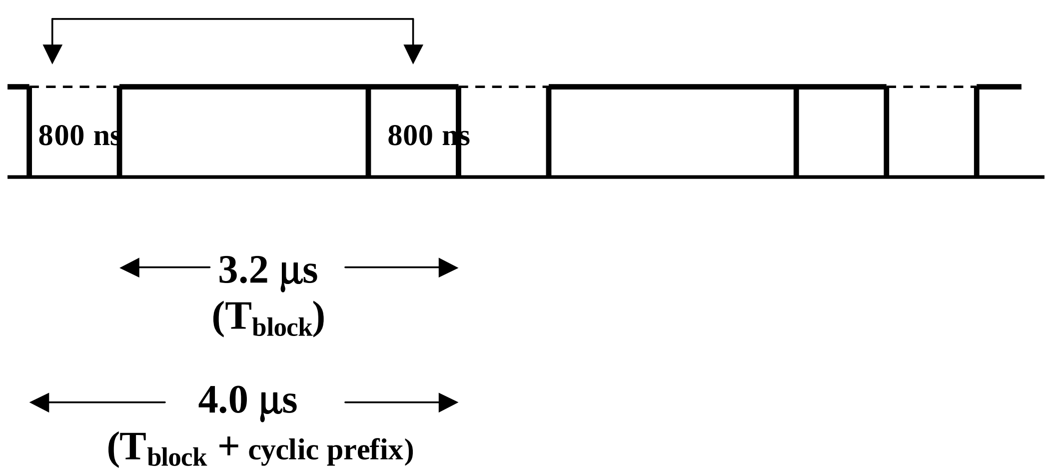
There are 64 complex samples in the time domain



- T_{block} = 1/Δf =1/.3125 MHz=3.2 μs
- T_{sample}= 3.2 μs/ 64= .05 μs
- $f_{sampling}$=1/T_{sample}=1/.05 μs =20 Mhz

Cyclic Prefix= 800 ns

Cyclic prefix (16 samples)



- **R_{block}=1/ 4.0 μs= 250 kblocks/sec**

IEEE 802.11a

($T_{\text{OFDM Block}}$= 4μs)

Info Data Rate (Mbps)	Modulation	Coding Rate	Coded bits per subcarrier	Total Bits per OFDM symbol	Total Info Bits per OFDM Symbol
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	64	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

Information data rate = 36 Mbps

- **16-QAM ⇒ 4 bits/frequency bin**
- **48 bins x 4 bits/symbol=192 bits/OFDM Symbol**
- **Rate ¾ code ⇒**
  Total Number of info bits/ OFDM Symbol=
  3/4 x192=144 info bits /OFDM Symbol

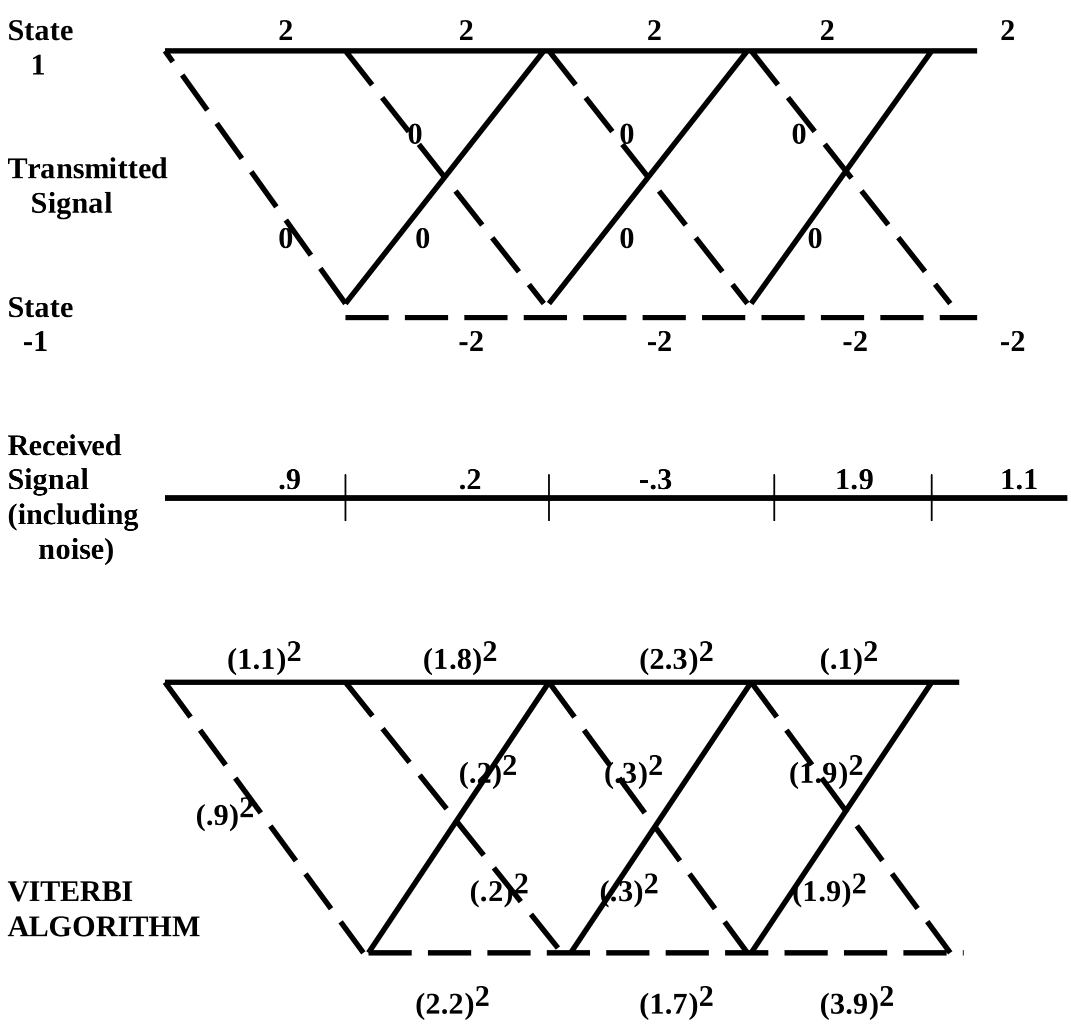
- **Total info bit rate**
  144 info bits/OFDM Symbol x 250 Ksymbols/sec
  = 36 Mbps

VITERBI ALGORITHM

Computation of d_{min}^{2} for Duobinary Signal

$a_n = +1$ ____

$a_n = -1$ _ _ _



Capacity for Rayleigh Fading Channels
(One antenna at transmitter and receiver-SISO)

A. J. Goldsmith and P. P. Varaiya, " Capacity of fading channels with channel side information", IEEE Transactions on Information Theory, November 1997, pp. 1986-1992.

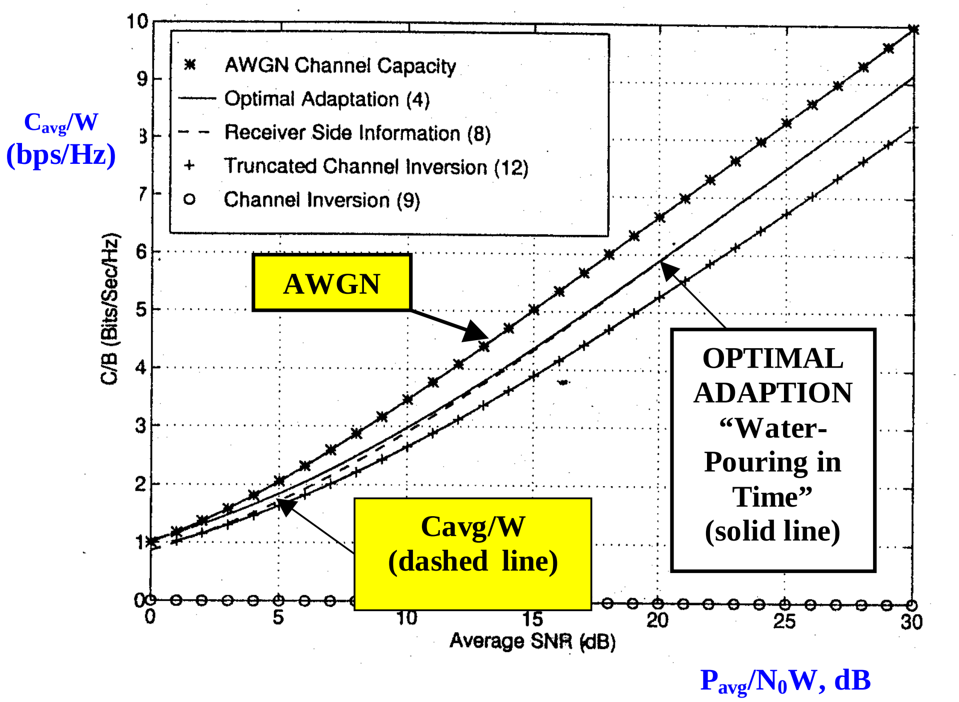


Fig. 4 Capacity in Rayleigh fading (m=1)

$$P_{avg}=\int_0^\infty r^2 P\, f(r)\, dr$$

$$C = W \log_2 [1 + (r^2 P/N_0 W)] \quad \text{bps}$$

$$C_{avg} = \int_0^\infty W \log_2 [1 + (r^2 P/N_0 W)]\, f(r)\, dr \quad \text{bps}$$

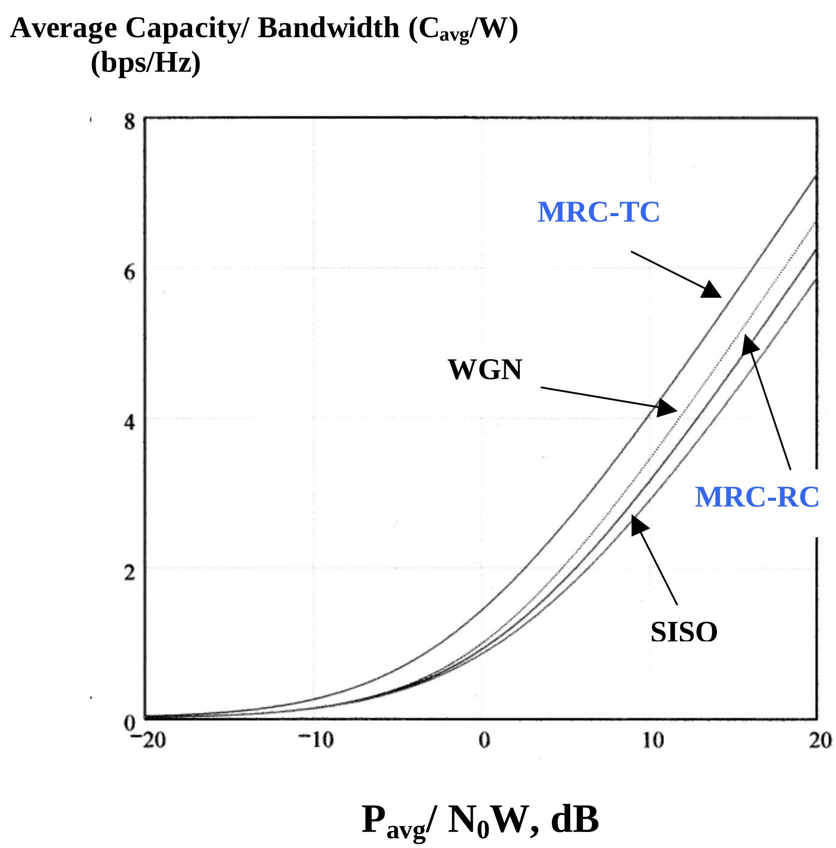
$$f(r) = (r/\sigma^2) \exp\{- r^2/2\sigma^2\}; \quad r \geq 0.$$

The variable "r" represents the Rayleigh fading variable at the receiver. The expression r^2P is the received power for a given value of "r".
$P_{avg} = 2\sigma^2 P$, is the average received power. If $2\sigma^2$ equals one then $P_{avg} = P$.

Capacity of Fading Channels and Diversity Schemes

- Classic WGN Channel (WGN)
- SISO Channel (SISO)
- MRC (Dual Antenna Diversity) –Total Received Power is Constant (CMRC-RC)
- MRC (Dual Antenna Diversity) –Transmit Power is Constant (MRC-TC)

(The difference between the two MRC curves is 3 dB)



Recent Results on the Capacity of Wideband Channels in the Low-Power Regime-SISO

S. Verdu, "Recent results on the capacity of wideband channels in the low-power regime", IEEE Wireless Communications, Vol. 9, No. 4, August 2002 pp.40-45.

<u>Spectral Efficiency of Rayleigh Fading Channels</u>

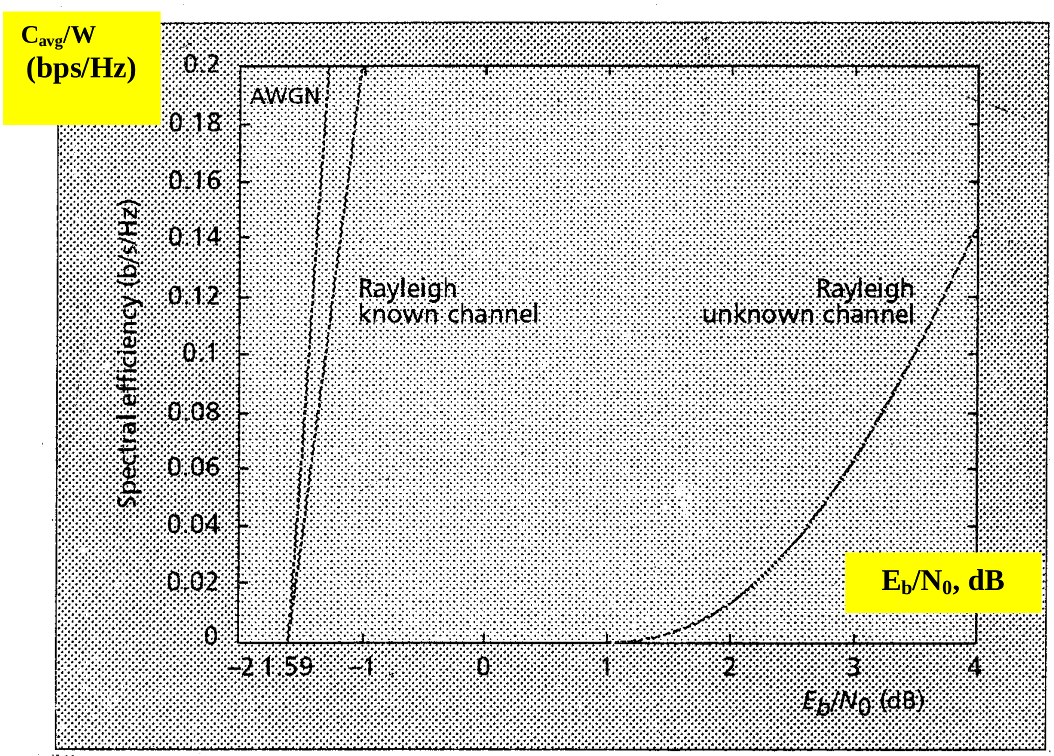


Figure 1. *Spectral efficiency of the AWGN channel and the Rayleigh flat fading channel with and without receiver knowledge of fading coefficients.*

Notice that the spectral efficiencies, which are being discussed, are very low.