

COLUMBIA UNIVERSITY
SPRING SEMESTER-2008

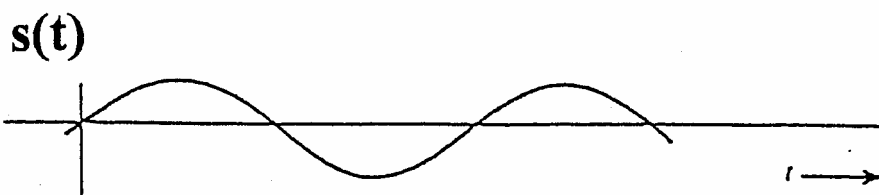
ELEN E3701
Introduction to Communication
Systems

FIGURES FOR THE COURSE

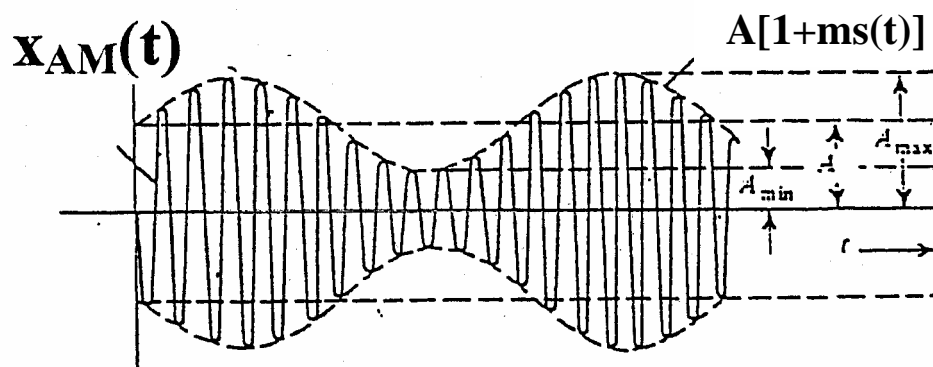
24 January 2008
Prof. I. Kalet

AMPLITUDE MODULATION

Not a Constant Envelope (or Amplitude) Modulation



(a) Sinusoidal Modulating Wave

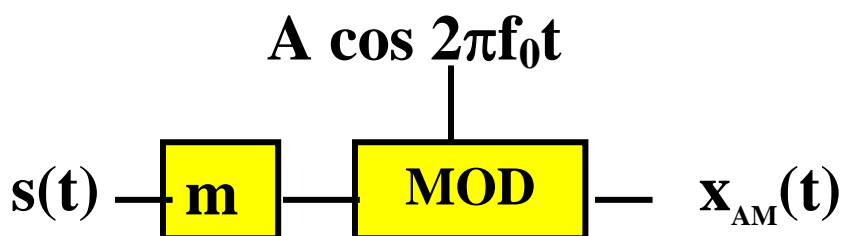


(b) Resulting AM Signal

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

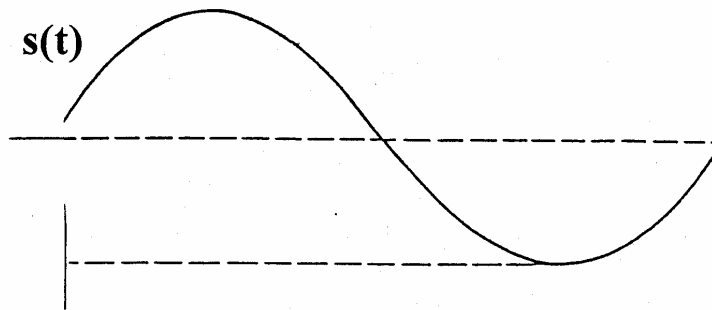
$$|s(t)|_{\max} = 1$$

$$0 \leq m \leq 1$$

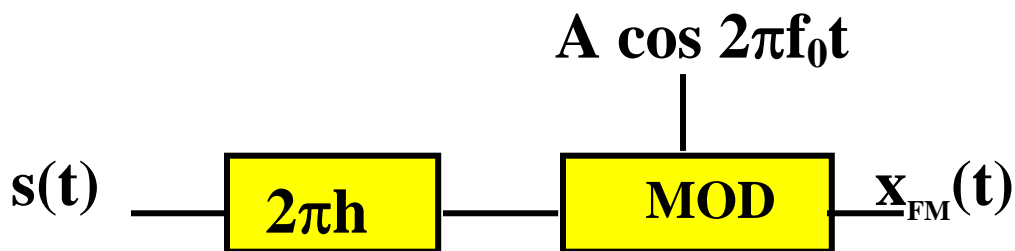
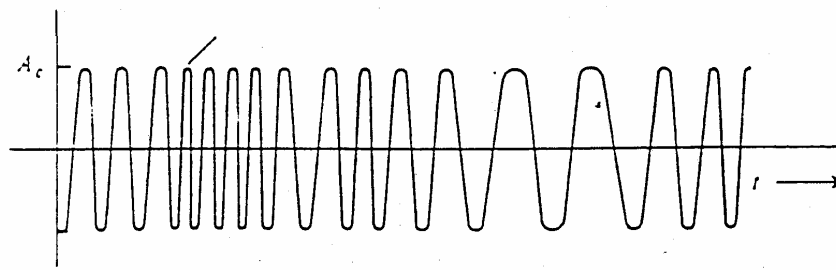


FREQUENCY MODULATION (Continuous Phase Modulation) Constant Envelope

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



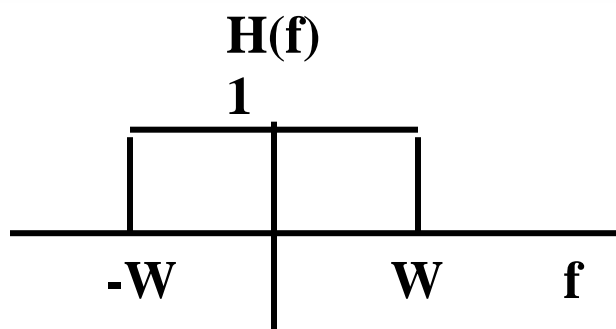
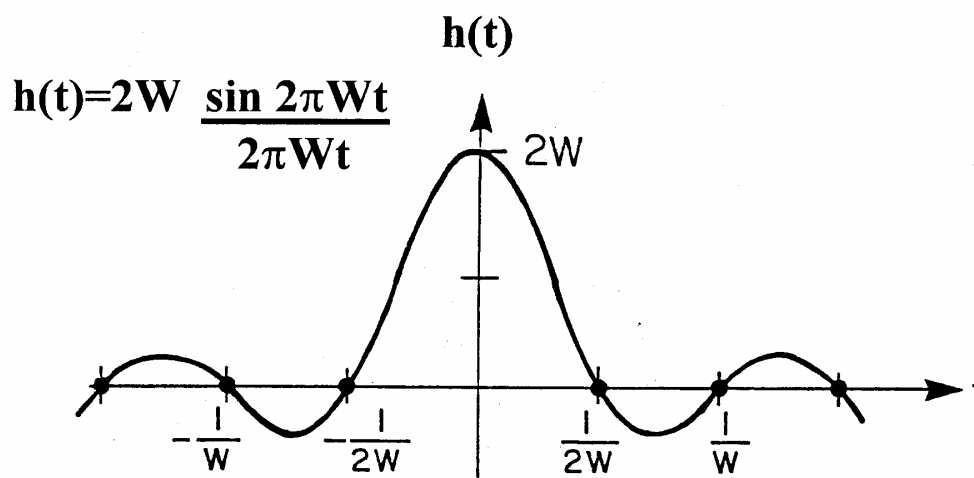
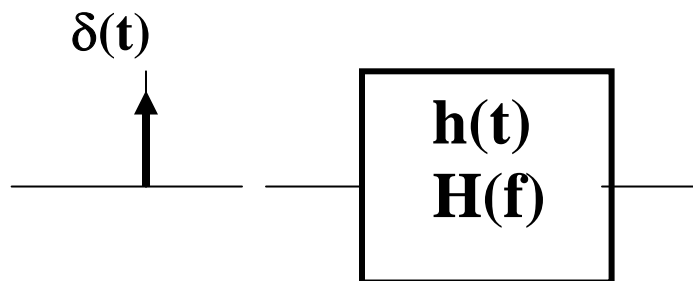
Transmitted FM Signal, $x_{FM}(t)$



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

NYQUIST I SIGNALS

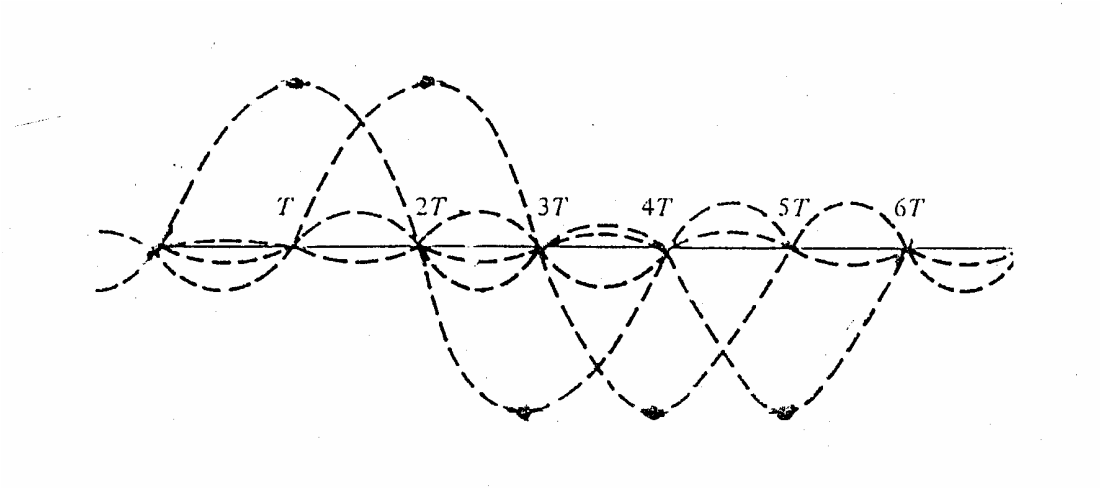
- The Sampling Pulse
- No Intersymbol Interference (ISI)



ENERGY=2W

SIGNALING WITH NYQUIST PULSE

- **Minimum Bandwidth**
($T=1/2W$ seconds)



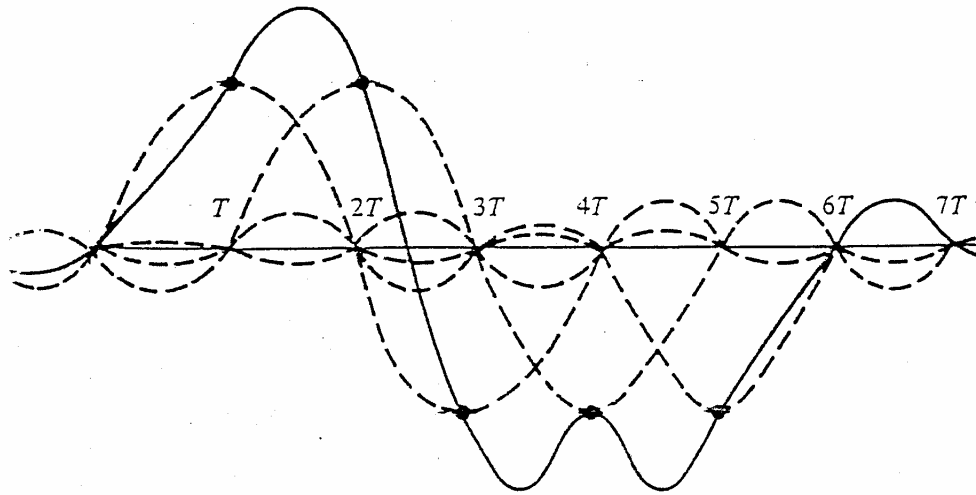
- If transmitted signal is sampled at the receiver at the correct times, there will be no intersymbol interference (ISI).

**We can transmit and receive
 $2W$ independent pulses (or values)/sec**

Each pulse may have any amplitude!

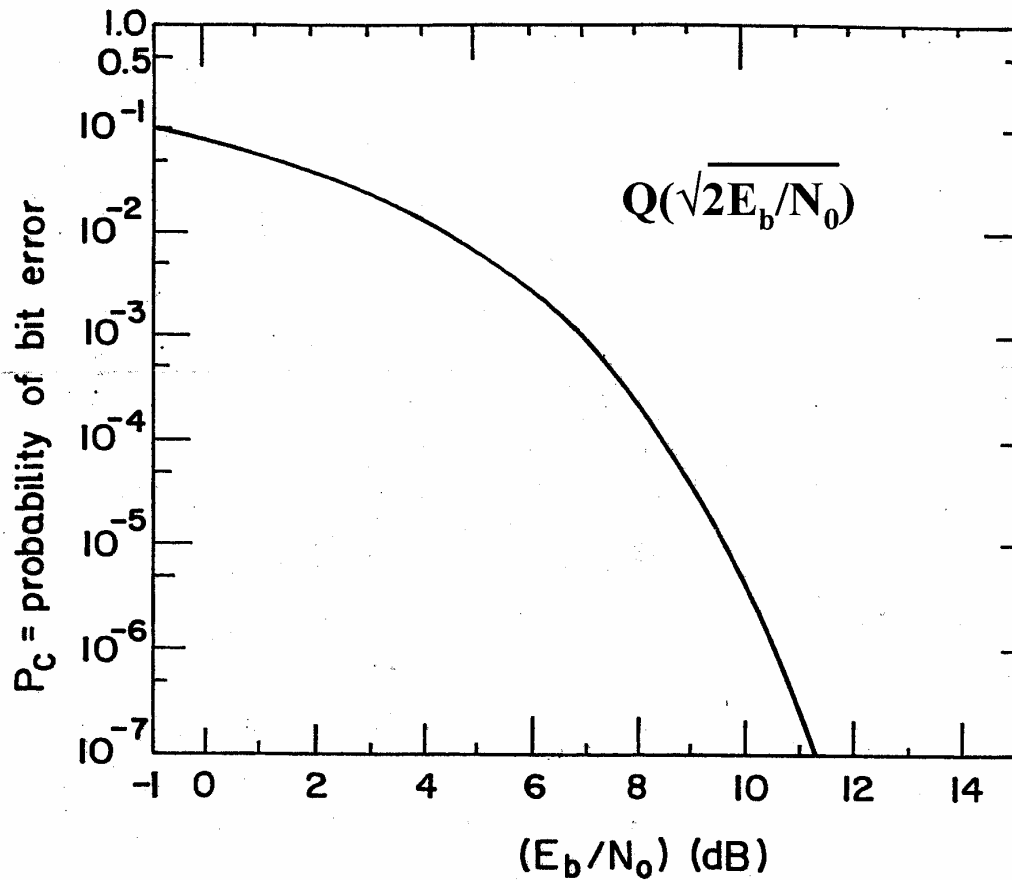
SIGNALING WITH NYQUIST PULSES

- **Minimum Bandwidth**



- **The actual transmitted signal is the sum of all the Nyquist signals.**
- **The overshoots, between the sampling times at $T, 2T, 3T, \dots$, theoretically may reach infinity!**

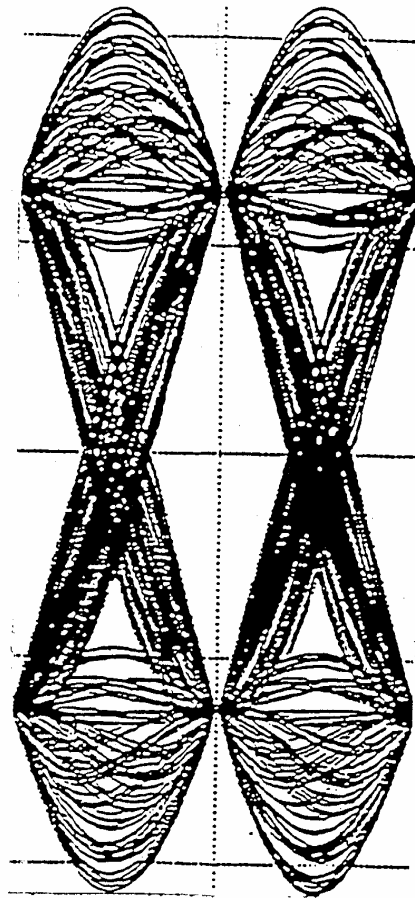
DETECTABILITY PERFORMANCE NYQUIST SIGNALS



The Probability of Error, $\Pr_b\{\varepsilon\}$, is

$$\Pr_b\{\varepsilon\} = Q(\sqrt{2E_b/N_0})$$

EYE PATTERN



EYE PATTERN

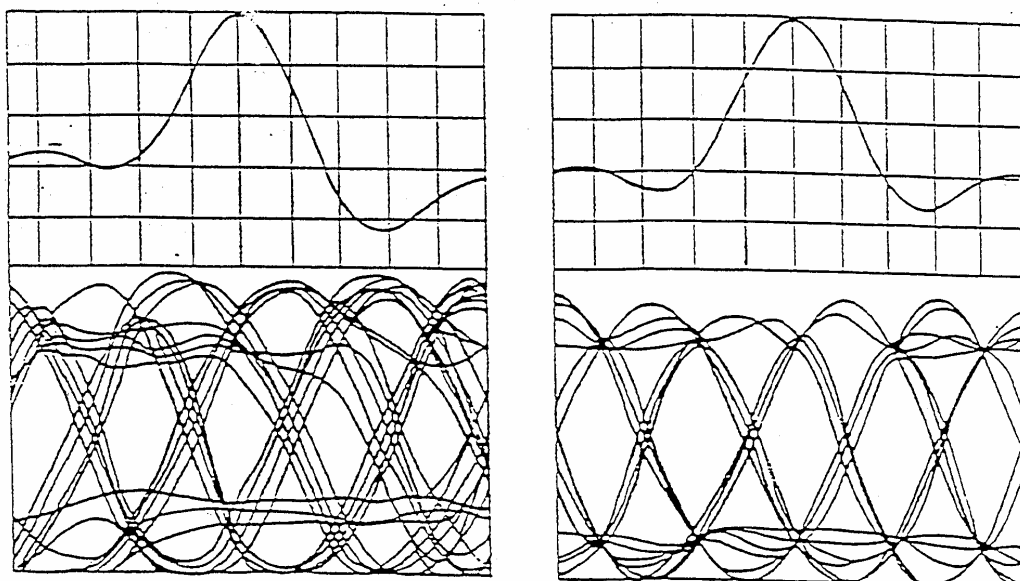


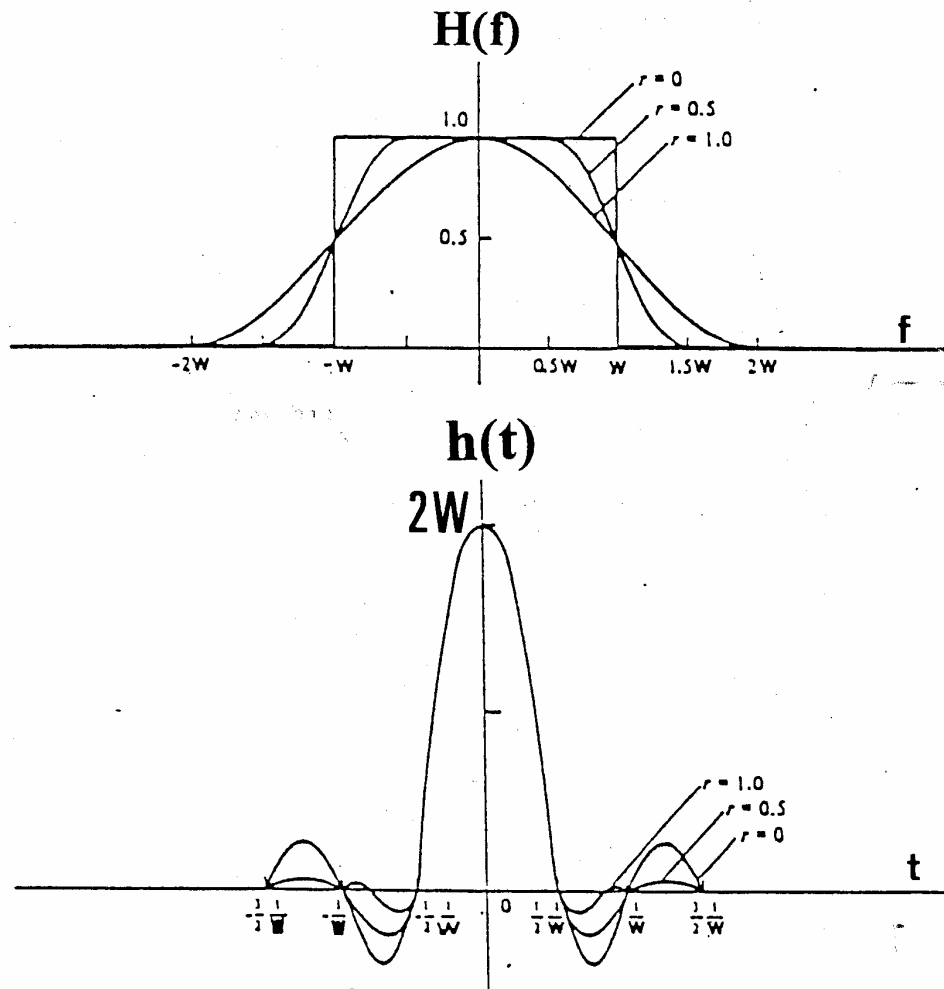
Fig. 3-17. Sketch of oscillograms of received eye pattern and after autoequalization. (From "Common Carrier Data Communication" by R.W. Lucky; Chapter 5 in *Computer-Communication Networks*, F.F. Kuo, Editor, Prentice Hall, 1973.)

"BAD"-CLOSED

"GOOD"- OPEN

NYQUIST I FILTERS

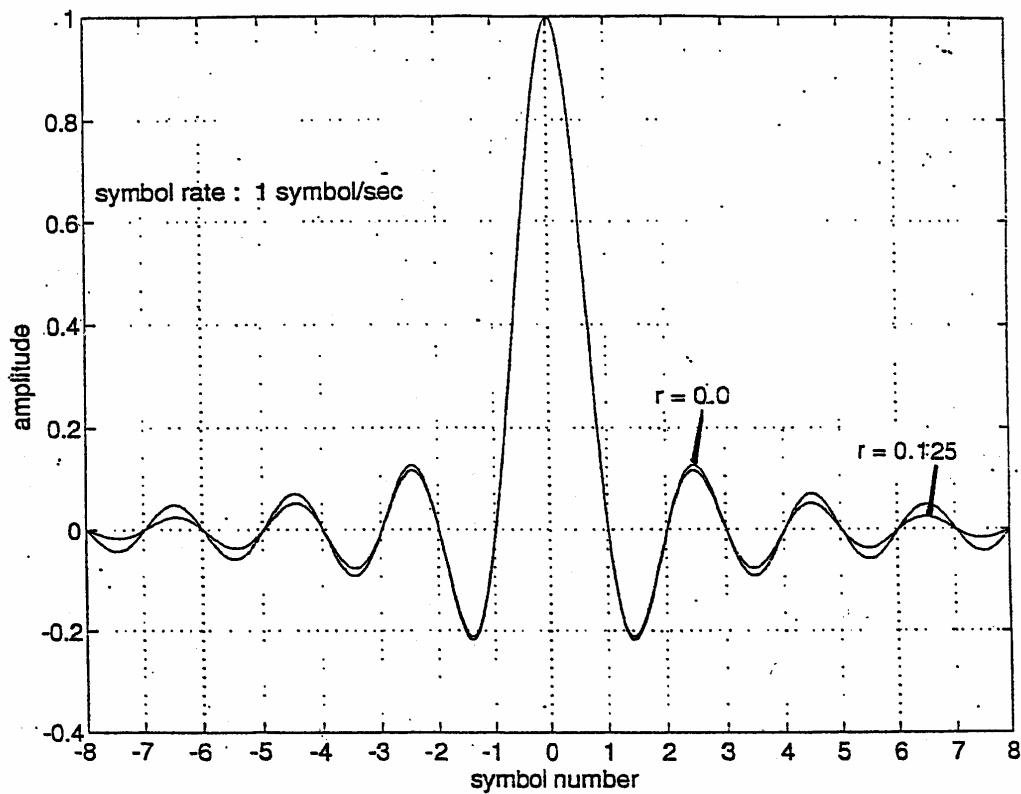
- **Raised Cosine Filter**
(r = rolloff factor, e.g., 50%)



$$h(t) = 2W \frac{\sin 2\pi Wt}{2\pi Wt} \frac{\cos 2\pi r Wt}{1 - 4r^2(2Wt)^2}$$

RAISED COSINE PULSES

Rolloff Factor = 0%, 12.5%

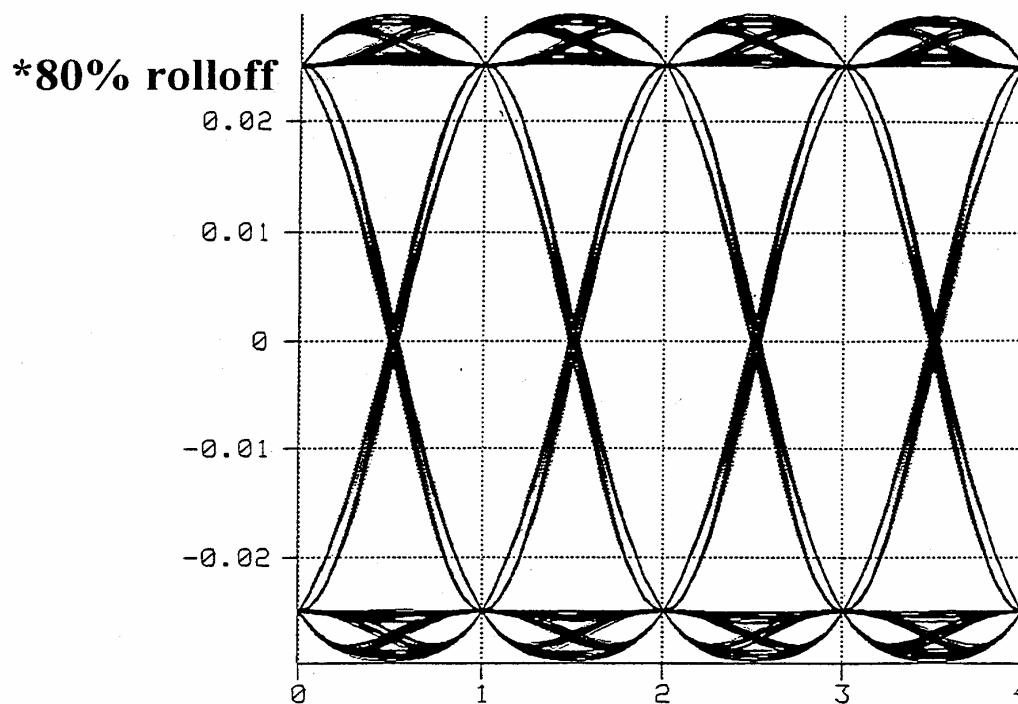


QAM SYSTEMS

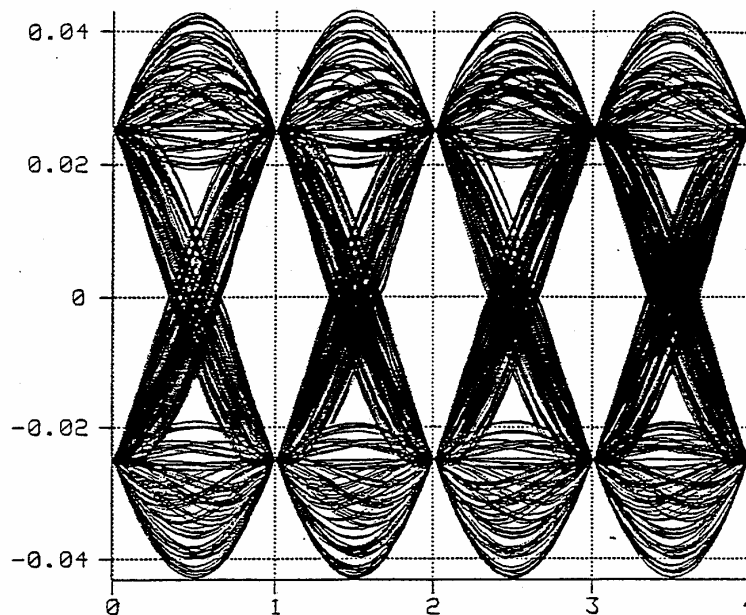
System	Rolloff Factor	<u>no.of bits</u> symbol	R_b (bps)
Modems (telephone)	12.5%	4,6	9.6 Kbps 14.4 Kbps
Intelsat	40%	2	120 Mbps
MSATX	100%	2	4.8 Kbps
IS-136(54)	35%	2	48.6 Kbps
VDSL	20%	≥ 6	≥ 1.5 Mbps
IS-95	$\approx 0\%$	2	1.2288 Mcps

WCDMA-IMT2000 (r=22%)

EYE PATTERN



***35% rolloff**



A “Better Than” Nyquist Pulse

N. C. Beaulieu, C. C. Tan and M. O. Damen, “A “ better than” Nyquist pulse”, IEEE Communications Letters, September 2001, Vol.5, No. 9, pp.367-368.

$$S(f) = \begin{cases} 1; & 0 \leq |f| \leq W(1-r) \\ e^{(\ln 2/W)[f-W(1-r)]}; & W(1-r) \leq |f| \leq W \\ 1 - e^{(\ln 2/W)[W(1+r)-f]}; & W \leq |f| \leq W(1+r) \\ 0; & W(1+r) \leq |f| \end{cases}$$

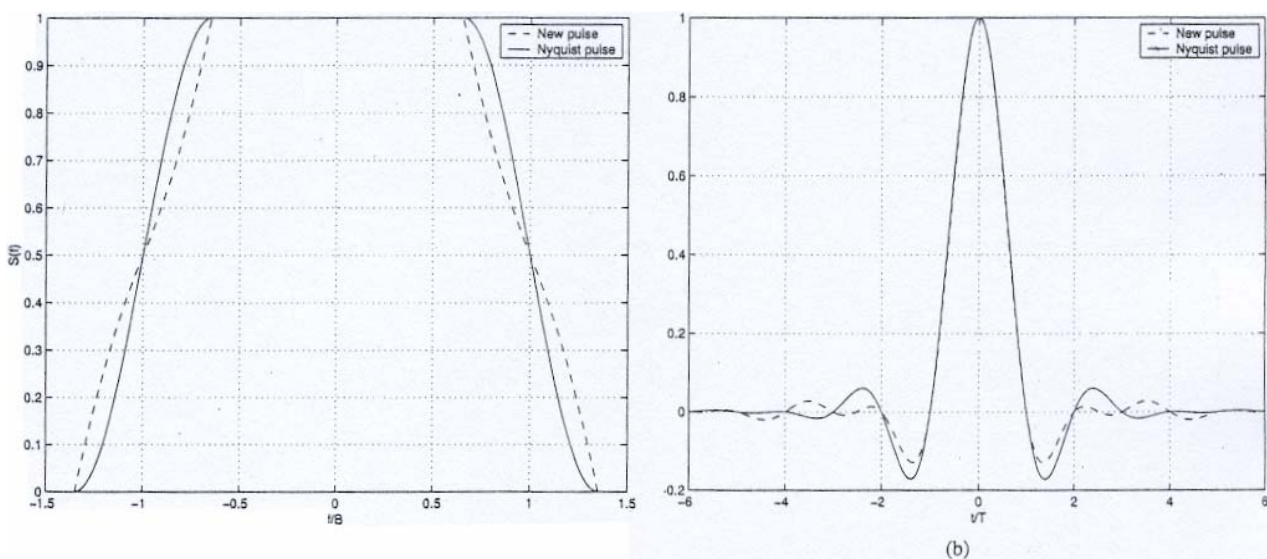


Fig. 1. Frequency and time characteristics of the new and Nyquist pulses for an excess bandwidth $\alpha = 0.35$. (a) Frequency domain. (b) Time domain.

A "Better Than" Nyquist Pulse

$$s(t) = \frac{2W \sin 2\pi Wt}{2\pi Wt} \bullet$$

$$\frac{4\beta\pi t \sin(2\pi rWt) + 2\beta^2 \cos(2\pi rWt) - \beta^2}{4\pi^2 t^2 + \beta^2}$$

where $\beta = \ln 2/rW$

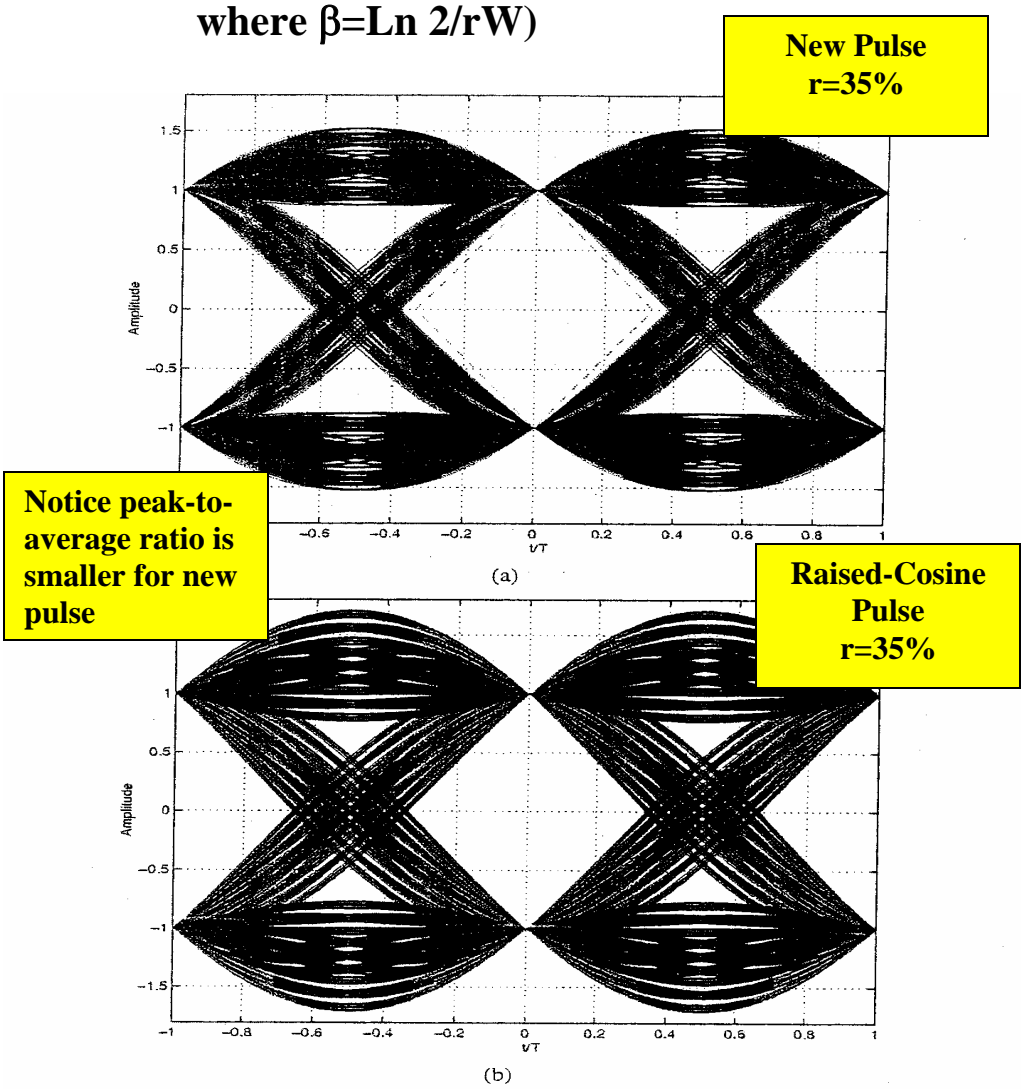


Fig. 2. Eye diagrams of pulses sequences for an excess bandwidth $\alpha = 0.35$. (a) New pulse. (b) Nyquist pulse. The dotted line in (a) is the inner boundary of the eye in (b).

Square-Root Raised Cosine Pulse, $g(t)$

$$g(t) = \frac{\sin[\pi(1-r)t'] + 4rt' \cos[\pi(1+r)t']}{\pi t' [1 - (4rt')^2]}$$

where $t' = t/T$ and $0 \leq r \leq 1$.

The spectrum $G(f)$, is

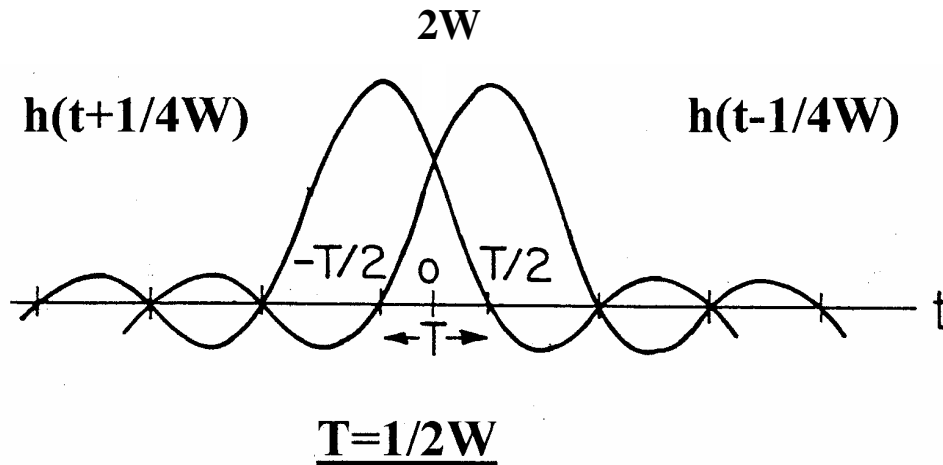
$$G(f) = \begin{cases} T, & 0 \leq |f| \leq (1-r)(1/2T) \\ T/2 \sqrt{1 - \sin [(\pi T/r) \{ |f| - (1/2T) \}]}, & \text{for } (1-r)(1/2T) \leq |f| \leq (1+r)(1/2T) \end{cases}$$

* $G(f)$ is the Square-Root Nyquist Spectrum,

i.e., $G(f) = \sqrt{H(f)}$

PARTIAL RESPONSE SIGNALS

Duobinary Signal

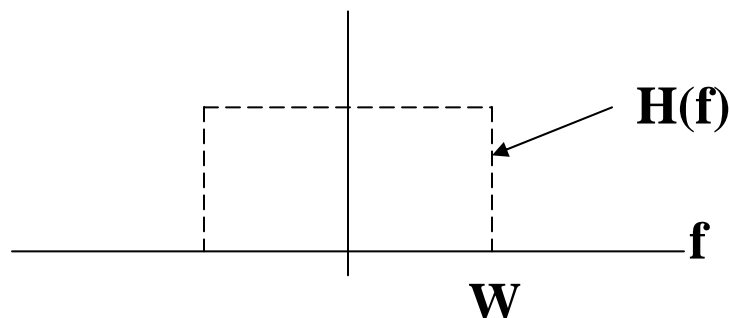


$$p(t) = h(t-1/4W) + h(t+1/4W)$$

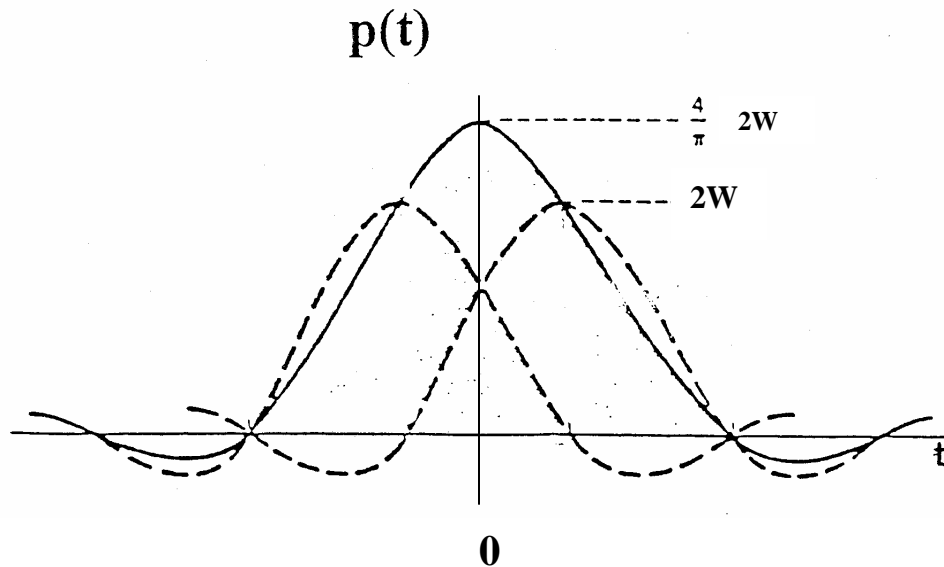
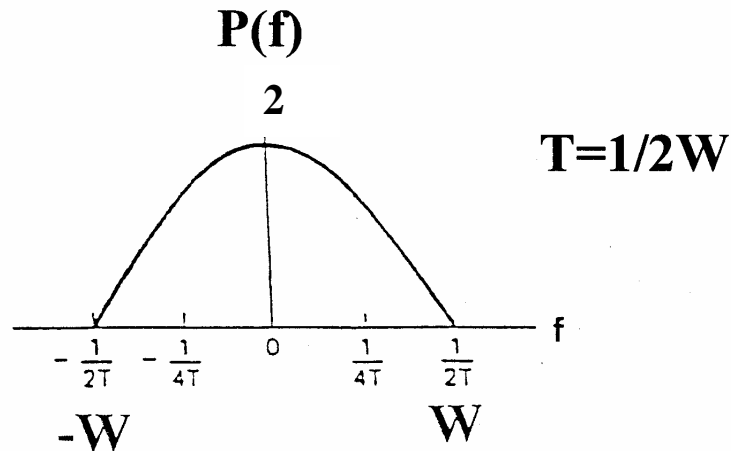
$$P(f) = H(f) e^{-j2\pi f/4W} + H(f) e^{j2\pi f/4W}$$

$$P(f) = 2 H(f) \cos 2\pi f/4W$$

• Introduces controlled ISI



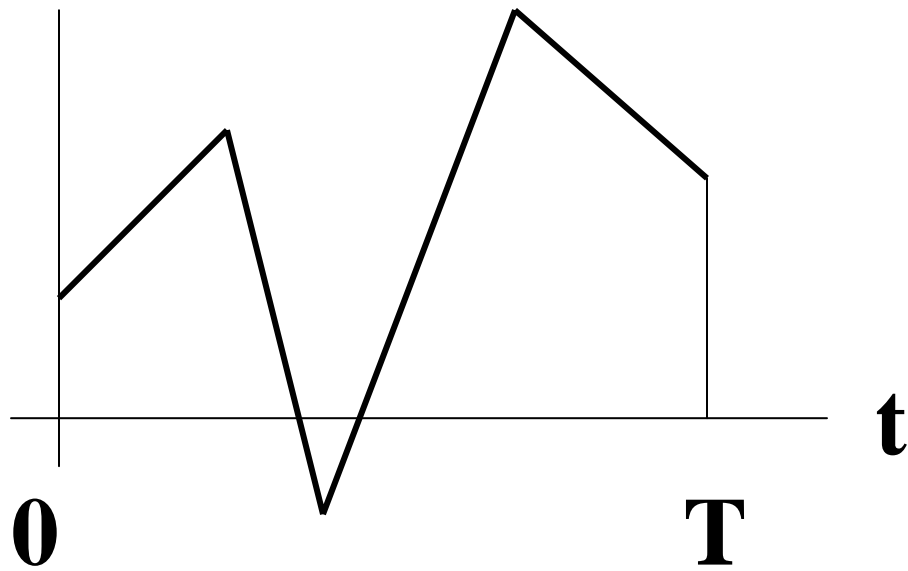
DUOBINARY SIGNAL



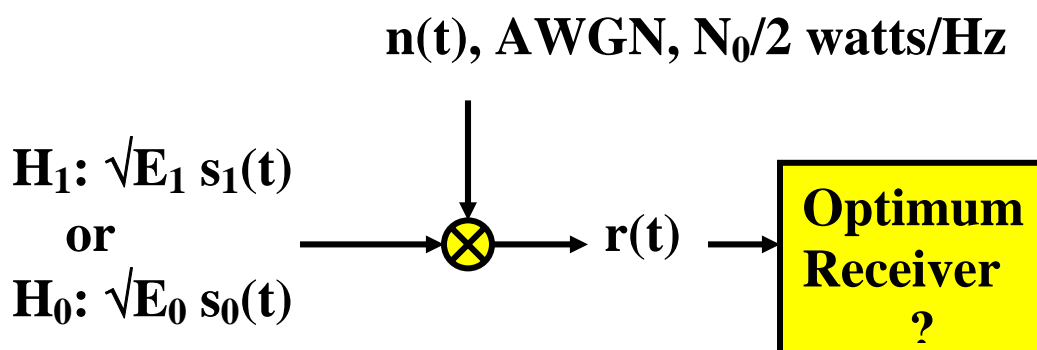
$$p(t) = \frac{4}{\pi} (2W) \frac{\cos 2\pi Wt}{1-(4Wt)^2}$$

- There is actually a 2.1 dB detectability loss

Perfectly Time-limited Signals



OPTIMUM DETECTION OF BINARY SIGNALS



$$\int_0^T s_1^2(t) dt = \int_0^T s_0^2(t) dt = 1$$

• THE OPTIMUM RECEIVER DECIDES WHETHER H_1 OR H_0 WAS SENT, WITH A MINIMUM PROBABILITY OF ERROR

- H_i stands for Hypothesis “i”
- We will assume that all hypotheses have equally a priori probabilities.

ADDITIVE WGN CHANNELS

- Probability of Error depends on "distance" between signals

$$\min \Pr\{\varepsilon\} = Q[d_{1,0} / \sqrt{2N_0}] = Q[\sqrt{d_{1,0}^2 / 2N_0}]$$

$$d^2 = \int_0^T (\mathbf{x}(t) - \mathbf{y}(t))^2 dt$$

In general, d^2 is the Mean - Square Error or d , is the Euclidean Distance between any two functions $\mathbf{x}(t)$ and $\mathbf{y}(t)$.

In the equation for $\min \Pr\{\varepsilon\}$, shown above, $\mathbf{x}(t)$ and $\mathbf{y}(t)$ are defined by the equations below.

$$\mathbf{x}(t) = \sqrt{E_1} s_1(t)$$

$$\mathbf{y}(t) = \sqrt{E_0} s_0(t)$$

$$\int_0^T s_1^2(t) dt = \int_0^T s_0^2(t) dt = 1$$

WALSH FUNCTIONS

- 64 Walsh Functions
 - 64 chips per function
- ## IS-95

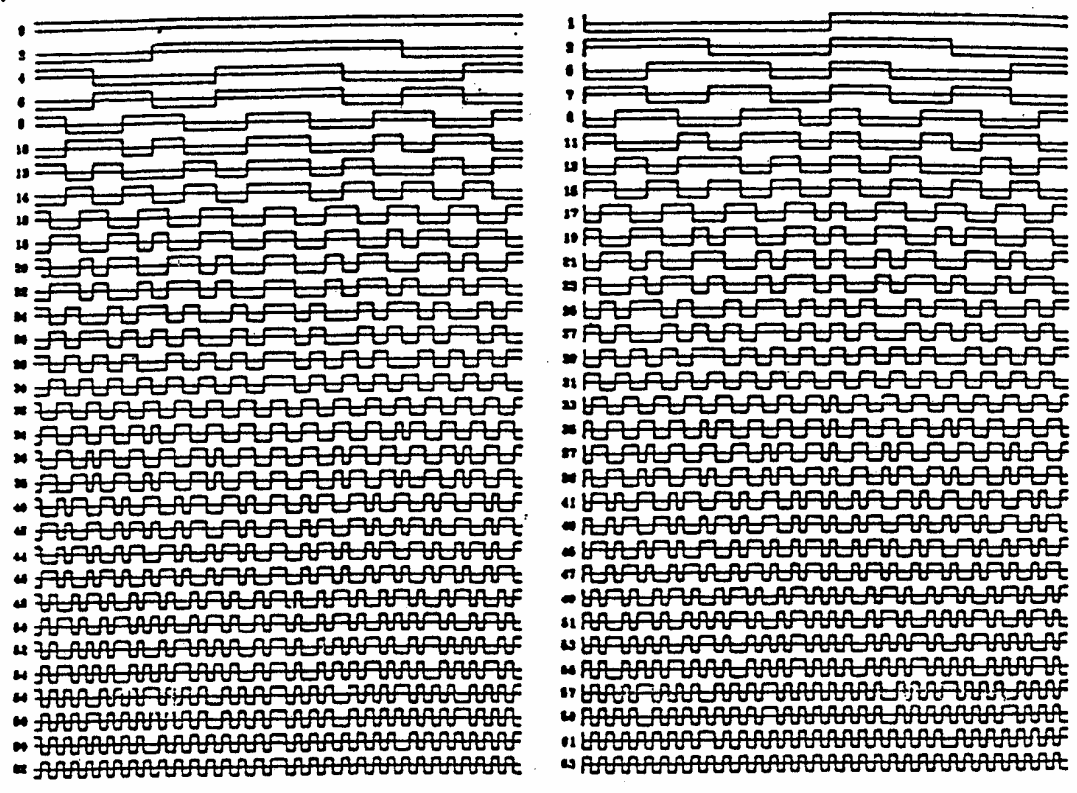
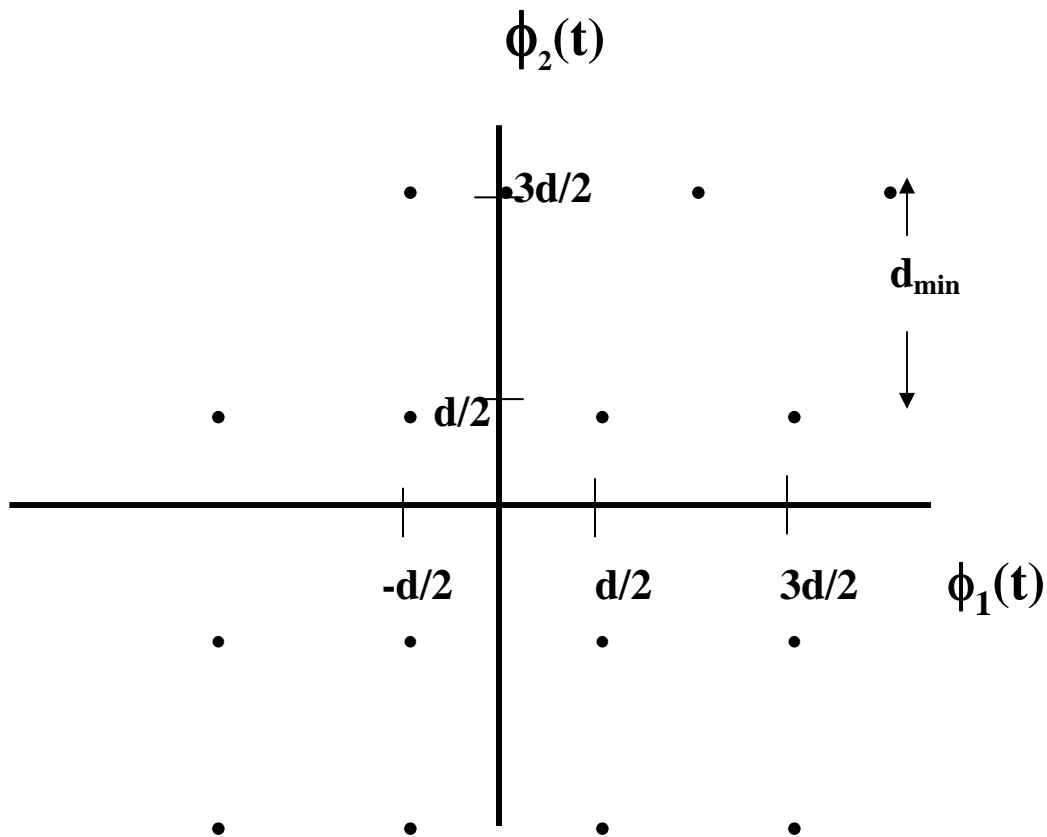


Figure 1.41: The first 64 Walsh basis functions.

$$\mathbf{C} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{array}{c} \text{---} \\ \text{---} \end{array} \begin{array}{c} t \\ t \end{array}$$

Quadrature Amplitude Modulation



• 16-QAM

$$E_{\text{avg}} = 1/4[2(d/2)^2] + 1/4[2(3d/2)^2] + 1/2[(d/2)^2 + (3d/2)^2]$$

$$E_{\text{avg}} = 5/2 d^2$$

$$d = \sqrt{2/5 E_{\text{avg}}}$$

$$R_b = 4 (1/T) \text{ bps}$$

QAM-MPSK COMPARISON

The additional energy required by MPSK to achieve the same minimum distance, d_{\min}^2 , as that of the equivalent QAM constellation.

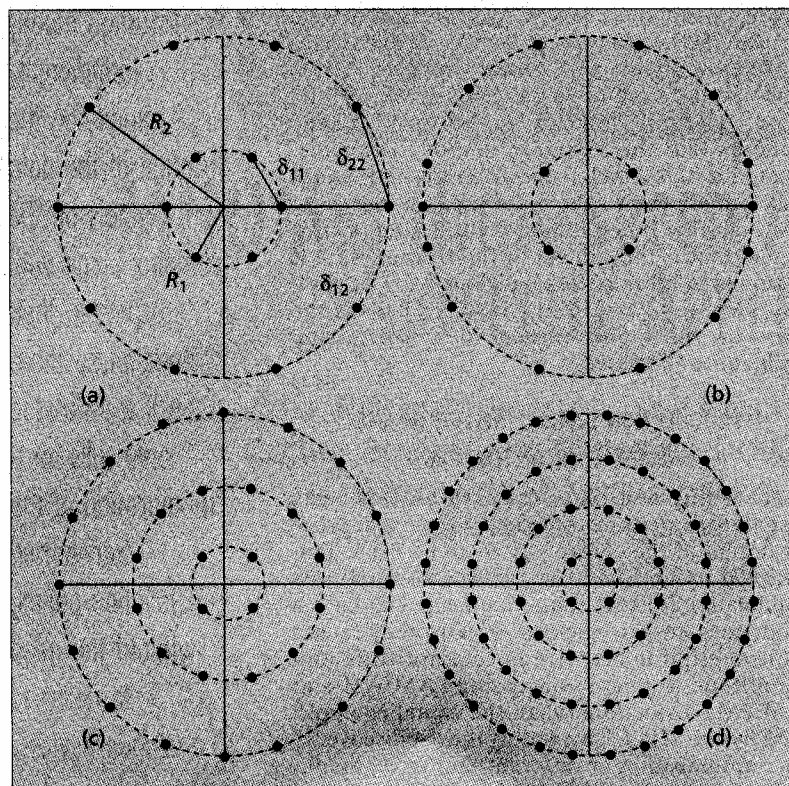
$$d_{\min} = \sqrt{[6/(M-1)] E_s}$$

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

M	Additional Energy (db)
4	0.0
8	1.6
<u>16</u>	<u>4.14</u>
32	7.01
64	9.95
128	12.89
<u>256</u>	<u>15.90</u>

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.

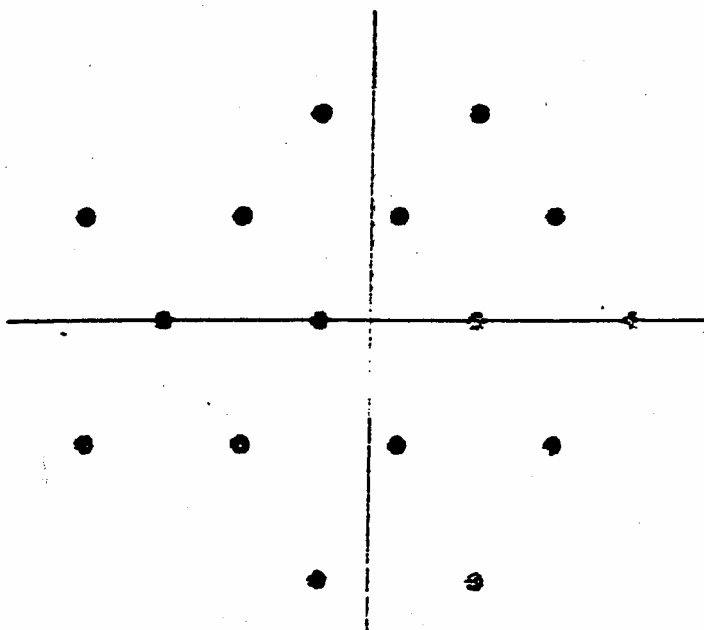


■ **Figure 1.** Multi-ring APSK constellations: a) Euclidean distances; b) 16-point 4-12-APSK; c) 32-point 4-12-16-APSK; d) 64-point 4-12-20-28-APSK.

OPTIMUM CONSTELLATION 16 QAM

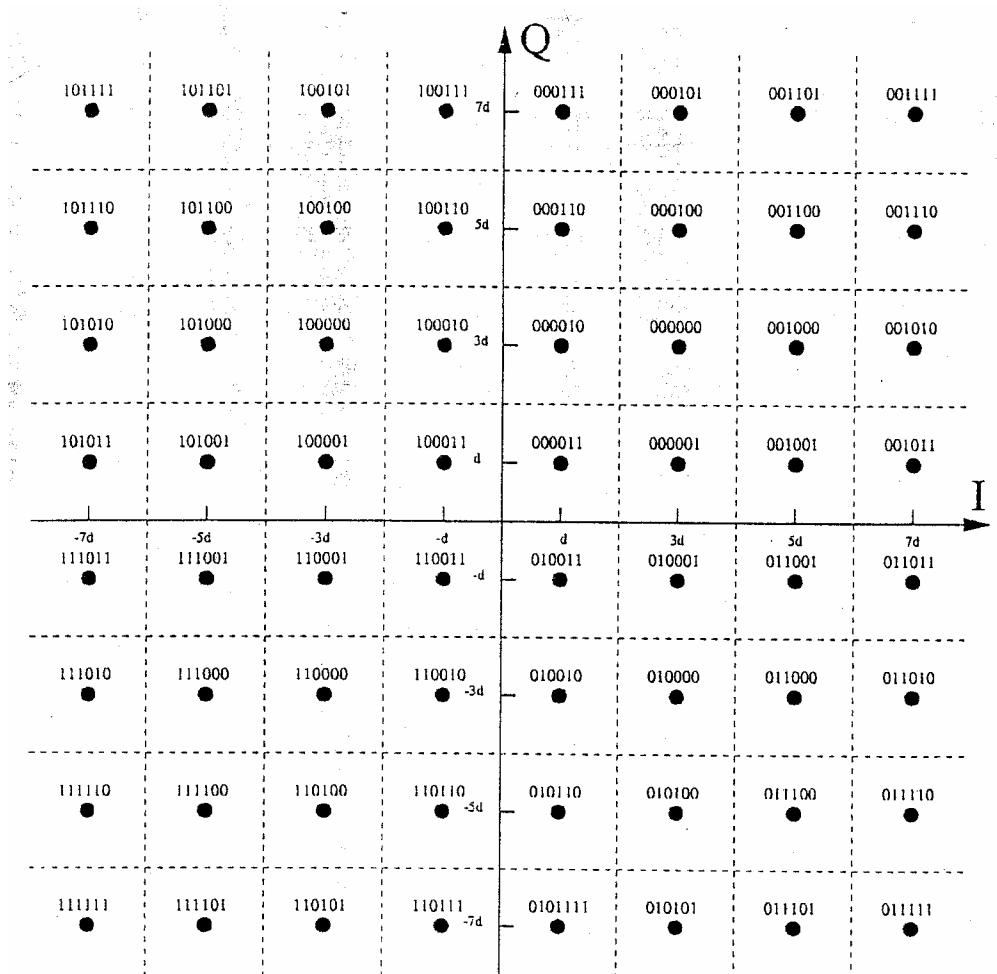
About a **.5 dB improvement** over a Square- 16-QAM Constellation

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.



QAM CONSTELLATION (64-QAM)

GRAY CODING



MATCHED FILTER

Frequency Domain

$$h_m(t) = s(T-t)$$

Therefore

$$H_M(f) = S^*(f) e^{-j2\pi fT}$$

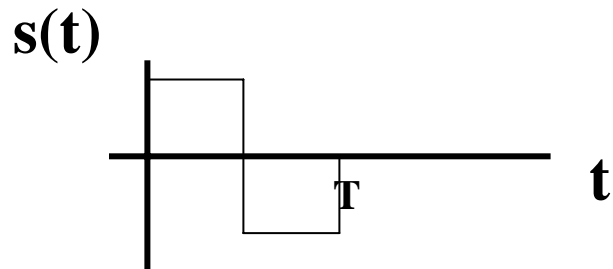
The absolute value of $S^*(f)e^{-j2\pi fT}$ is the same as that of $S(f)$.

$$s(t) \Rightarrow$$

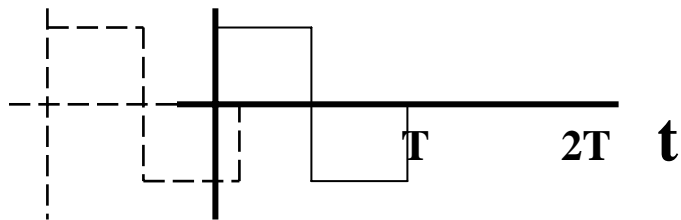
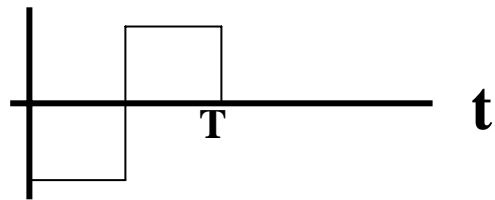
$$s(-t) \Rightarrow$$

$$s(-(t-T)) = s(T-t) \Rightarrow$$

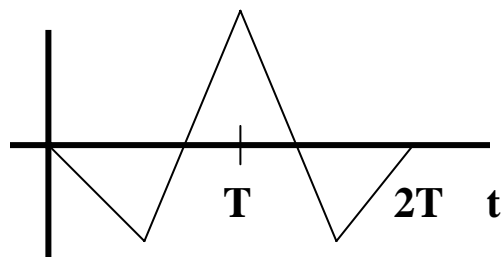
EXAMPLE



$$h_m(t) = k s(T-t)$$

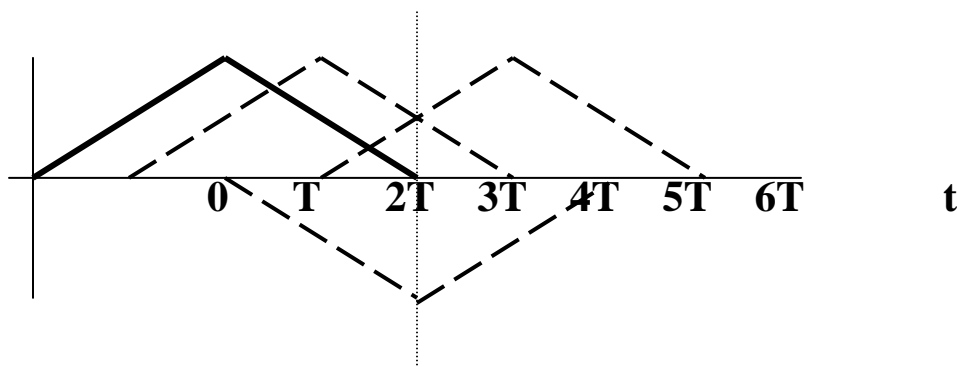
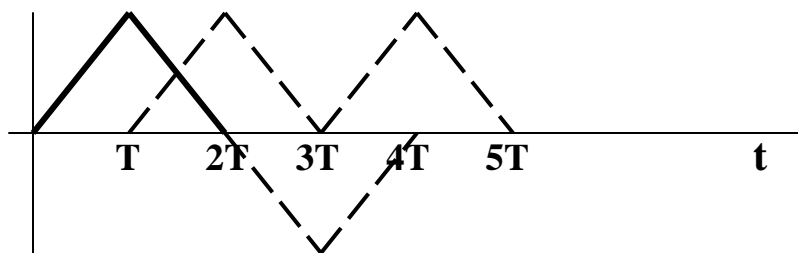


$$h_m(t) * s(t)$$

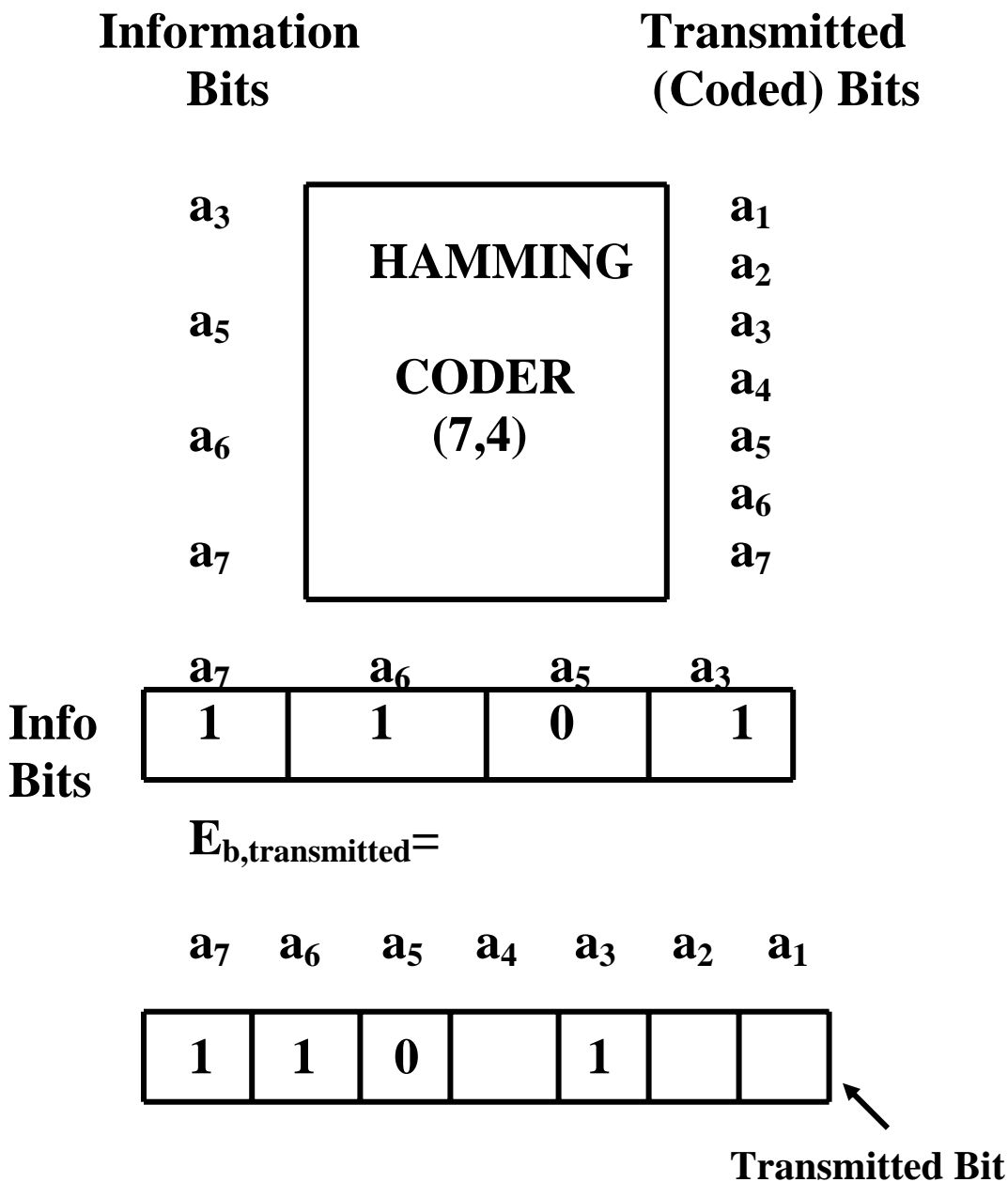


- *Maximum output at time $t+T$
- *Length of output is twice $T= 2T$.
- *Symmetric response around $t=T$

What happens if the pulse $s(t)$ lasts for longer than T seconds?



Hamming (7,4) Code



ENCODER

$$a_1 = a_3 \oplus a_5 \oplus a_7$$

$$a_2 = a_3 \oplus a_6 \oplus a_7$$

$$a_4 = a_5 \oplus a_6 \oplus a_7$$

PROBABILITY OF ERROR HAMMING (7,4) CODE

$E_b/N_0, \text{trans, dB}$ CODED	$E_b/N_0, \text{info, dB}$ CODED	$P_{\text{bit,trans}}$ CODED	P_{block} CODED	$P_{\text{dec-info}}$ CODED	$E_b/N_0, \text{info, dB}$ UNCODED
-1 dB	+1.43 dB	10^{-1}	.15	.08	+5 dB
+4.3	6.73	10^{-2}	$2 \cdot 10^{-3}$	10^{-3}	+6.8
+6.8	9.23	10^{-3}	$2.1 \cdot 10^{-5}$	10^{-5}	+9.6
+8.4	10.83	10^{-4}	$2.2 \cdot 10^{-7}$	10^{-7}	+11.2

- $E_b/N_0, \text{ info, dB} = E_b/N_0, \text{ trans, dB} + 2.43 \text{ dB}$
- $P_{\text{dec}} = \text{Pr}\{\text{error in decoded bits}\} \approx (1/2) P_{\text{block}}$

BLOCK CODE PERFORMANCE

In general, the minimum Hamming distance, $\min d_H$, determines the $\Pr\{\varepsilon\}$

$$\min d_H = 2t + 1$$

where "t" is the number of errors that we can detect and correct.

Block Codes Coding Performance

B. Sklar, Digital Communications-Fundamentals and Applications-
Prentice -Hall, New York, 1988

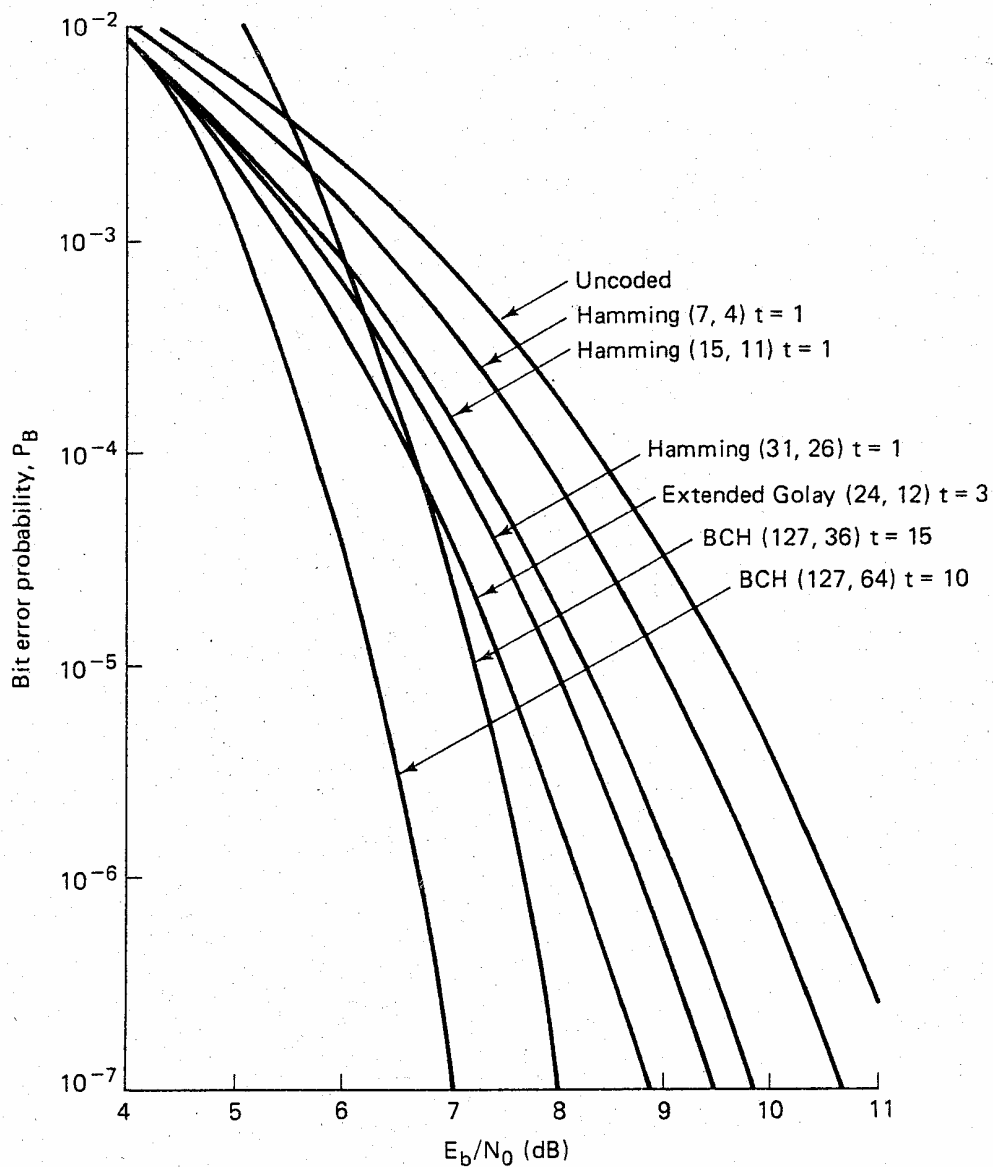
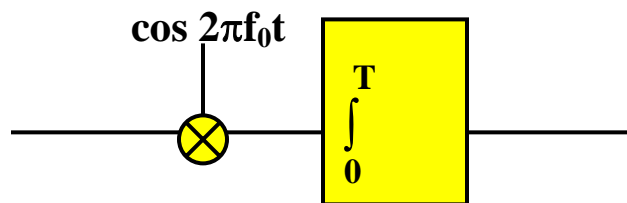


Figure 5.23 P_B versus E_b/N_0 for coherently demodulated BPSK over a Gaussian channel for several block codes.

Soft Decision versus Hard Decision

Detected Bits

1 0 0 0 1 1 0



The BER performance of soft-decision decoding is about two and a half dB better than that of hard-decision decoding (@ 10^{-5}) but requires a lot of DSP.

However, the Viterbi Algorithm makes soft-decoding possible for convolutional codes.

SOFT DECISION IS ABOUT 2.5 DB BETTER THAN HARD DECISION AT (10^{-5}).

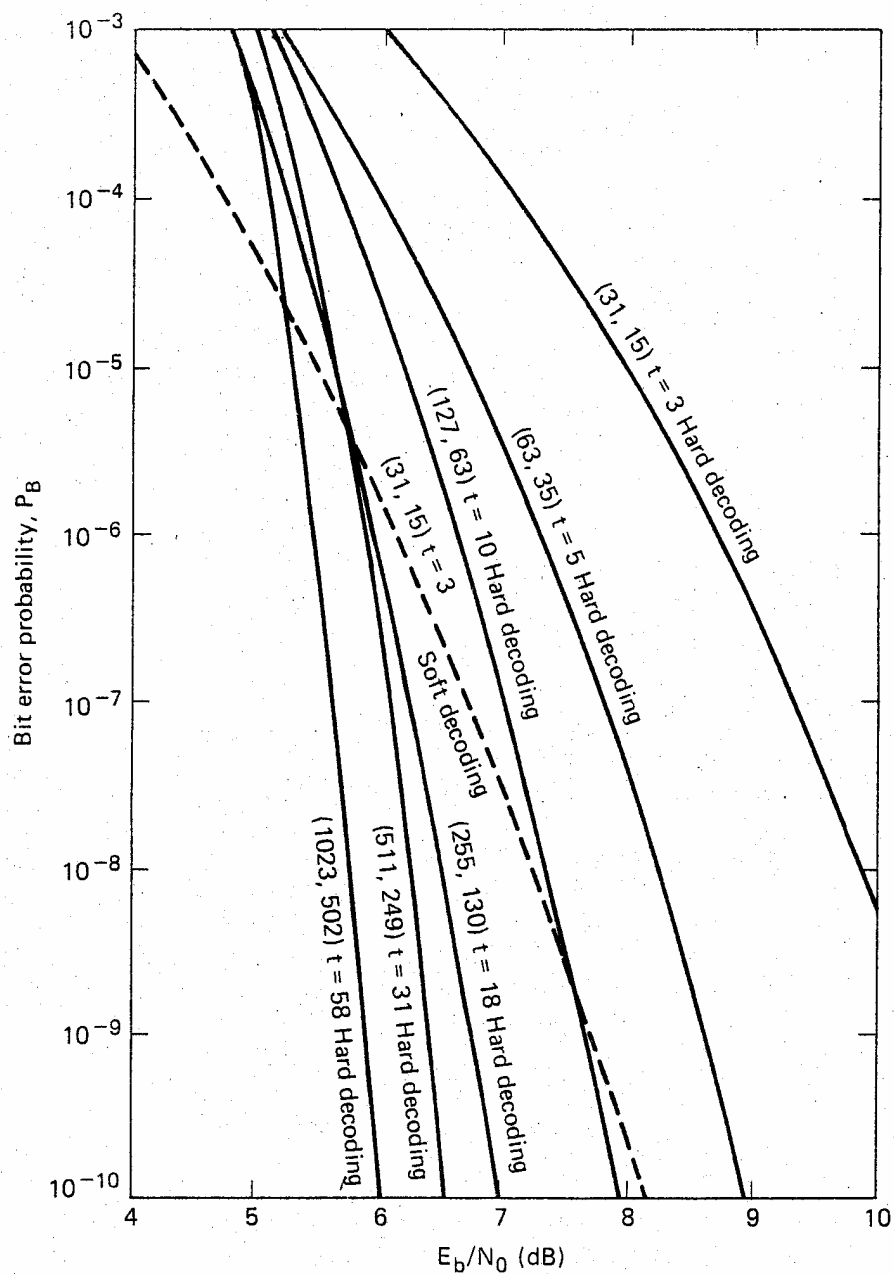


Figure 5.24 P_B versus E_b/N_0 for coherently demodulated BPSK over a Gaussian channel using BCH codes. (Reprinted with permission from L. J. Weng, "Soft and Hard Decoding Performance Comparisons for BCH Codes," *Proc. Int. Conf. Commun.*, 1979, Fig. 3, p. 25.5.5. © 1979 IEEE.)

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."

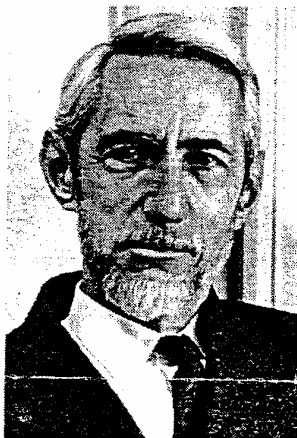
Born in Petoskey, Mich., on April 30, 1916, Claude Elwood Shannon got a bachelor's degree in mathematics and electrical engineering from the University of Michigan in 1936. He got both a master's degree in electrical engineering and his Ph.D. in mathematics from M.I.T. in 1940.

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."

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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 קמיונר**, כתב „דיעות אחרונות“
כוכבת הקולנוע חרי לאמר, שזכתה לתואר „האישה היפה ביותר בעולם“, מתה שלשום בביתה שבפלורידה בגיל 86. גופתה נמצאה על ידי חברים שבאו לבקרה.

לדברי השופר המקומי, מתה לאמר מוות טבעי, כנראה בשני תה. פרקטיקה של הכוכבת מסר כי היא לא סבלה ממצלות כלשהן והיתה צלולה עד רגעיה האחרונים.

לאמר הוזהרת, בעלת היופי האקזוטי האפל, כיכבה בסרטים רבים בשנות ה־30 וה־40, ובהם „אלג'יר“ ו„גערות זיגפילד“. במי וחד הרטיטה לבנות כשגילמה ב־1949 את דמותה של דלילה המ פתה בסרט „שמשון ודלילה“ של סטיל ב' דה מיל.

הקריירה שלה היתה רצופה בסטנדרים. היא חוללה סערה גור לה כששתתה בעידום ורצה מעורטלת בסרט „אקסטוזה“, והיתה בכך לאחת הנשים הראשונות שהעזו להופיע בעידום בקולנוע. בע לה ראשון, פריץ מנדל, טייקון החמושת האוסטרי שתמך בנא צים, ניסה בהמשך לרבוש את כל עותקי הסרט, אך ללא הצלחה.

בעקבות השערורייה הגיעה לאמר לליליווד, שם המשיכה לה שתתן בסרטים עד שלהי שנות ה־50. הטעות הגרה לה ביותר שלה היתה כש סירבה לככב בסרט הנרי דע „קובלנקה“ ב־1943.

לא פעם טענה כי הקריירה שלה דעכה מאחר „שסירבתי לשכב עם המ פיקים“.

לאמר נולדה בווינה בשם הדוויג אווה מריה קיולר. היא התחתנה והת גרשה שש פעמים, ילדה שני ילדים ואימצה ילד נר

סו. היא נאסרה לא פעם בשל גניבה מחנויות והופיעה בבתי ימשי פט גם בתביעות שהגישה נגד סופר הצללים שלה, בטענה שעי וות את סיפוריה, ונגד חברת המחשבים ויקב קליפורני, בטענה שהשתמשו בתמונתה ללא רשות. הכוכבת הוזהרת התפרסמה גם כממציאה פורה, ולא מעט פטנטים בתעשייה, במחשבים ובתקשר

דת נרשמו על שמה.



לאמר מעוררת שערורייה בהופעה בעידום

(צילום: רויטרס)

לאמר כדלילה המפתה בסרט „שמשון ודלילה“.

The Most Beautiful Woman in The World

Communications Week-International 7 February 2000

Cellular legacy of screen goddess

BY SHERIDAN NYE
• ORLANDO, FLORIDA

It's not often a movie star takes a leading role in the development of a telecoms technology. So when 1940s siren Hedy Lamarr died aged 86 in her Florida home last month, the obituaries puzzled over the glamorous actress who took time out between films to invent the complex spread-spectrum technology known today as CDMA (code division multiple access).

Lamarr, born Hedwig Klesler in Austria, was known in her heyday at MGM as "the world's most beautiful woman," and for her appearance in one of the earliest nude scenes in the 1933 art-film *Ecstasy*. By all accounts, she was a difficult artist who chafed at the hierarchy of the studios. She once dismissed her own billing by saying: "Any girl can look glamorous. All you have to do is stand still and look stupid."

But Lamarr was far from stupid. Despite having dropped out of high school to take up acting, she had no trouble following the conversations between her first husband, arms dealer Fritz Mandl, and his customers. During the Second World War, the German navy needed a way to control submarine torpedoes remotely using radio frequencies that



Hedy Lamarr

would be protected against interception or jamming. Mandl and his colleagues puzzled over the problem, while Lamarr was quietly inspired to devise a solution that, incredibly, would go on to become the foundation of third-generation cell-phone technology in the next century.

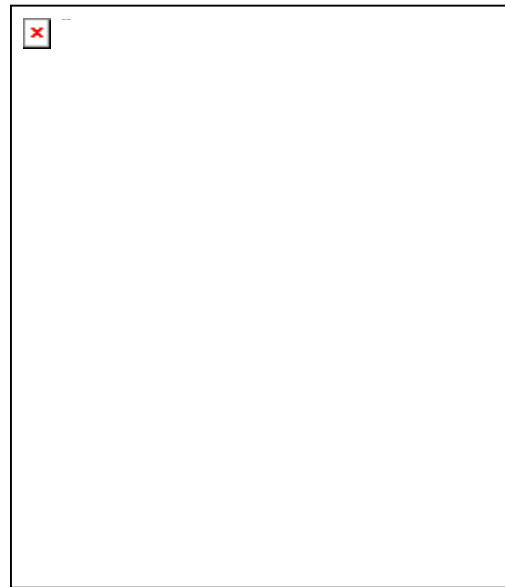
Horrified by the Nazi regime, Lamarr left Europe and Mandl to continue her acting career in the United States. There she met George Antheil, an avant garde composer with a fascination for "player pianos." Together they discussed her ideas and saw the potential to assist the United States against the Nazi war ma-

chine by triggering submarine torpedoes using a code cut into paper rolls.

They approached the military with their system—which used 88 frequencies, the number of keys on a piano—but the top brass were not convinced the system could be built. Antheil later commented that the generals probably couldn't see much beyond the idea of putting a piano in a submarine.

It was not until the 1960s that sophisticated electronics allowed the military to capitalize on Lamarr and Antheil's patented invention, and the benefits of secrecy and spectrum and power efficiency. The technology was declassified for commercial use in the 1980s, and Lamarr's original concept of sending scrambled signals over multiple, low-power radio frequencies is the foundation of CDMA today.

Engineers in the field have long known about her contribution, but public recognition only followed in 1997, when the Electronic Frontier Foundation (EFF) gave Lamarr a special pioneer award for her work. "Her reaction was, 'it's about time,'" said Mike Godwin, general counsel for the EFF at the time. "She was gratified," said Godwin. "But there was a clear sense that she knew she had made an important contribution, whether we acknowledged it or not." ■



WI-LAN PAYS TRIBUTE TO HEDY LAMARR

Spread spectrum pioneer's contributions to wireless communications were ahead of her time

Wi-LAN would like to offer their deepest condolences to the family and friends of spread spectrum pioneer and actress, Hedy Lamarr. Wi-LAN was honoured to have worked with Ms. Lamarr, building on her 1942 innovative patent on secure wireless transmissions to grow and forward our technology. [\[story\]](#)

On January 21, 2000, the CBC Calgary Eyeopener, a morning radio program, asked **Wi-LAN's** Chairman and CEO, Dr. Hatim Zaghoul, to speak about the relationship between Hedy Lamarr and **Wi-LAN**. This broadcast was taped in the studio, and is available for [download](#).

When people think of Hedy Lamarr, they usually think of her career in Hollywood, and, in particular, the 1933 sensual film, "Ecstasy", which sparked her reign as a star of the silver screen. Hedy Lamarr was a talented actress from 1930 to the late 1950s, and was Max Factor's "Girl of the Year" for 1938. At that time, she was considered an exotic and glamorous sex symbol. But many people don't realize that there was an innovative mind behind her winning smile.

Hedy gained her knowledge of radio communications and torpedo warfare by listening to her first husband, Fritz Mandl, as he spoke to his clients about advancements in European armament manufacturing. When she divorced him and moved to America shortly before World War II, Hedy wanted to help the war effort. Hedy learned that torpedoes were controlled by radio signals, which could be jammed by an enemy, rendering the torpedo inoperative.

One night, Hedy and her friend, American composer George Antheil, developed the idea now known as frequency hopping. Instead of sending the message over a single radio frequency, they devised a way to broadcast a signal over a seemingly random series of radio frequencies, hopping from frequency to frequency at split-second intervals. A receiver, hopping between frequencies in synchrony with the transmitter, picks up the message. Any eavesdroppers hear only unintelligible blips, and attempts to jam the signal succeed only in knocking out a few small bits of it. So effective is the concept that it is now the principal anti-jamming device used in the U.S. government's \$25 billion defense communications satellite system.

The concept on how to synchronize the transmitter and the receiver came from George Antheil's musical background. In 1927, George caused quite a stir with his composition called the "Ballet Mechanique", which is one of the very first times anyone had ever scored a musical piece using machines; in this piece, the machines used were sixteen synchronized player pianos. Antheil understood instantly that synchronizing a series of split-second hops between radio frequencies would be no more difficult than synchronizing player pianos. As a matter of fact, the patent specifies the use of slotted paper rolls, similar to player piano rolls, to synchronize the jumps in frequency in the transmitter and receiver. As well, the number of frequencies proposed was 88, which matches precisely the number of keys on a piano.

This invention was patented on August 11, 1942, and the patent expired seventeen years later. Even though the term of the patent lapsed without either of them realizing any money from their invention, their innovation formed the basis of what was to later become spread-spectrum communications, and it is the keystone for thousands of spread spectrum patents in existence today.

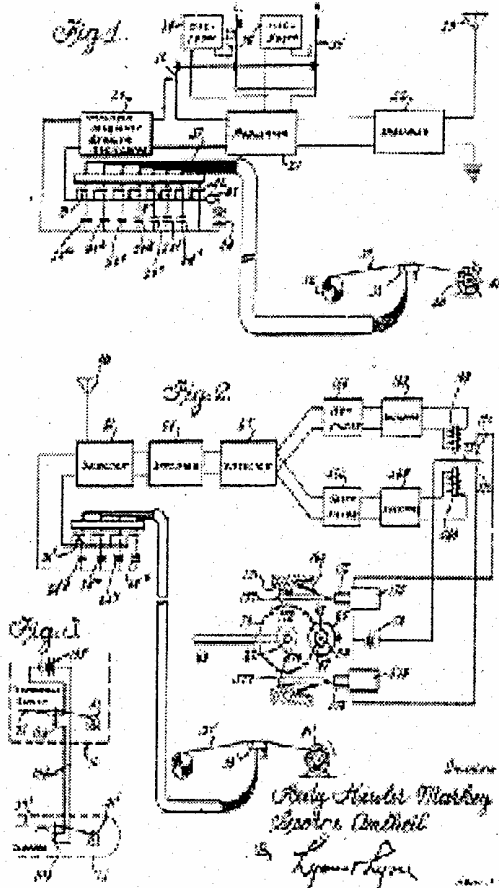
In June 1998, **Wi-LAN** announced that it had agreed to acquire the original patent rights for spread spectrum technology from Hedy Lamarr. Under the terms of the agreement, **Wi-LAN** received a 49% claim to US Patent 2,292,387, which was titled "**Secret Communications System**". In exchange, Ms. Lamarr has agreed to allow **Wi-LAN** to promote her role as a wireless pioneer. Hedy Lamarr died in her home on January 19, 2000. She was 86.

If you'd like to know more about **Hedy Lamarr**, please visit these sites:

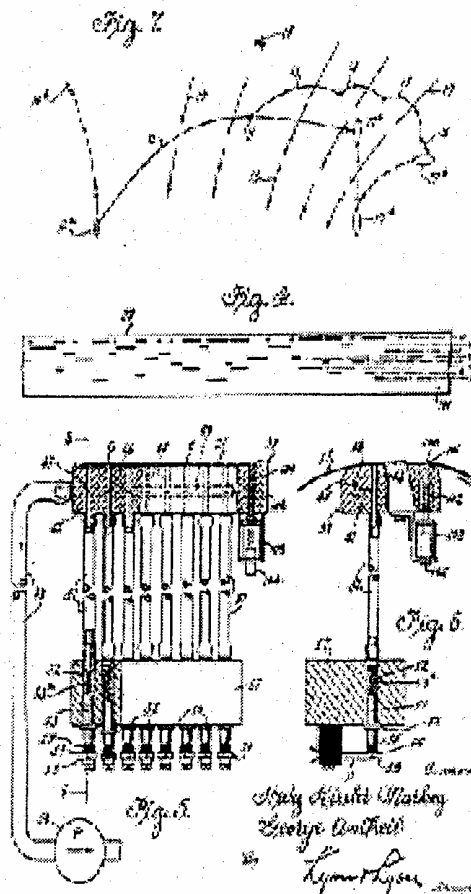
- [Press Release: Wi-LAN Pays Tribute to Hedy Lamarr](#)
- [Press Release: Hollywood Legend and Spread Spectrum Pioneer Hedy LaMarr Recognized by Wi-LAN](#)
- [See the original patent for the "Secret Communications System"](#)
- [Glamorous Film Star Hedy Lamarr Wins Bulbie Award at the 11th Annual Invention Convention](#)

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

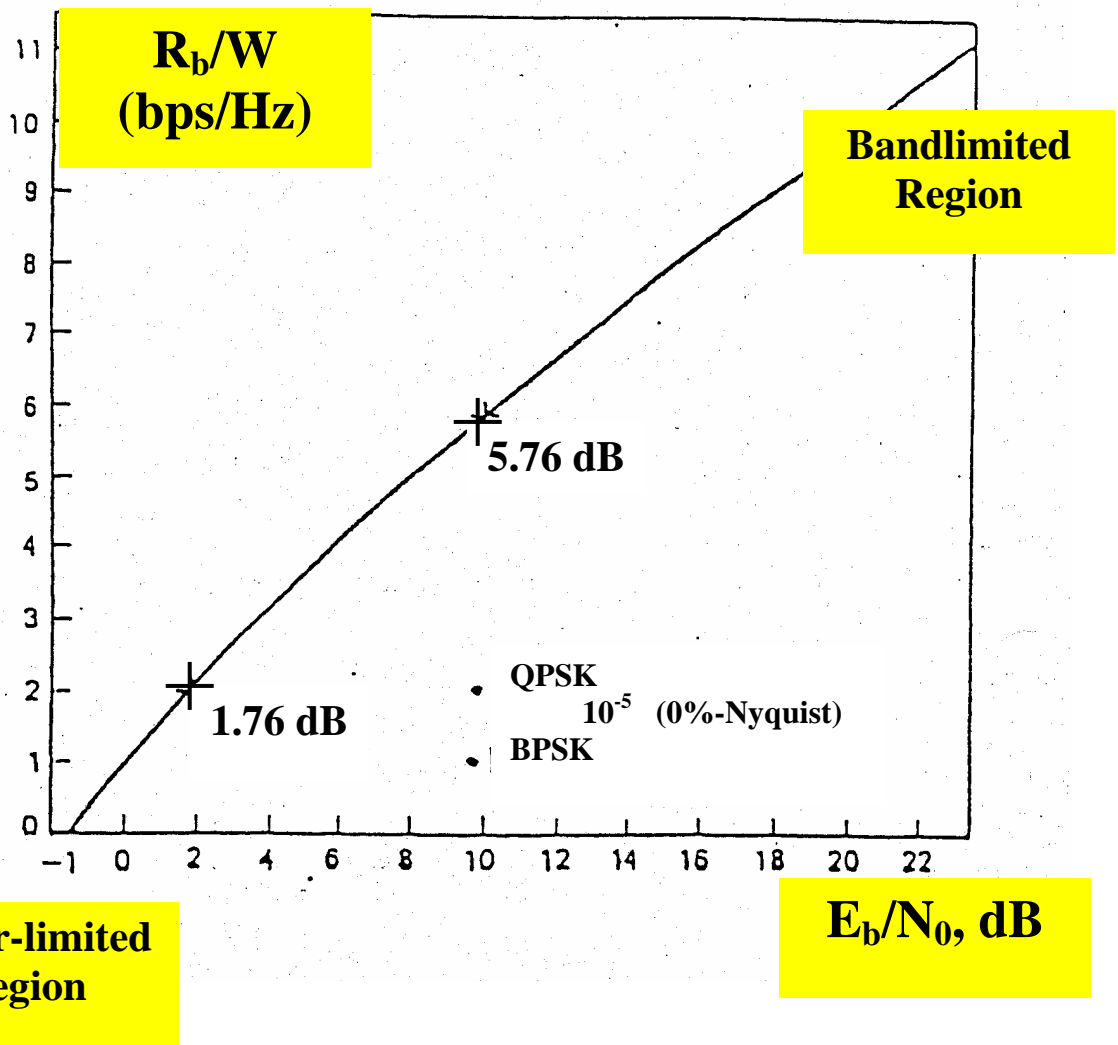
Aug. 11, 1942. H. K. MARNEY ET AL. 2,292,387
 SECRET COMMUNICATION SYSTEM
 Filed June 17, 1941 (Serial 5788)



Aug. 11, 1942. H. K. MARNEY ET AL. 2,292,387
 SECRET COMMUNICATION SYSTEM
 Filed June 17, 1941 (Serial 5788)



CAPACITY



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