Communications Theory

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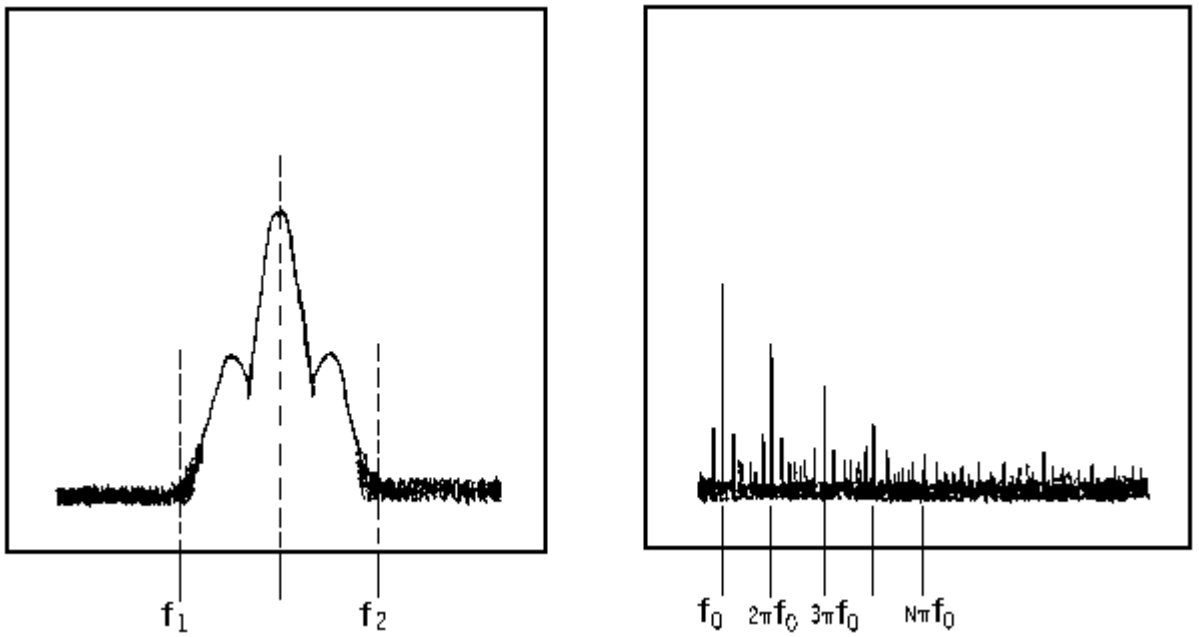
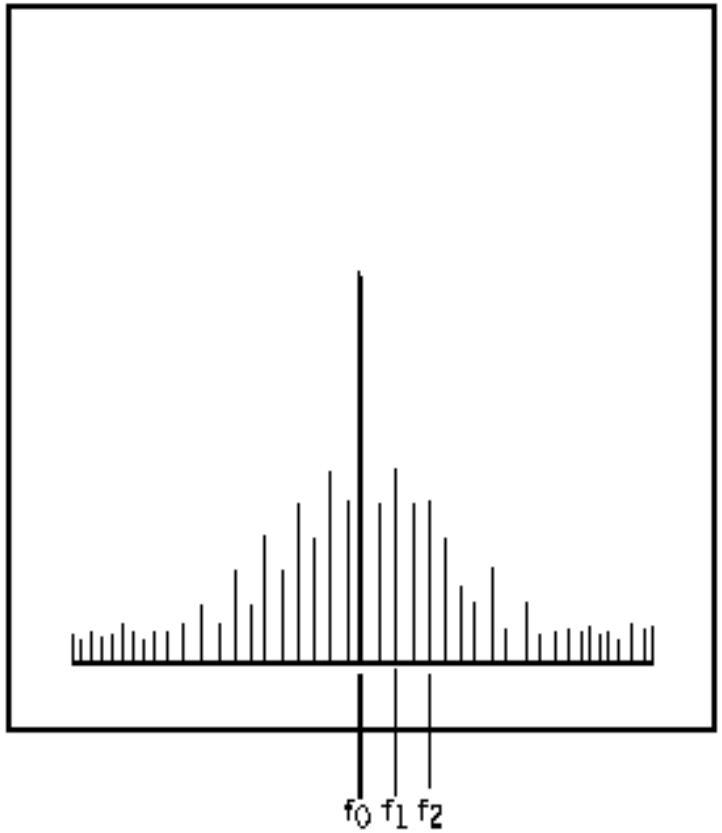
Spectrum Analyzer Display



Modulated sidebands between f_1 and f_2.

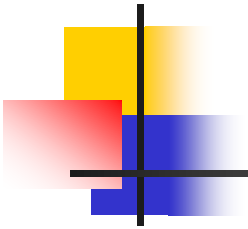
Increasing display bandwidth shows carrier with sideband modulation.

Analyzer With Wide Bandwidth



Increasing analyzer display further shows decreasing carrier amplitude.

When the analyzer bandwidth is 1 MHz, the display is broadband.

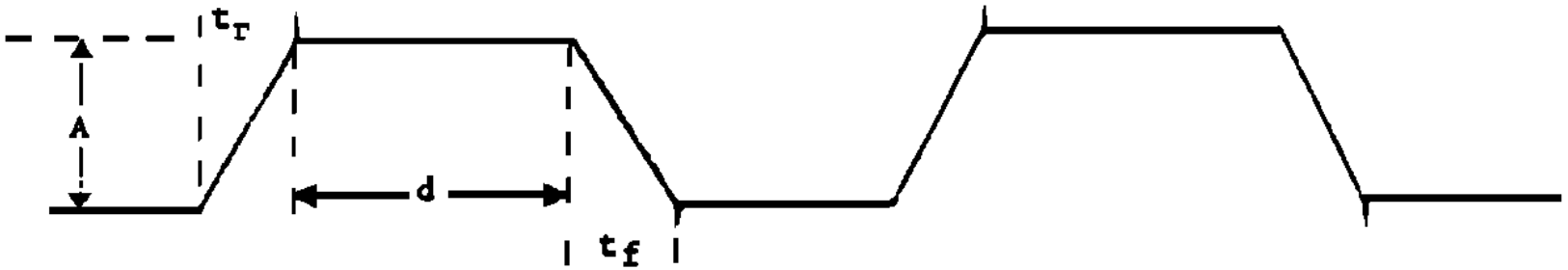


Definitions

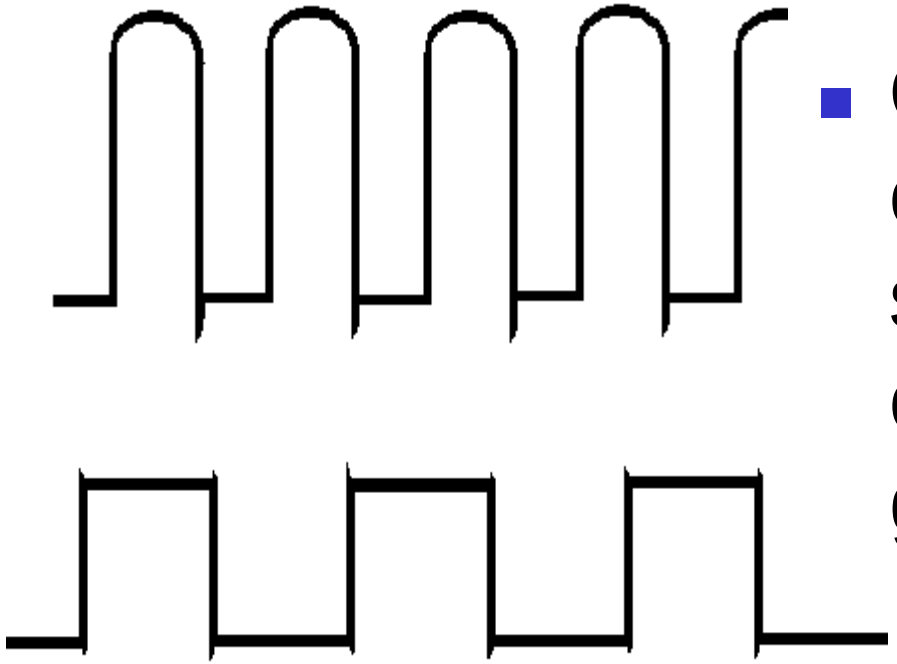
- Carrier
  - *A wave having at least one characteristic that may be varied from a known reference value by modulation*
- Modulation
  - *The process by which some characteristic of a carrier is varied in accordance with a modulating wave*

The TEMPEST Signal

- Typical waveform with duration, amplitude, rise time and fall time
  - Harmonics are the modulation source

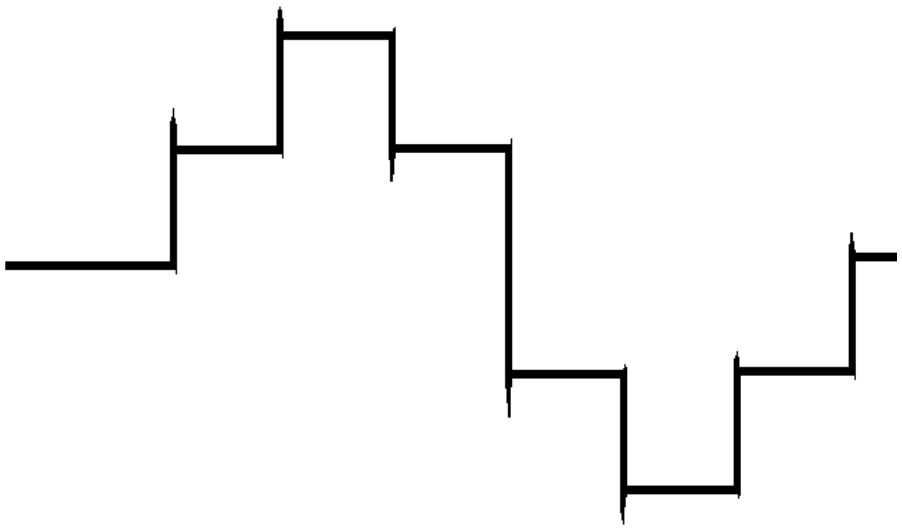


Common Carriers

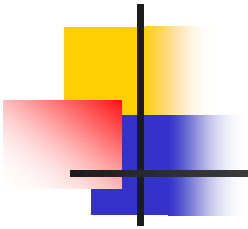


- Oscillators and clocks are major sources of carrier energy in ground planes

Switching Regulator Waveform

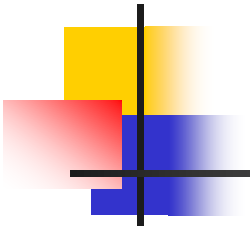


- The largest single source of carrier energy is the switching regulator power supply.



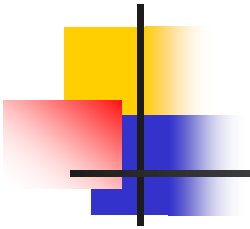
Definitions

- Complex Modulation
  - Any combination of modulation techniques applied to a single carrier
- Multiplex
  - To interleave or simultaneously transmit two or more messages on a single channel



Definitions

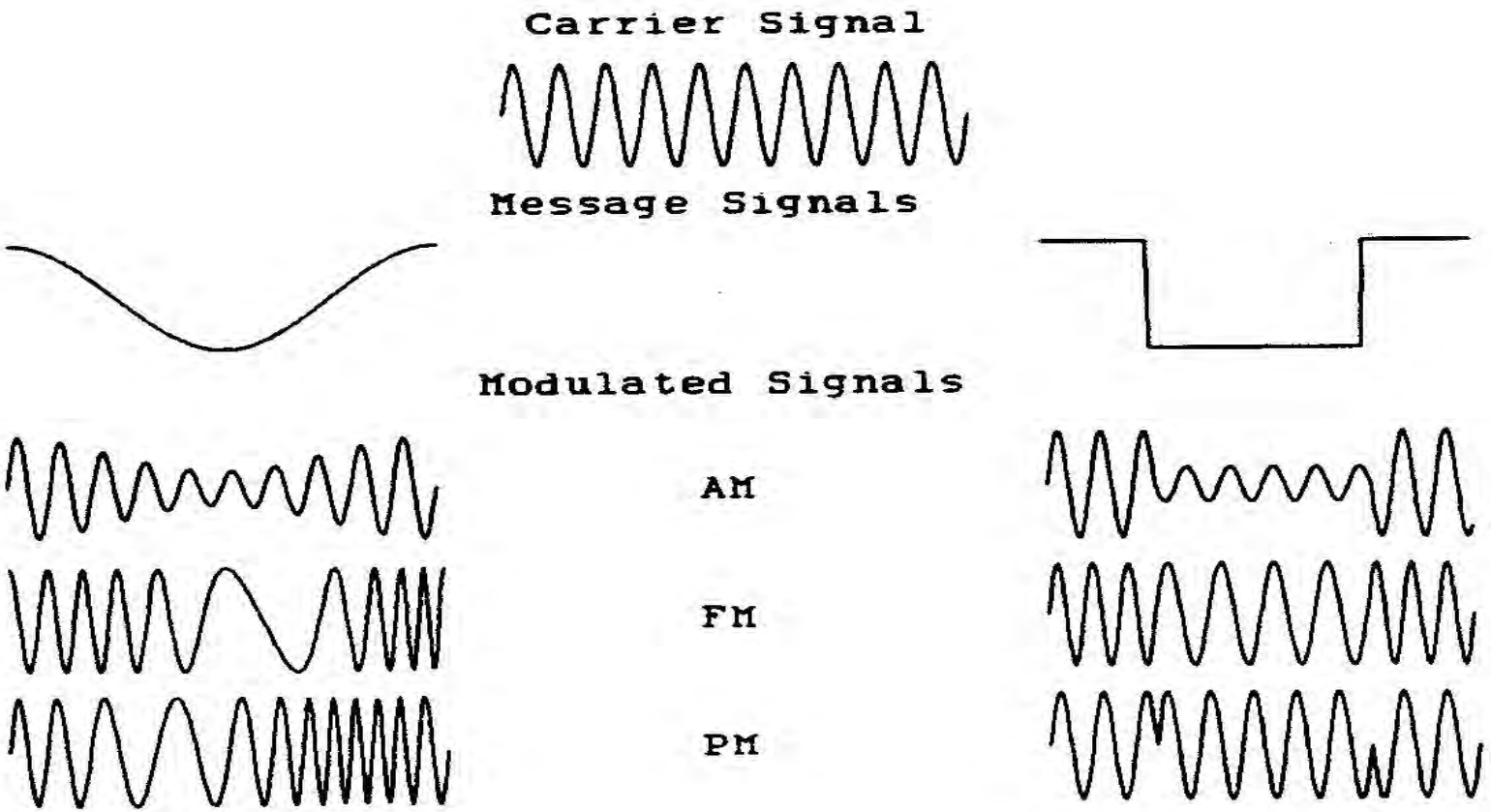
- Amplitude Modulation (AM)
  - the signal amplitude is varied by the modulating signal while the phase remains unchanged
- Frequency Modulation (FM)
  - the frequency deviation of the carrier is proportional to the message signal
- Phase Modulation (PM)
  - the phase deviation of the carrier is proportional to the message signal



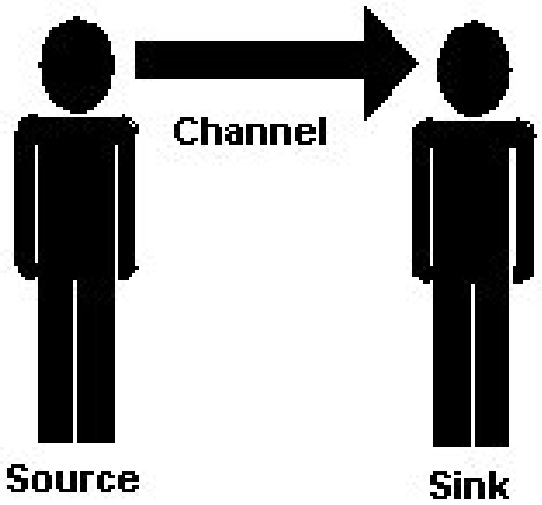
Spread Spectrum

- A modulation technique for multiple access, or for increasing immunity to noise or interference.
- The signal appears as broadband noise.
- Combining frequency hopping and encryption with spread spectrum is the most secure communications technique available.

AM, FM, and PM

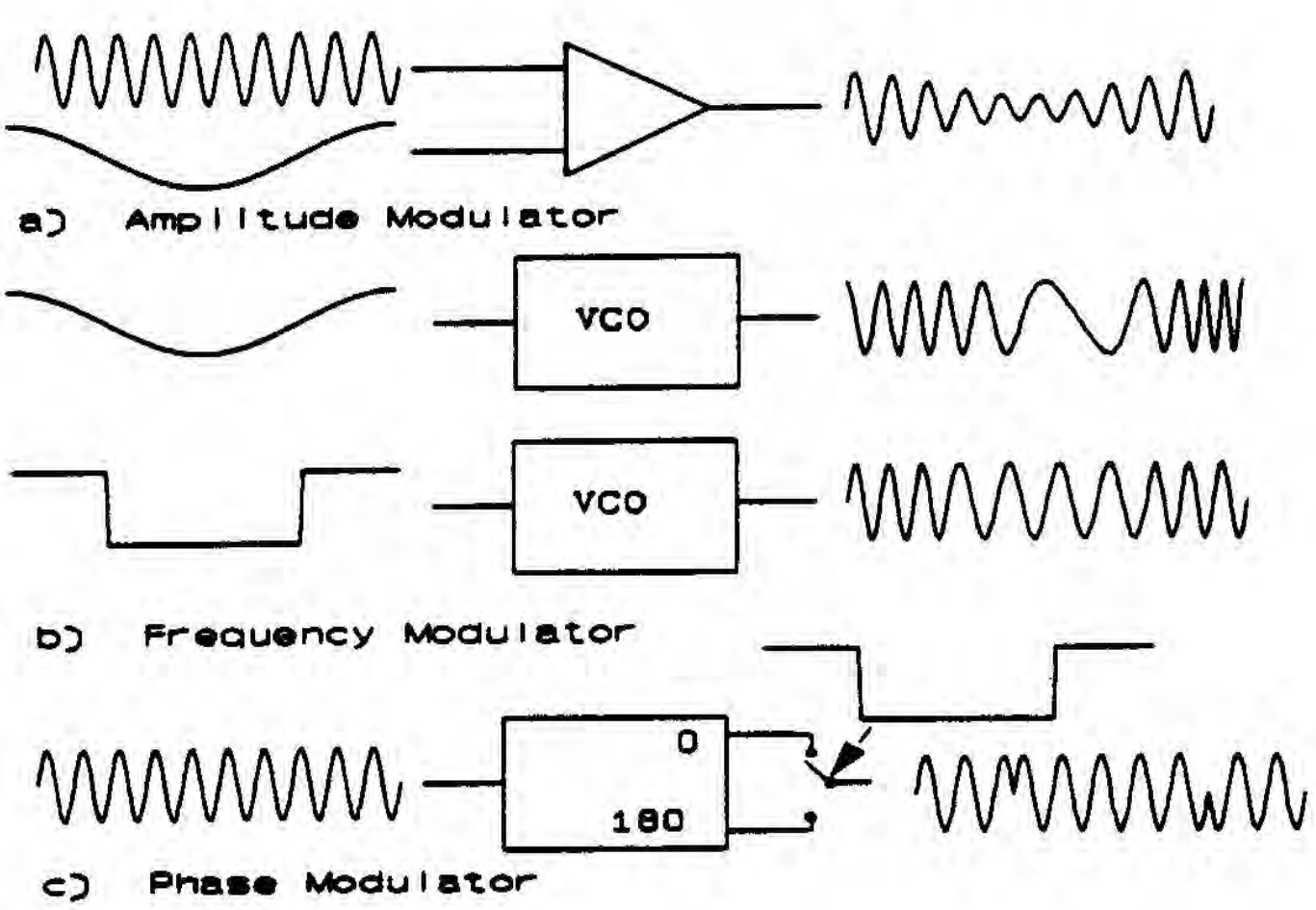


An Information System



- For information to get from one place to another, there must be a transmission medium or channel between the source and receptor (information sink)

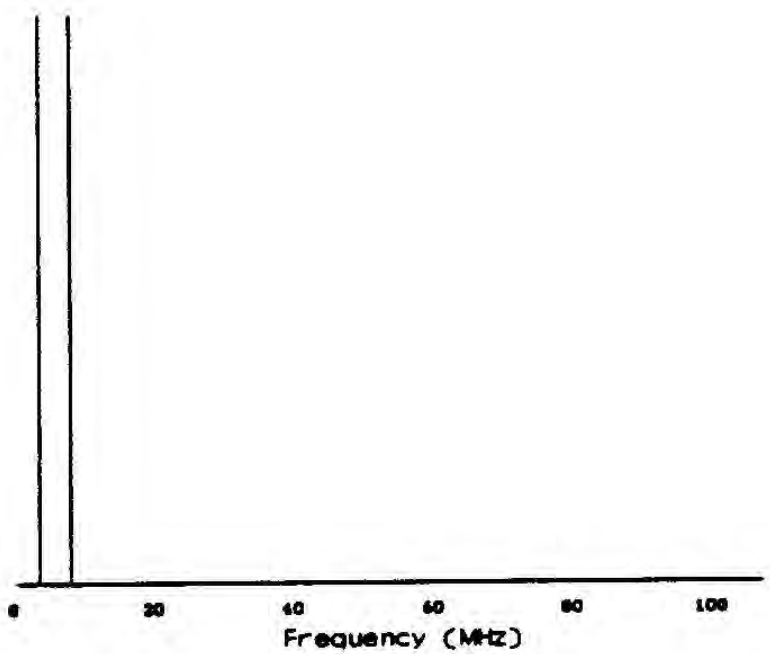
Techniques to Modulate



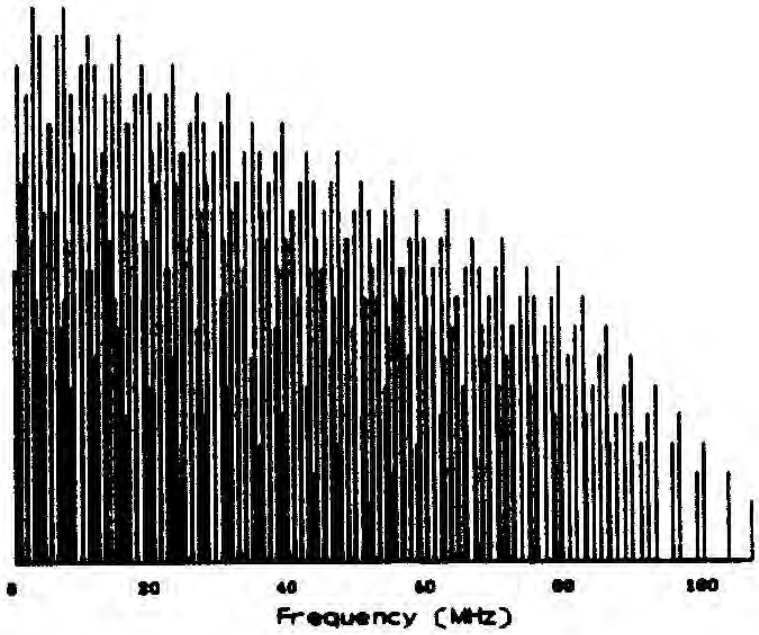
Spectrum Signature

- When two frequencies, f_1 and f_2, are mixed in a nonlinear junction, such as a diode or transistor, the resulting output signals consist of:
  - the two fundamental frequencies: f_1 and f_2
  - all the harmonics of both fundamentals: $2f_1$, $2f_2$, $3f_1$, $3f_2$, $4f_1$, $4f_2$,....
  - all the inter-mediation frequencies: $f_1 \pm f_2$, $f_1 \pm 2f_2$, $2f_1 \pm f_2$,...., $mf_1 \pm nf_2$, ..., where m and n are integers and $-\infty < m, n < \infty$.

Frequency Domain of Intermodulation Products



a. Fundamental Frequencies

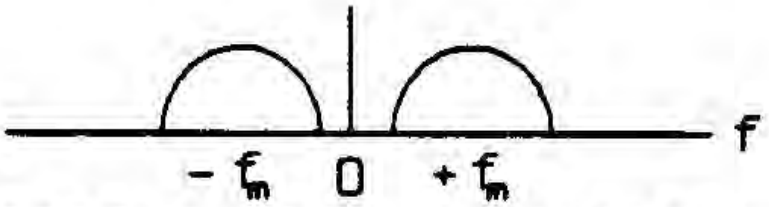


b. Intermodulation Products

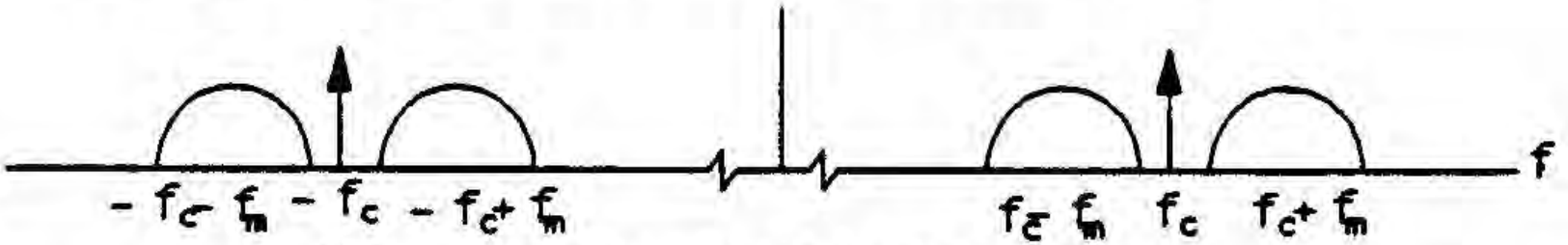
Linear (Amplitude) Modulation

- AM is the simplest form of modulation and is the form normally found in unintentional modulation and propagation situations.
- Other forms are:
  - **Double Sideband** (DSB) appears similar to AM but without the carrier
  - **Single Sideband** (SSB) has only one sideband and no carrier
  - **Vestigial Sideband** (VSB) has one sideband greatly attenuated.

Spectrum of an AM Signal



Message spectrum for an arbitrary x(f).



Modulated signal spectrum

Bandwidth Determination

- One of the most important parameters associated with a modulation envelope is the transmitter nominal (3dB) bandwidth.
  - For AM modulation, the spectrum occupied is twice (+ and -) that of the highest frequency contained in the baseband information.
  - For FM, the bandwidth in which most energy is contained is a function of the frequency deviation and the highest modulating baseband frequency.

Bandwidth Selection Criteria

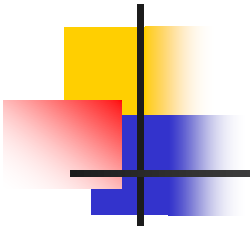
$$M_f = \frac{f_d}{f_m}$$ frequency deviation/modulation frequency

The transmitter will have a bandwidth B_T for an FM signal:

$$B_T = 2(1 + M_f) \qquad M_f \rangle 1$$

$$B_T \approx 2M_f \qquad M_f \rangle\rangle 1$$

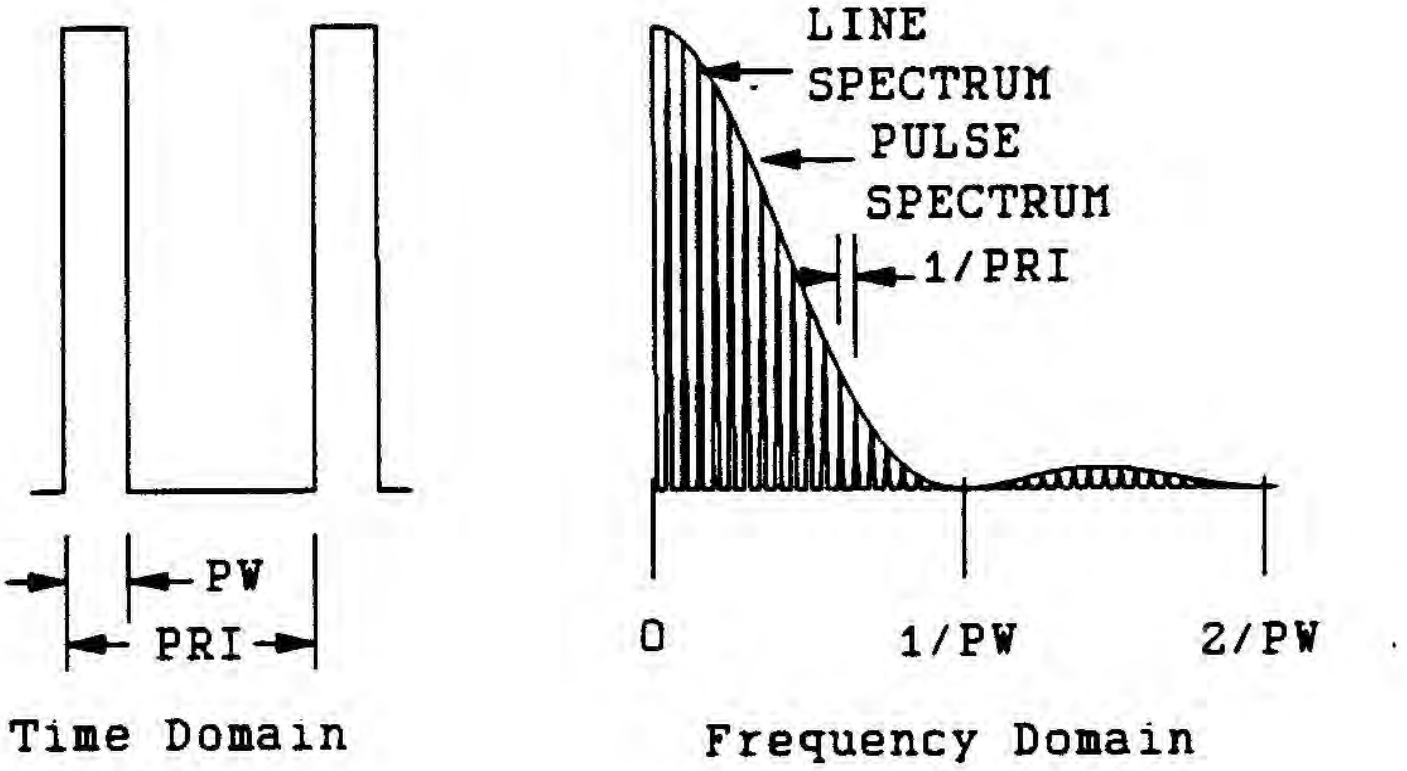
Since a receiver requires the same bandwidth to detect the Maximum possible signal strength, the same bandwidth Criteria for selection is employed.

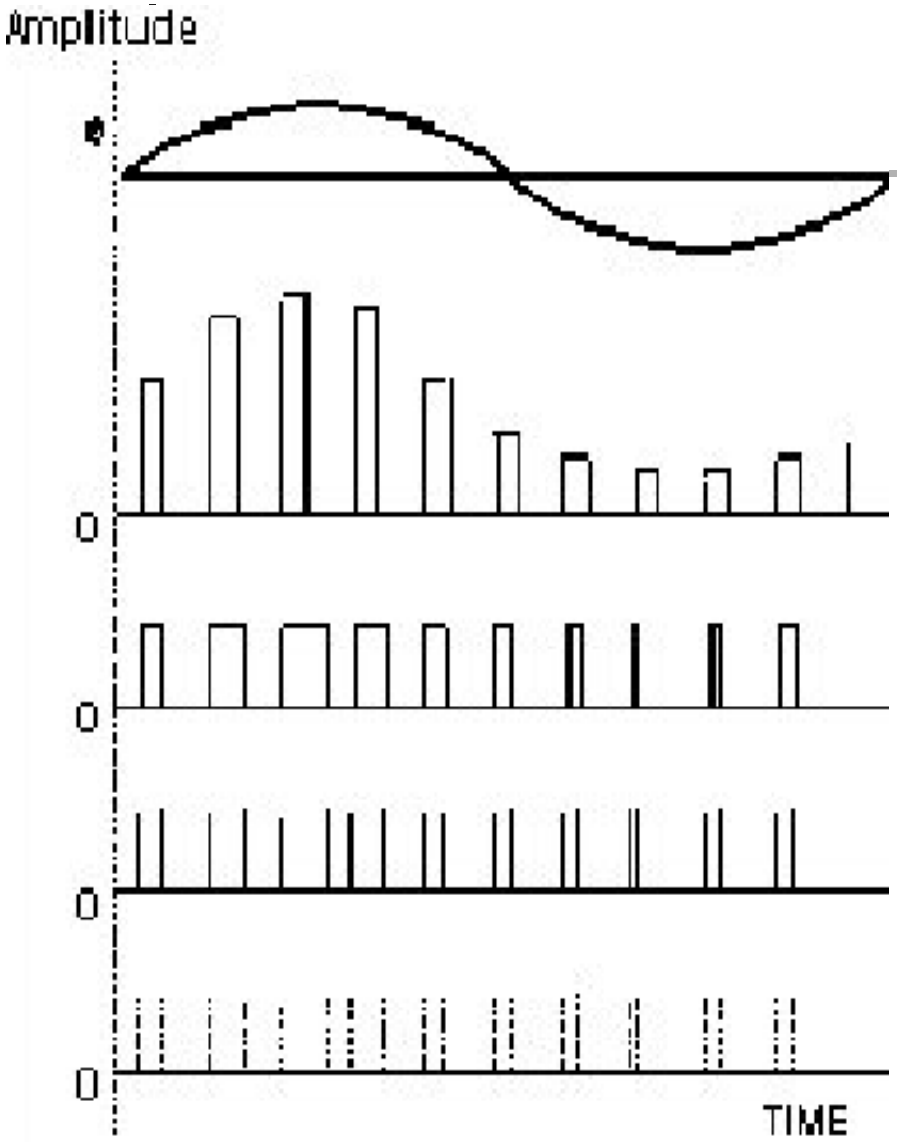


Digital AM

- A special case of linear AM in which the instantaneous amplitude, x(t), is constrained to a finite number of discrete values, such as:
  - Pulse modulation (PM)
  - On-Off Keying (OOK)
  - Amplitude shift keying (ASK)

A Rectangular Pulse

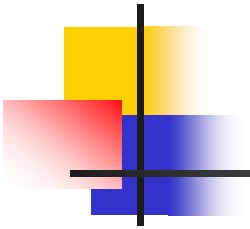




- Pulse modulation systems sample the input sinewave to yield a close approximation of the original analog waveform
  - PAM
  - PWM
  - PPM
  - PCM

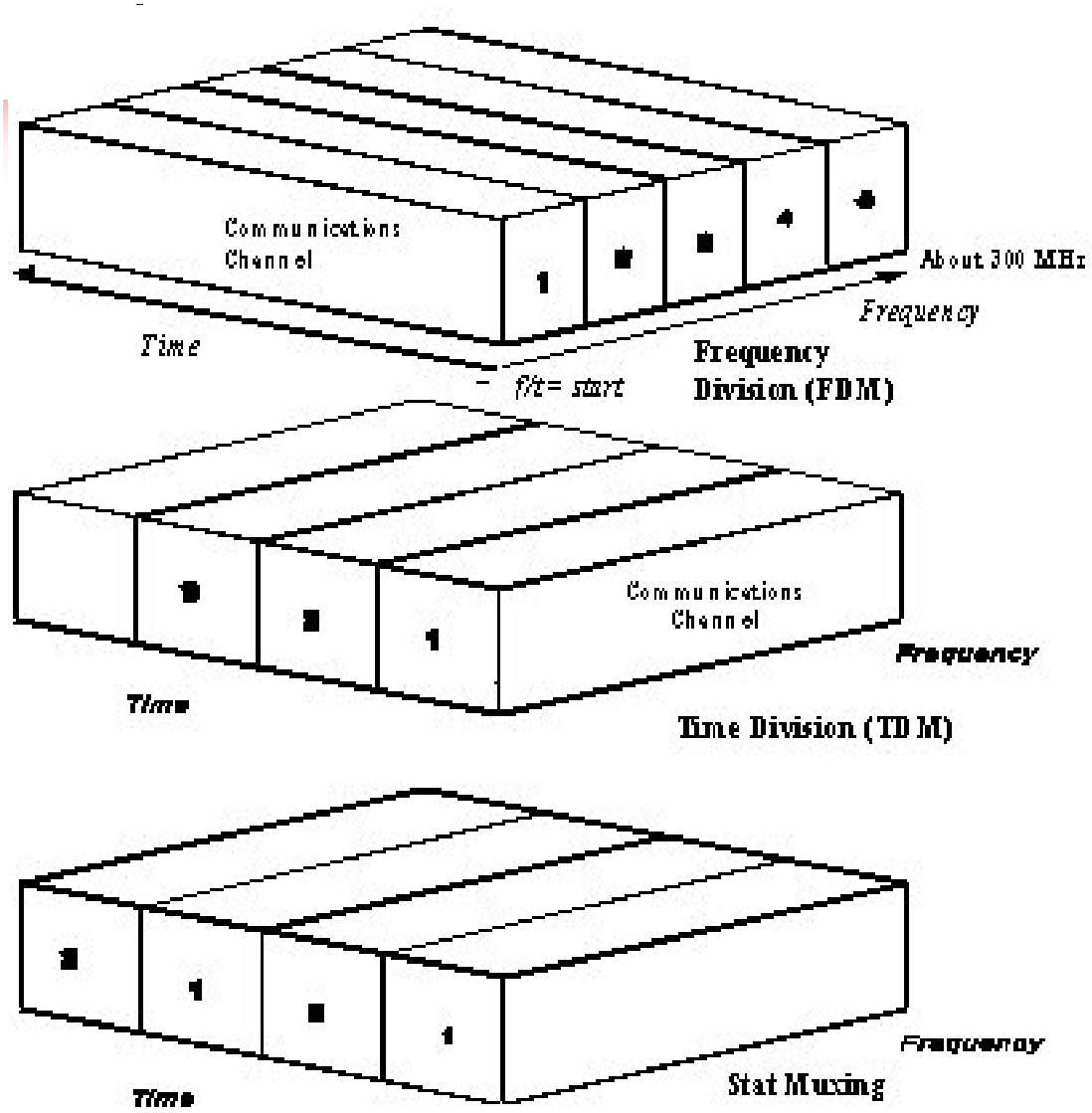
Data Transmission

- When information is put into a language understood by machines it becomes data.
- Data transmission occurs when data is moved electronically between two points.
- The resulting electronic information system can be a telemetry system, computer/digital system, or telecommunications system.

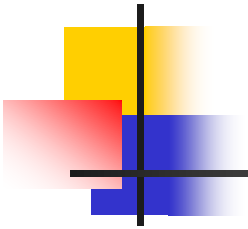


Data Transmission

- Transmission over wirelines can occur in one or both directions at the same time.
- A simplex circuit allows one direction information flow between source and sink.
- Half-duplex systems can send and receive, but only in one direction at a time.
- Full-duplex transmissions can occur in both directions simultaneously.

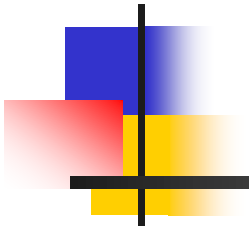


- For increased efficiency, data multiplexing allows the combination of several channels of information into one channel.



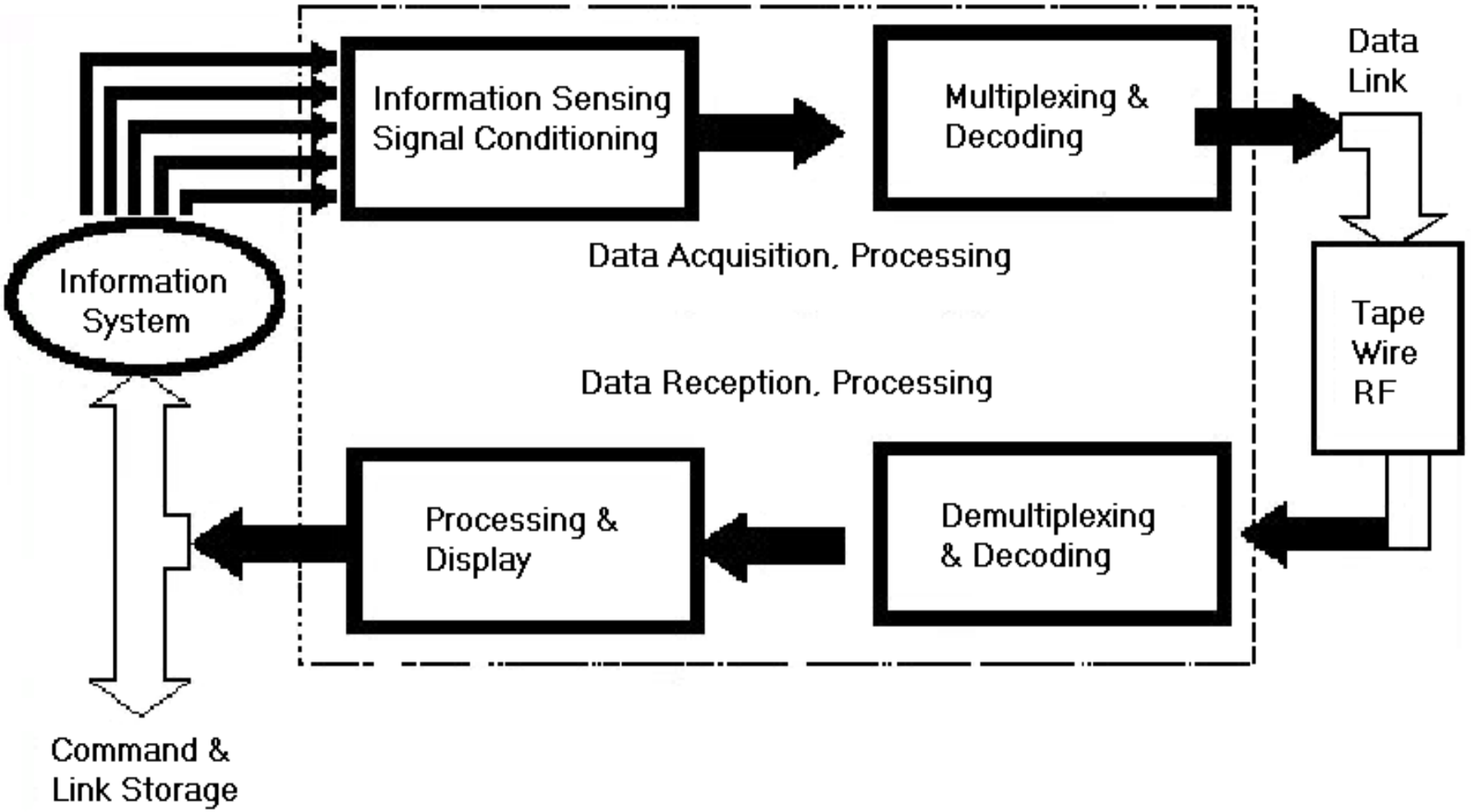
Multiplexing

- Time Domain Multiplexing (TDM)
  - Multiple users on same frequency at the same time. Each user's message segments are located in specific time slots.
- Frequency Domain Multiplexing (FDM)
  - Each user is assigned a separate frequency within an allocated band. All frequencies are transmitted simultaneously.
- Time Domain Multiple Access (TDMA)
  - One frequency, multiple users, sequential messaging.



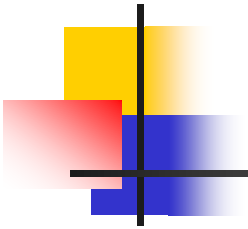
Propagation

Typical Telemetry System



Wave Creation

- Current flow through a conductive substance creates an electromagnetic field around the substance
- The field is made up of mutually perpendicular electric and magnetic waves
- Neither field can exist independently



Propagation

- Propagation results when a modulated signal is impedance matched to the air (or the transmission line) at a specific frequency.
- When the communications medium is air, there is little impedance to prevent a particular pulse shape from reaching its destination in the same form as when it was transmitted
- A problem occurs when the medium is not air (or optical fiber), but a hardwire cable.

Definitions

- Wave
  - A group of disturbances that occur at one place at a given time and are reproduced at other places at later times.
- Propagation
  - The motion of the disturbances.

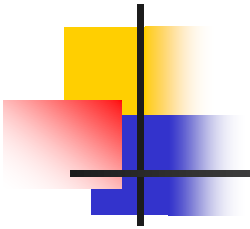
Impedance & Propagation

- Propagation is based on the ability to deliver power to an object that is loaded with respect to free space impedance.
  - Antenna's are used to match the impedance of the transmission source to that of free space
  - Maximum antenna pickup results when the antenna is oriented in the same direction as the radiated field

Uneven Loading

- Another problem is caused when there is a mismatch between the source impedance of the signal generator, the distributed impedance of the wire and the load impedance of the line.

Requirements for Secure Communications

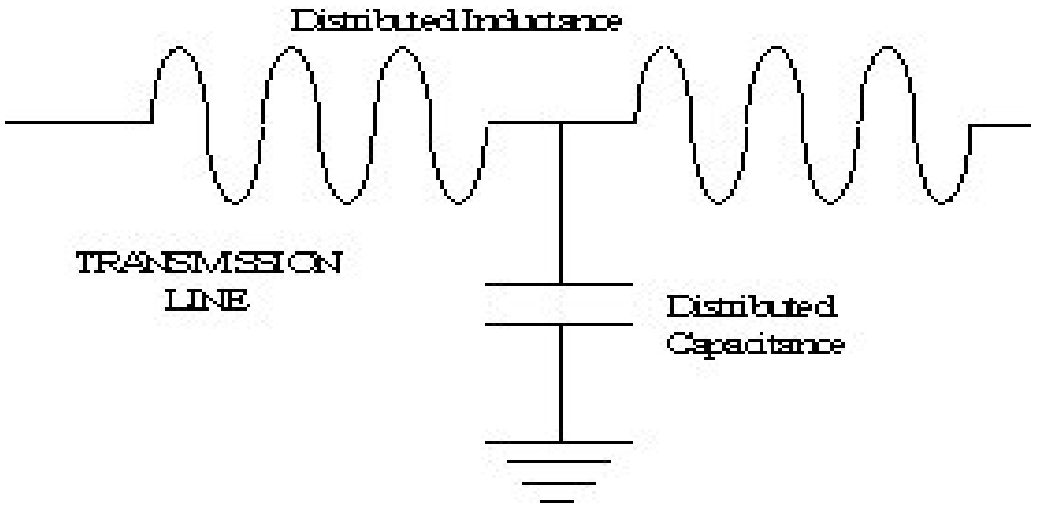


- An information source
  - The protected information
- A format representing the information
  - Modulation adds the information to a carrier
- A channel for the data to be transmitted through
  - Propagation can occur in the air or any conductor
- A means of recovering the information from the received signals
  - How to visualize information in noise

Direct & Reflected Waves

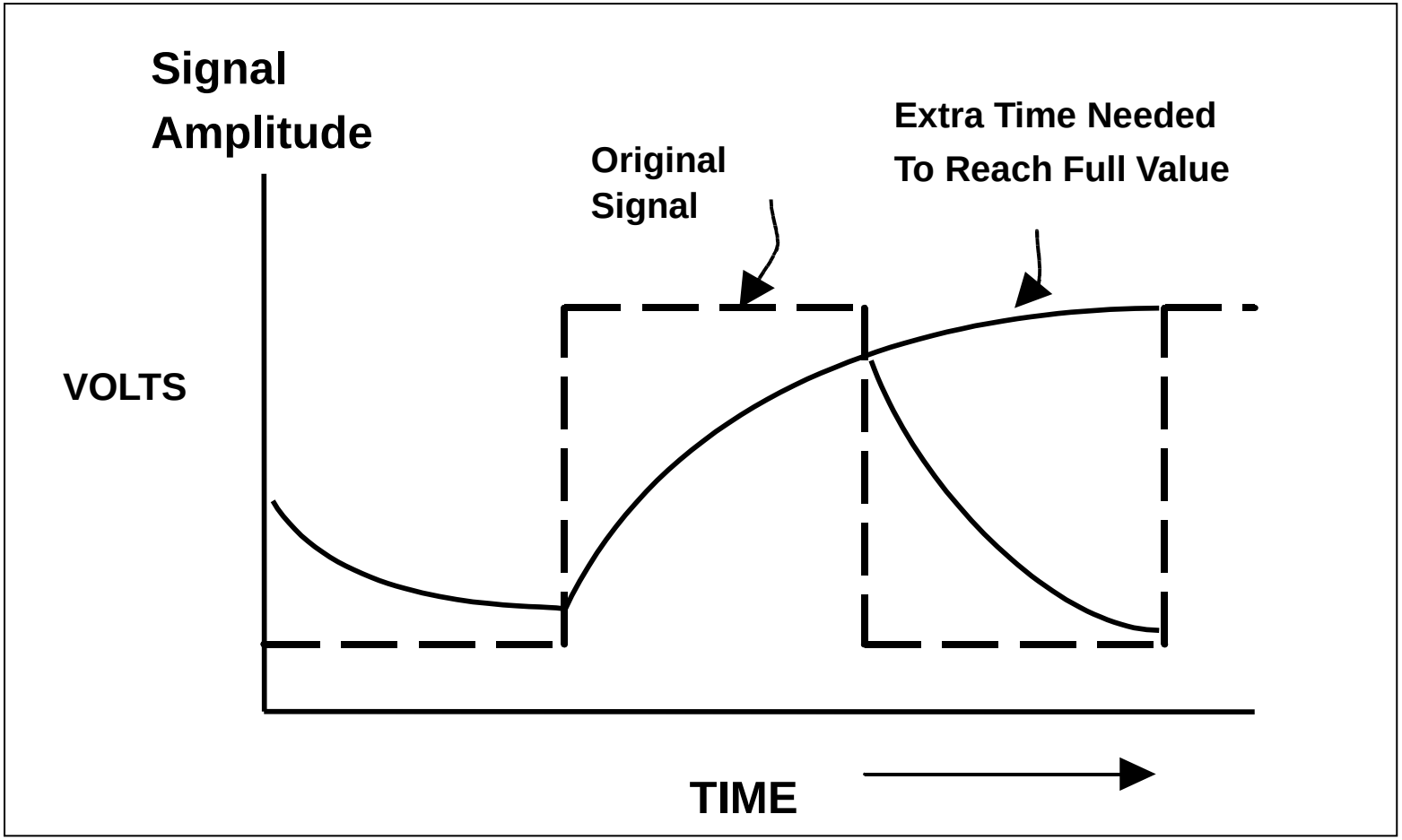
- The direct wave is the signal on a transmission line traveling from source to load.
- The reflected wave is the wave generated by the direct wave but traveling from load to source.
- Waves will reinforce or reduce each other at various points along the line.

Wire Transmission Line

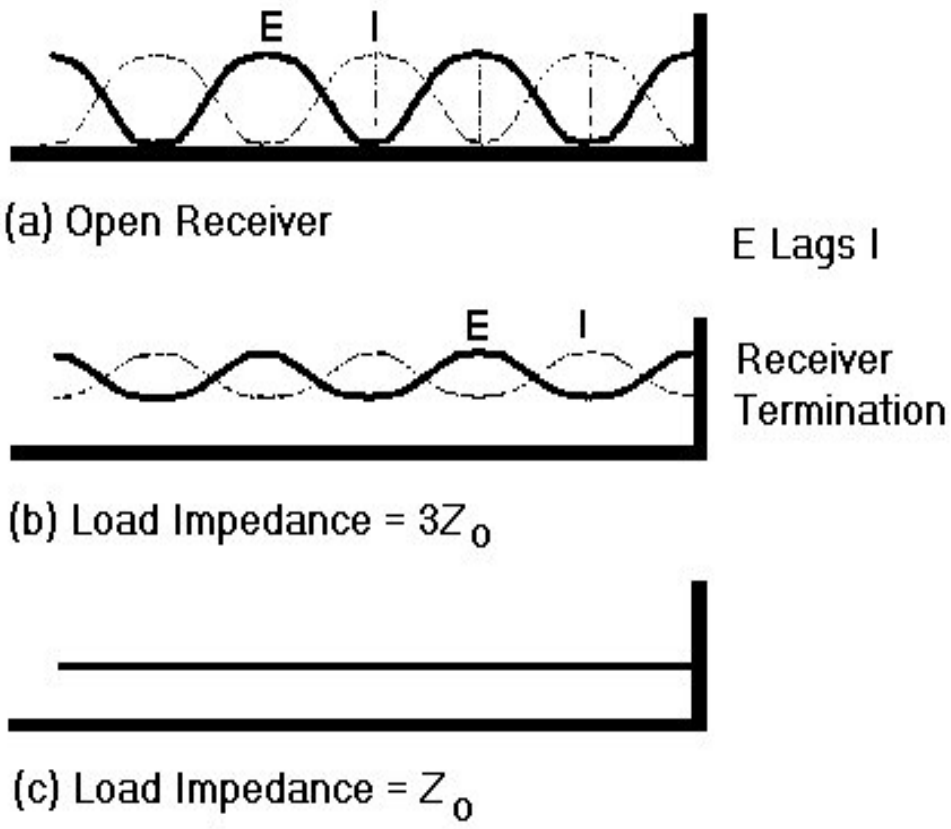


Wires contain distributed inductance and capacitance causing some of the initial pulse frequencies to reach their destination slightly out of phase with respect to the other frequencies

As Signals Travel They Distort



Mismatched Impedances Cause Reflections



Types of voltage and current distribution produced on a transmission line by different load impedances

- This is for the case of a transmission line having low attenuation and a characteristic impedance that is resistive.

Definitions

- Phase velocity
  - The rate of change in distance with respect to time of a wave along a transmission line. For parallel wire lines:

$$\vartheta_p = \frac{3x10^8}{\sqrt{\mu_r \in_r}}$$

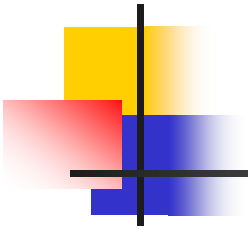
Where $\mu_r = \in_r = 1$

μ_r = relative permeability

$\in_r$ = dielectric constant

What Causes the Emission

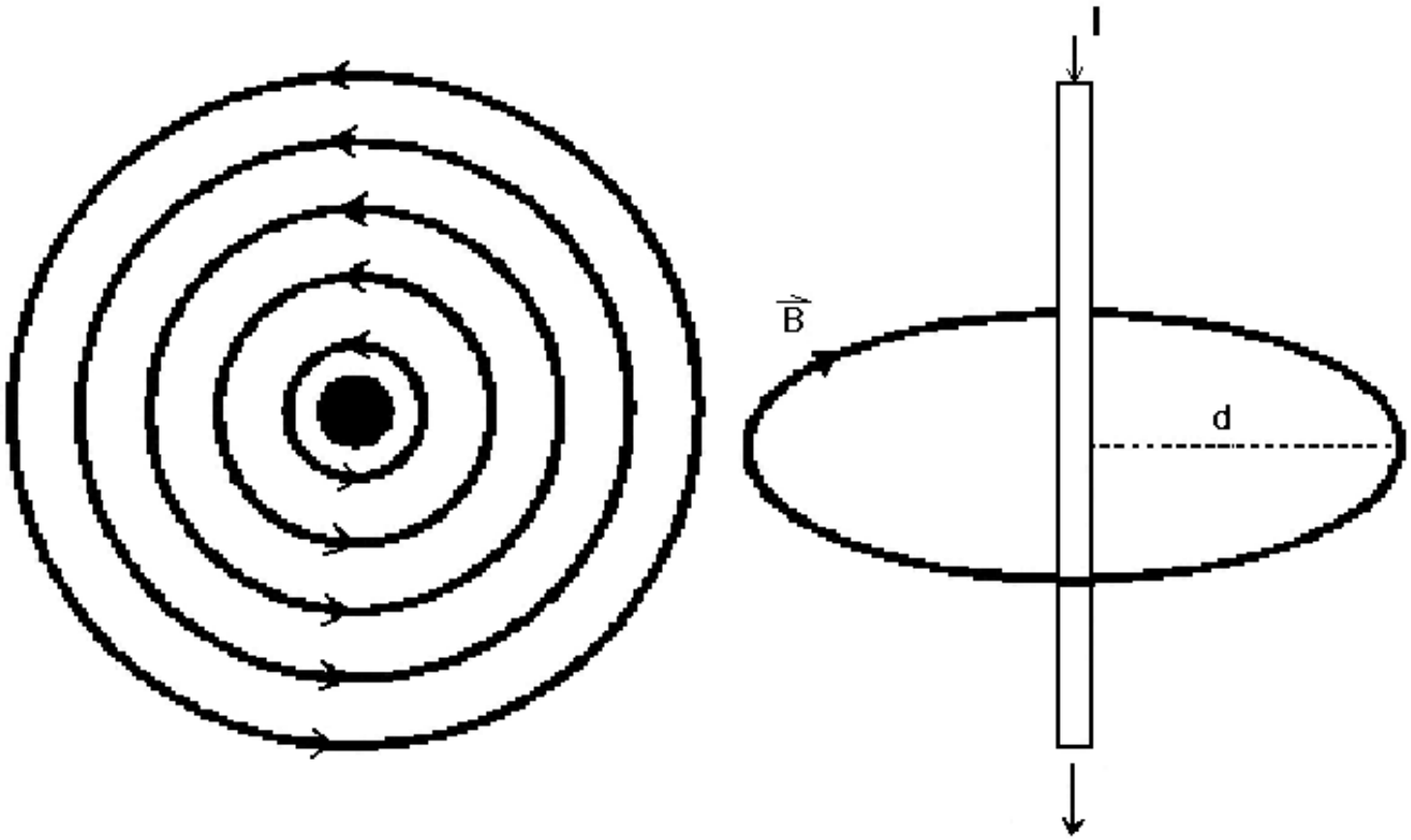
- If the current flowing through the conductor is sinusoidal, the E-field around the conductor will expand and contract.
- As the E-field expands and collapses, completely closed loops of E-flux lines are formed and "pushed" into space by subsequent expanding flux lines.



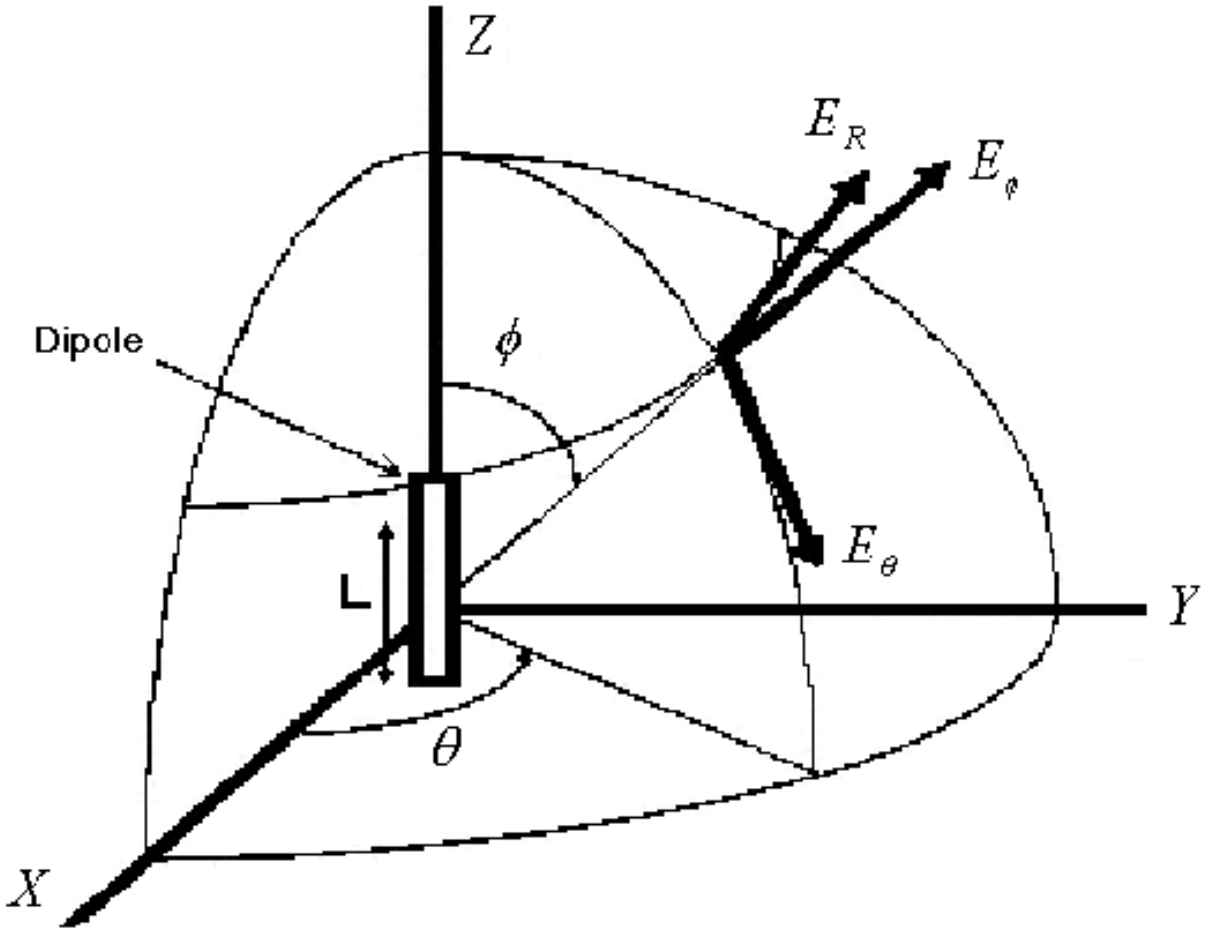
Field Types

- Static and induction fields associated with the collapse of stored energy are called "near" fields.
- The radiation field due to current flow is called the "far" field.
- Static fields vary inversely as the third power of the distance from their source.

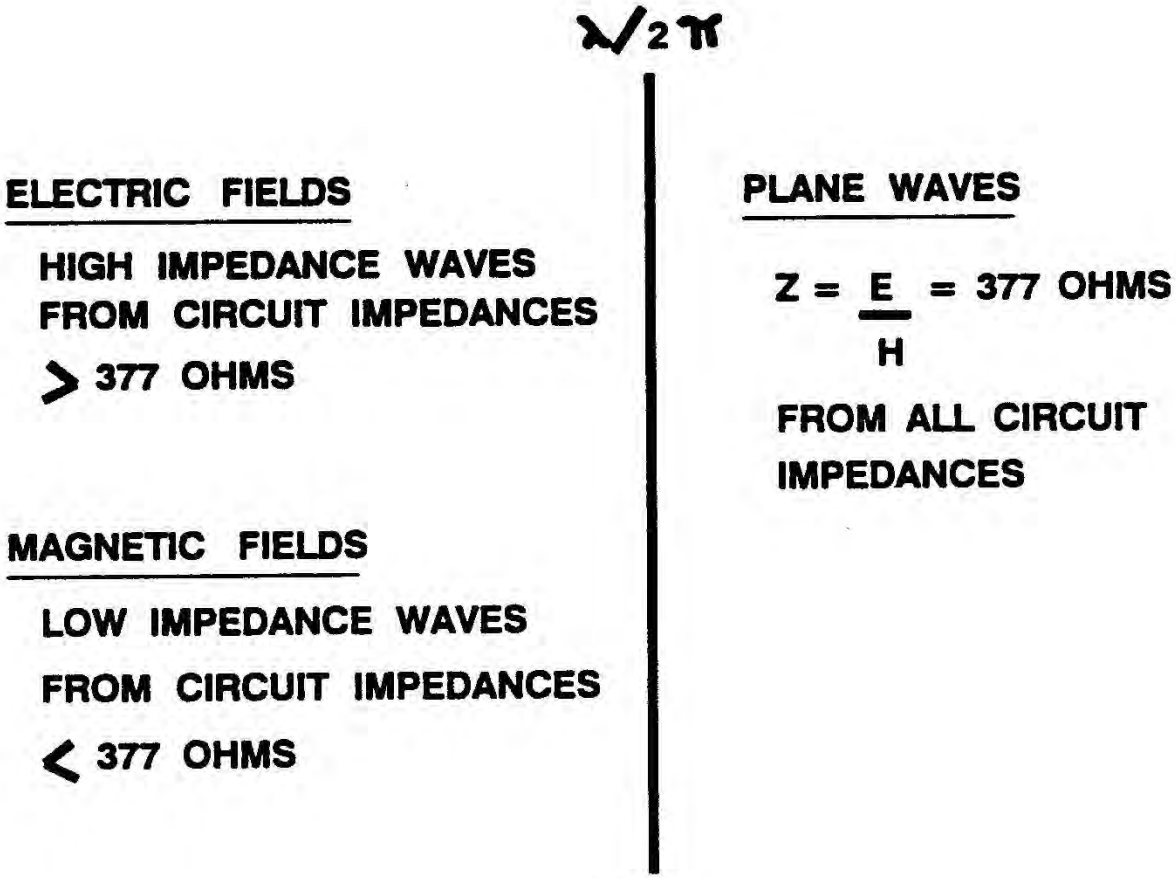
Fields & Current Flow Around a Conductor

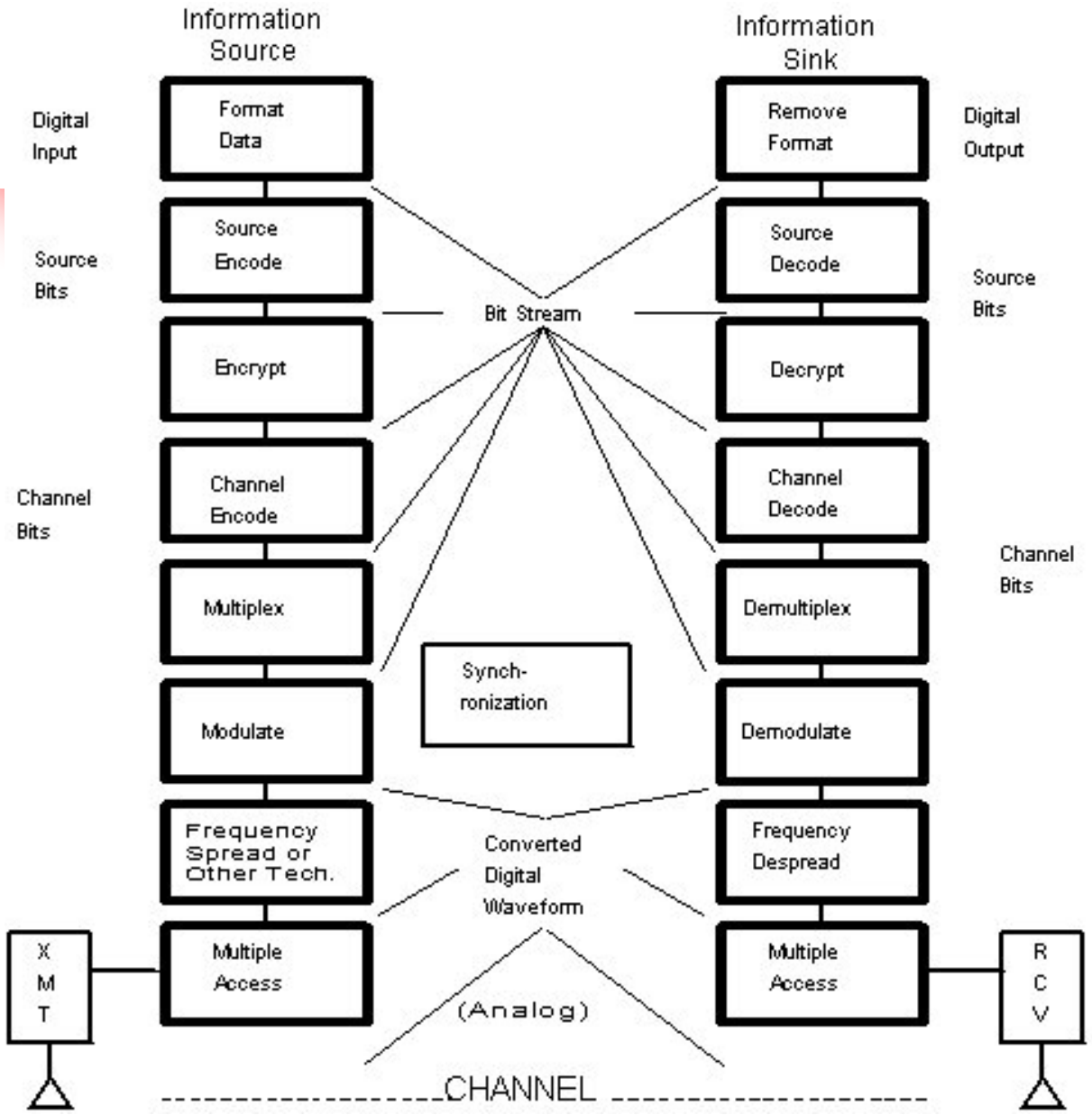


Three Dimensional View of Fields Around Wire Source



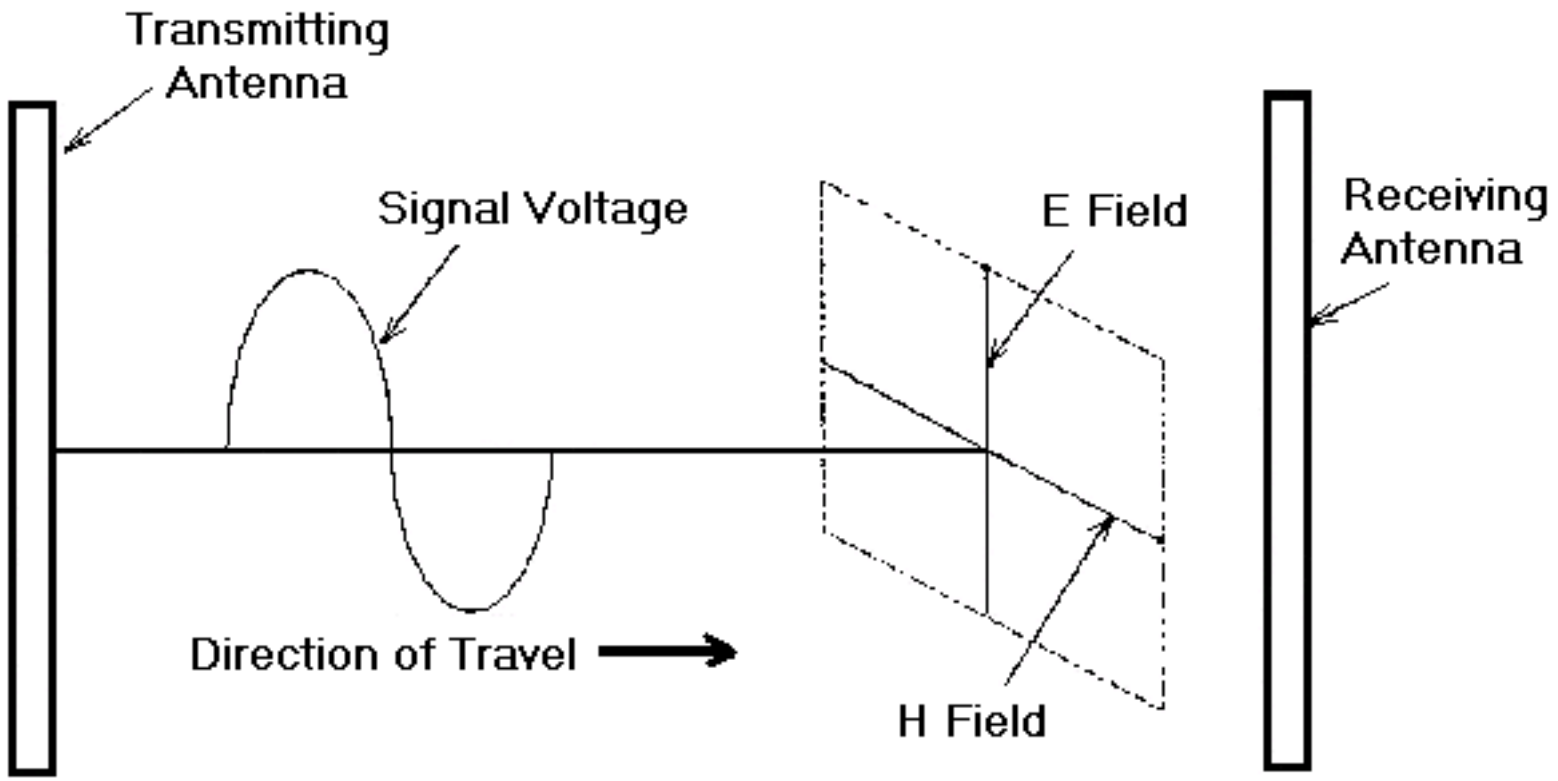
Wave Components Relative to Impedances





Signal Flow Through a Typical Digital Communications System

Components of an Electromagnetic Wave



General Rules

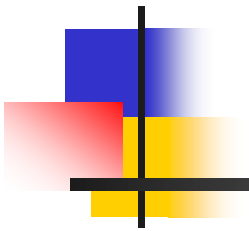
- Energy propagation is based on impedance mismatch.
  - If the transmission line is only slightly mismatched, as is the case with the majority of sensitive emission problems encountered, only small higher frequency emissions will propagate into space.
  - If the mismatch is large, such as an unterminated wire, or if the wire is terminated by an antenna, then significantly more energy radiates outside.

Characteristic Impedance

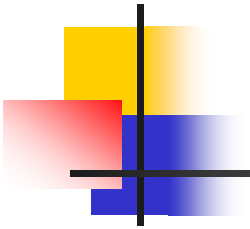
- For two parallel wire lines:

$$Z_0 = 120\sqrt{\frac{\mu_r}{\in_r}}\ln\left(D/r\right) \quad \text{ohms}$$

D = the distance between wire centers
R = the radius of each wire



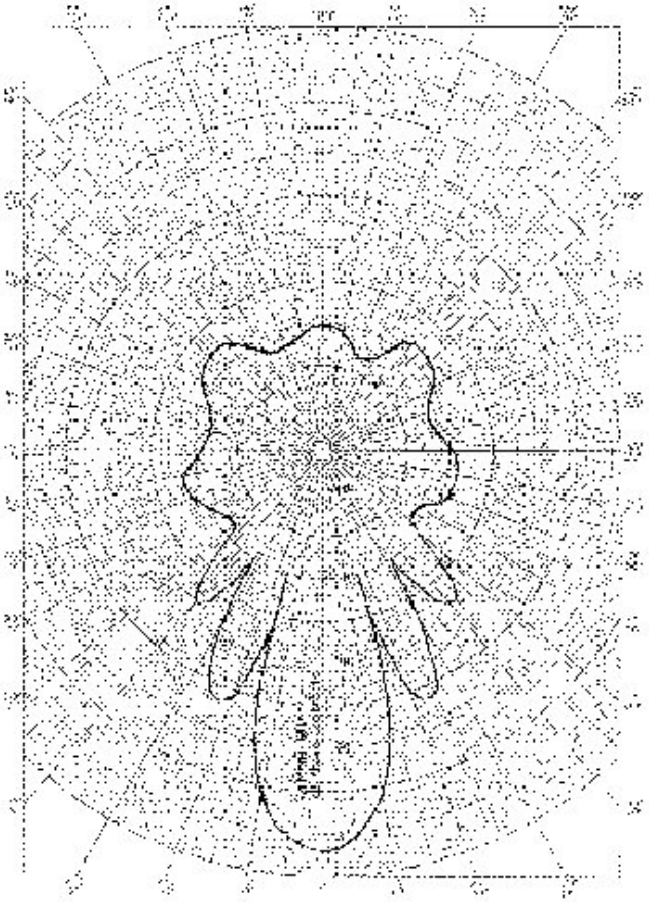
Antennas



Directed Radiation

- A directive antenna concentrates the radiated power in one or more directions.
- If the antenna concentrates its power into a small cone, the corresponding part of the radiation pattern is called the main lobe.
- There are always a number of smaller secondary maxima called side lobes.

Antenna Patterns

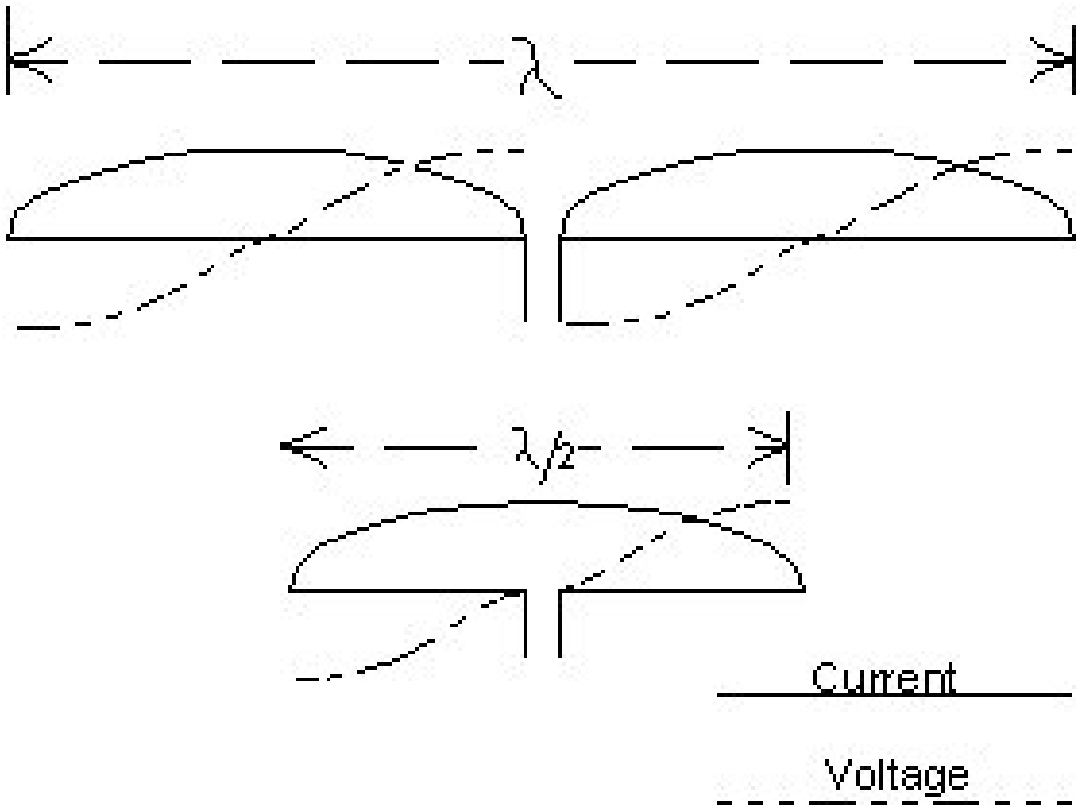


- Most real antenna patterns are directional.
  - Emissions are always higher in one direction then another.

Traveling (Standing-wave) Antennas

- When the emitted wave reaches the end of the antenna it is reflected back to its source. The combination of the forward and reflected wave sets up a standing wave pattern.
  - An unintentional standing-wave antenna can occur if rf is capacitive coupled into a parallel conductor carrying rf energy.

Standing-wave Antenna

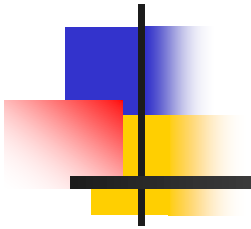


Wave Elimination

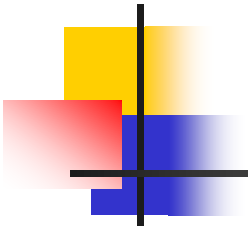
- Standing waves are eliminated by terminating the antenna in its characteristic impedance.
- Any impedance matched wire that is not shielded and is carrying rf current will radiate directionally as a traveling wave antenna.

Resonant Antenna

- An antenna operating near resonance has a reactive component of its input impedance either zero or very small compared with the resistive component.
  - As frequency is increased, the wavelength becomes shorter and eventually a frequency is reached at which circuit conductors become an appreciable factor of their wavelength.
  - At this point they become radiating elements.



Modulation



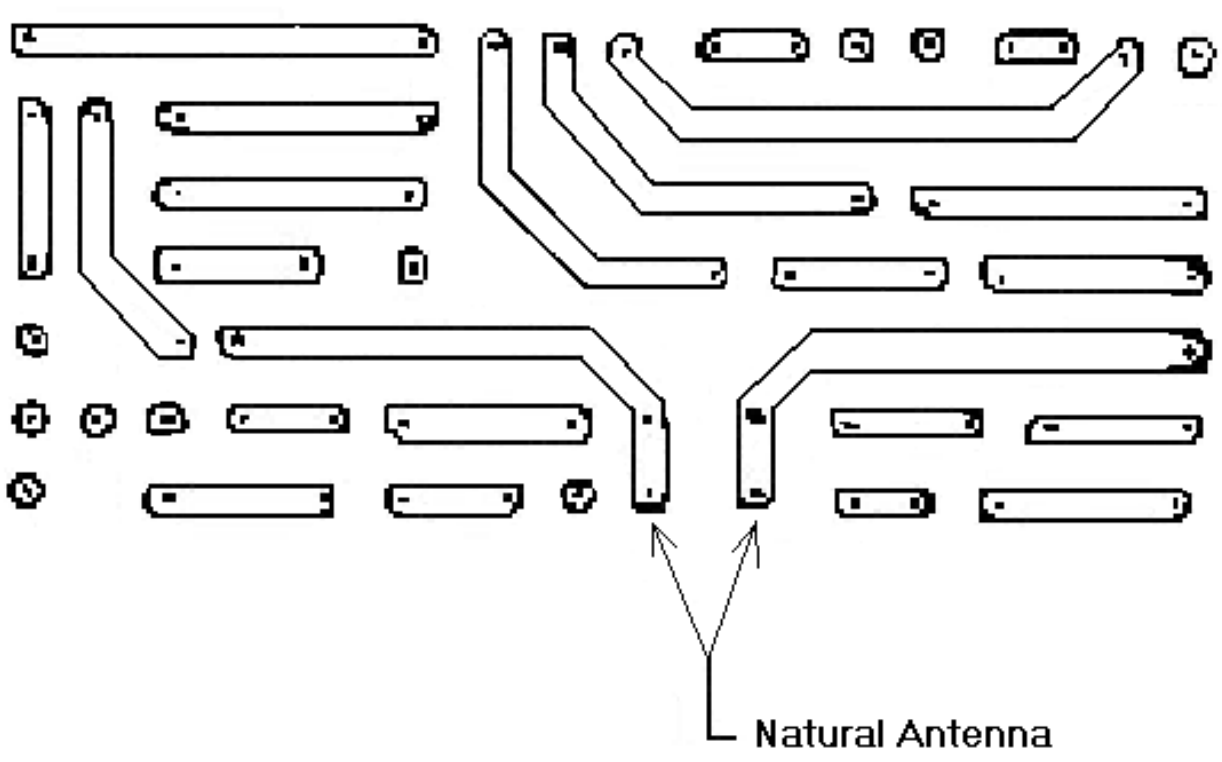
PC Board Antennas

- Common mode current in a circuit trace can be the driving source for an antenna formed by cables connected to the circuit board.
  - Voltage drop across the circuit board trace, by virtue of its inductance and the current flowing through it, forms the driving source for the antenna formed by these cables.

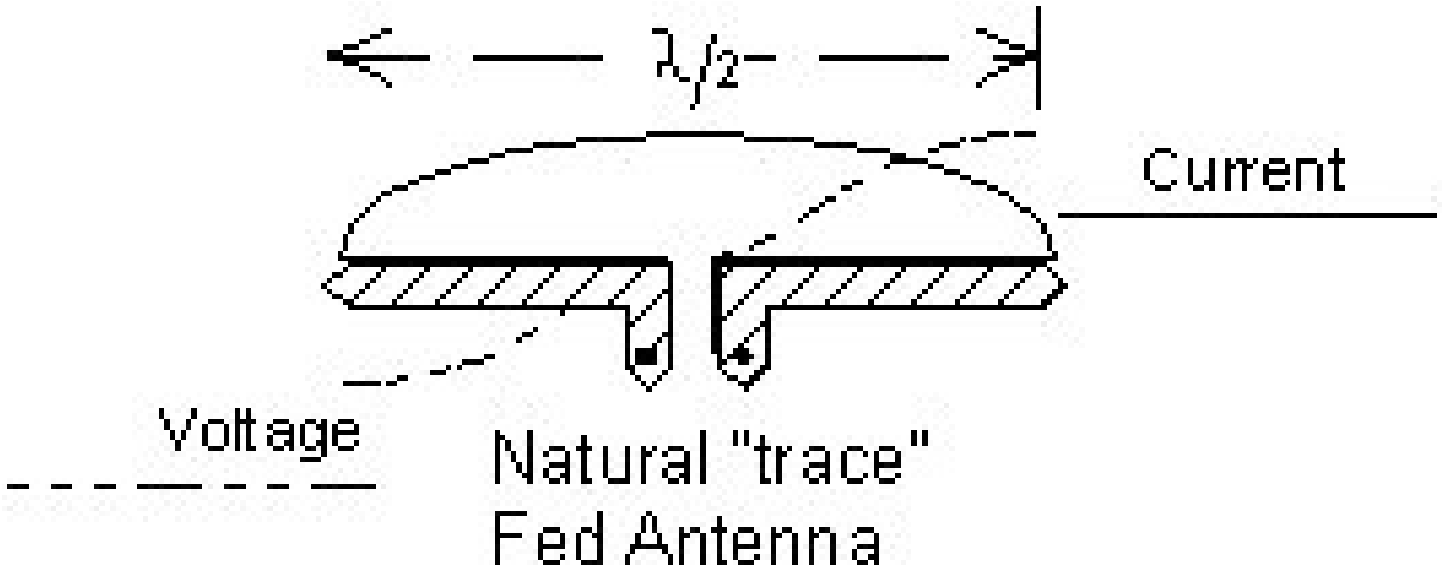
Half-Wave Antennas

- Half-wave dipoles radiate proportional to their length and frequency.
- Digital signals contain harmonics well into the microwave region.
- It is likely half-wave antennas always exist on circuit boards.
  - At 3 GHZ a half wavelength is two inches.

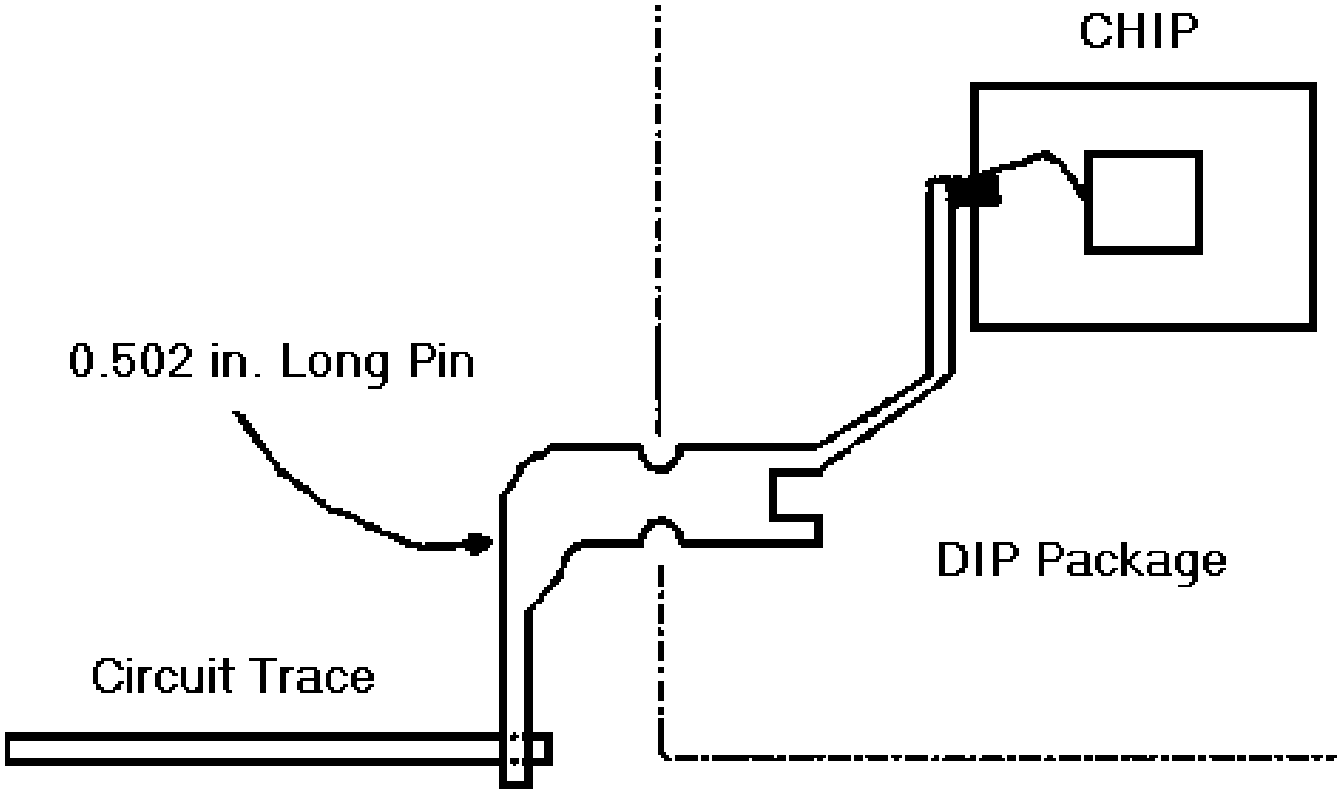
Trace Formed Natural Antenna



PC Board Antenna Showing Standing Waves



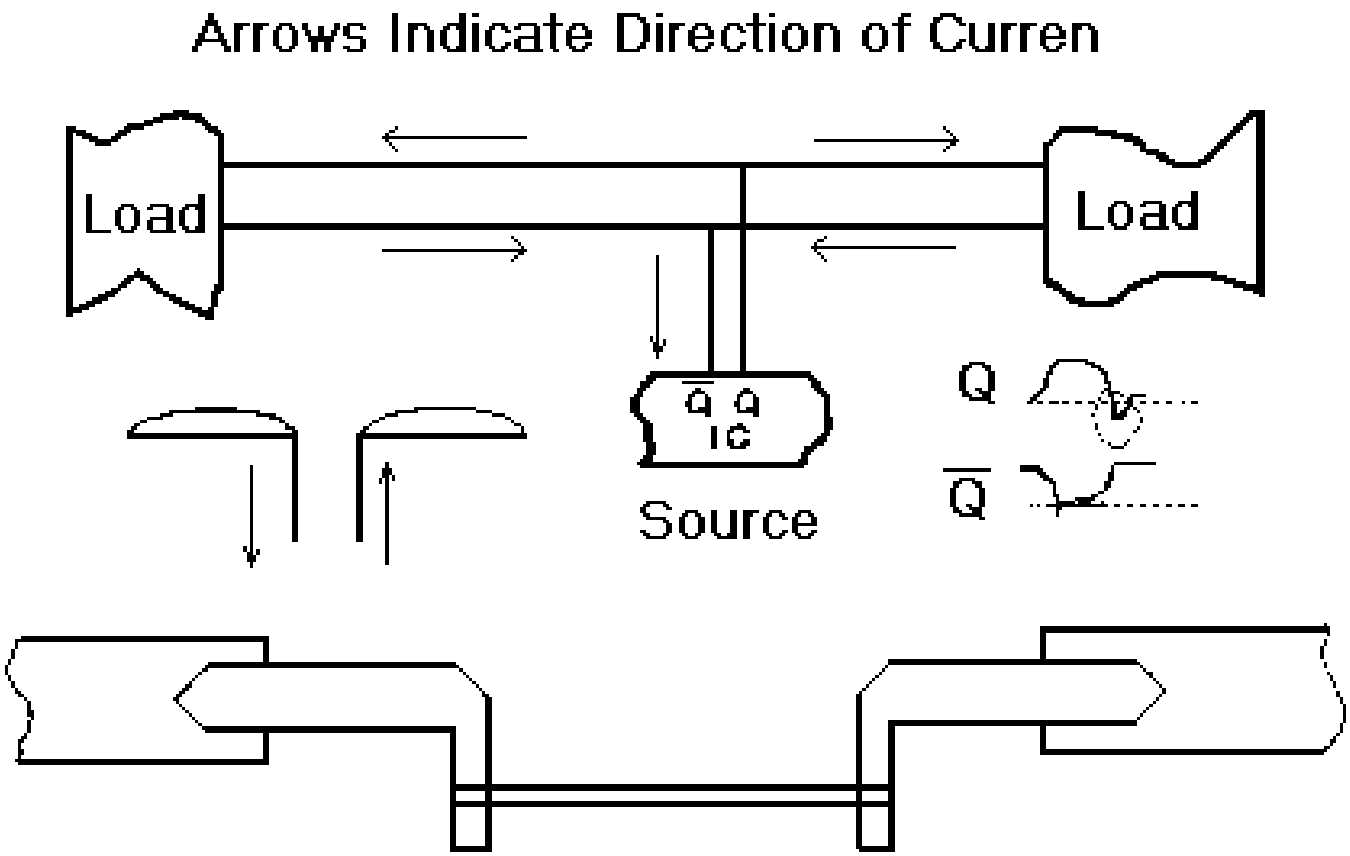
Abrupt Impedance At Lead



Loop Antennas

- Formed when a conductor contains one or more turns and its two ends are close or one is grounded.
- If a conductor runs parallel to and is connected to the ground plane it forms a loop with the ground plane.
- Ground loops are formed when currents from different parts of the circuit flow through a common ground path.

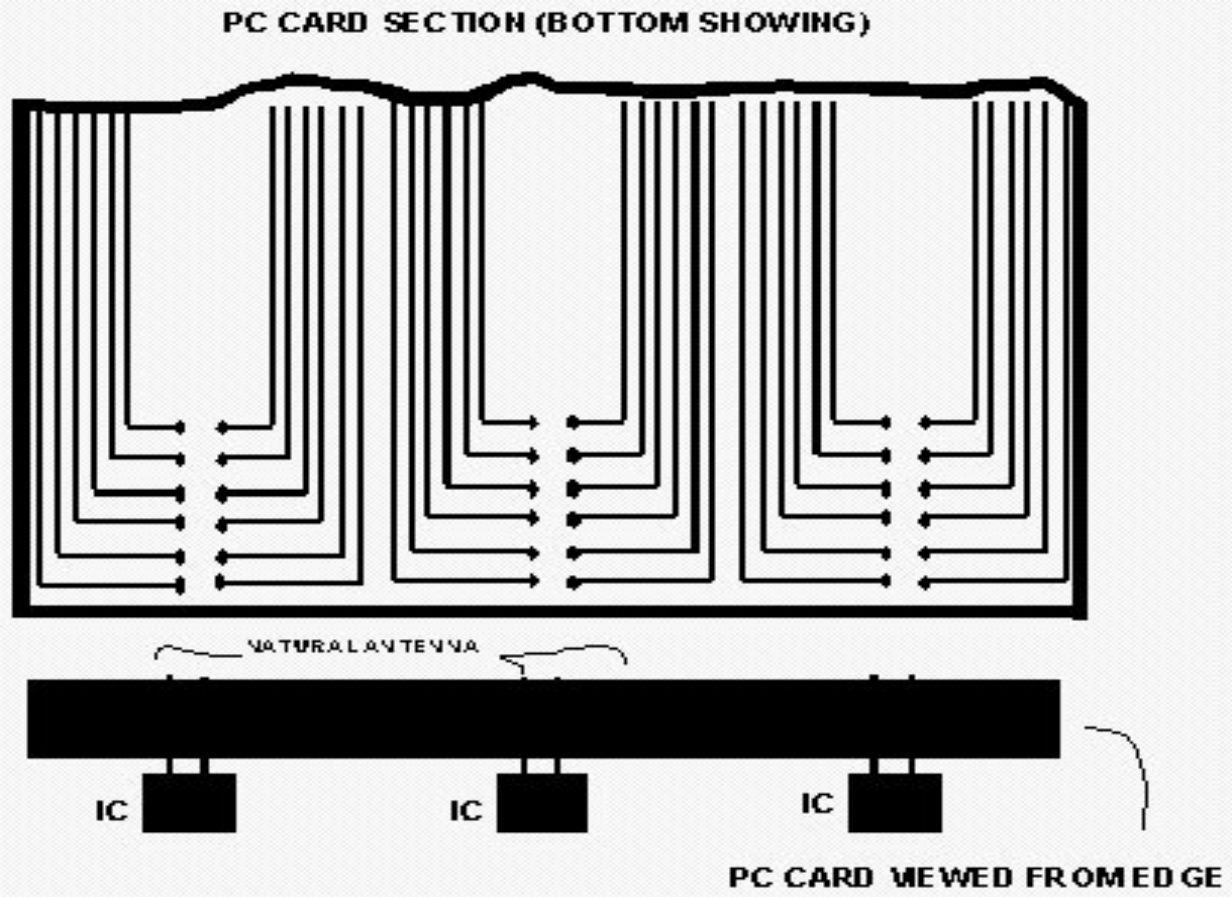
Equivalent Center Fed Dipole



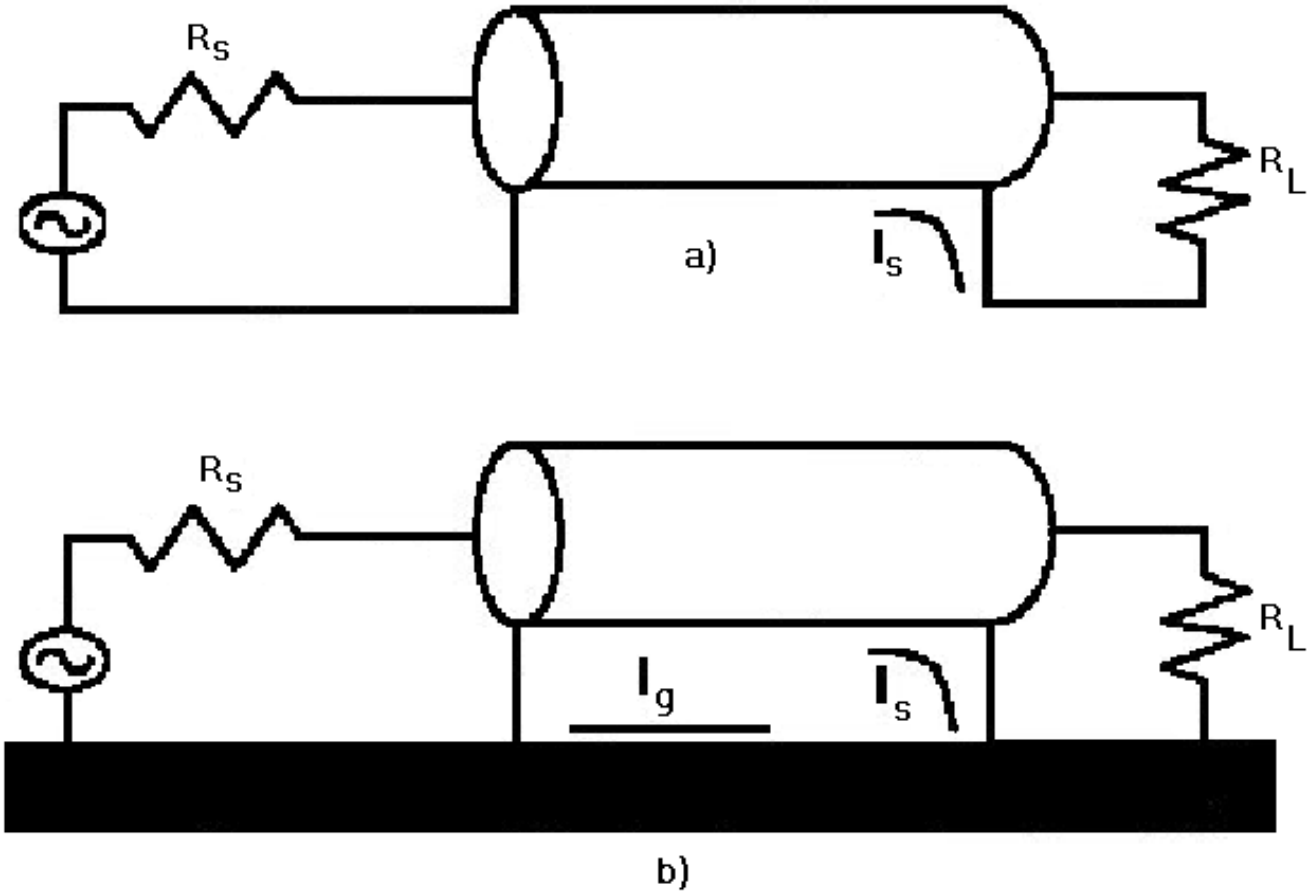
Linear Antennas

- A linear antenna is a straight thin rod fed by an rf source.
- Unintentional antennas can be linear antennas if they are straight thin conductors such as pc or ribbon cable traces.

Natural Linear Antenna



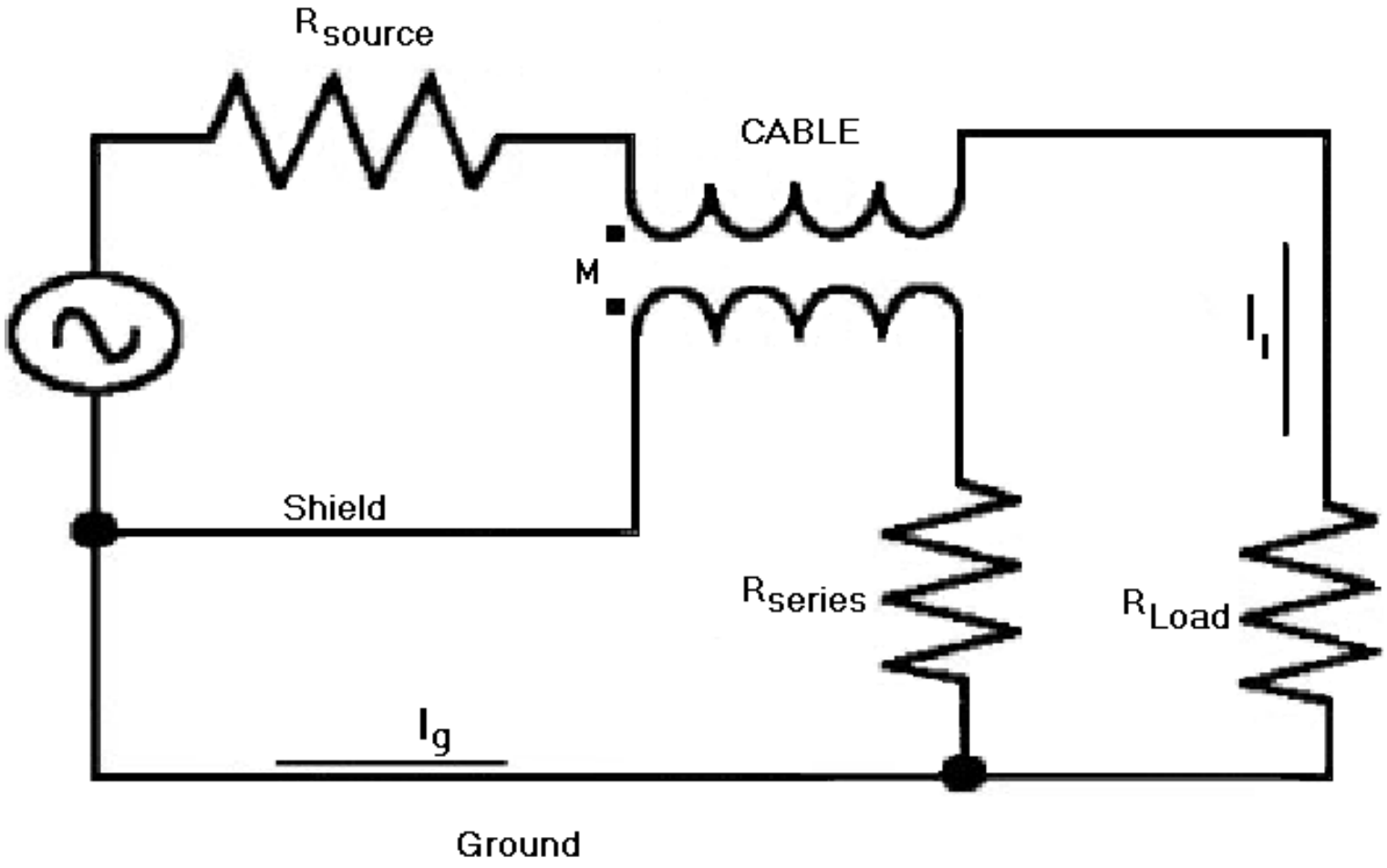
Shielded Cables as Antennas

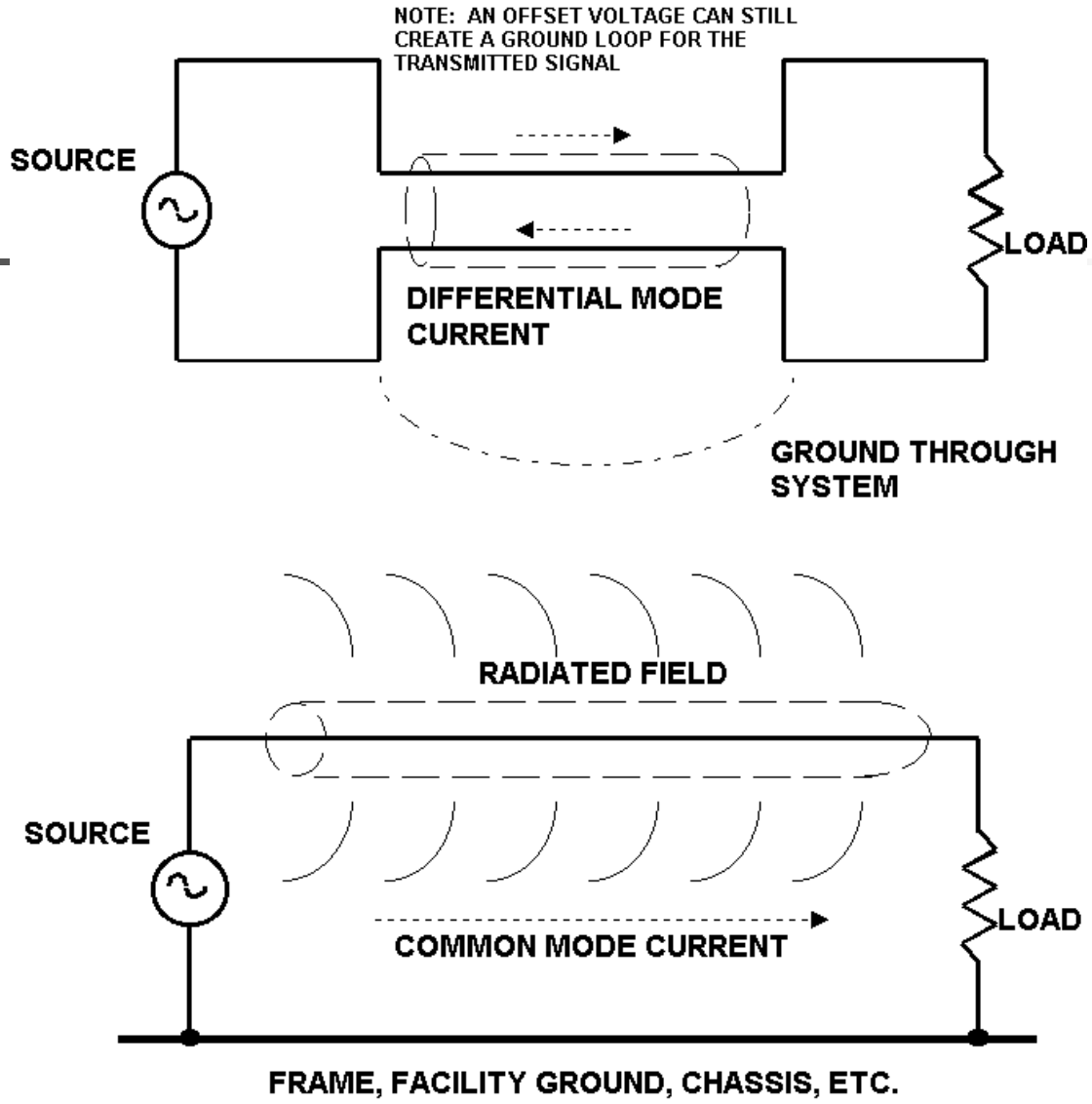


Wave Components

- A frequency is the number of times a sinusoidal waveform repeats during a one second interval (cycles per second).
- An analog signal is a continuously varying voltage waveform that can be made up of one or more frequencies.
- A digital signal has a high or low state and is made up of many analog waveforms.

Cables Are Prone to Coupling



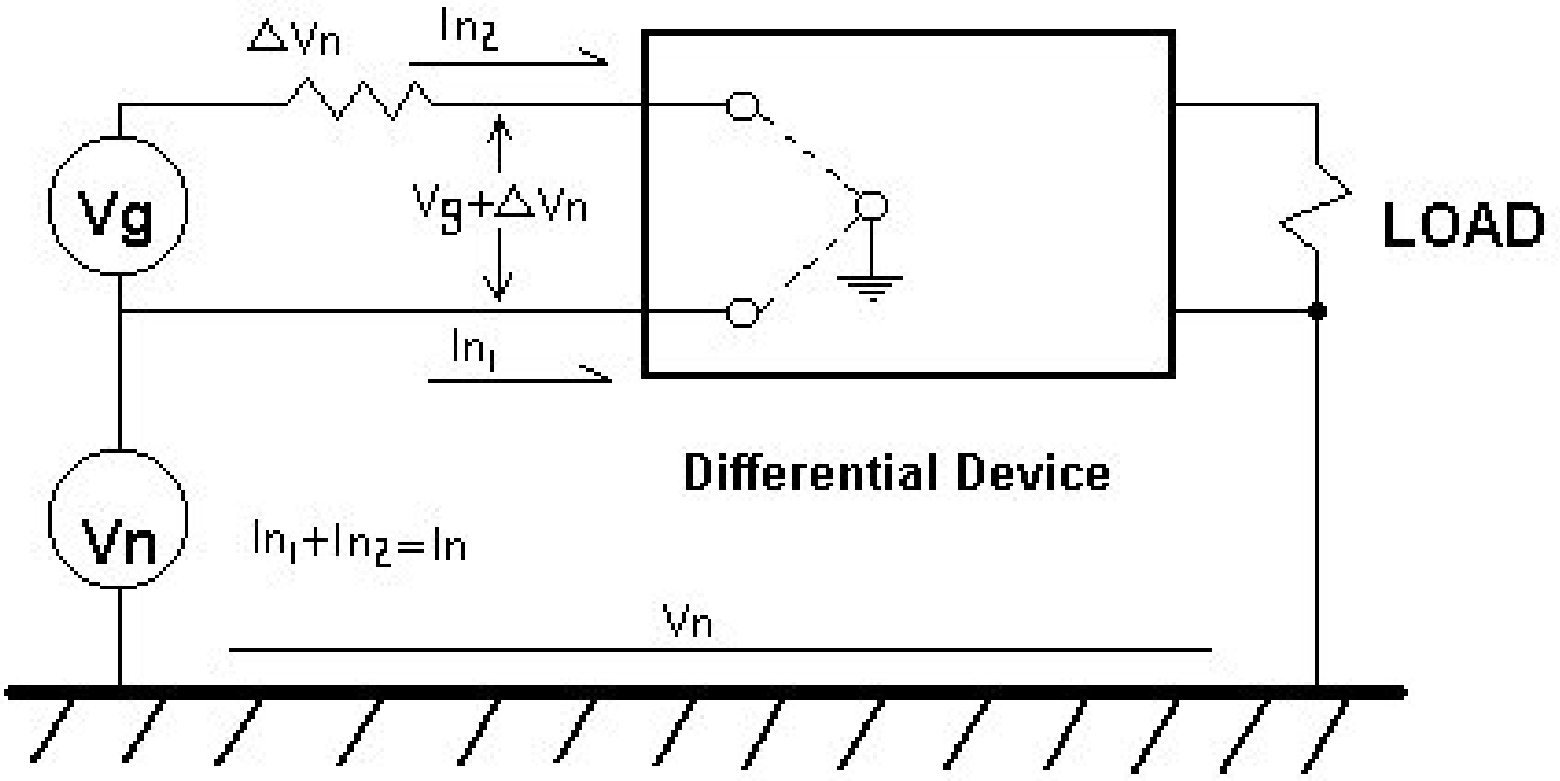


SYSTEM GROUND LOOP ANTENNA

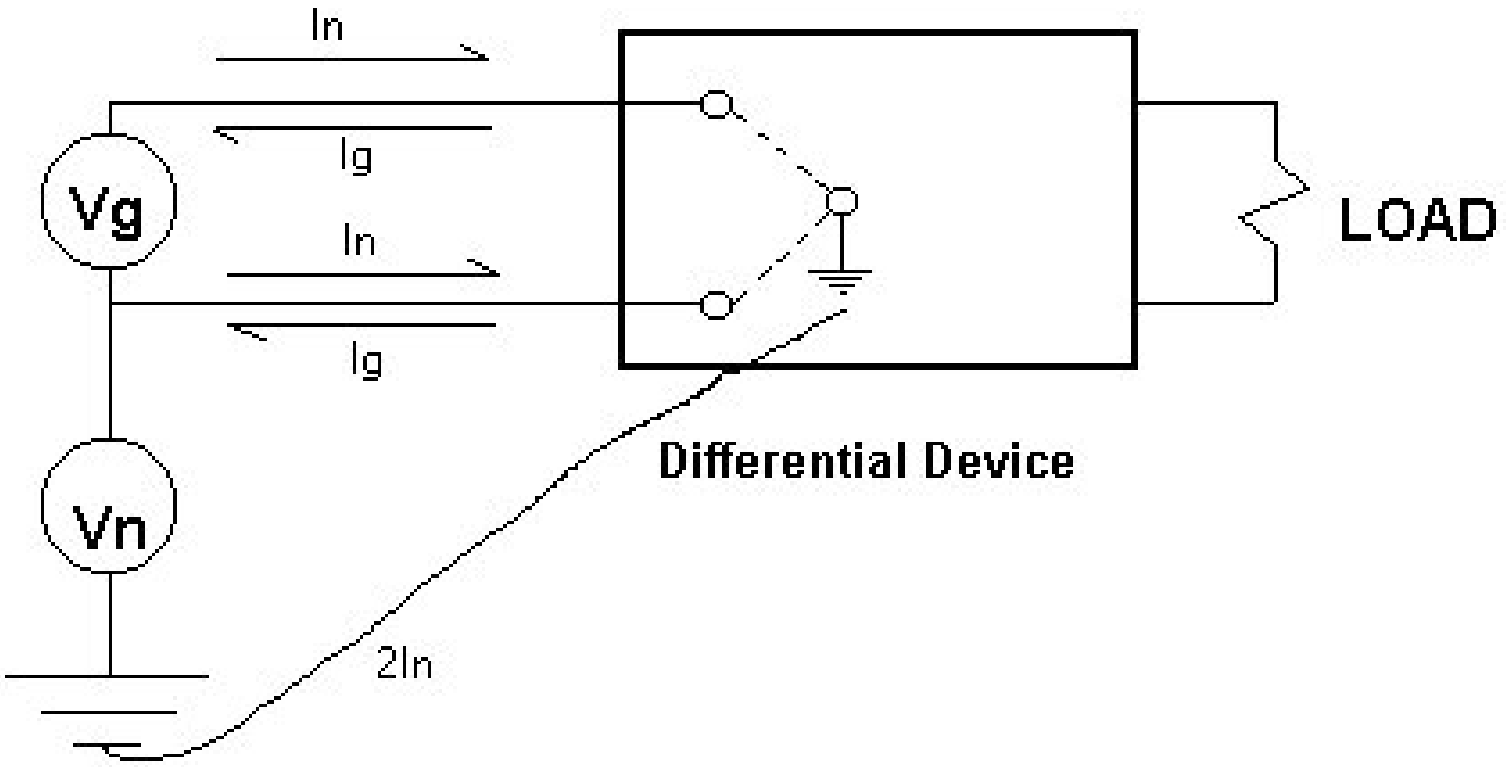
Nearby Grounds

- Nearby grounds reduce antenna radiation since potential radiated energy is absorbed into the ground.
- Coupling from antenna to ground greatly decreases with increasing distance.

Ground Current Modulation

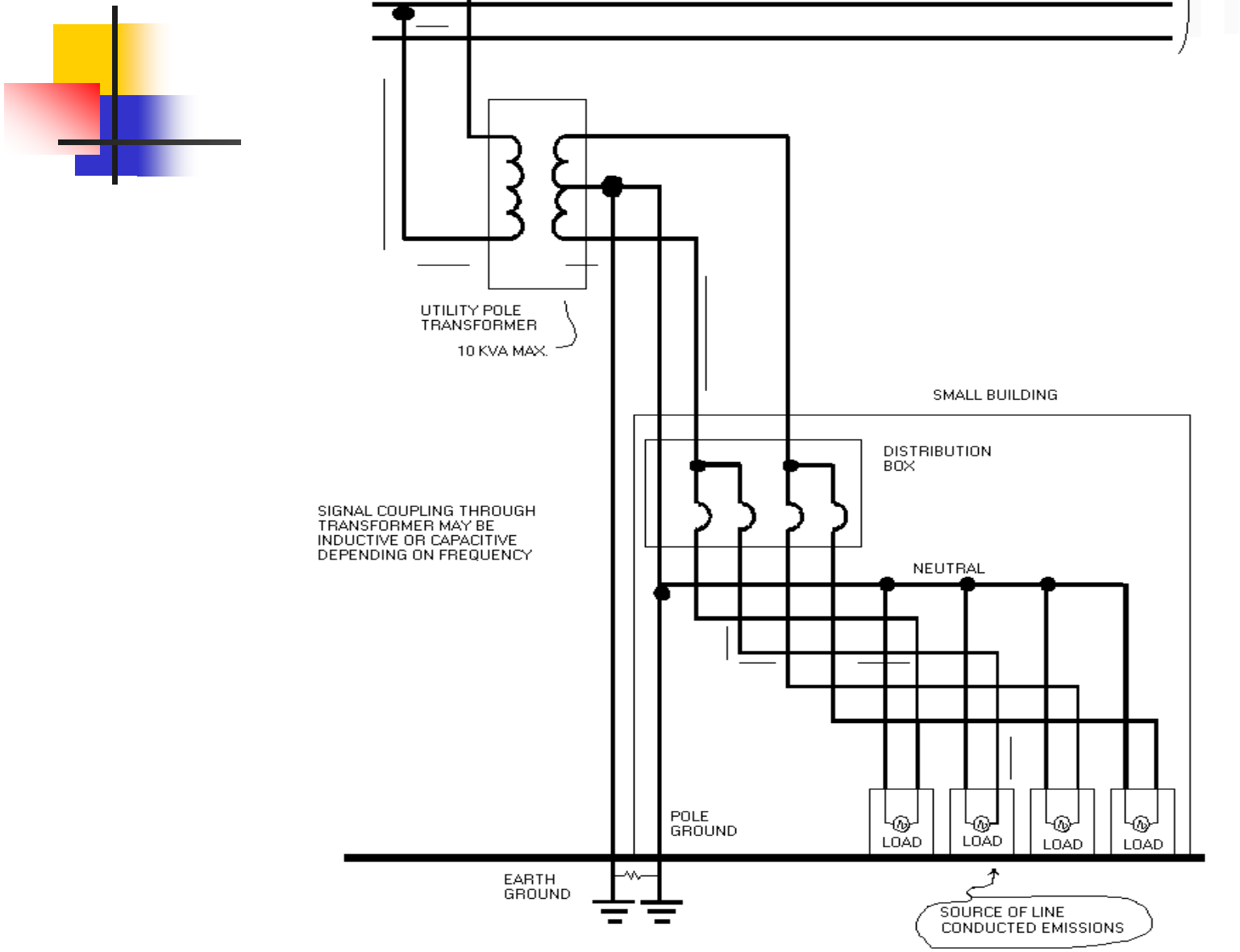


Unmodulated Balanced Load

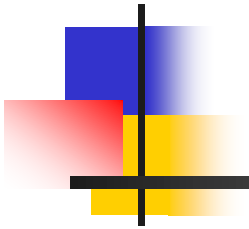


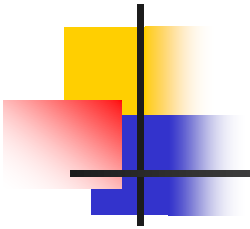
Extended Antennas

- Natural extended antennas occur on power wiring connecting electronic equipment to the primary feeder lines.
- RF conducted emissions on the power line couple back to the primary power feeder line through the utility pole transformer.
- The coupling will be inductive at low frequencies and capacitive at high frequencies.


2400 VOLT PRIMARY FEEDER
VOLTAGE STANDING WAVE SET UP ON POWER FEEDER
UTILITY POLE
TRANSFORMER
10 KVA MAX.
SMALL BUILDING
DISTRIBUTION
BOX
SIGNAL COUPLING THROUGH
TRANSFORMER MAY BE
INDUCTIVE OR CAPACITIVE
DEPENDING ON FREQUENCY
NEUTRAL
POLE
GROUND
LOAD
LOAD
LOAD
LOAD
EARTH
GROUND
SOURCE OF LINE
CONDUCTED EMISSIONS

Information Theory & Understanding





Simple Data Exchanges

- For a simple information exchange to work, the interface, code, protocol, and synchronization must be compatible.
- A compatible interface means that the receiver must also use the same media channel the sender is using, and must interconnect to the channel the same way.

Understanding

- Getting the message to a receiver doesn't ensure it will be understood, particularly if it is in a form difficult to immediately translate.
- Information is a quantitative term measuring the degree to which it clarifies that which is unknown.
- A totally predictable event contains no information

Time/Frequency Domain

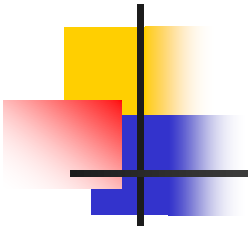
- When all individual frequencies making up a waveform are combined in a time period, the resulting time domain signal over the period can be visualized on an oscilloscope.
- When all individual frequencies making up a waveform are combined at a single point in time, the resulting frequency domain signal can be visualized on a spectrum analyzer.

Entropy

- The source entropy, H is the average information content per symbol.
- If the probability of an event, E, occurring is P(E), then the information obtained when E occurs is:

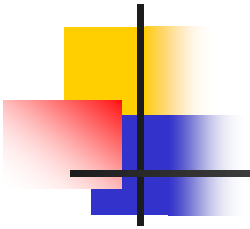
$$H(E) = \log_n \left(\frac{1}{P(E)} \right)$$

Where n = 2 for information in Bits



Bits – Bauds – Bytes

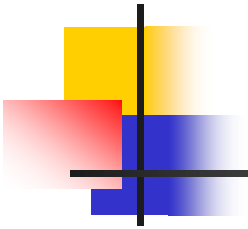
- A bit is the abbreviation for binary digit.
- Baud is a measure of the maximum rate of pulses (code elements) per second in a channel.
- Byte is used to describe a group of consecutive bits that are treated as a unit.



Required Bits

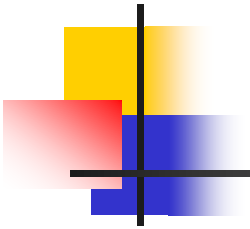
- Both binary states are called bit since both contain the same amount of information.
- The number of bits required to identify any particular selection from a group of N possible selections is:

$$I = \log_2 N$$



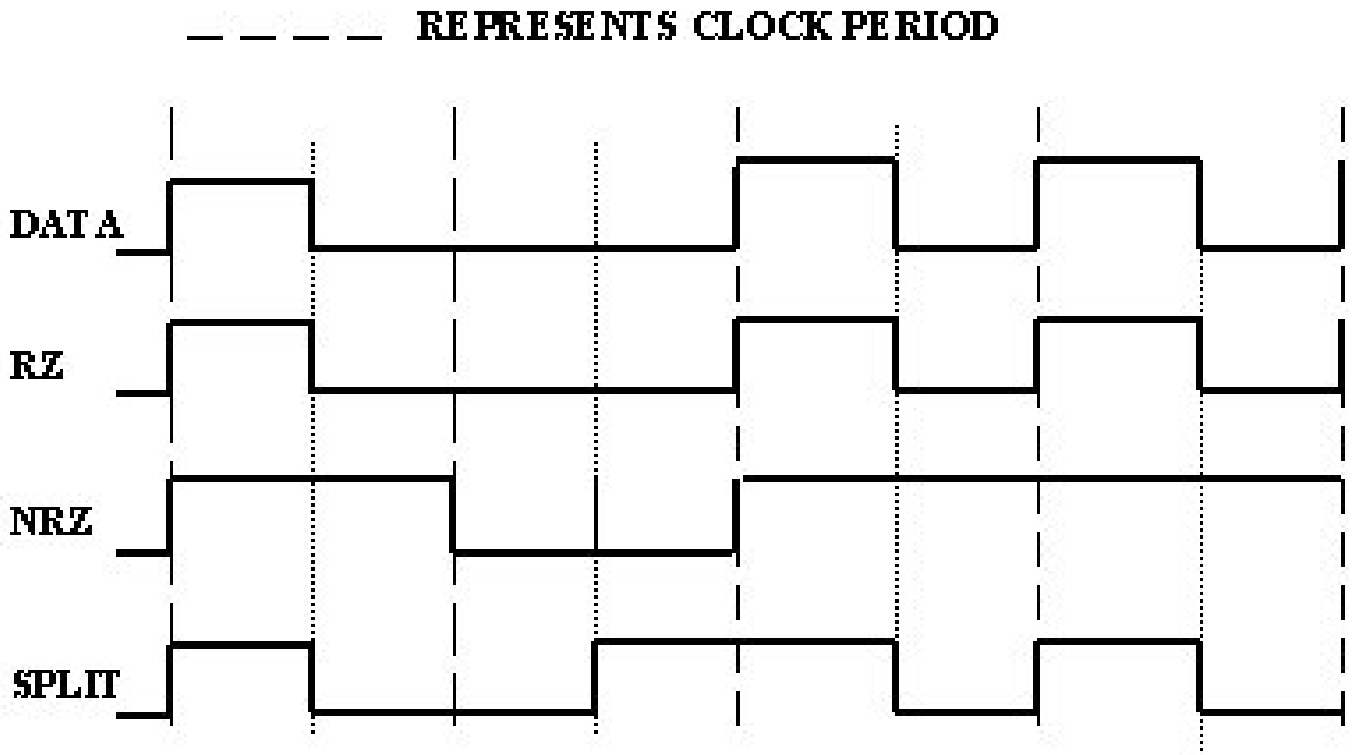
Bit Density

- Density is defined as the number of units of useful information contained within a linear dimension, usually expressed as units per inch.
  - When dealing with parallel data transfer, the bit density relates to the number of high states on the bus during a character transfer.
  - Since the overall energy state is cumulative, the resulting emission will be larger or smaller depending on the number of high states that exist.

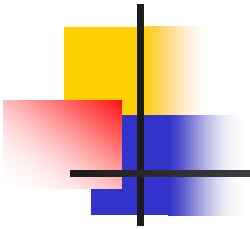


Coding

- Although digital and analog signals can be propagated continuously, in the real world messages from a computer based system are normally combined with other massages and then sent in packets of information.
- Codes are used to make up this packeted message format for information exchanges.



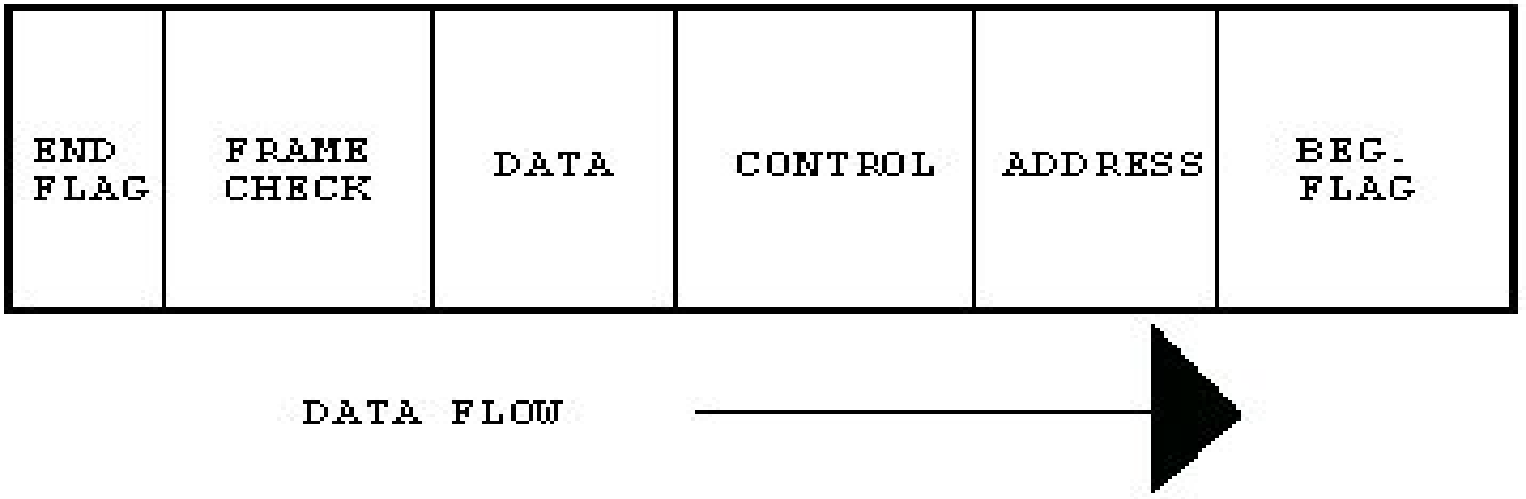
PCM coding, return-to-zero (RZ), non-return-to-zero (NRZ), and split-phase are the three common methods of coding in pulse modulation systems

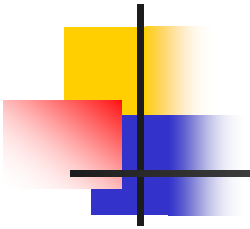


Protocols

- A protocol is a collection of rules and conventions for correctly transferring information.
- Protocols for digital communications comprise three areas:
  - Method of coding.
  - Method of transmission and reception.
  - Method of controlling information exchanges.

Data is Formatted in a Protocol





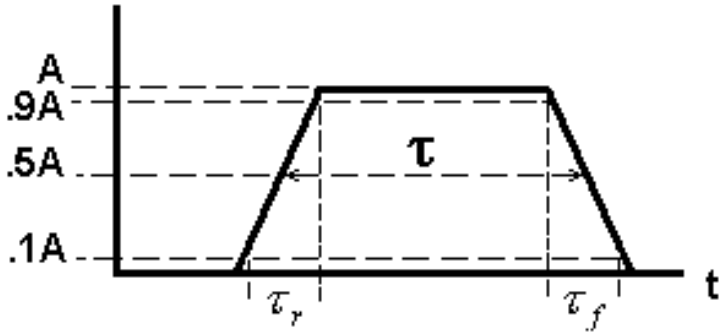
Message Value

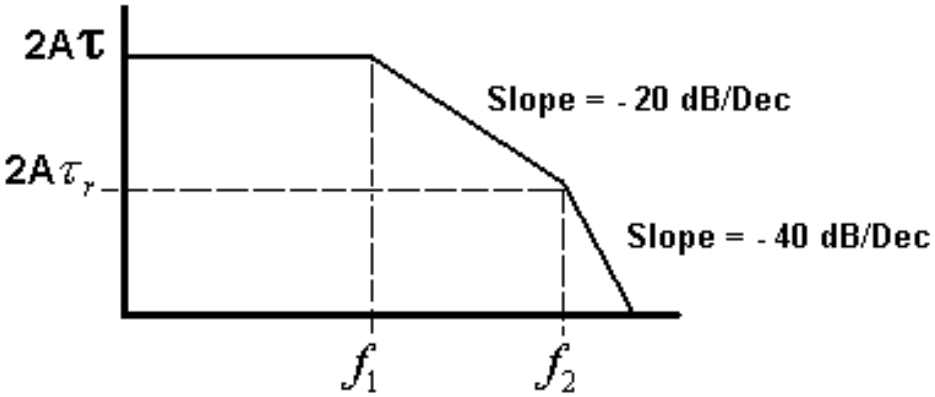
- The value of a message is based on how much was known about the message before it was received, how many messages were in the set of messages, and the probability of each event the messages could describe.
- An information ratio is a figure of merit describing how detectible the symbol sequence is.

Breaking the Message Down

- If the message is considered an ASCII character, we know there are eight bits in the character (two possible states for each bit), plus we know the language (such as English), and we know that a group of messages make up a word in the language we are considering.

Time-Frequency Domain Transform





$\tau = PulseDuration$

$\tau_r = RiseTime$

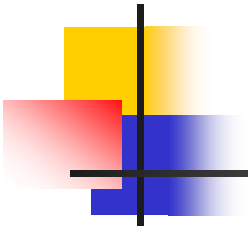
$\tau_f = FallTime$

$$f_2 = \frac{1}{\pi\tau_r}$$

$$f_1 = \frac{1}{\pi\tau}$$

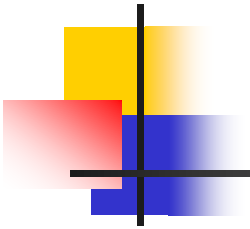
$$A(f_1) = 2A\tau(dB) = 20\log(2A\tau)$$

$$A(f_2) = 2A\tau(db) - 20\log\left(\frac{f_2}{f_1}\right) = 20\log(2A\tau_r)$$



Bottom Line

- The important point is that regardless of code used (ASCII, etc.), the intent of reducing uncertainty is the decoding of a symbol sequence.

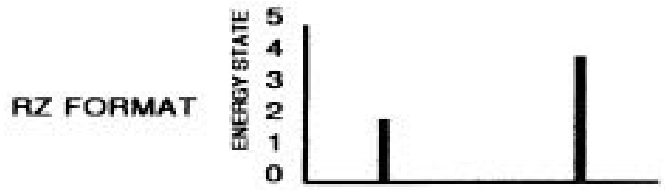


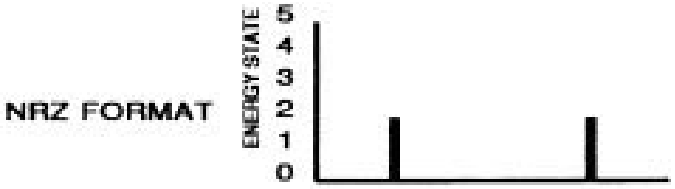
Synchronization

- Transmission involves sending a series of characters across the channel under a timing control initiated at the transmitter.
- The clock must be in synchronization at both ends to avoid the loss of any data bits.
- When all transfers are synchronized, maximum energy will propagate at the clock/data transfers.

Visualization of the Information

		TIME	t_1	t_2
CHANNEL	0		1	1
	1		0	0
	2		0	1
	3		0	0
	4		0	0
	5		0	0
	6		1	1
PARITY	7		0	1
CHARACTER			A	E



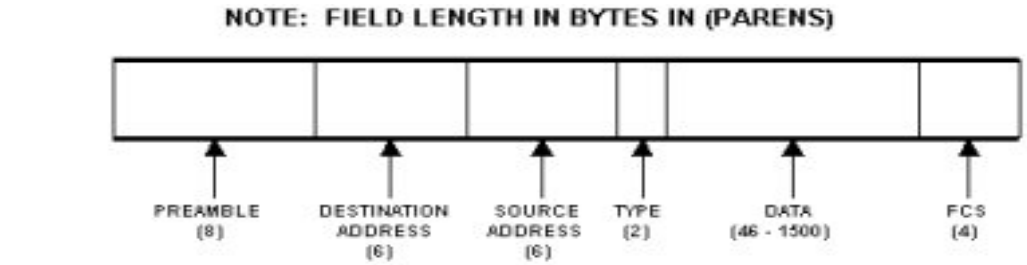


- Bit Energy States
  - **The amount of energy emitted is directly proportional to the number of bits changed from “1” to “0” or “0” to “1” states.**
  - **The energy is transmitted during the transition**
- Probability theory can be used to help predict the ASCII character associated with a particular energy pattern

General Rule

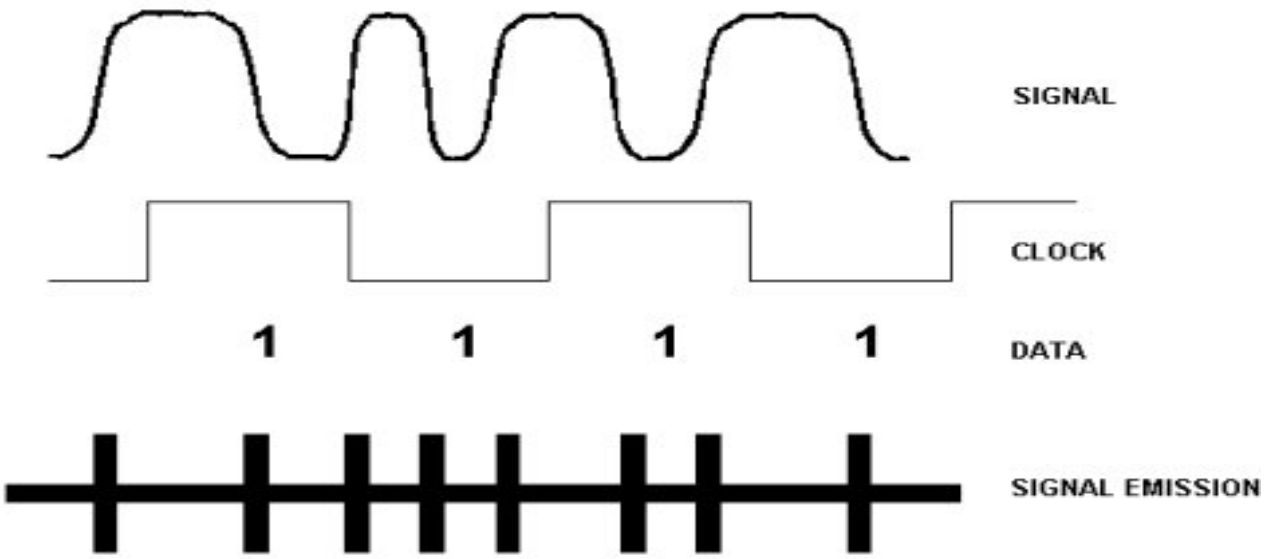
- If a detected signal represents a binary change of state for an ASCII character in a language, and if this change of state is detected at a level 4.8 db above the noise floor with the correct bandwidth for a known bit rate, and if there is a strong probability of correlation to a known series of characters, then the massage is likely to be identifiable.

Putting It All Together

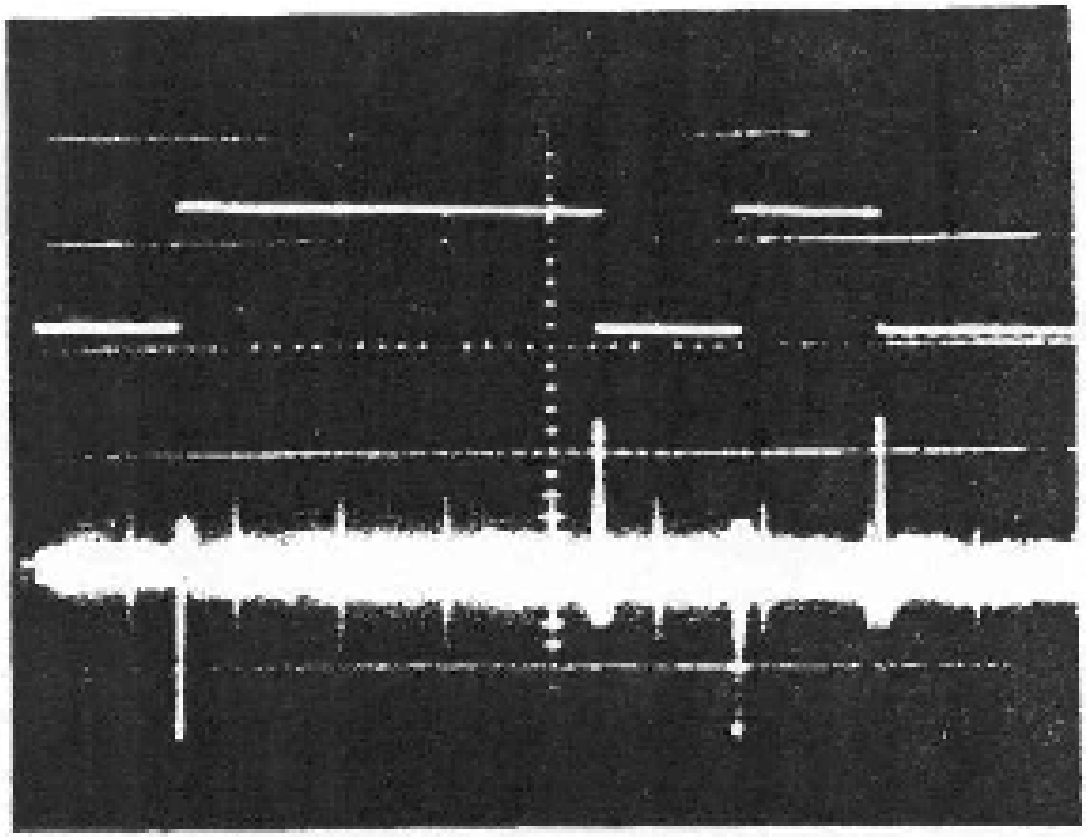


ETHERNET FRAME FORMAT

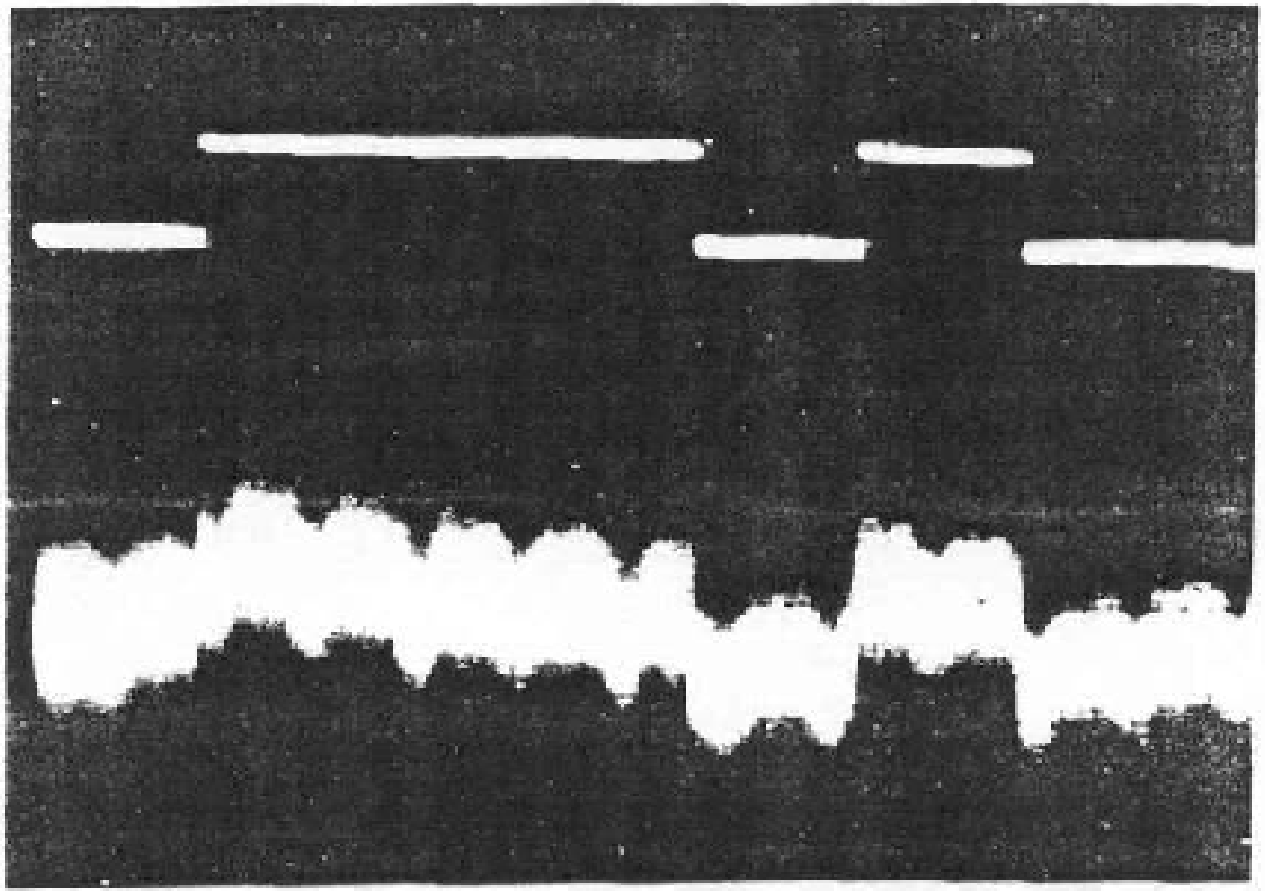
FIGURE 6

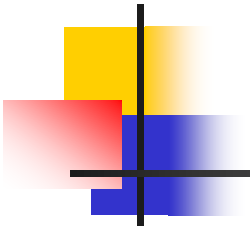


Wideband Detected Signal



Narrowband Detected Signal

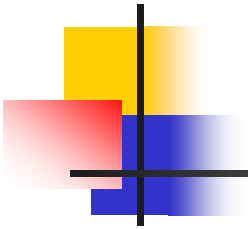




Channel Noise Power

- Noise
  - Any undesired energy within the channel.
- As signal and noise approach the same power level, with constant channel bandwidth, the signal must exist for longer periods of time to be detected.
- Average white Gaussian noise.

  $N = kTBW$
  - K = Boltzmann's Constant
  - T = Channel Temperature in Kelvin
  - BW = Channel Bandwidth in Hz



Channel Capacity

- The maximum bit rate C, through a channel of bandwidth, BW and signal-to-noise power ration S/N is:

$$C = BW \log_2 (1 + S/N) \quad \text{in bits/sec.}$$

- The required minimum S/N power ratio from a known bit rate and bandwidth is:

$$S/N = 2^{(C/BW)}$$