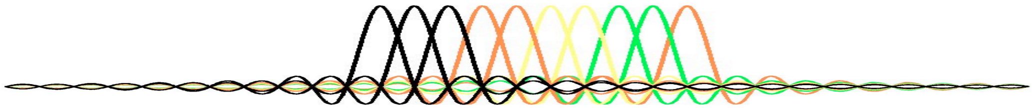


# EHB 453, Introduction to Mobile Communications

## Lecture 2: Wireless Communication

Prof. Mustafa Ergen



# Outline

- The ultimate objective of wireless communication is to host large number of users in a wide coverage….

- Next: Main point of the previous lecture

# FCC Chairman Powell statement

- We are still living under a spectrum "management" regime that is 90 years old. It needs a hard look, and in my opinion, a new direction.
- Historically, I believe there have been four core assumptions underlying spectrum policy:
- Unregulated radio interference will lead to chaos;
- Spectrum is scarce
- Government command and control of the scarce spectrum resource is the only way chaos can be avoided
- The public interest centers on government choosing the highest and best use of the spectrum.

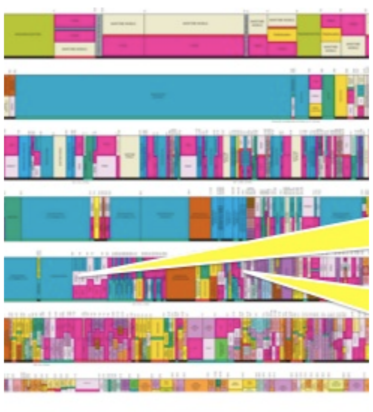
# Powell's statement (cont.)

- Today's environment has strained these assumptions to the breaking point.
- Modern technology has fundamentally changed the nature and extent of spectrum use. So the real question is, how do we fundamentally alter our spectrum policy to adapt to this reality?
- The good news is that while the proliferation of technology strains the old paradigm, it is also technology that will ultimately free spectrum from its former shackles.

# Cellular Concept

An operator buys a "land" from the spectrum map…

"Land" size is **F**



Spectrum is split into channels and same channel is not allowed in adjacent base stations but reused in other base stations.

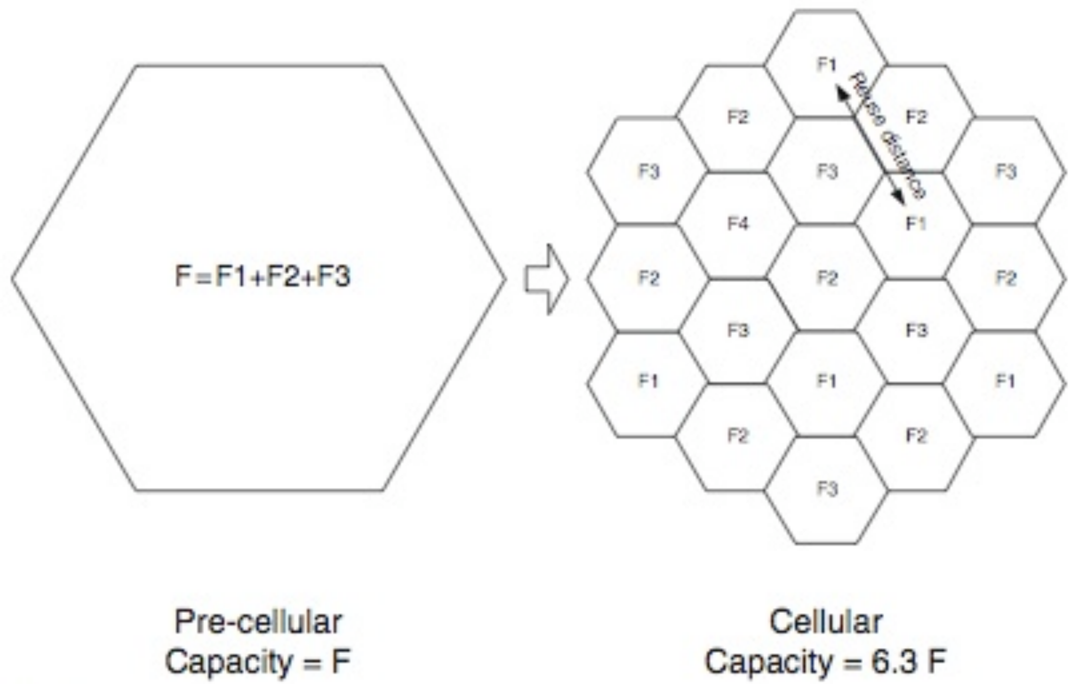



**Fig. 2.1** Cellular concept

A cell can host limited number of users

# Cellular Concepts

- Pros
  - Operator gets more performance versus price paid for the spectrum ☺
- Cons
  - Operator has to deploy more base stations ☹ Hence, needs more investment…
  - Needs handover mechanism….

- Number of cells
  - Directly affects the capacity and infrastructure investment
- Degree of spatial separation is *reuse distance.*
  - *Directly affects the capacity and interference*

What is the other way to increase capacity?:
Advance in technology to host more users within a cell

# Cellular Concepts

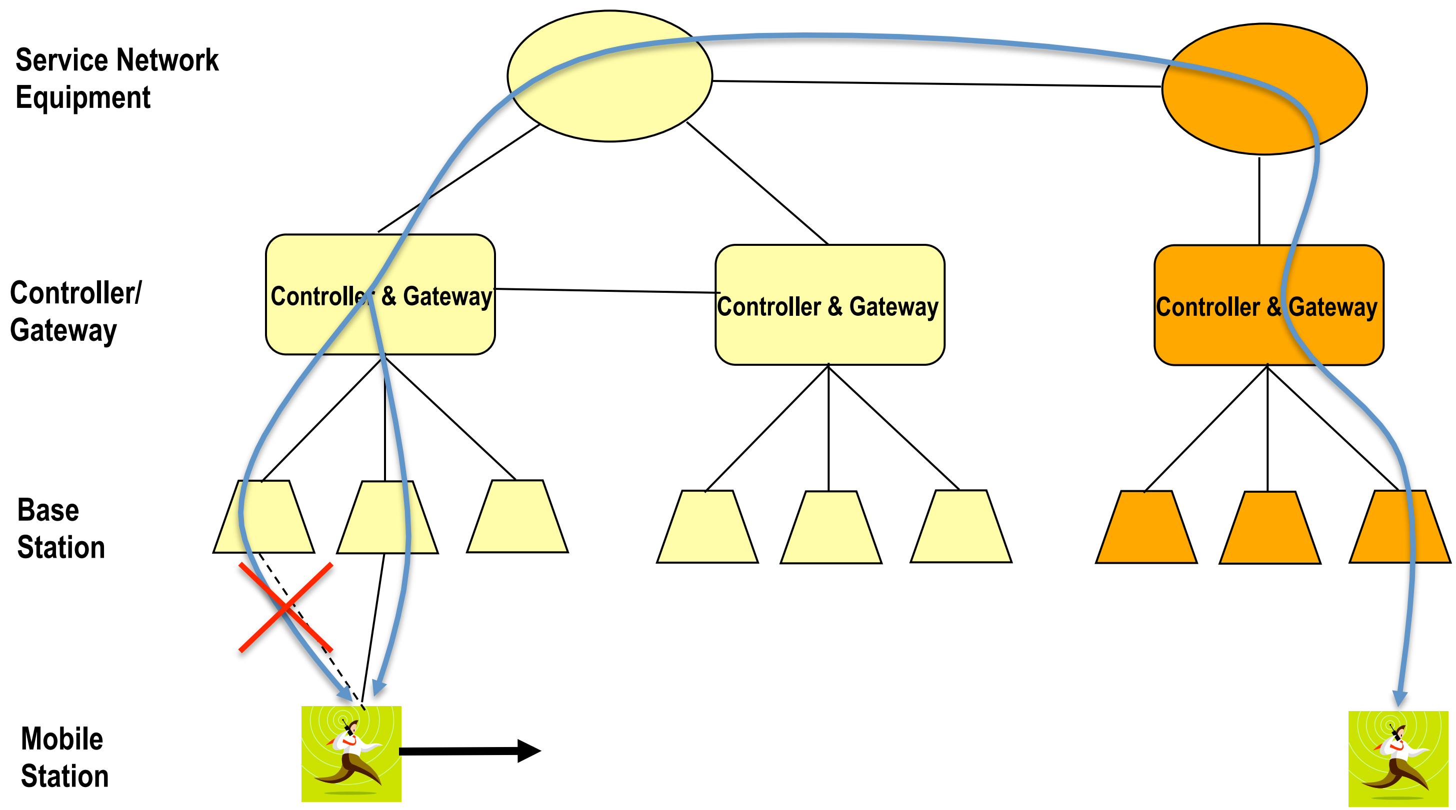
- Theoretically yes!
    - Allocated spectrum is F
    - F is split into n channels
    - n channels is distributed to N adjacent base stations.
    - N adjacent base station is called a cluster
    - Cluster is replicated m times to cover the area
    - Total capacity C is mxF
    - Pre-Cellular -> Total Capacity C is F since m=1 and n=1
- However, it is not that smooth!!
    - Cells operating with the same channel cause *co-channel interference* to each other
    - Also, a leak from adjacent channel causes *adjacent channel interference*.
    - Hence, real capacity in a cell is less than F ☹

# Mitigation Techniques

- Keep the frequency separation between each channel as large as possible
- Control the power of mobile subscriber
  - If close to BS, reduce the power, otherwise increase it to maintain a good quality link.
    - Reduce the adjacent channel interference
- Separate the cells operating with the same channel
    - Reduce the co-channel interference

# Mitigation Techniques

- Handover
  - A mobile subscriber will cross multiple cells

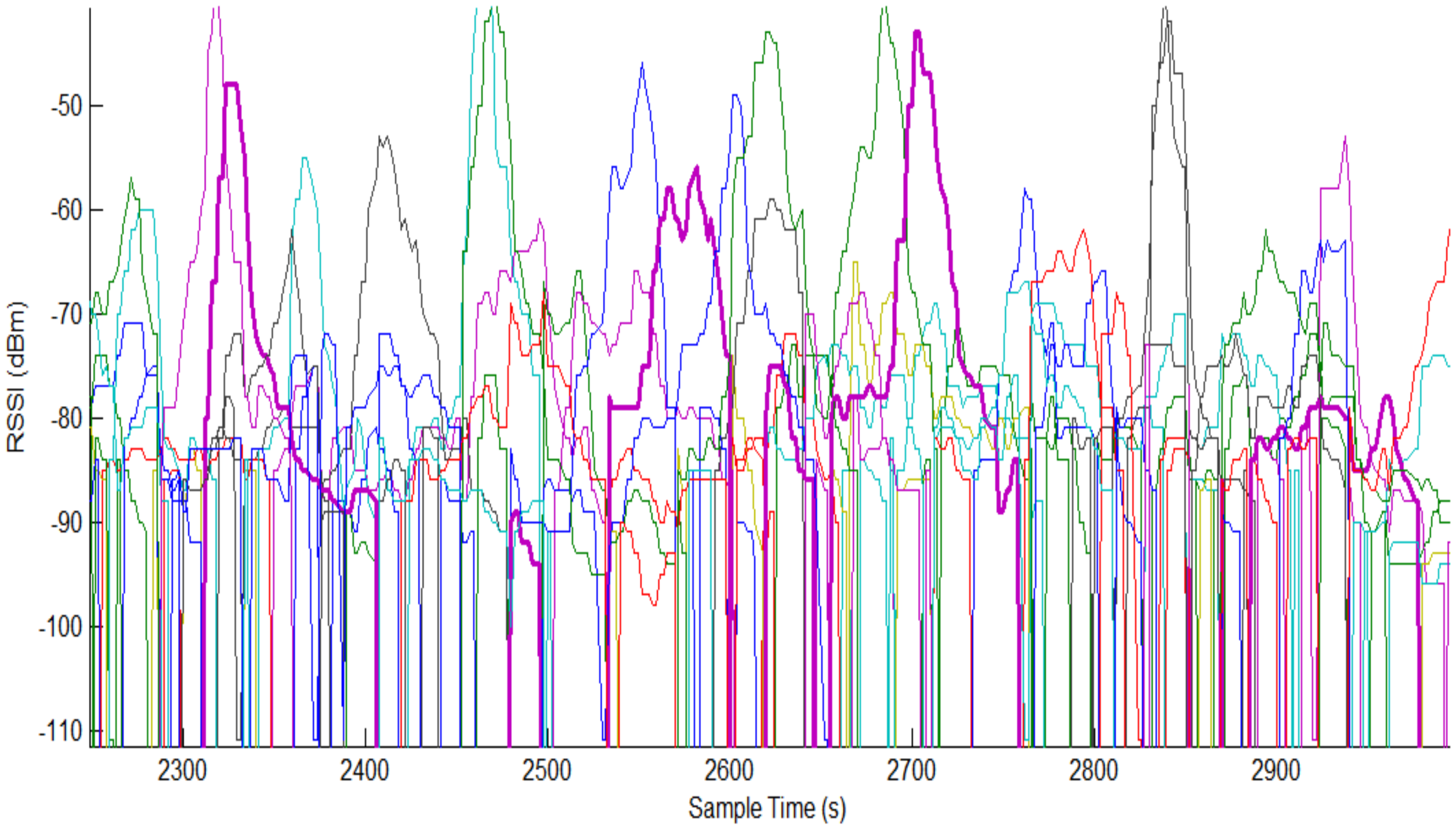


# Mitigation Techniques

- Why Handover?
  - Loosing the signal strength of the serving base station
  - Load balancing due to the congested serving base station

- How?
  - Requires a handover decision algorithm
    - "Secret sauce" of a vendor
    - The decision could be based on several parameters
      - Signal strength: (RSSI) Received Signal Strength Indicator
      - Signal to interference noise ratio: SINR
      - Distance to the serving base station
      - Velocity
      - Load
      - Etc.

# Handover: RSSI readings




Base Station Readings – 101N Bay Area, California –

# Handover

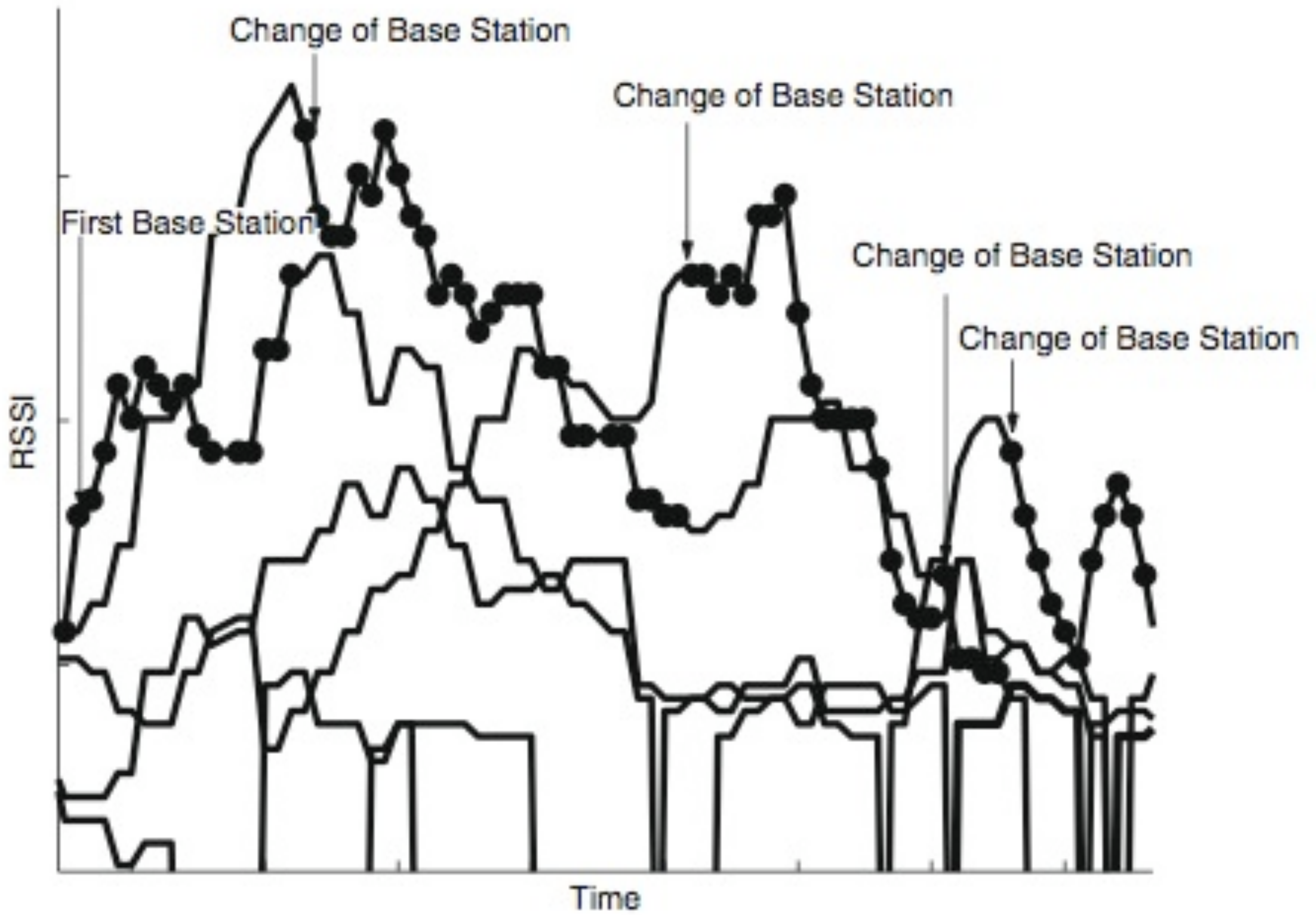
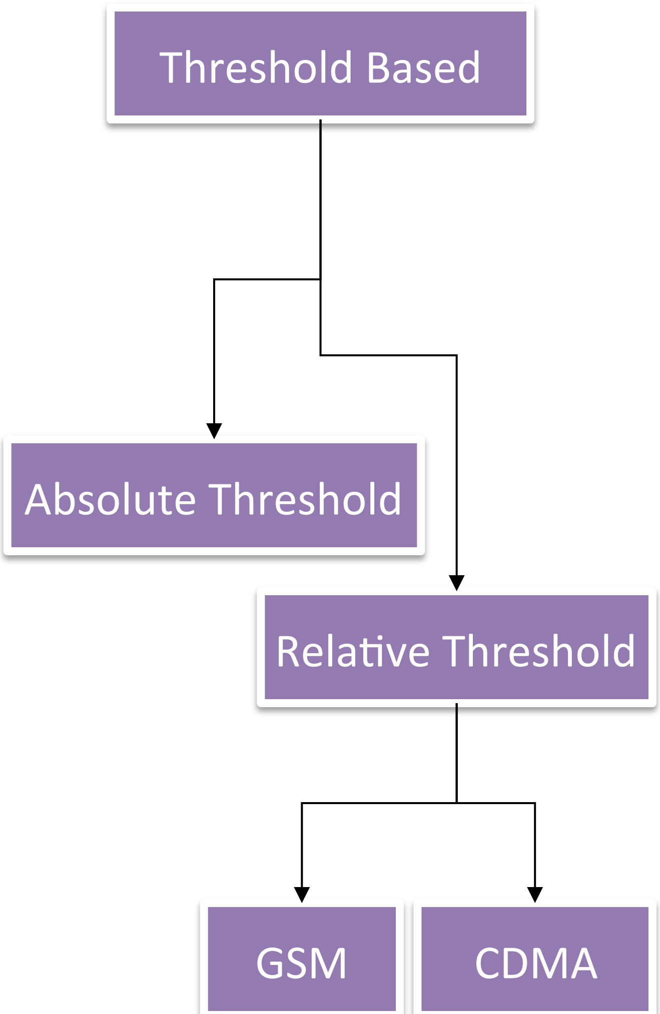



Fig. 2.2 RSSI readings and handover decision

# Handover Decision Algorithms



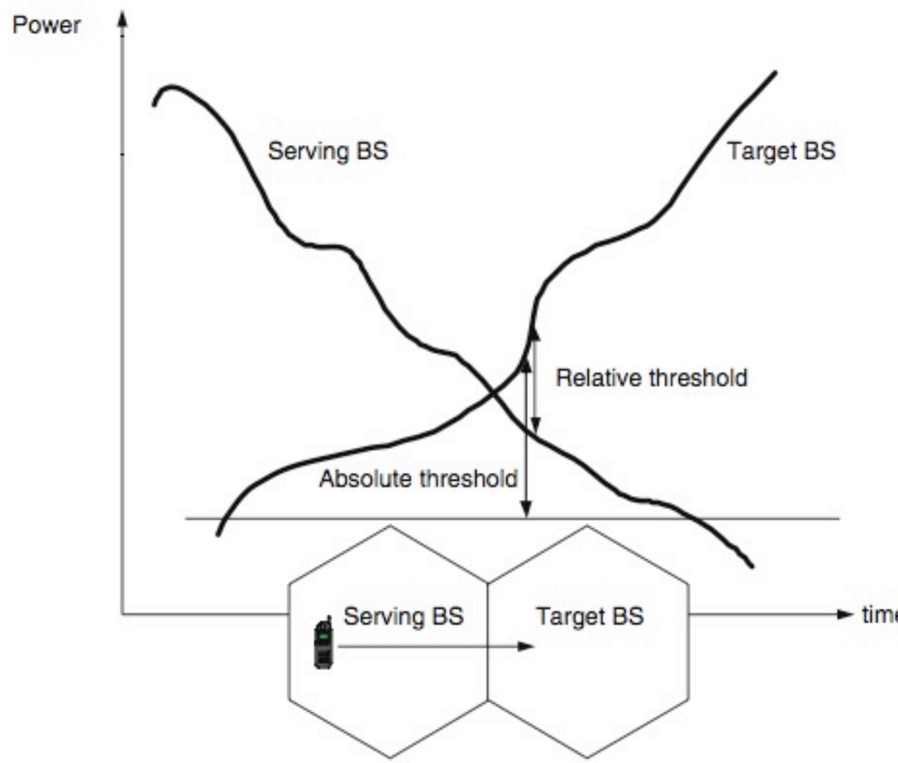




**Fig. 2.3** HO decision

# GSM Handover Algorithm Parameters

**C1(Path Loss-Criterion): Used it for network entry**

C2 = C1 + Cell_Reselect_Offset – Temporary_offset * H(Penality_Duration)

**C1 = RX – RX_Threshold – MAX (MS_Allowed_TX_PWR – MS_Max_TX_PWR, 0)**

RX Margin

Discourage low power MS from connecting to high power B

**C2 (cell-reselection criterion): Used it for Handover**

Only applied to Target BS

Following are specified in the BCH (Broadcast Control Channel):
- -Temporary_Offset
- -Penalty_Duration
- -Cell_Reselect_Offset
- -MS_ALLOWED_TX_PWR
- - Cell_Reselect_Hysteresis

Following are measured by the MS:
- -RX

Physical property of the chip:
- -RX_Threshold
- -MS_Max_TX_PWR

# Handover Decision

- When target signal is higher than serving signal
  - Relative Threshold
    - Early handover
    - Better quality
    - False trigger due to wireless channel: Ping-pong effect
      - Increase the overhead in the network
      - Degrade the overall throughput
- When serving signal falls below a threshold
  - Absolute Threshold
    - Late handover
    - Robust communication with less overhead in the infrastructure
    - Poor signal

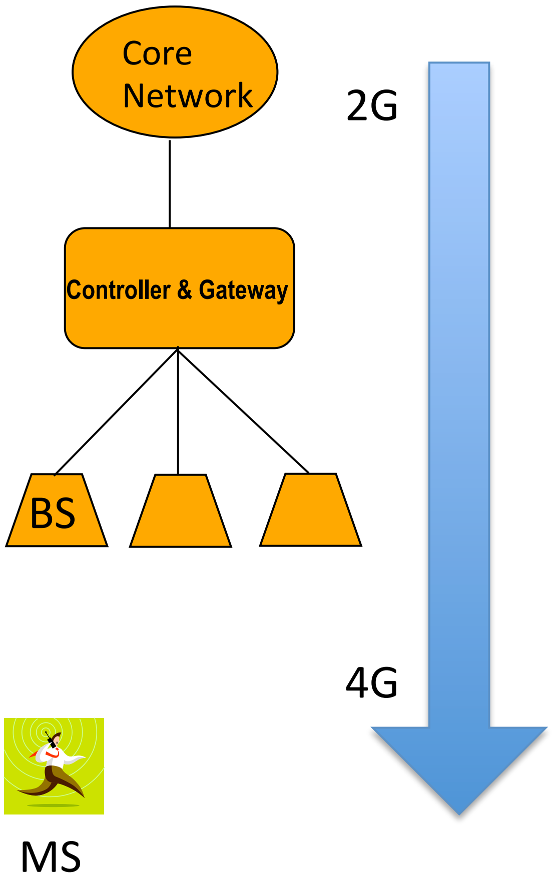
Typically, a good handover decision algorithm uses both in a smart way.

# Handover Types

- Hard Handover
  - Break before make
- Soft Handover
  - Make before break
- Vertical Handover
  - Between different networks
    - Ex: GSM and WiMAX,
    - Ex: WiMAX and LTE
    - Ex: GSM and WiFi
- Horizontal Handover
  - Between same networks
    - Ex: One GSM operator to another GSM operator

# Handover Decision Algorithm

- Which entity is deciding?
  - RSSI readings will be sent to?
  - In 2G, it is controller
    - – Network based handover
    - – Ex: BSC in GSM
  - In 3G, it is moving from controller to base station
    - – Network based handover
    - – Ex: RNC and HNB in UMTS
  - In 4G, it is mobile station
    - – Client based handover
    - – Ex: MS in WiMAX
      - » Although network based is supported in 4G, client based decision mechanisms are preferred– Hence mobile station is becoming more intelligence.



# Cellular Deployments

- Capacity of cellular system can be increased further

When there is a demand for more capacity

To handle mobility

Increase capacity with sectoral antenna: C x S

Where S is number of sectors

Indoor coverage

Increase efficiency: SDMA, AAS, MIMO

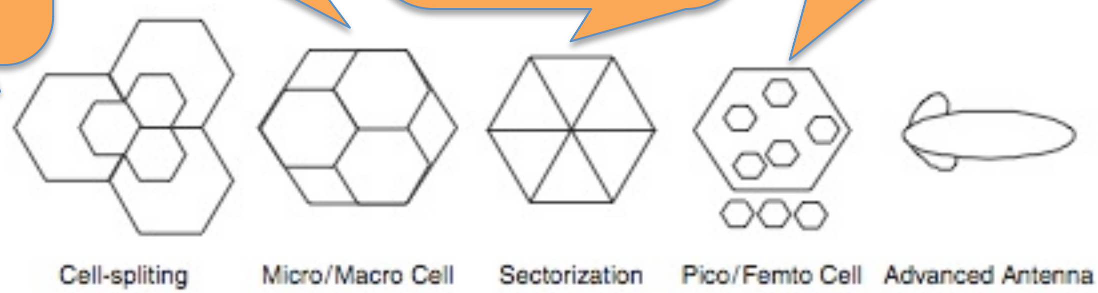



**Fig. 2.4** Advanced Techniques to increase the capacity in cellular networks

# Cellular Deployments

Sectorization: Previously within one coverage the capacity was F1 but now F=F1+F2+F3

Multi Antenna Systems: Transmit better signal or increase the data rate – Further, address more than one mobile station at the same time, Hence, increase the number of mobile that is served within the cell.

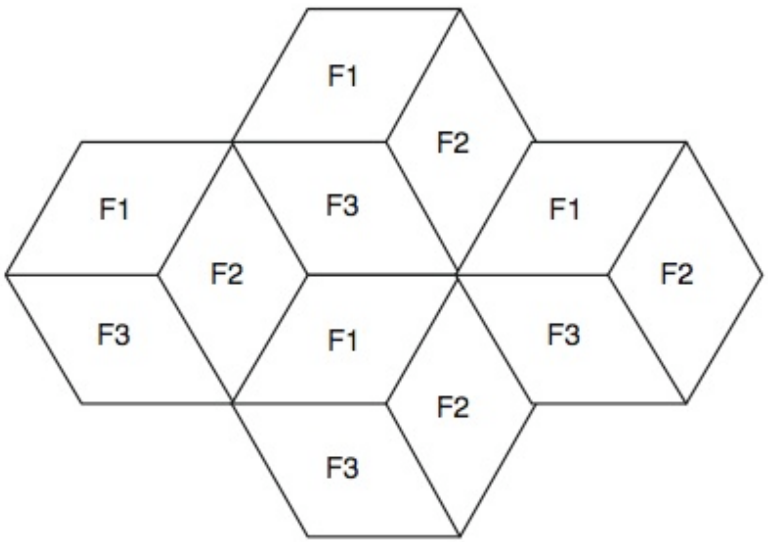



Fig. 2.5 Three sector deployment

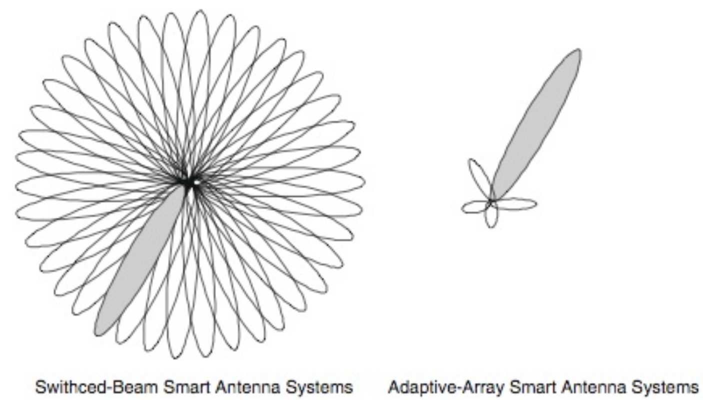



Fig. 2.6 Adaptive antenna systems

# Multi Antenna Systems

- Spatial Division Multiple Access – *SDMA*
  - Another multiple access scheme
- AAS: Adaptive Antenna Systems
  - Adaptively change the radiation pattern
    - Switched-beam
    - Adaptive array
  - Increase RSSI
  - Customized antennas
- MIMO: Multiple-Input-Multiple-Output
  - Increase capacity – linearly increases with the number of antennas
  - Or Increase RSSI
  - Standard off-the-shelf antennas

**EX: Wimax Throughput**

- SISO BS > 25Mbps
- 4-column AAS > 33Mbps
- 8-column AAS > 38Mbps
- 2x2 MIMO > 50Mbps
- 4x4 MIMO > 100Mbps

# Spectral Efficiency

- When designing a cellular network – there are so many trade-offs
  - Capacity
  - Service definition and quality
  - Capital expenditures (CAPEX)
  - Operational expenditures (OPEX)
  - Resource requirements
    - Spectrum
    - End-user price/affordability

With new technologies such as MIMO and femtocell, this trade-off has to be revisited.

# Spectral Efficiency

- Efficiency of the cellular network is quantified by a metric called – spectral efficiency.
  - Spectral efficiency is a measure of the amount of information-billable services that carried by a cellular system per unit of spectrum.
  - Measure is bits/second/Hz/cell
    - Includes effects of
      - Multiple Access Methods
      - Digital Communication Methods
      - Channel Organization
      - Resource Reuse

# Spectral Efficiency

- Example: 1900 GSM sytem
  - 200KHz carriers
  - 8 time slots per carrier
  - 13.3 Kbps of user data per slot
  - Effective reuse of 7
    - 1/7the total throughput per cell
  - Spectral efficiency is
    - 8slots x 13.3Kbps/slot / 200KHz / 7 reuse = 0.08 b/s/Hz/cell.
    - Number of cells/km2= offered-load (bits/s/km2) / available-spectrum (Hz) / efficiency (bits/s/Hz/cell)

# Recap: Cellular Network Design

- Three dimensions
  - Spatial
    - Cellularization, sectorization, power control, multiple antennas, etc.
  - Spectral
  - Temporal

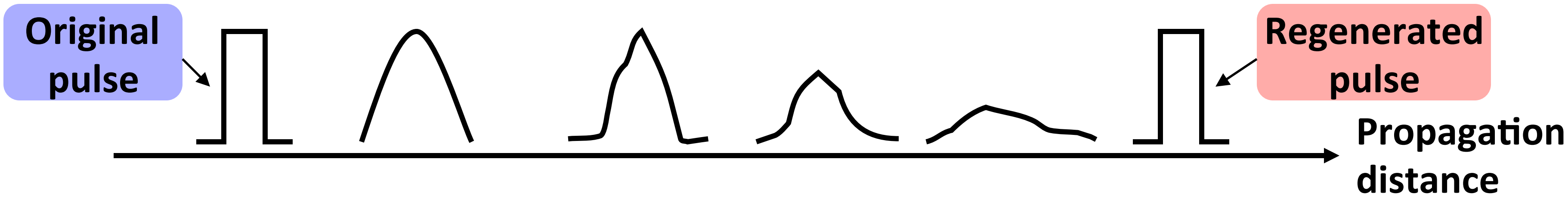
Digital Communication including modulation, channel coding and multiple access methods address the spectral and temporal components of the design.

# Digital Communication

- Designed to transmit information sources to some destination in digital form whether the source is analog or digital.

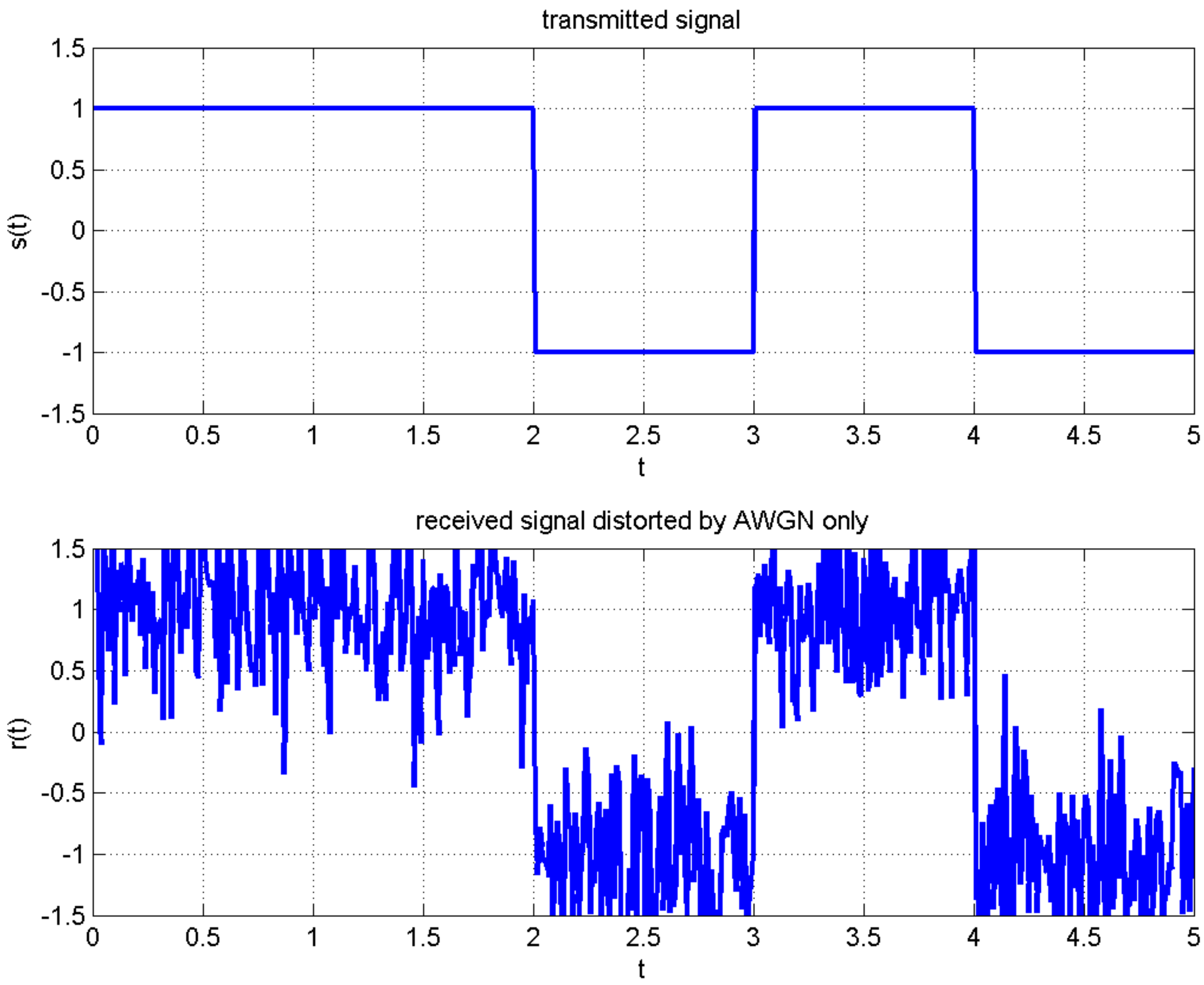
# Digital versus analog

- Advantages of digital communications:
  - Regenerator receiver

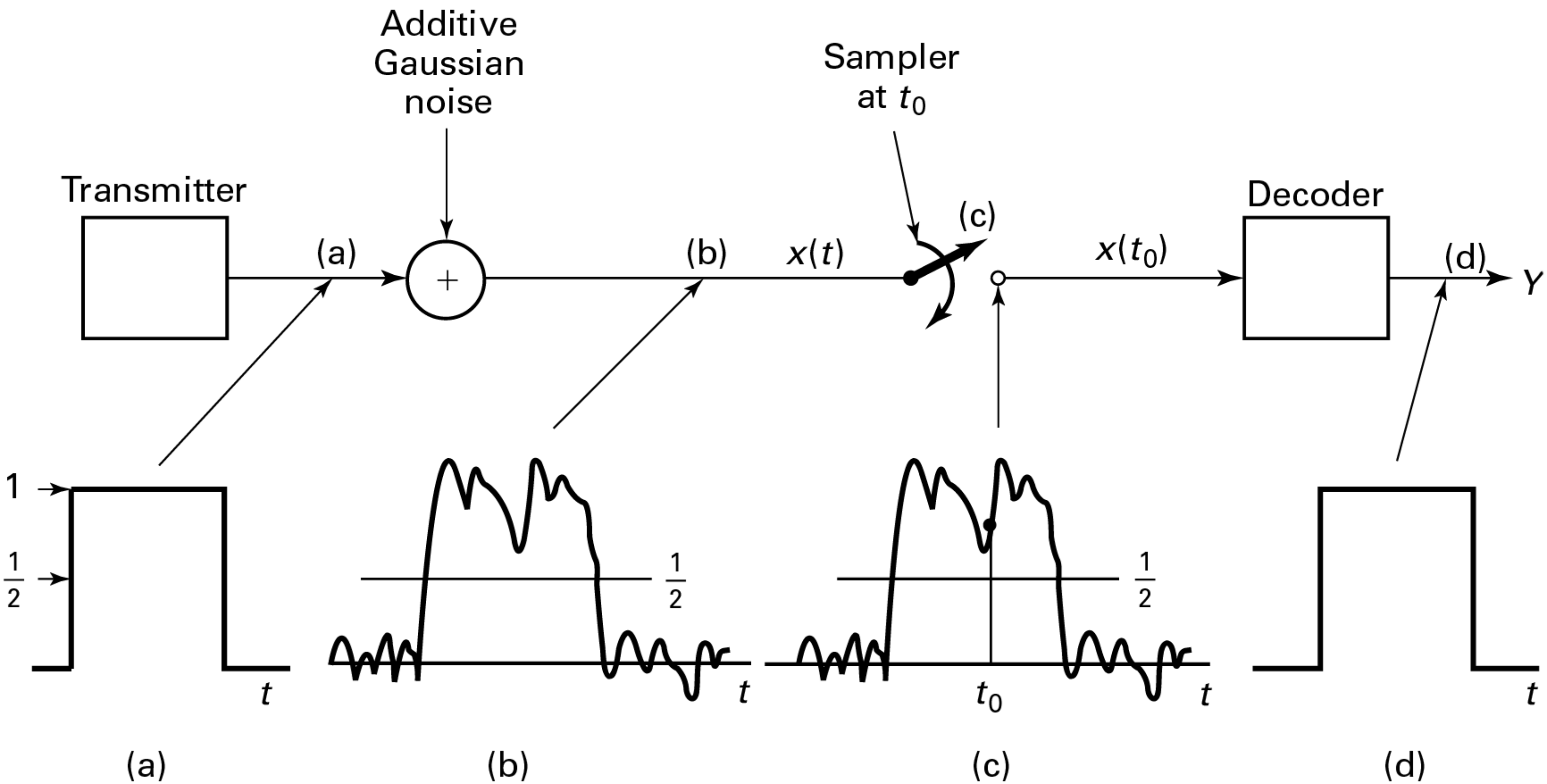



  - Different kinds of digital signal are treated identically.

# Impact of AWGN



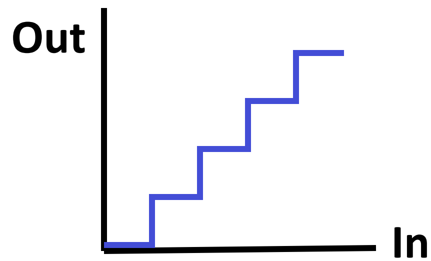
# Detection under AWGN

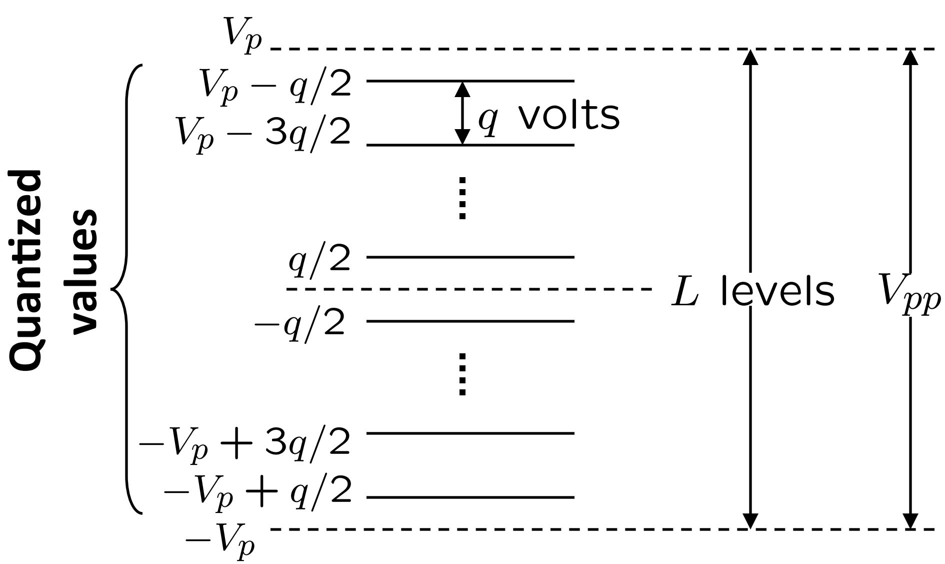



Decoding of a noise-corrupted digital pulse by sampling and hard clipping.

# Quantization

- Amplitude quantizing: Mapping samples of a continuous amplitude waveform to a finite set of amplitudes.




- Average quantization noise power

$$\sigma^2 = \frac{q^2}{12}$$

- Signal peak power

$$V_p^2 = \frac{L^2 q^2}{4}$$

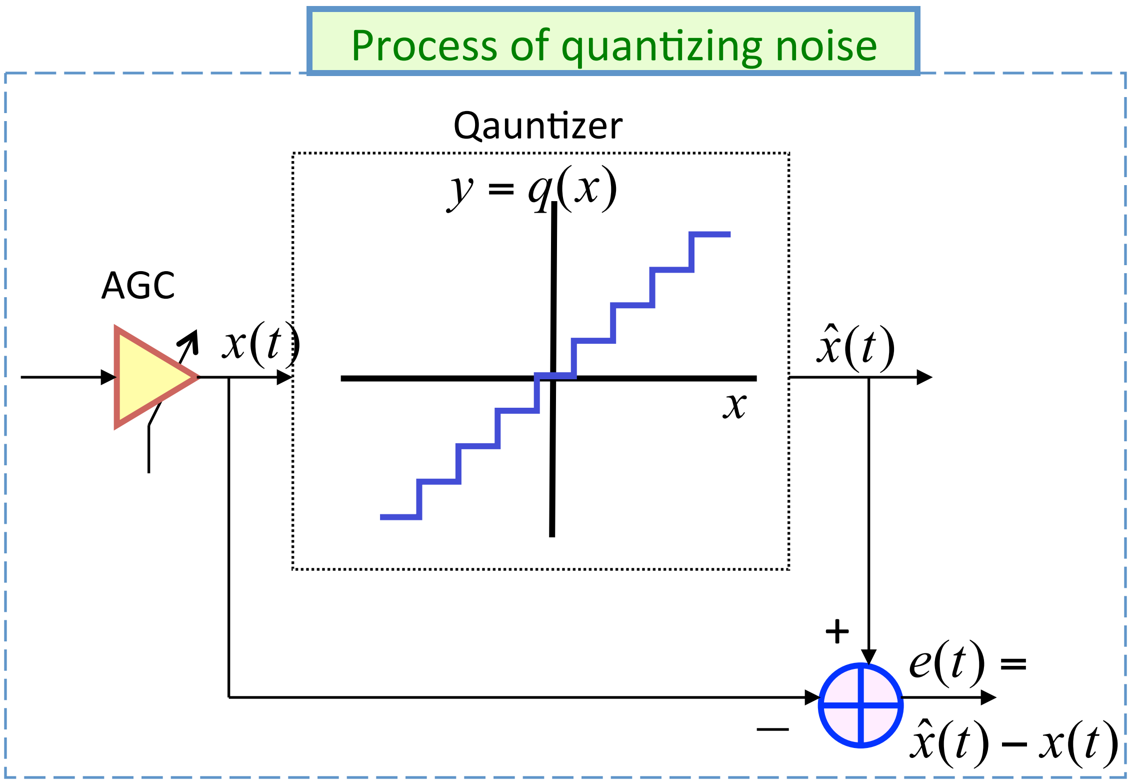
- Signal power to average quantization noise power

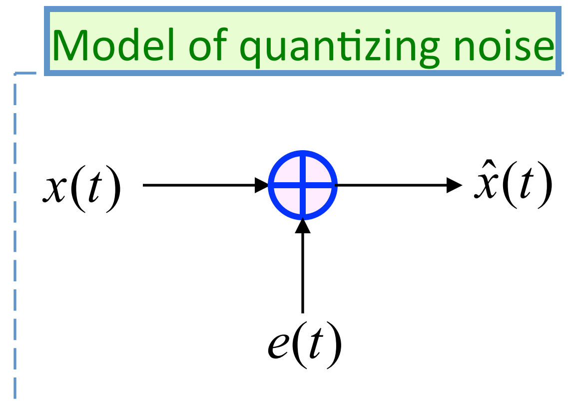
$$\left(\frac{S}{N}\right)_q = \frac{V_p^2}{\sigma^2} = 3L^2$$

# Quantization error

- Quantizing error: The difference between the input and output of a quantizer

$$\Rightarrow e(t) = \hat{x}(t) - x(t)$$

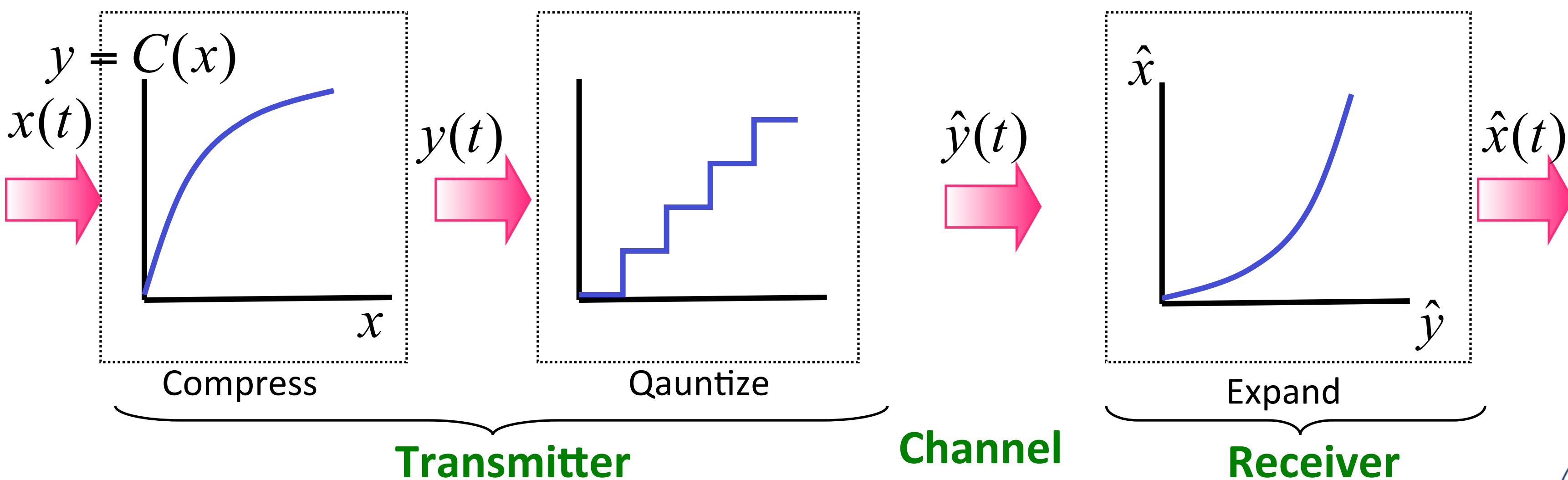


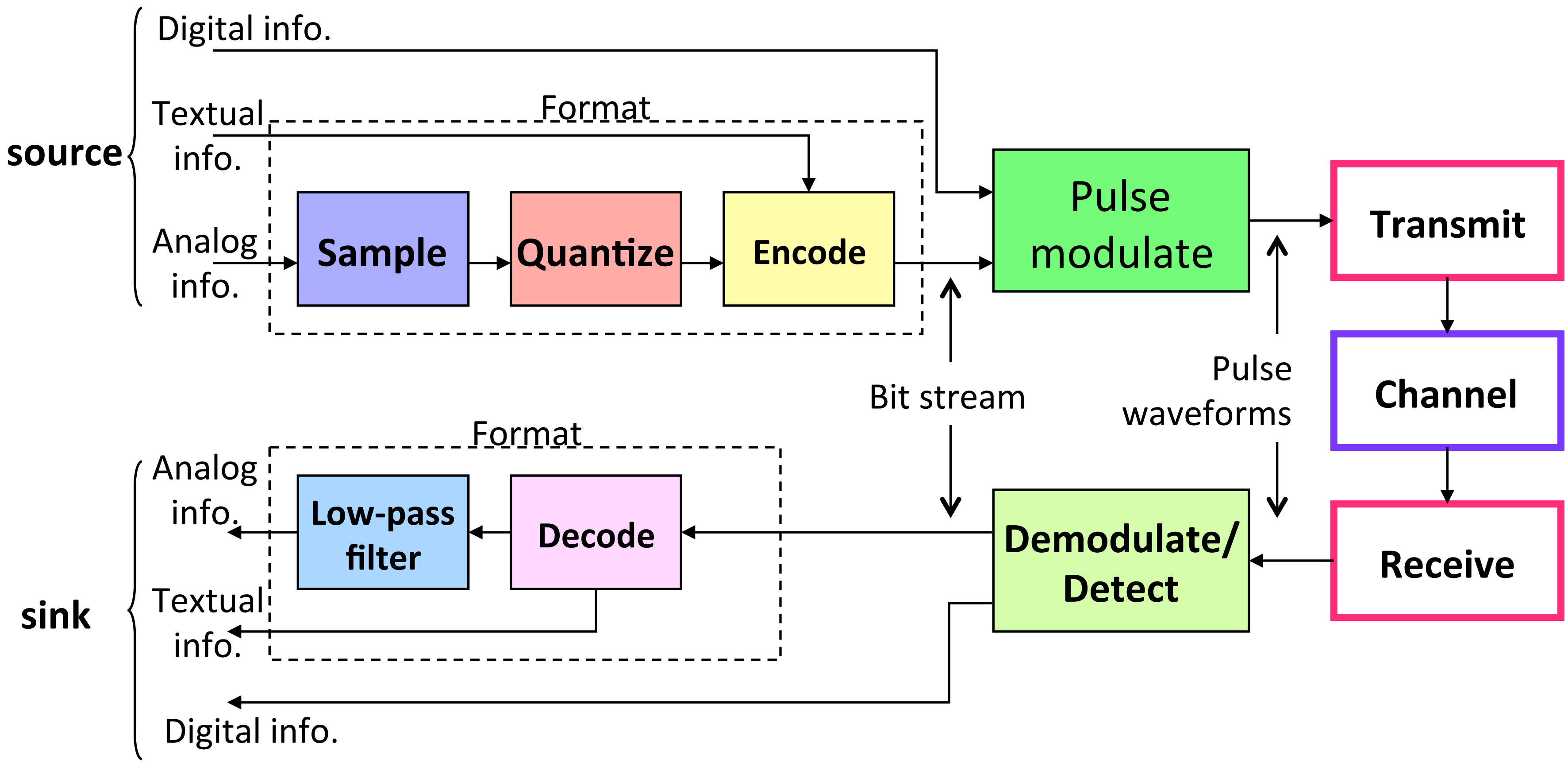
# Non-uniform quantization

- It is done by uniformly quantizing the "compressed" signal.
- At the receiver, an inverse compression characteristic, called "expansion" is employed to avoid signal distortion.

compression+expansion ⇨ companding



# Conversion to digital and transmission



# Digital Communication: Foundation Blocks

At the age of 35 in AT&T, PhD, Yale

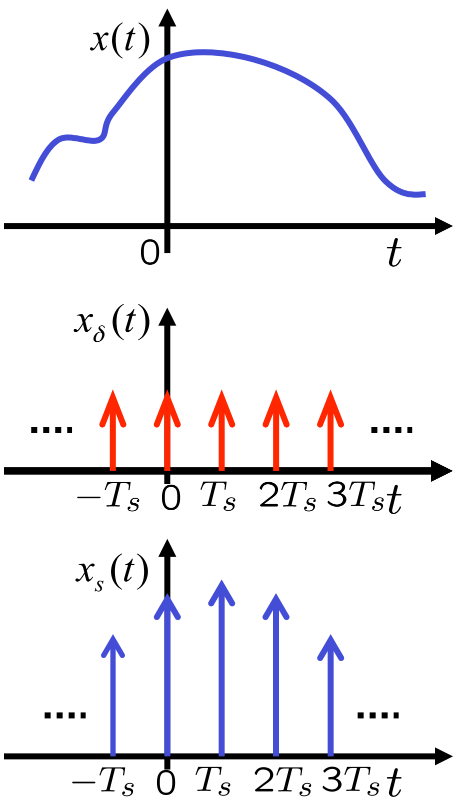
At the age of 32 in AT&T Bell Labs PhD, MIT

- In 1924, modern digital communication has started with <u>Nyquist sampling theorem</u>.
  - » Nyquist Theorem: A signal bandlimited to W Hz can be reconstructed from the samples taken at 2W pulses/s.
  - » Samples are continuous, hence quantized with distortion.
- In 1948, <u>Shannon</u> introduced <u>channel capacity formula</u>.
  - » C=W $log_2$ (1+SNR) bits/s.
  - » Ex: W= 5 MHz, SNR=20dB then C = 22Mbps

# Sampling of Analog Signals

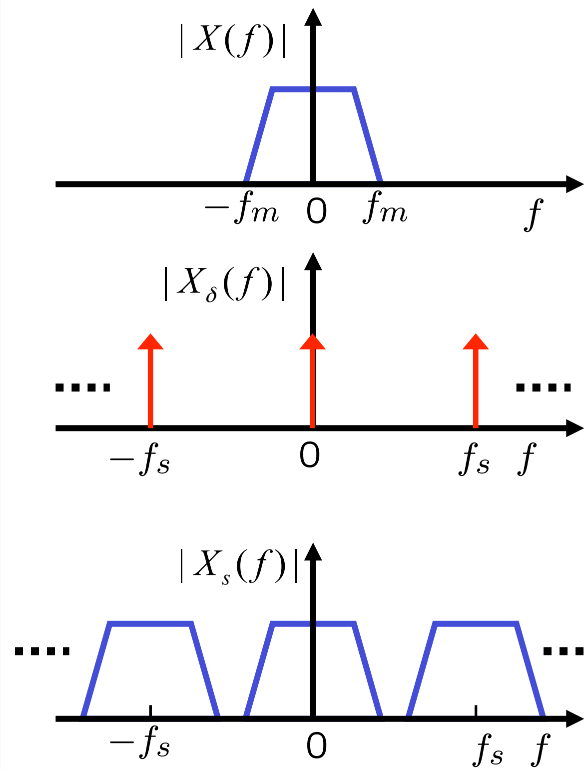
**Time domain**

$$x_s(t) = x_\delta(t) \times x(t)$$

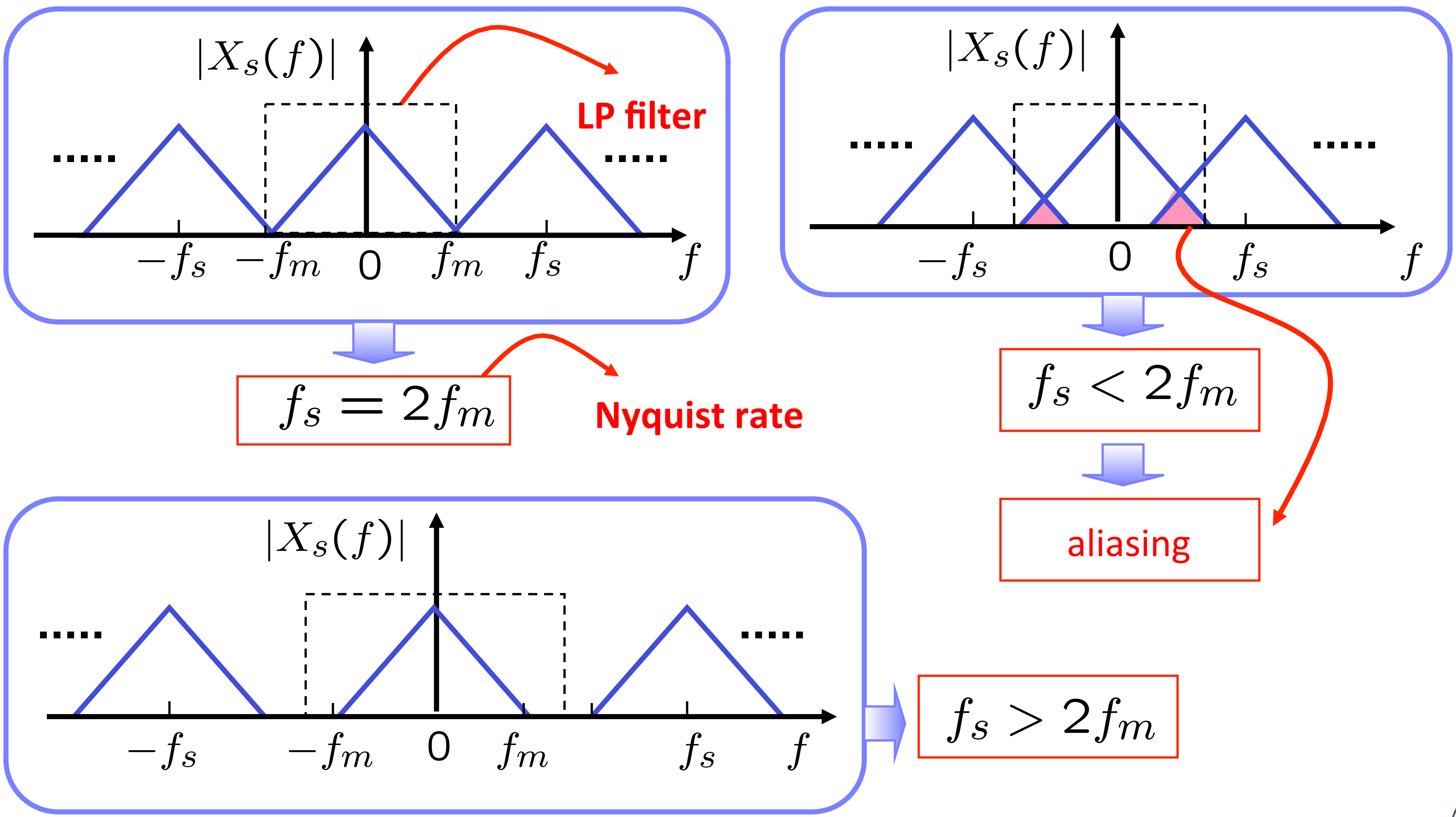



**Frequency domain**

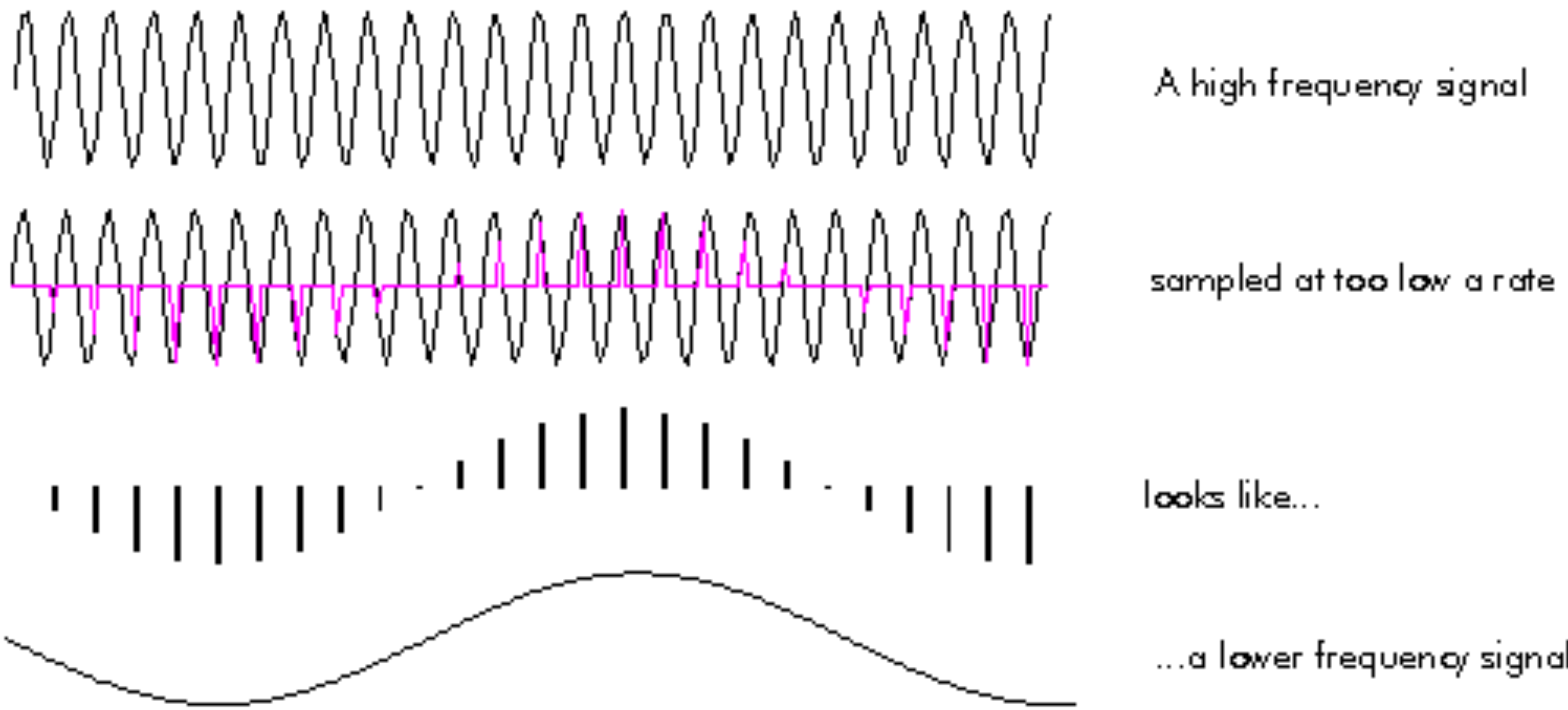
$$X_s(f) = X_\delta(f) * X(f)$$



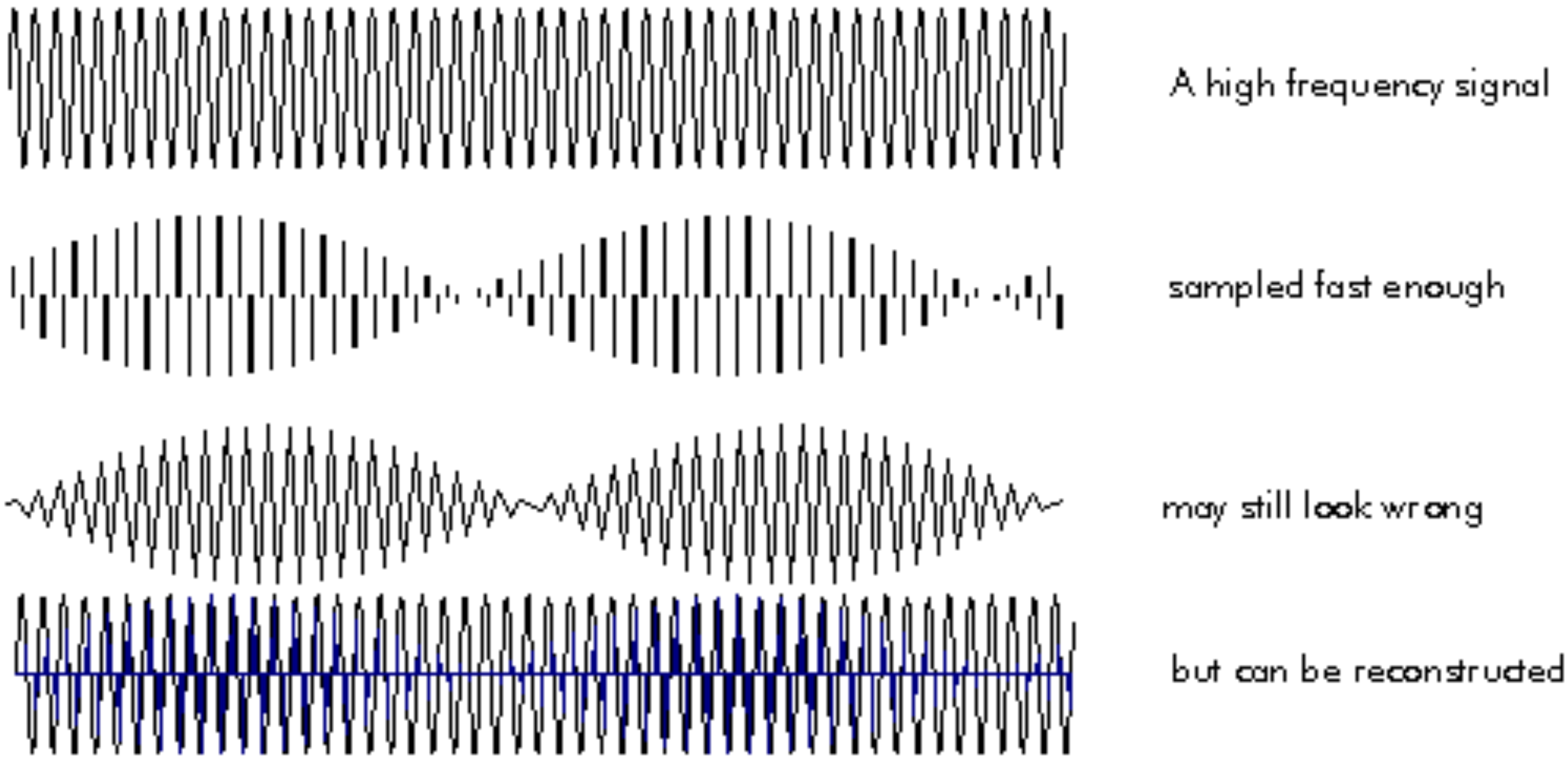
# Aliasing effect & Nyquist Rate



# Undersampling &Aliasing in Time Domain

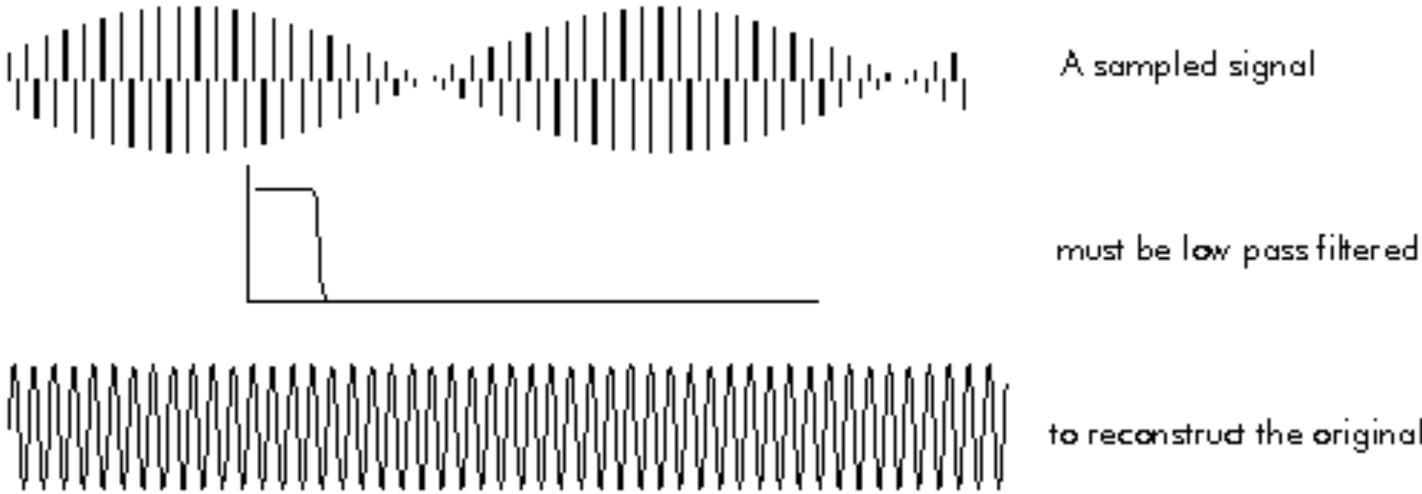


# Nyquist Sampling & Reconstruction: Time Domain



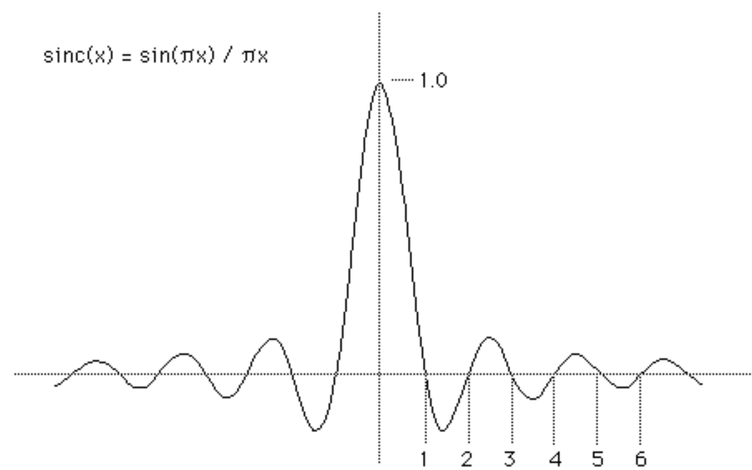

Note: correct reconstruction does not draw straight lines between samples.
Key: use sinc() pulses for reconstruction/interpolation

# Nyquist Reconstruction: Frequency Domain

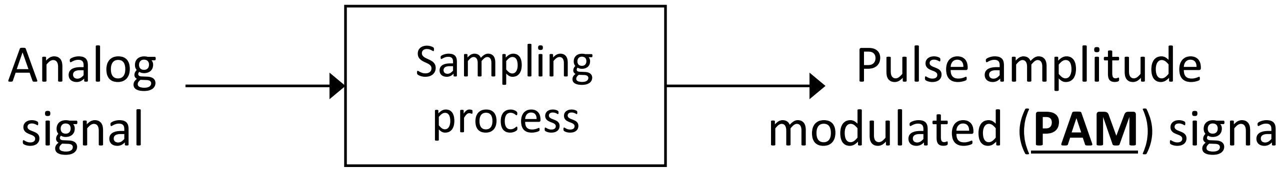



The impulse response of the reconstruction filter has a classic 'sin(x)/x shape.

The stimulus fed to this filter is the series of discrete impulses which are the samples.



# Sampling theorem




- Sampling theorem: A bandlimited signal with no spectral components beyond $f_m$, can be uniquely determined by values sampled at uniform intervals of

$$T_s \leq \frac{1}{2f_m}$$

- The sampling rate,

$$f_s = \frac{1}{T_s} = 2f_m$$

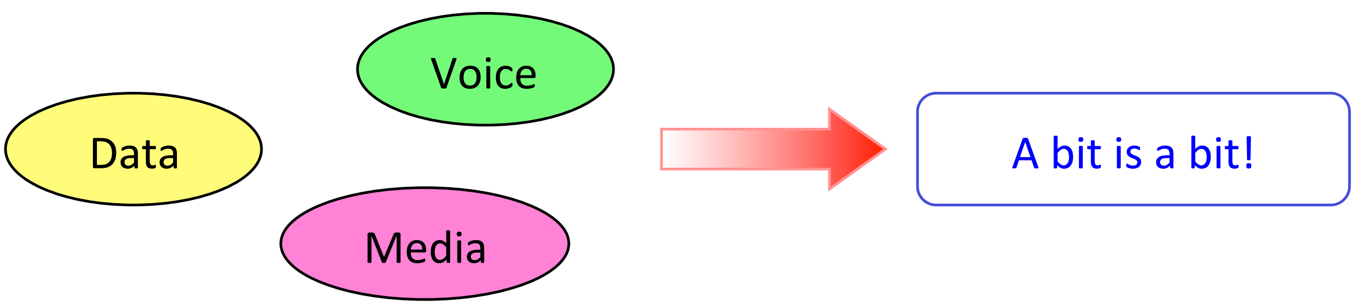
is called Nyquist rate.

- In practice need to sample faster than this because the receiving filter will not be sharp.

# Recap – Source to Digital

- We created bits out of a source – Now what?

- We need to transmit to other end…
  - Error-free
  - Efficient

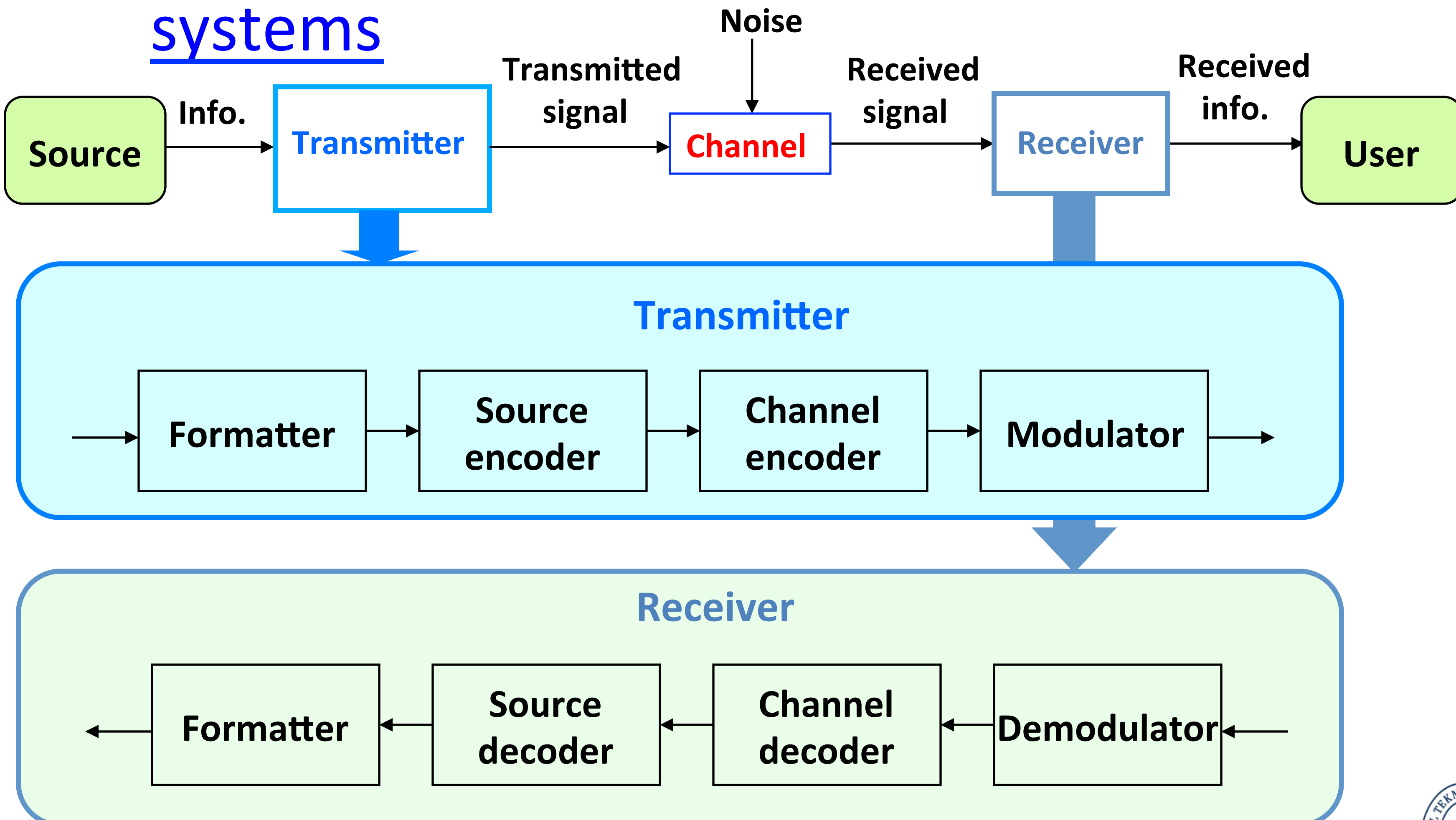


# Digital Communication

- Source Coding
- Channel Coding
- Error Detection Coding
- Forward Error Correction
- Hard and Soft Decision Decoding
- Puncturing
- Hybrid ARQ
- Interleaving
- Encryption and Authentication
- Digital Modulation

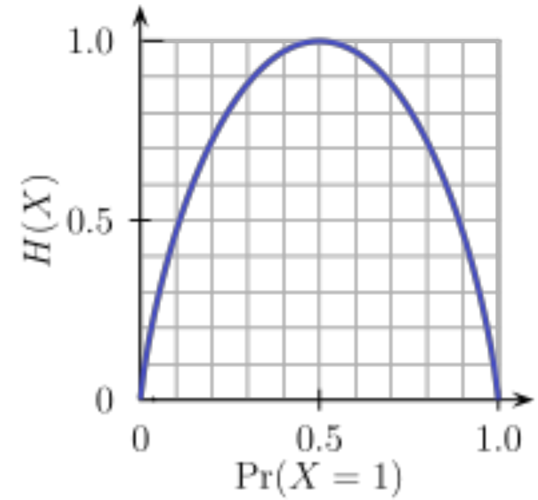
# Bigger Picture

## General structure of a communication systems



# Source Coding

- Before Shannon, in 1928, Hartley introduced a measure of the **information**
  - **Scale is between 0 to 1**
    - **What does that mean?**
      - **If you think that some one is speaking random**
        - » **Then the measure of that information is 1**
      - **If you know what someone will speak next**
        - » **Then the measure of that information is 0**
      - **If you think, he is following a content when speaking**
        - » **Then the measure of that information is between 0 and 1.**



# Source Coding

- Hartley Formula for Information
  - Self information of the event $x_i$ is given by

$$I(x_i) = -\log_2(p(x_i))$$

  - Average self information

$$H(X) = \sum_{i=1}^{m} p(x_i) I(x_i)$$

  - Mutual Information is
    - **Mutual information** measures the amount of information that can be obtained about one random variable by observing another.

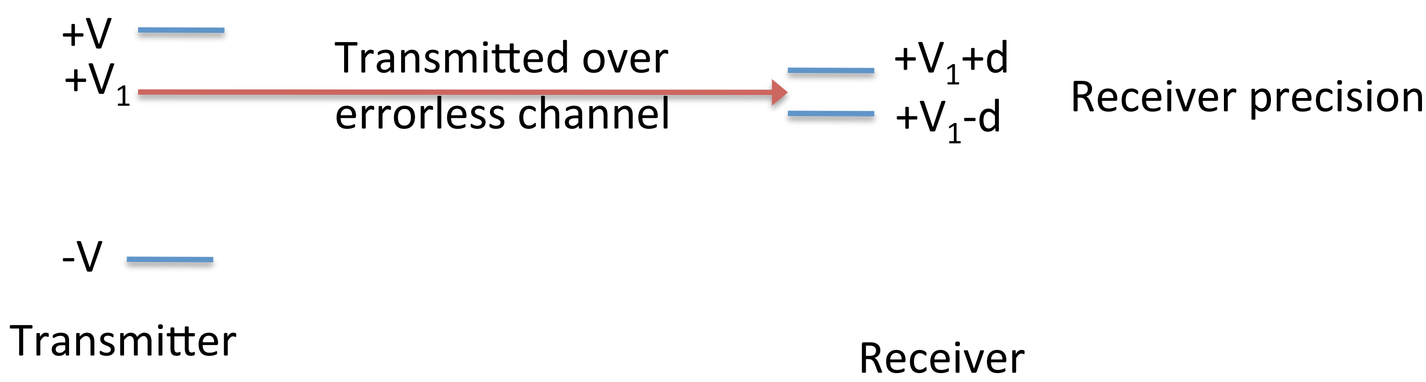
$$I(X,Y) = H(Y) - H(Y \mid X$$

$$H(X|Y) = \mathbb{E}_Y[H(X|y)] = -\sum_{y\in Y} p(y) \sum_{x\in X} p(x|y) \log p(x|y) = -\sum_{x,y} p(x,y) \log \frac{p(x,y)}{p(y)}.$$

*X* given random variable *Y*

# Source Coding

- Hartley Formula for Rate




$$R < 2W \, log_2(M) \text{ bits where } M = 1 + V/d$$

Nyquist rate pulse/s

Information in bits/ pulse

Maximum Number of Distinct Pulses

# Source Coding

- Hartley doesn't address
  - how the number *M* should depend on the noise statistics of the channel,
  - how the communication could be made reliable even when individual symbol pulses could not be reliably distinguished to *M* levels;
  - with Gaussian noise statistics, system designers had to choose a very conservative value of *M* to achieve a low error rate.
- The concept of an error-free capacity awaited Claude Shannon,
  - » built on Hartley's observations about a logarithmic measure of information and Nyquist's observations about the effect of bandwidth limitations.
  - » Developed in World War II
  - R < C - there is a coding technique to achieve this
  - R > C - the communication is erroneous

# Shannon's Theorem

- Revisit Shannon's theorem

$$C = \max_{p(x)} I(X;Y) = H(Y) - H(Y \mid X) = W \log_2(1 + SNR)$$

  - Finite Capacity due to finite bandwidth and non-zero noise
  - Additive White Gaussian Noise
    - » Input is Gaussian RV with power S
    - » White Noise N is $WN_o$
    - » Received Signal is S + N where S is transmitted signal

What is this?

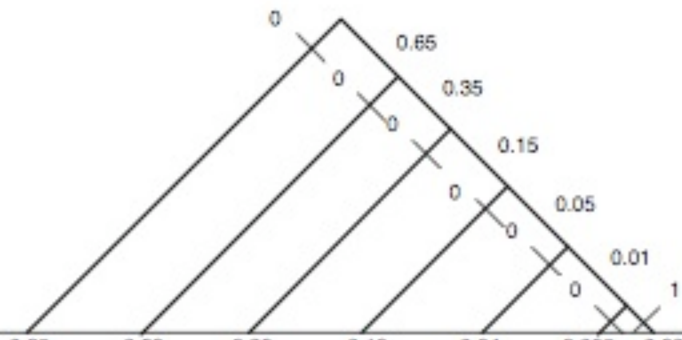
$$2W \log_2(M) = W \log_2(1 + SNR)$$

# Source Coding

- We have source and we will send bits.
  - What is the average number of binary digits required per output of the source
    - Why this is needed?
      - Channel bandwidth is lower than the input signal bandwidth
        - » Hence, we need to represent the source with less number of binary digits so that we can send via the channel
          - This is called source coding which reduces the redundancy in the information source.
            - Assumes source memoryless – a source produces symbols that are statistically independent to each other.
            - Fixed or variable lengths
              - If fixed, If there are m symbols then at max it requires $R=\log_2 m$ bits
              - However, $R > H(x)$

# Source Coding

- Huffman in 1952
  - Variable length encoding
  - If you know the source alphabet probabilities you can construct a tree




| Probability | 0.35 | 0.30 | 0.20 | 0.10 | 0.04 | 0.005 | 0.005 |
|---|---|---|---|---|---|---|---|
| Self-information | 1.5146 | 1.7370 | 2.3219 | 3.3219 | 4.6439 | 7.6439 | 7.6439 |
| **Code** | **0** | **10** | **110** | **1110** | **11110** | **111110** | **111111** |
| Symbols | x1 | x2 | x3 | x4 | x5 | x6 | x7 |

H(X)=2.11
Average R =2.21

**Fig. 2.9** A code for DMS

- Lempel-Ziv in 1977 and 1978
  - introduced universal source coding which does not require the source statistics where both compressor and decompressor create a dictionary on the fly.

# Channel Coding

- When a code is transmitted over noisy channel, error will occur.
- To achieve lossless transmission, additional redundancy needs to be introduced.
- Channel coding restructures the source information to minimize the error probability in the decoding.
  - Channel coding is longer than the source code
  - If we revisit the Shannon,
    - There exists a channel code to permit error-free transmission across the channel at a rate R, provided that $R \leq C$
    - Equality is achieved when?

# Channel Coding

- What is the use of channel coding?
  - Detect error
  - Correct error

# Error Detection Coding

- Receiver detects the error and requires a retransmission
  - ARQ: Automatice Repeat Request mechanism
  - The most common is parity check coding
    - Appends one bit to the end of m data bits to make (m+1) bits to make even (or odd)
  - Polynomical codes
    - Appends additional bits to the end of each frame
    - CRC: Cyclic Redundancy Check
      - » Divides the frame with a generator polynomial
        - 9 bits for CRC-8
        - 17 bits for CRC-16 : TCP/IP, WiMAX
        - 33 bits for CRC-32 : Ethernet, TCP/IP, WiMAX
        - 65 bits for CRC-64

# Forward Error Correction

- Correct errors
  - Block-coding
    - Reed-Solomon (RS) coding
  - Convolutional coding

- We will see later in detail

# Puncturing

- Code rate: Identifies the error correction coding:
  - Original length of the symbol over coded symbol length
  - A code rate ½ is one additional bit per an input bit.
  - With puncturing we can further remove the parity bits to increase the coding rate.
    - Allows some low rate and low complexity decoder to be used for high rate encoded signal.
    - Same puncturing pattern is used in the decoder
    - Construct a ¾ out of ½.

# Hybrid ARQ

- ARQ is typically in MAC layer:
  - HARQ is in physical layer - mitigated from MAC to PHY
    - In order to reduce the retransmission with redundancy.
    - Chase combining
    - Incremental Redundancy

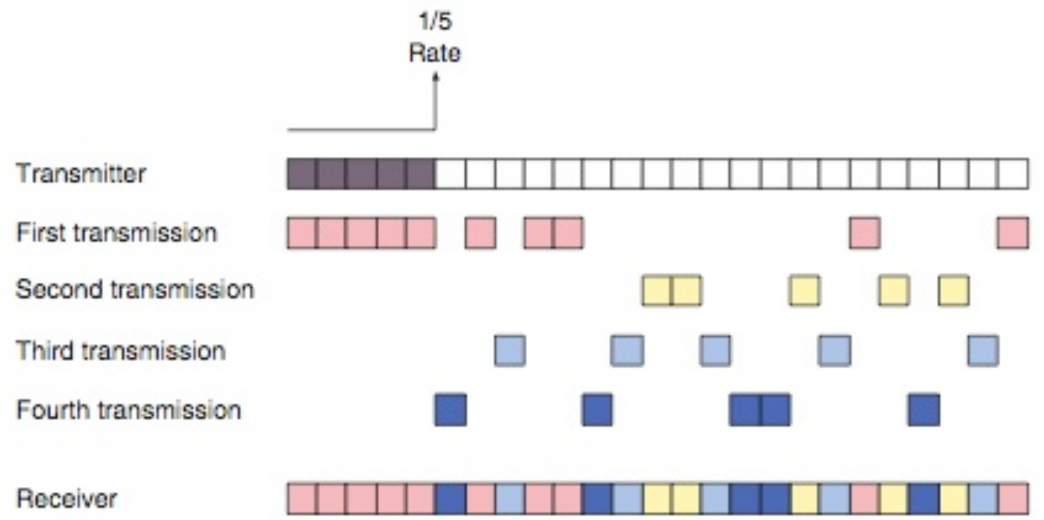



Fig. 2.11 HARQ Type II: Incremental redundancy

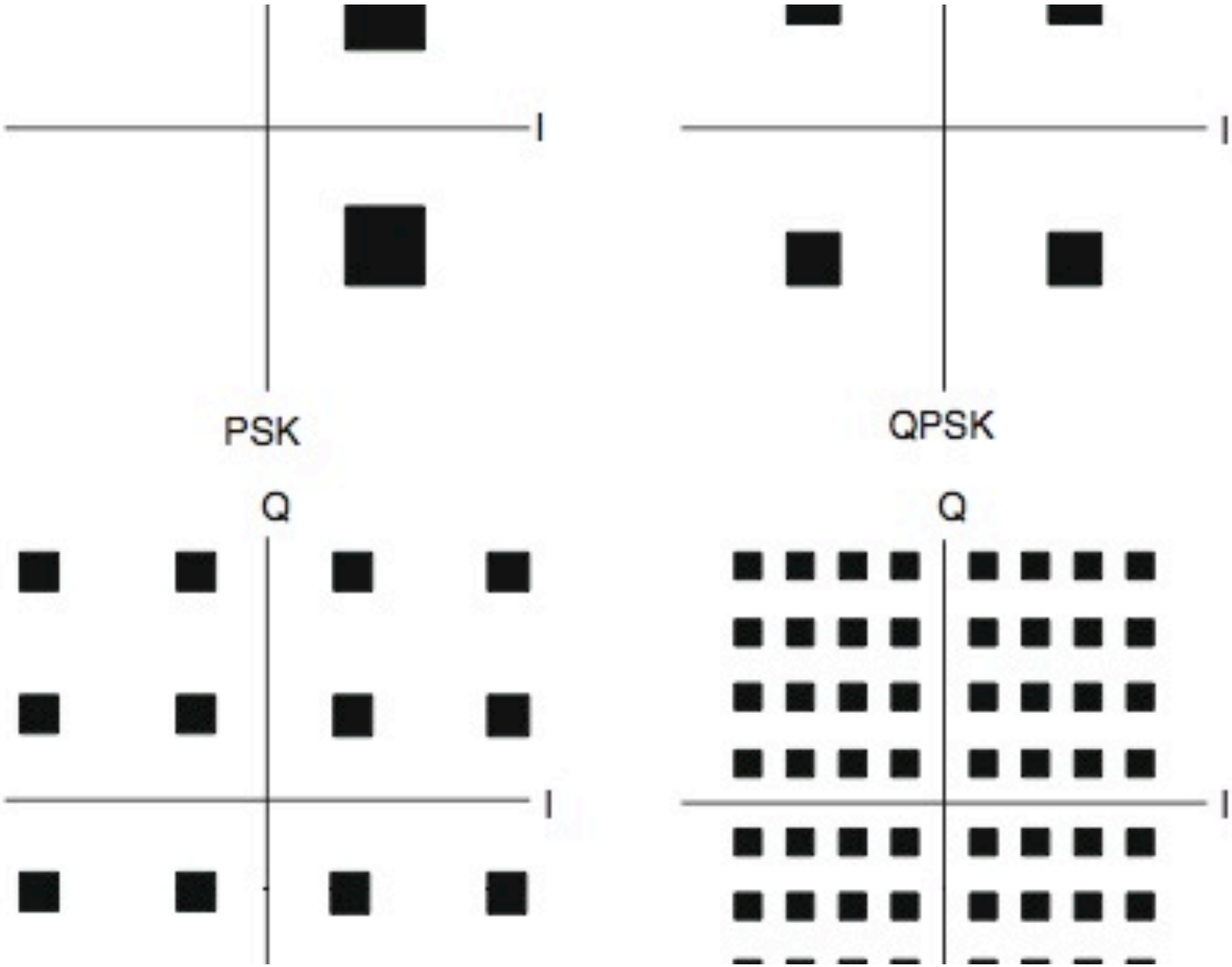
# Interleaving

| | |
|---|---|
| Error-free transmission | mmmmuuuusssstttteeeerrrrgggg |
| Transmission with a burst error | mmmmuuuusss____teeeerrrrgggg |
| Interleaved | mustergmustergmustergmusterg |
| Interleaved Transmission with a burst error | mustergmust____ustergmusterg |
| After deinterleaving | mm_muuuusssstttte_eer_rrg_gg |

# Encryption and Authentication

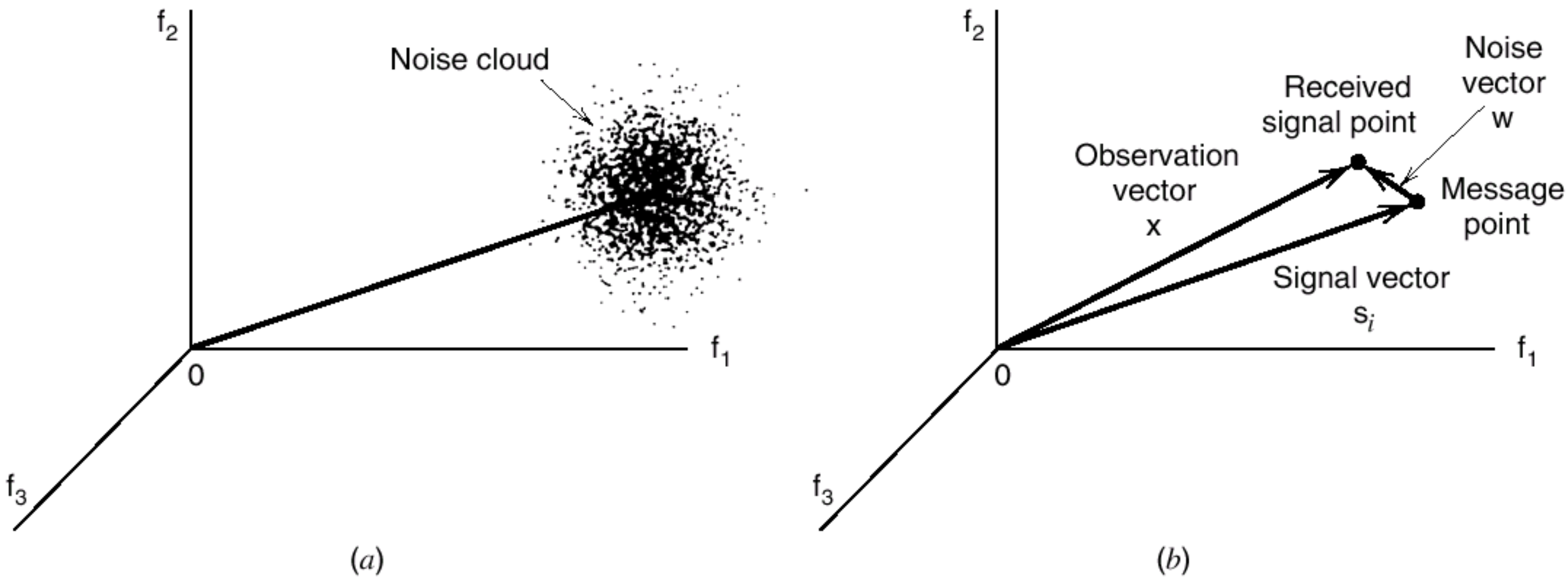
- Encryption
  - Protect bits with another level of manipulation
  - Cipher: encrypts the plaintext and decrypt the ciphertext
    - Block ciphers or continuous stream ciphers.
- Authentication
  - Against unprotected altering during transmission

# Digital Modulation



# Effect of Noise in Signal Space

- The cloud falls off exponentially (gaussian).
- Vector viewpoint can be used in signal space, with a random noise vector **w**



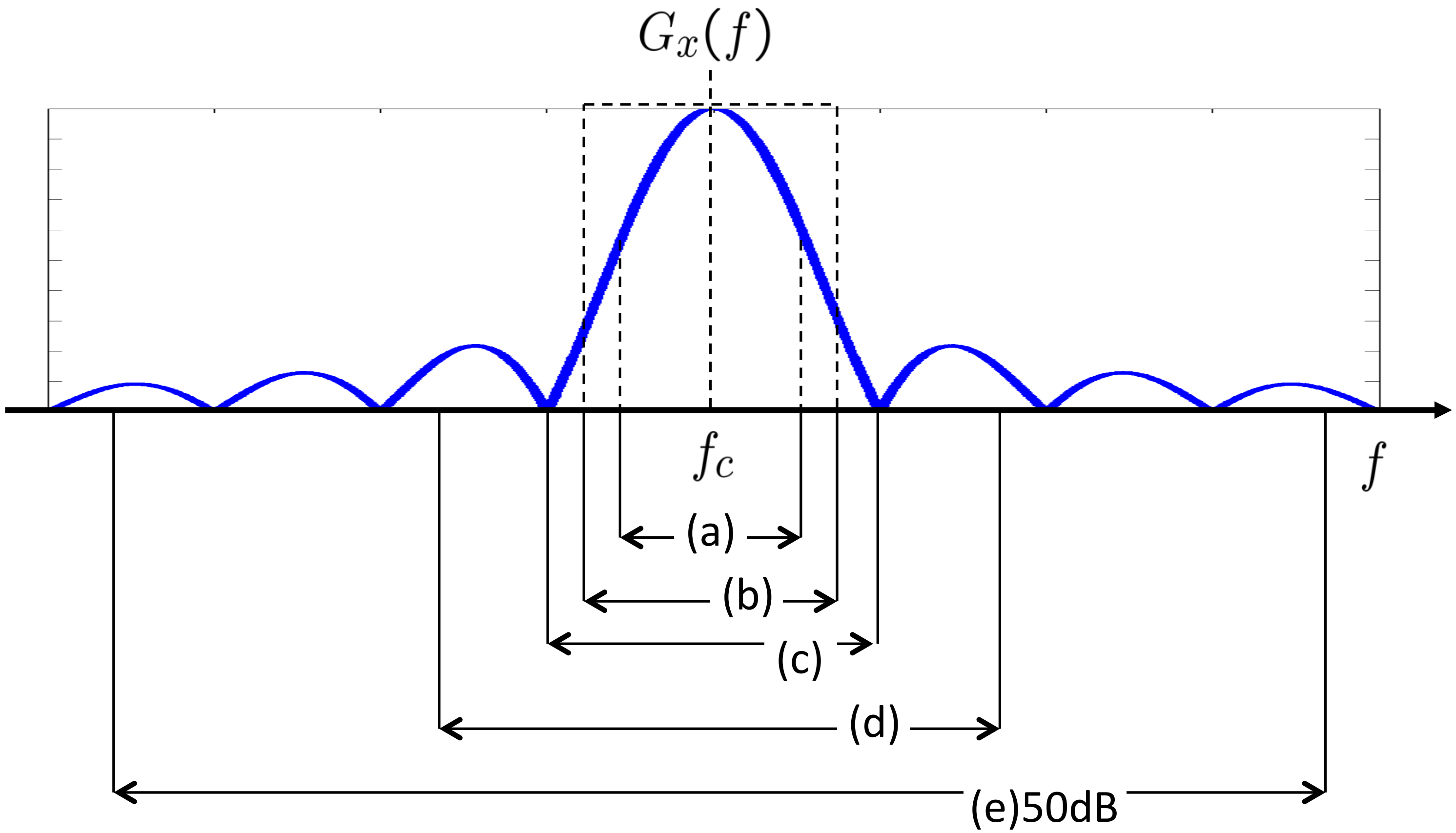
# Hard and Soft Decision Decoding

- Hard Decoding
  - Just considers binary output of the decoder
- Soft Decoding
  - Considers binary output as well as the analog error

# Bandwidth of signal: Approximations

- Different definition of bandwidth:

a) Half-power bandwidth
b) Noise equivalent bandwidth
c) Null-to-null bandwidth
d) Fractional power containment bandwidth
e) Bounded power spectral density
f) Absolute bandwidth

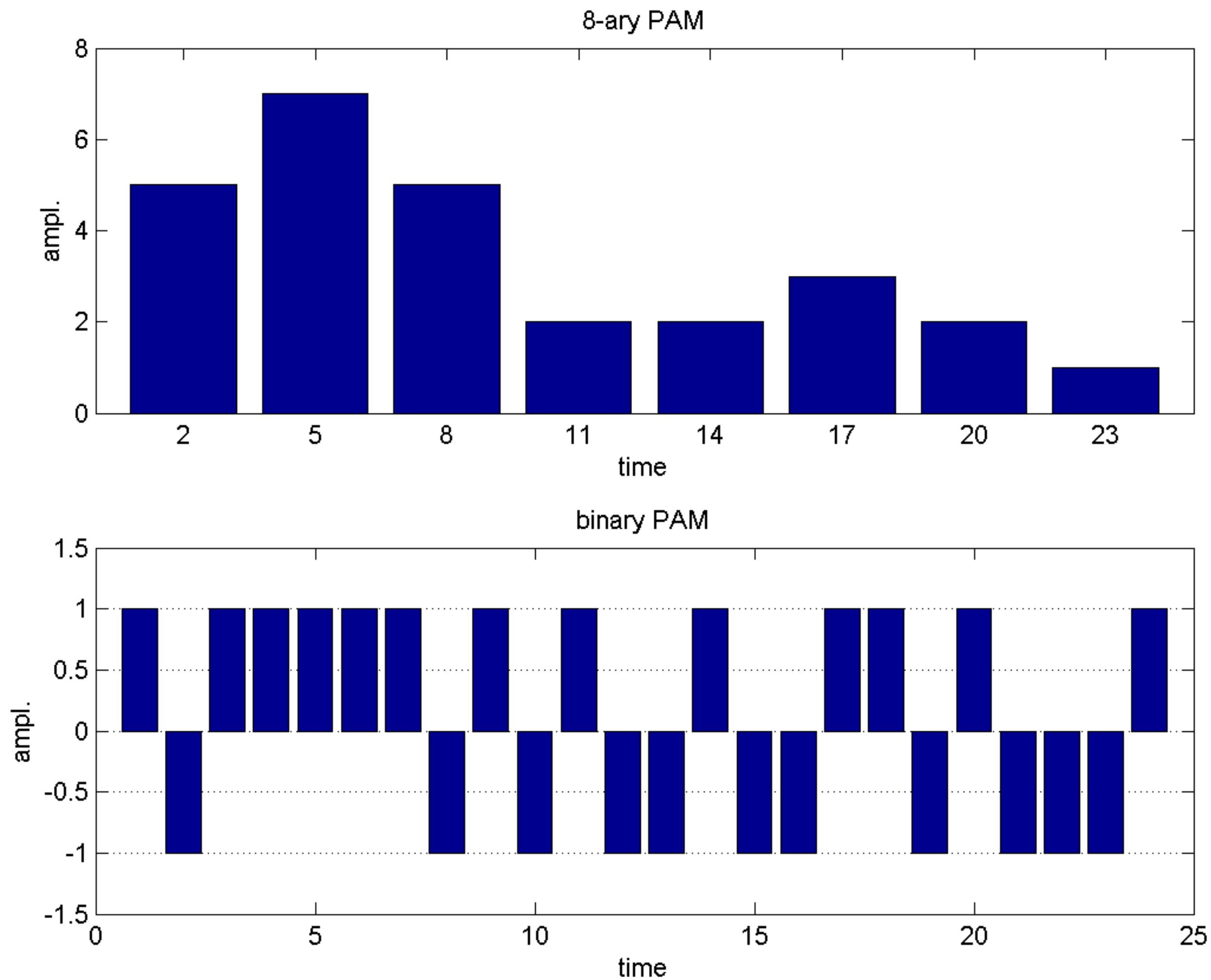


# Baseband transmission

- To transmit information thru physical channels, PCM sequences (codewords) are transformed to pulses (waveforms).
  - Each waveform carries a symbol from a set of size M.
  - Each transmit symbol represents $k = \log_2 M$ bits of the PCM words.
  - PCM waveforms (line codes) are used for binary symbols (M=2).

- M-ary pulse modulation are used for non-binary symbols (M>2). Eg: M-ary PAM.
  - For a given data rate, M-ary PAM (*M>2*) requires less bandwidth than binary PCM.
  - For a given average pulse power, binary PCM is easier to detect than M-ary PAM (*M>2*).

# PAM example: Binary vs 8-ary



# Receiver job

- Demodulation and sampling:
  - Waveform recovery and preparing the received signal for detection:
    - Improving the signal power to the noise power (SNR) using matched filter (project to signal space)
    - Reducing ISI using equalizer (remove channel distortion)
    - Sampling the recovered waveform

- Detection:
  - Estimate the transmitted symbol based on the received sample

# References


- *Mobile Broadband,* Ergen
- *Slides of* Sorour Falahati, A. Goldsmith,