Fundamentals of Wireless Transmissions

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Overview (1)

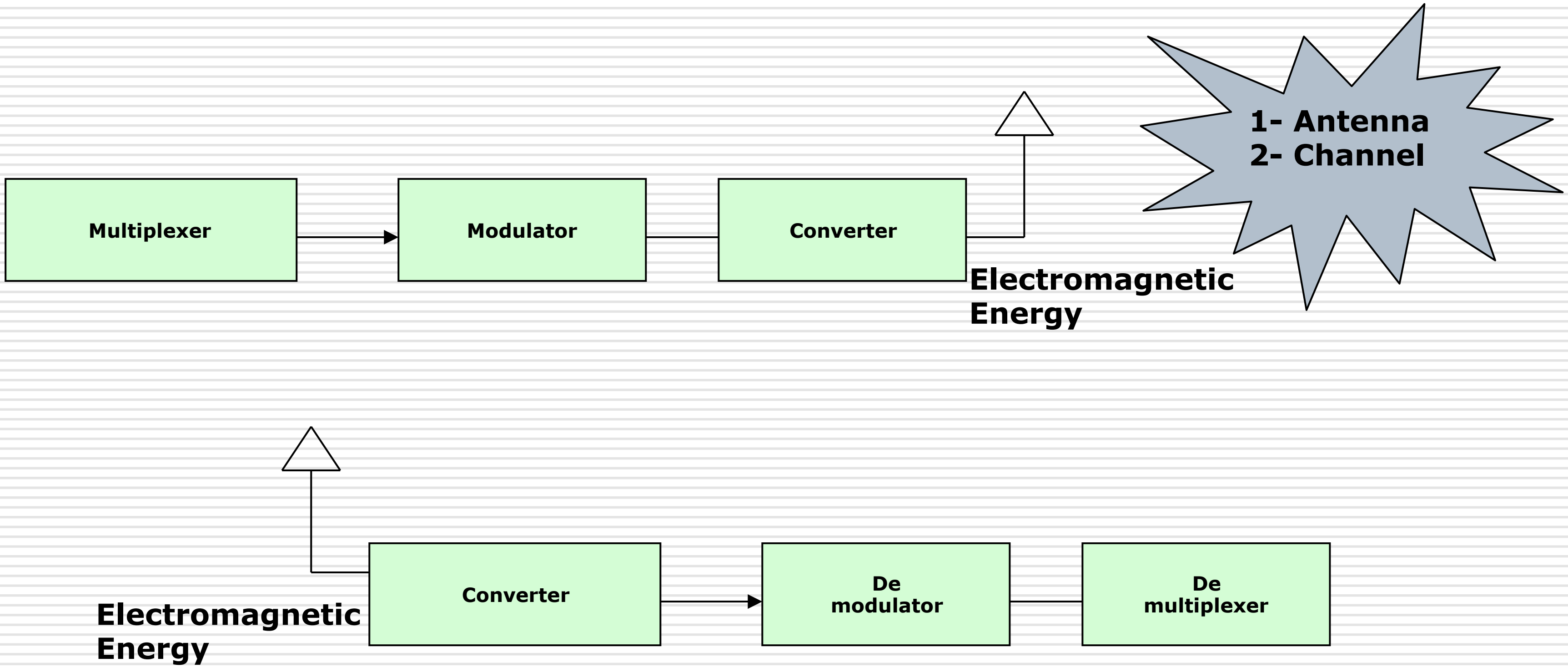
Week 1

- Energy and waves
- Signal characteristics and spectrum
- Bandwidth
- Signal power (Vpeak and Vrms)
- Antenna concept
- Signal propagation
- Free Space Transmission Model
- Isotropic and other types of antenna
- Antenna Gain and efficiency
- Loss and attenuation
- Receiver sensitivity
- Maximum separation

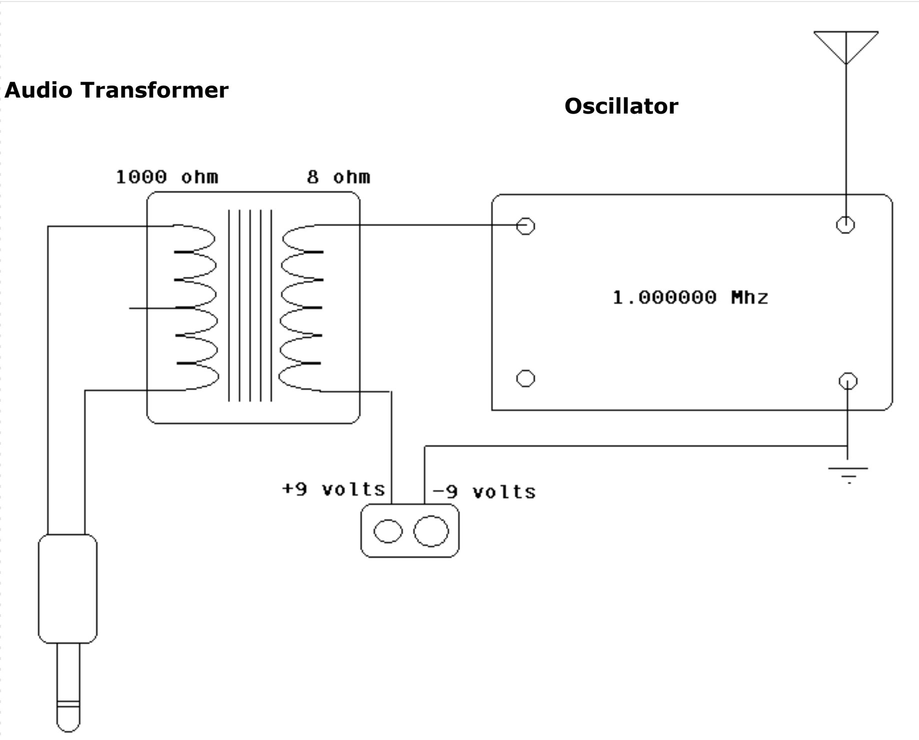
Demo

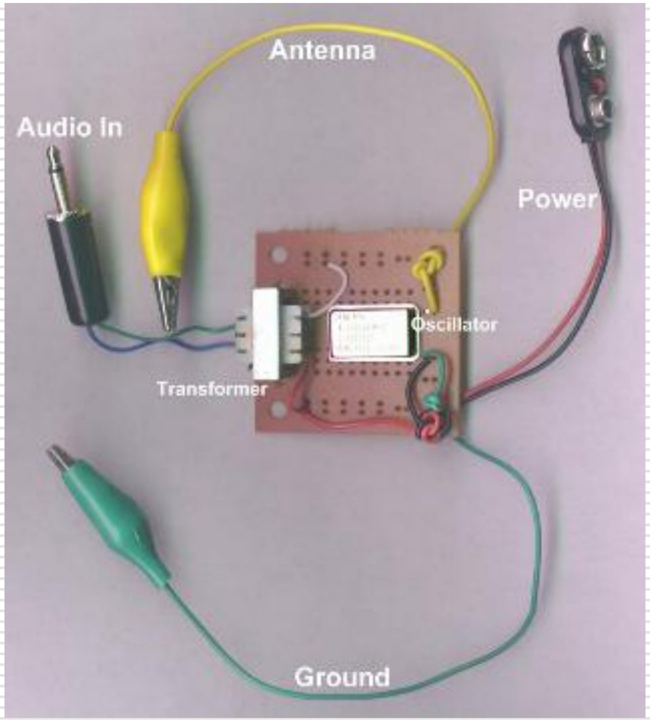
- Dipole Antennas
- XBEE modules
- TinyOS
- RF Transceivers
- Antenna Cables

Wireless Communication Systems



A simple Wireless Transmitter

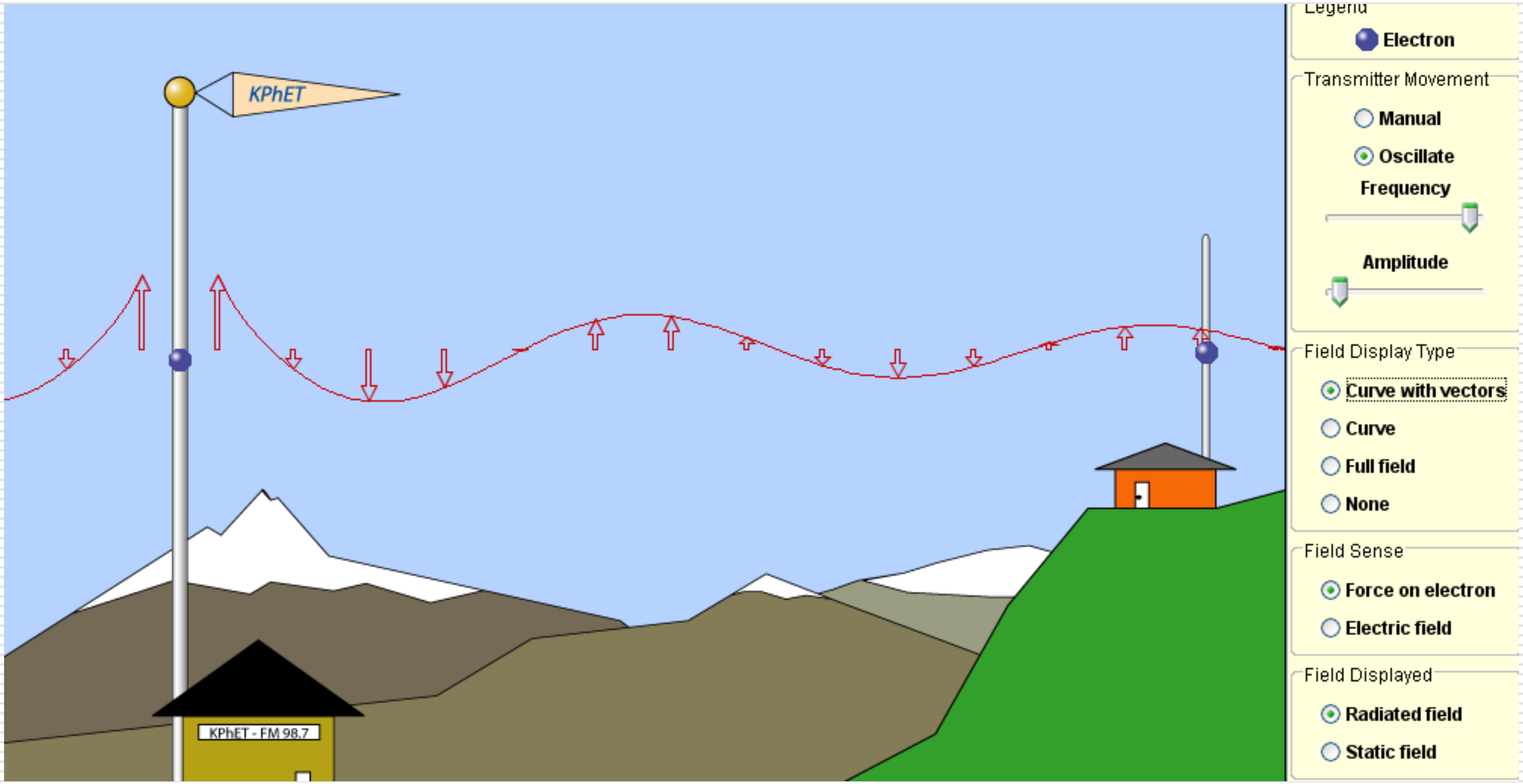




Waves and Propagation

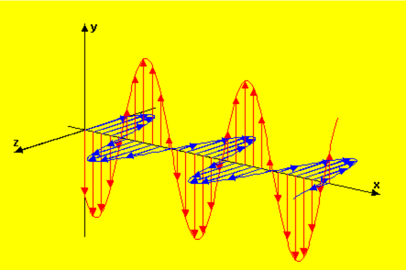
- Consider waving a “charged” ping pong ball at 10 hertz [1]
  - Using an megameter-wave receiver we can detect a signal
- Let’s pretend vibrating a single electron at radio frequency …….

Waves and Propagation - Demo



http://phet.colorado.edu/simulations/sims.php?sim=Radio_Waves_and_Electromagnetic_Fields

Electromagnetic Energy (Radio Waves)



- Electromagnetic waves are used to transmit signals (electric impulses)
- Waves are deformation (disturbance) of medium
  - Temporary disturbance of medium (e.g., Heat Waves)
  - This is how energy is being transmitted
- EM Wave consists of
  - Electric field (red)
  - Magnetic Field (blue)
  - Both traveling at the speed of light (3x10^8 m/s)
  - plane polarized wave travels in X direction
- Remember: Visible light is EM energy with very high frequency
- The basic idea behind an electromagnet is simple: By running electric current through a wire, you can create a magnetic field.

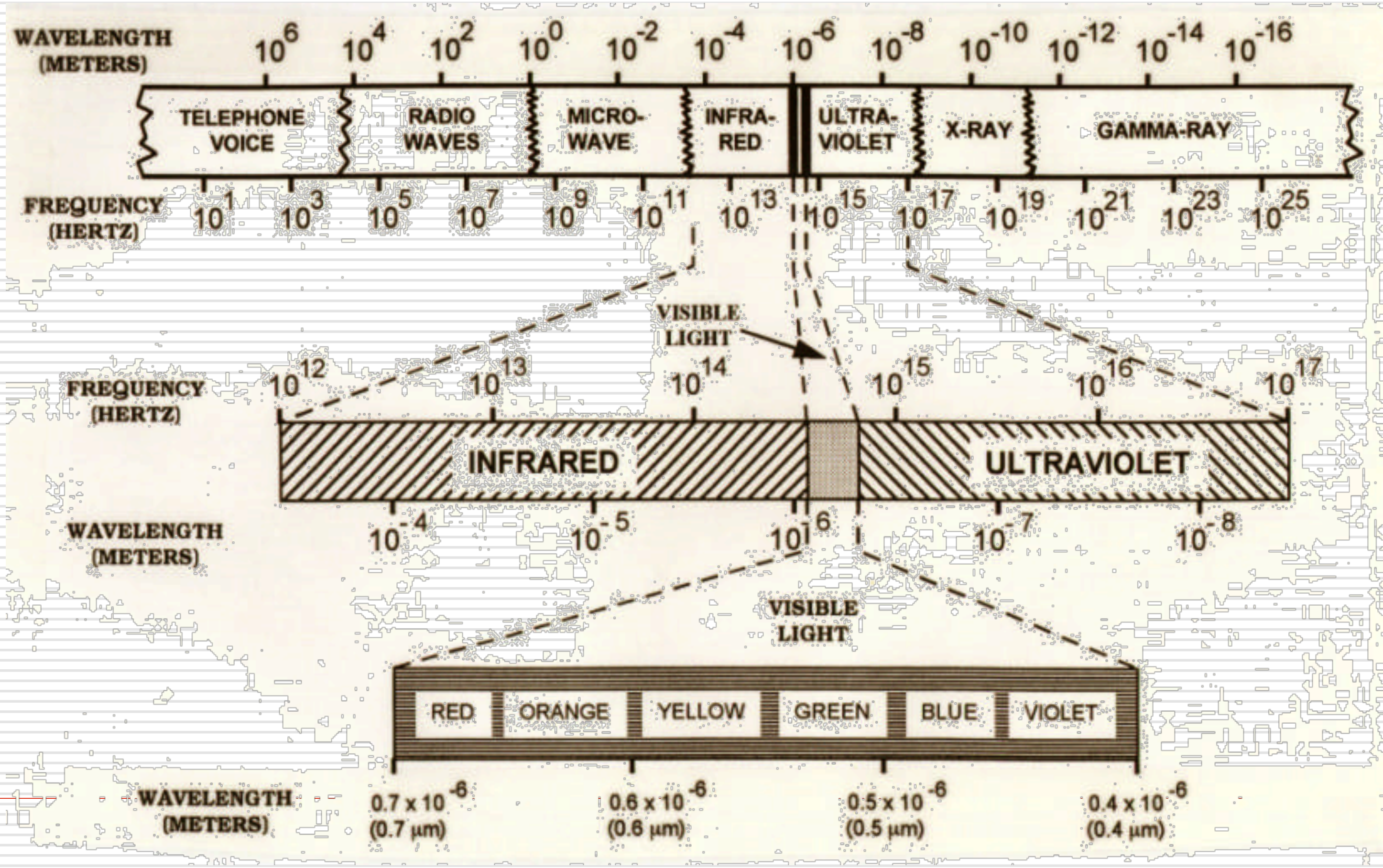
Applet: http://www.walter-fendt.de/ph14e/emwave.htm

EM Radiation Properties

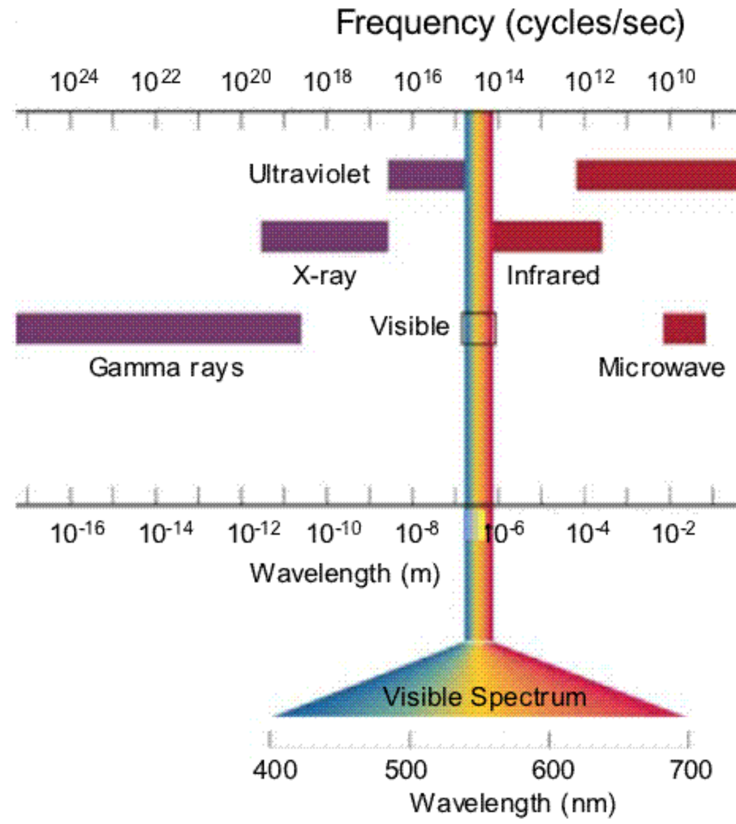
- Wave Model
  - When radiation distance and time scale is large
  - Wave properties (speed, freq, wavelength)
- Particle Model
  - When radiation distance and time scale is small
  - Discrete packets of energy is released (photons)
  - Described by photon-energy expression (E=hf) – this is energy per photon
  - Remember photons transport energy
    - Atom absorbs photon→ excites electrons→ photoionization
    - Atom losses energy →atom emits a photon→ generating light

EM Waves Classification

- EM waves can be classified according to their frequencies



Colors and Wavelengths

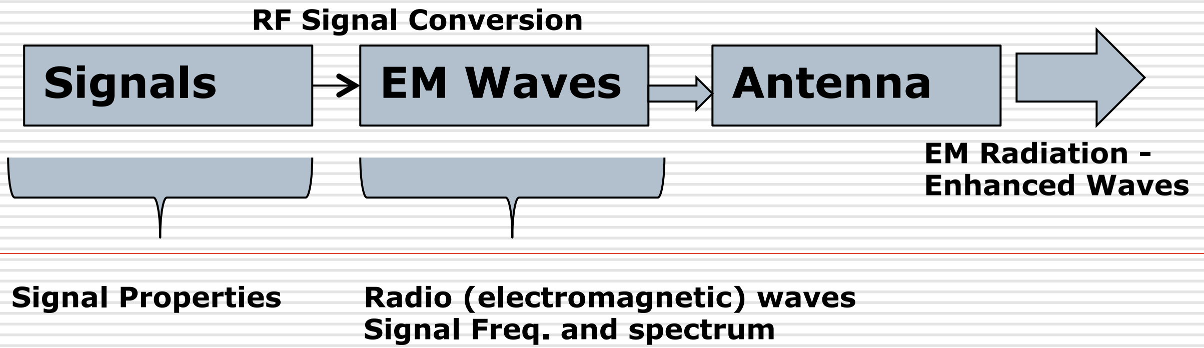


Color	Peak Wavelength [nm]
Blue	470
Cyan	525
Green	560
Yellow	585
Orange	600
Red	645
Deep Red	700

http://www.britannica.com/EBchecked/topic-art/585825/3697/Commercially-exploited-bands-of-the-radio-frequency-spectrum

EM Radiation

- Signals can be converted →EM waves
- Antennas are used to enhance radiated waves
- Radiated waves have typical signal properties
- → We need to learn about signal properties first!
- → Given such properties how is the system capacity impacted!



Wave-properties
Signal Characteristics

- Analog (continuous) or digital (discrete)
- Periodic or aperiodic
- Components of a periodic electromagnet wave signal
  - Amplitude (maximum signal strength) – e.g., in V
  - Frequency (rate at which the a periodic signal repeats itself) – expressed in Hz
  - Phase (measure of relative position in time within a single period) – in deg or radian (2π = 360 = 1 period)

Periodic:

$$S(t) = S(t + T)$$

$$S(t) = A \sin(2\pi f t + \varphi)$$

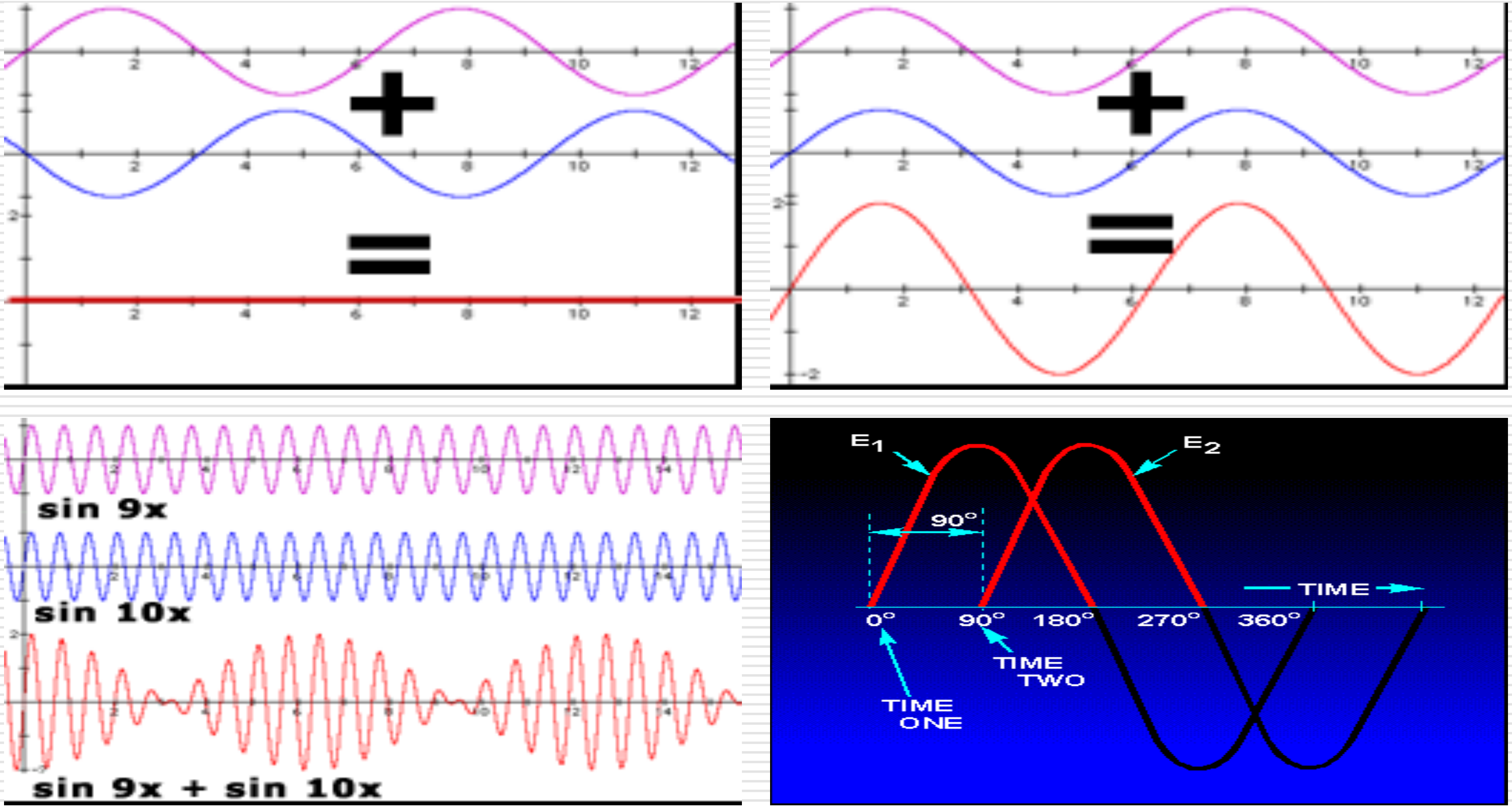
φ = *phase*

A = *amplitude*

f = *frequncy*

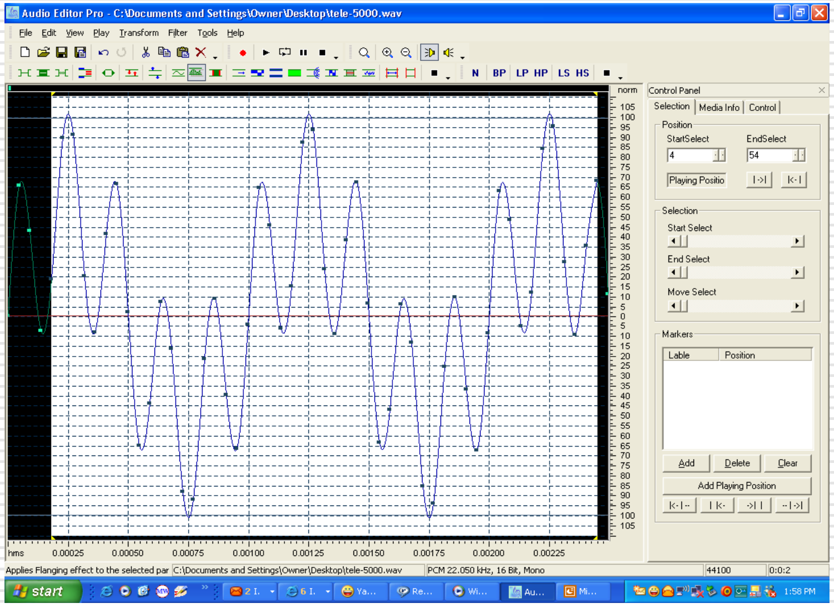
T = *period* = $1/f$

Sine Waves

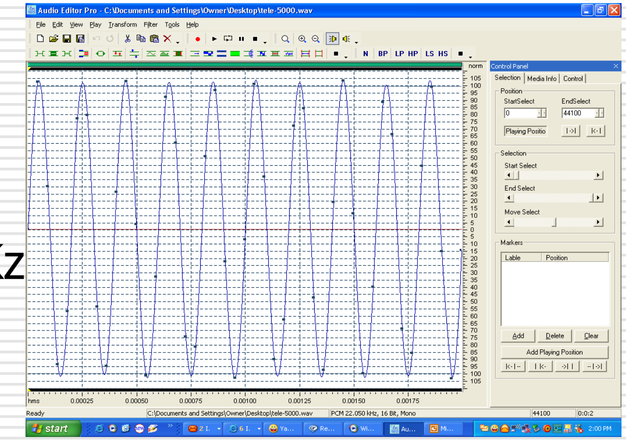

sin 9x
sin 10x
sin 9x + sin 10x
E1
E2
90°
TIME
0°
90°
180°
270°
360°
TIME TWO
TIME ONE

Sound Wave Examples

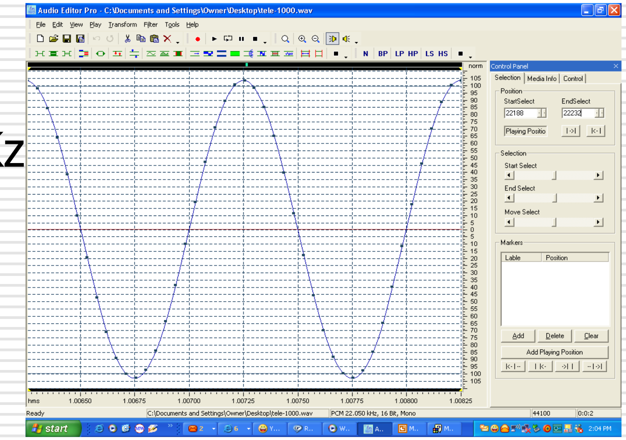
Each signal is represented by $x(t) = \sin(2\pi f.t)$



f = 5Kz



f = 1Kz



A dual tone signal with f1 and f2 is represented by $x(t) = \sin(2\pi f1.t) + \sin(2\pi f2.t)$

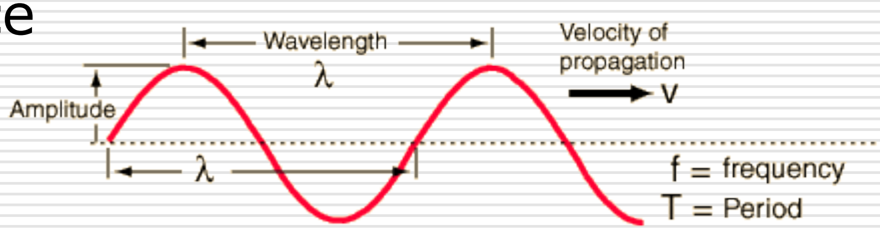
Periodic Signal Characteristics

- The simplest signal is a sinusoidal wave
- A sine wave can be expressed in time or space (wavelength)
  - Wavelength is the distance the signal travels over a single cycle
  - Wavelength is a function of speed and depends on the medium (signal velocity)

λf=v

$$T = 1/f$$

$$v = 3x10^8 m/\sec$$



Exact speed light through vacuum is 299,792,458 m/s

More about signals….

Taylor Series

- Complex signals are often broken into simple pieces
- Signal requirements
  - Can be expressed into simpler problems
  - Is linear
  - The first few terms can approximate the signal

- Example: The Taylor series of a real or complex function $f(x)$ is the power series

$$f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f^{(3)}(a)}{3!}(x-a)^3 + \cdots.$$

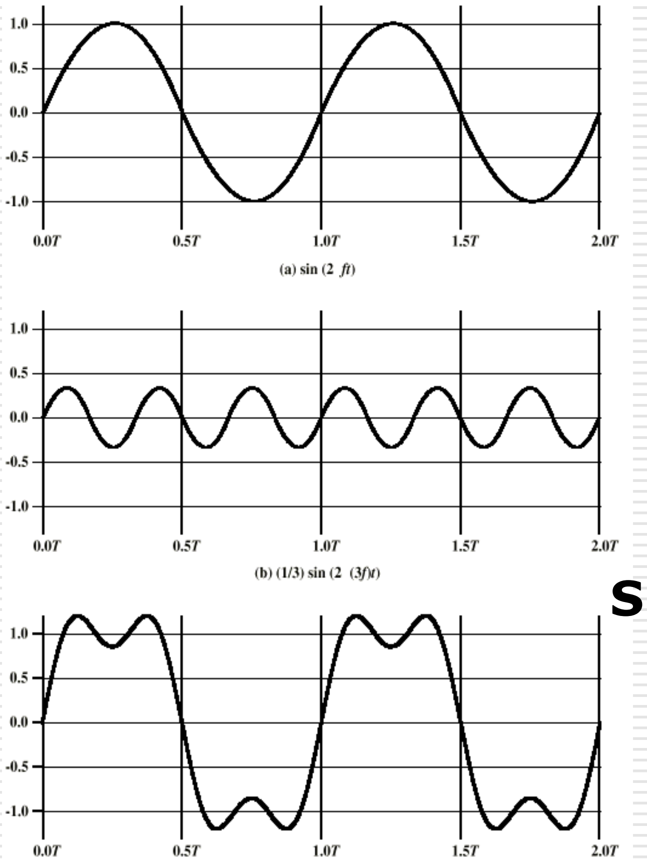
$$\sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}(x-a)^n$$

Signal Representation

- We can represent all complex signals as harmonic series of simpler signals
- Frequency components of the square wave with amplitude A can be expressed as

$$s(t) = A \times \frac{4}{\pi} \sum_{K=1/odd}^{\infty} \frac{\sin(2\pi k f t)}{k}$$

Square Wave



(a) sin (2 ft)

(b) (1/3) sin (2 (3f)t)

(c) (4/) [sin (2 ft) + (1/3) sin (2 (3f)t)]

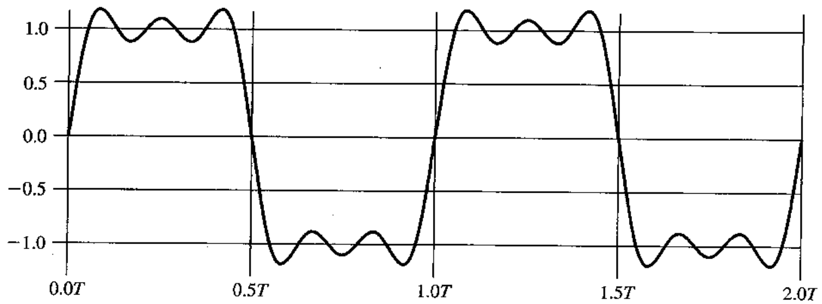
S(t)=sin(2πft)

S(t)=1/3[sin(2π(3f)t)]

S(t)= 4/π{sin(2πft) +1/3[sin(2π(3f)t)]}

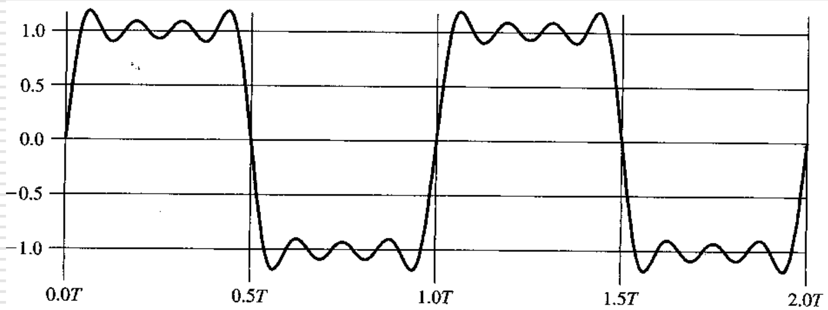
$$s(t) = A \times \frac{4}{\pi} \sum_{K=1/odd}^{\infty} \frac{\sin(2\pi kft)}{k}$$

Square Wave



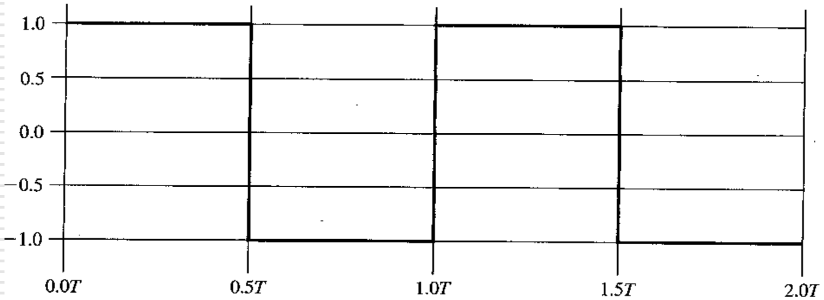
(a) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$

K=1,3,5



(b) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t) + (1/7)\sin(2\pi(7f)t)]$

K=1,3,5, 7



(c) $(4/\pi)\,\Sigma\,(1/k)\sin(2\pi(kf)t)$, for k odd

K=1,3,5, 7, 9, …..

Frequency Components of Square Wave

$$s(t) = A \times \frac{4}{\pi} \sum_{K=1/odd}^{\infty} \frac{\sin(2\pi kft)}{k}$$

Fourier Expansion

Periodic Signals

- A Periodic signal/function can be approximated by a sum (possible infinite) sinusoidal signals.
- Consider a periodic signal with period T
- A periodic signal can be Real or Complex
- The fundamental frequency: ωo
- Example:
  - Prove that x(t) is periodic: $x(t) = \cos(\omega_o t + \theta)$

$$Periodic \Rightarrow x(t + nT) = x(t)$$

$$\text{Real} \rightarrow x(t) = \cos(\omega_o t + \theta)$$

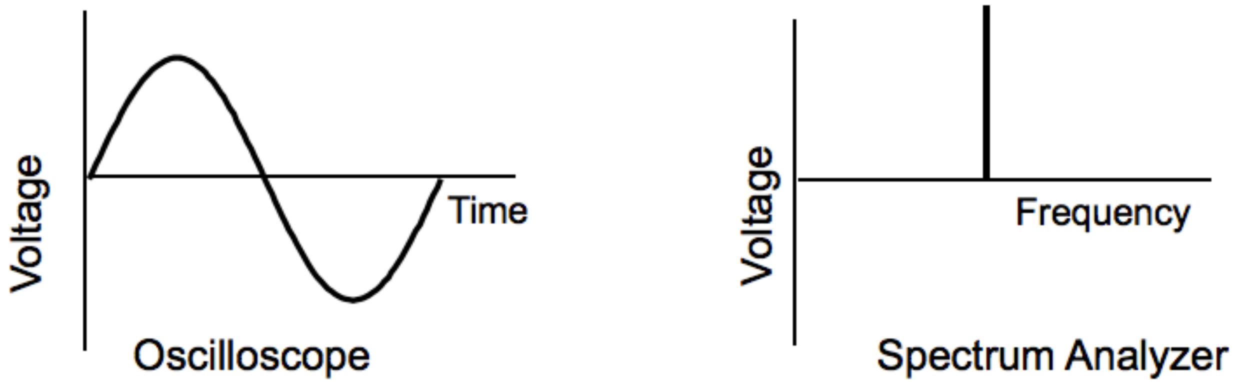
$$Complex \rightarrow x(t) = Ae^{j\omega_o t}$$

$$\omega_o = 2\pi / T_o$$

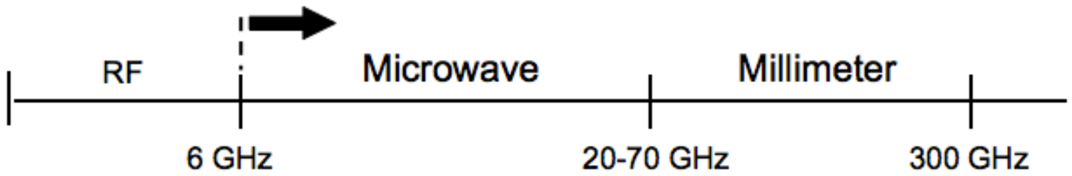
$$T_o = 2\pi / \omega_o$$

Signal Generation – No Modulation

Continuous Wave (CW)



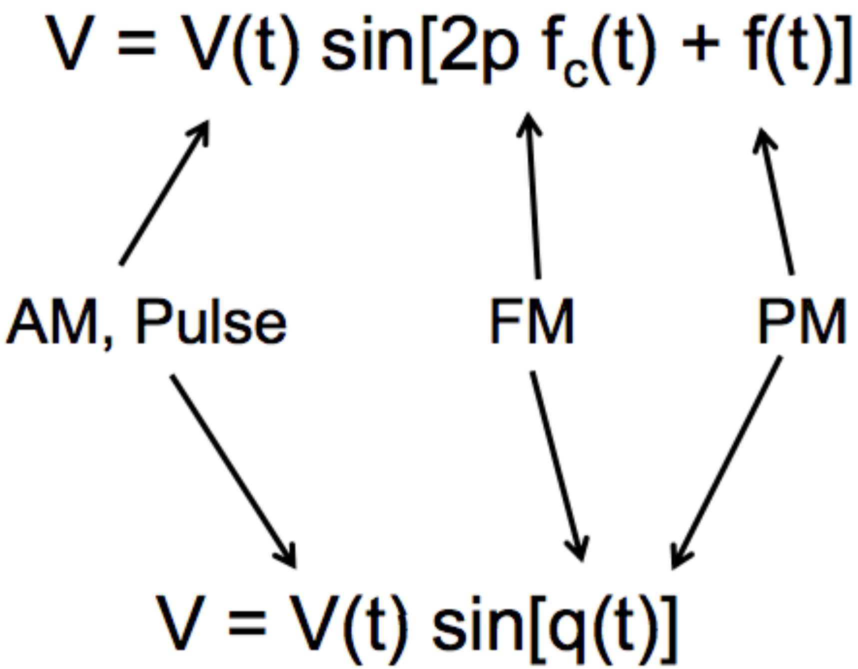
The sine wave is the basic, non-modulated signal: It is useful for stimulus/response testing of linear components and for Local Oscillator substitution. Available frequencies range from low RF to Millimeter.



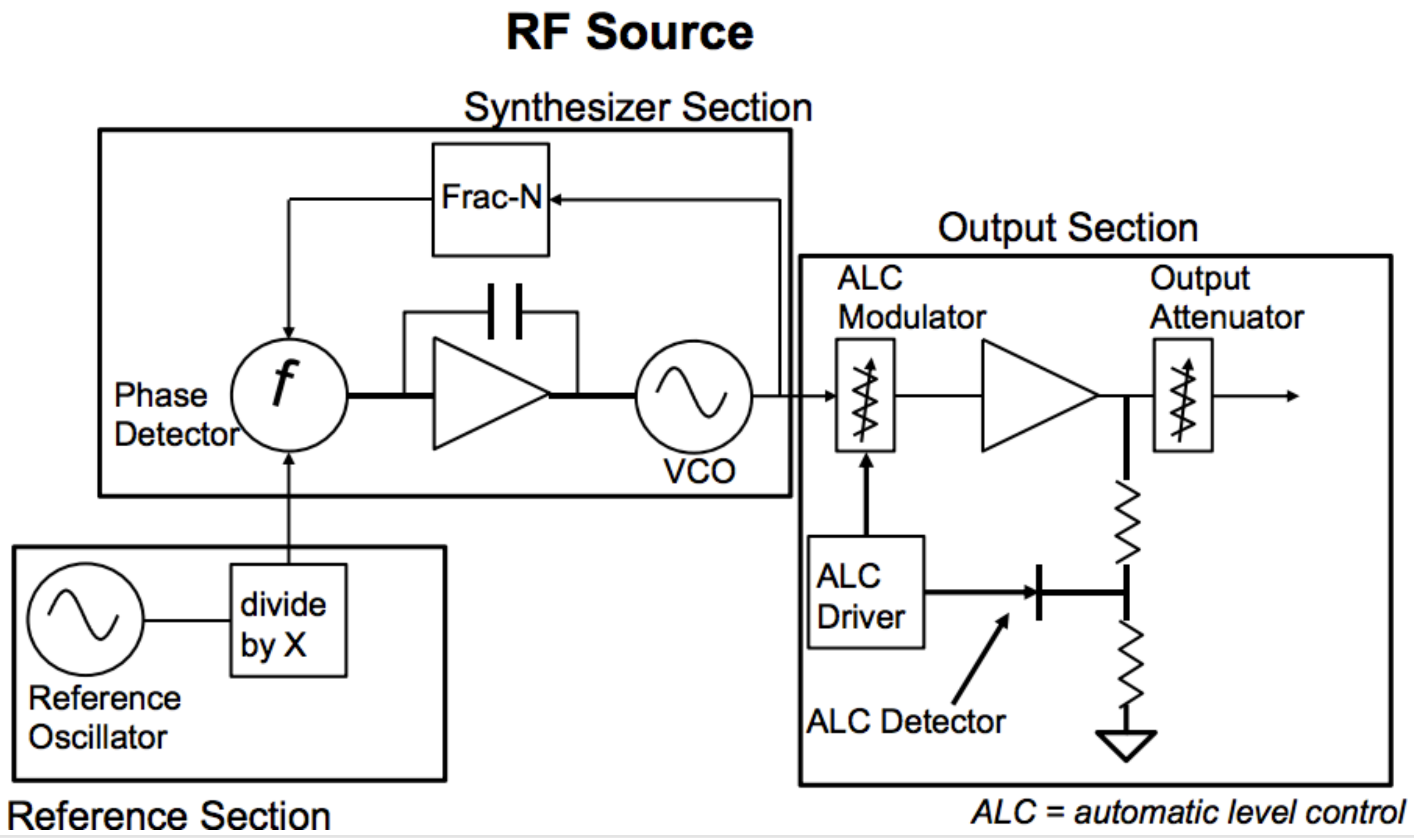
http://www.keysight.com/upload/cmc_upload/All/PPT3_AGILENT_Les-bases-de-la-generation-RF-et-Hyperfrequence.pdf?&cc=US&lc=eng

Signal Generation - Modulated

Modulation: Where the Information Resides



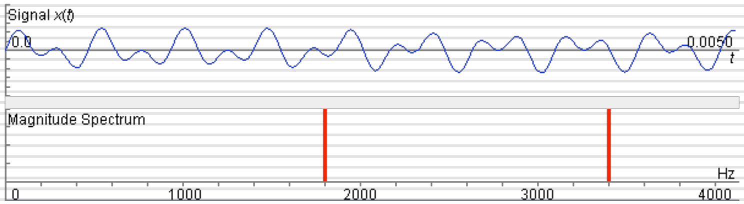
RF Source


RF Source
Synthesizer Section
Frac-N
f
Phase
Detector
VCO
Output Section
ALC
Modulator
Output
Attenuator
ALC
Driver
ALC Detector
divide
by X
Reference
Oscillator
Reference Section
ALC = automatic level control

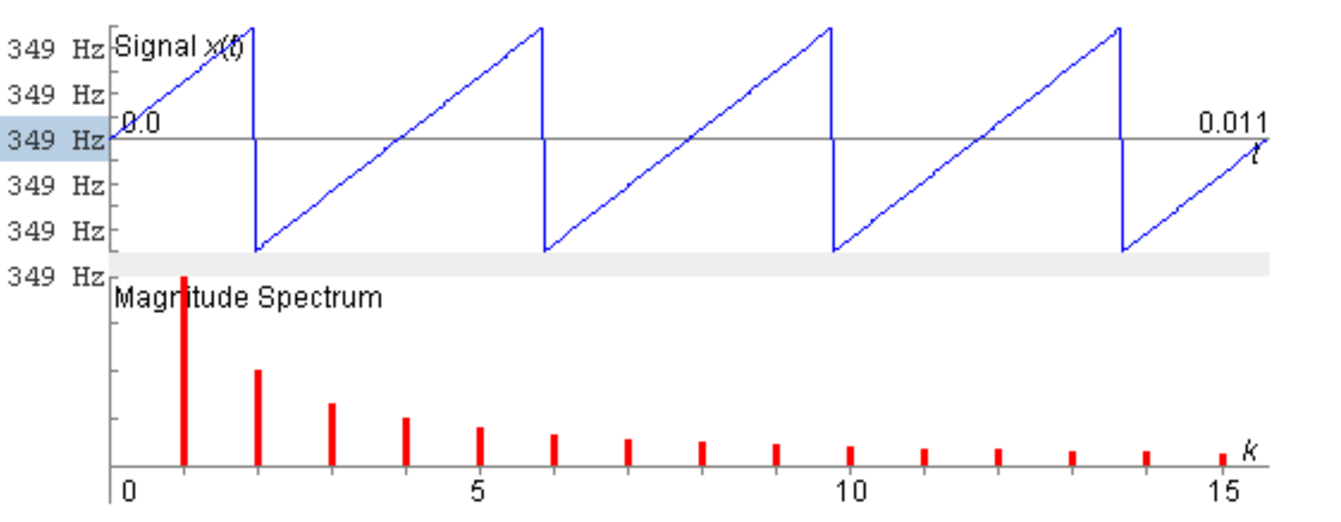
Frequency Spectrum

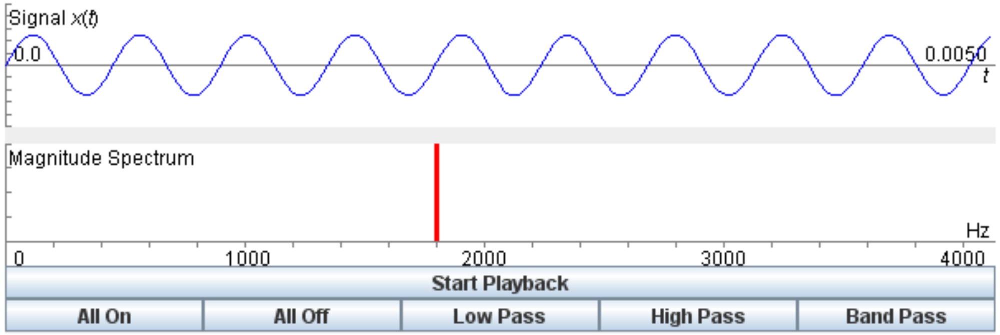
- We can plot the *frequency spectrum* or *line spectrum* of a signal
  - In Fourier Series k represent harmonics
  - Frequency spectrum is a graph that shows the amplitudes and/or phases of the Fourier Series coefficients *Ck*.
    - Amplitude spectrum **|Ck| =4A/k.pi**
    - The lines |Ck| are called line spectra because we indicate the values by lines

$$s(t) = A \times \frac{4}{\pi} \sum_{K=1/odd}^{\infty} \frac{\sin(2\pi kft)}{k}$$



Examples



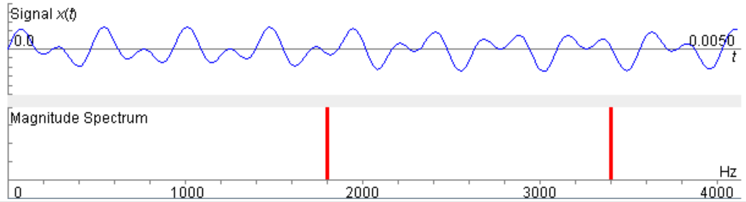


http://www.jhu.edu/~signals/listen-new/listen-newindex.htm

Periodic Signal Characteristics

- A signal can be made of many frequencies
  - All frequencies are multiple integer of the *fundamental frequency*
  - Spectrum of a signal identifies the range of frequencies the signal contains
  - Absolute bandwidth is defined as: Highest_Freq – Lowest_Freq
  - 3-dB Bandwidth in general is defined as the frequency ranges where a signal has its most of energies
- Signal data rate
  - Information carrying capacity of a signal
  - Expressed in bits per second (bps)
  - Typically, the larger frequency → larger data rate

Example →



Periodic Signal Characteristics

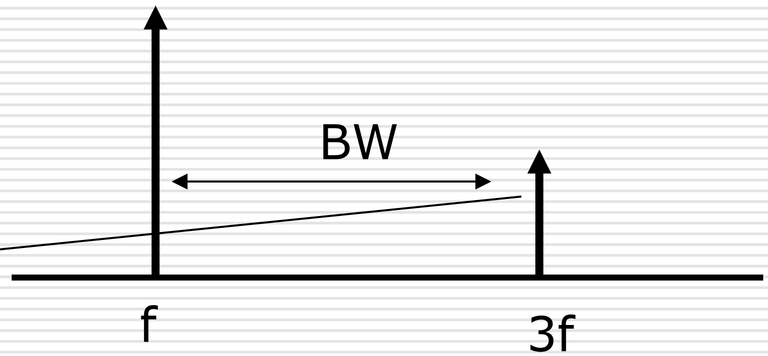
- Consider the following signal
  - Consists of two freq. component (f) and (3f) with BW = 2f

$$S(t) = (4/\pi)\sin(2\pi ft) + (4/3\pi)\sin(2\pi(3f)t)$$

$$Fundamental\_freq = f$$

$$Max\_freq = 3f$$

$$Abs\_BW = 3f - f = 2f$$



What is the Max amplitude of this component?

http://www.jhu.edu/~signals/listen-new/listen-newindex.htm

Calculating Signal Power – Sinusoidal signals

- RMS (Root Mean Square) or effective value of the sine waveform (single tone):
- Average Power is calculated using RMS value and expressed in Watts
- Instantaneous power is V^2/2

$$V_{RMS} = Vp / \sqrt{2} = 0.707Vp$$

$$P = {V_{RMS}}^2 / R$$

Vp=Vpeak (not peak-to-peak)

Read for more information: http://www.eznec.com/Amateur/RMS_Power.pdf

RMS Concept

In the case of a set of n values $\{x_1, x_2, \ldots, x_n\}$, the RMS value is given by this formula:

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

The corresponding formula for a continuous function (or waveform) $f(t)$ defined over the interval $T_1 \leq t \leq T_2$ is

$$f_{\mathrm{rms}} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} [f(t)]^2 \, dt},$$

and the RMS for a function over all time is

$$f_{\mathrm{rms}} = \lim_{T\to\infty} \sqrt{\frac{1}{T}\int_0^{T} [f(t)]^2 \, dt}.$$

Examples

Waveform	Equation	RMS
DC, constant	$y = a$	a
Sine wave	$y = a\sin(2\pi f t)$	$\frac{a}{\sqrt{2}}$
Square wave	$y = \begin{cases} a & \{ft\} < 0.5 \\ -a & \{ft\} > 0.5 \end{cases}$	a

Find the Vrms for a square wave signal!

http://en.wikipedia.org/wiki/Root_mean_square

Power in Telecommunication Systems – Power change can have large dynamic range

- Remember:

$$10^x = y \xrightarrow{then} \log(10^x) = \log y \xrightarrow{Hence} x = \log y$$

- Example 1: if P2=2mW and P1 = 1mW →

  $10\log_{10}(P2/P1)=3.01$ dB
- Example 2: if P2=1KW and P1=10W →20dB
- What if dB is given and you must find P2/P1?
  - P2/P1 = Antilog(dB/10) = $10^{dB/10}$.
- Example 3: if dB is +10 what is P2/P1?
  - P2/P1 = Antilog(+10/10) = $10^{+10/10}$ = 10

We tend to express power in dBW or dBm

Converting and Amplification Watt, dBW, dBm, dB

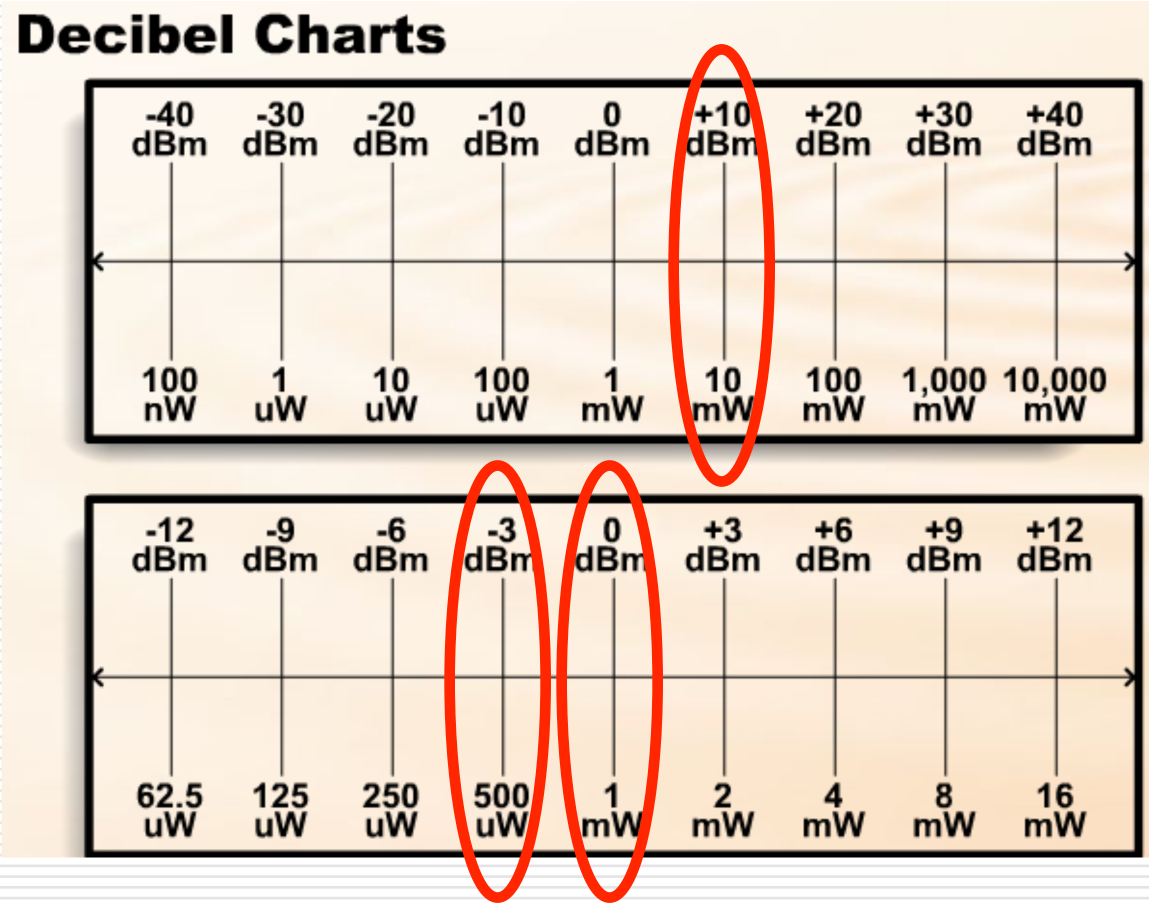
- Conversions: Watt to dBW & dBm

$$P = 10(W) = 10\log(10) = 10dBW$$

$$= 10\log(10 \cdot 10^{3} mW / 1mW) = 10 \cdot 4 = 40dBm$$

For more see: http://www.giangrandi.ch/electronics/anttool/decibel.html

dBm


Decibel Charts
-40 dBm
-30 dBm
-20 dBm
-10 dBm
0 dBm
+10 dBm
+20 dBm
+30 dBm
+40 dBm
100 nW
1 uW
10 uW
100 uW
1 mW
10 mW
100 mW
1,000 mW
10,000 mW
-12 dBm
-9 dBm
-6 dBm
-3 dBm
0 dBm
+3 dBm
+6 dBm
+9 dBm
+12 dBm
62.5 uW
125 uW
250 uW
500 uW
1 mW
2 mW
4 mW
8 mW
16 mW

Wireless Systems

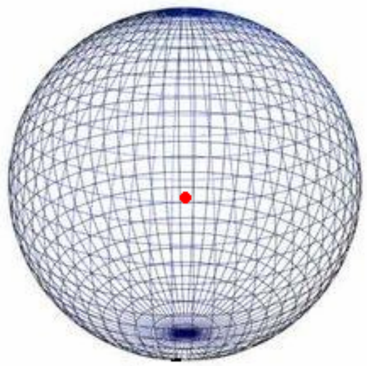
Antenna

- An antenna is an electrical conductor (transducer)
  - Converts time-varying current/voltage signals into EM waves (and vise versa)
- Antennas RX and TX EM EM waves
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception
  - Antenna characteristics are the same for transmitting or receiving electromagnetic energy
- The antenna can receive on one frequency and transmit on another

Isotropic Radiation

- We assume power is radiated spherically
  - The source be surrounded by a sphere or radius *d*
  - A perfect Omni directional power (isotropic antenna)
- We measure directionality based on how much of the isotropic radiation is focused in a certain direction
  - This is referred to as the *antenna directionality or antenna Gain*

Isotropic Antenna



- A single source of transmission
  - Sphere of radiation with radius d
  - Uniform flux lines (just like the sun)
- Power flux density $= P_{den} =$ Transmit Power/A_{Sphere} (W/m^2)
- Received power (W):
  - Also called power intercepted
  - Aer is effective aperture or area (m^2)
  - Aer is based on the physical area

$$P_{den} = \frac{P_t}{4\pi \cdot d^2}$$

$$P_r = \frac{P_t}{4\pi \cdot d^2} \times A_{er}$$

Antenna Directionality or Gain

- Power density can be increased by changing its directionality
  - That is transmitting or receiving more in certain directions
  - This is referred to as the antenna gain (Gt)
- Equivalent Isotropic Radiated Power (EIRP)

$$P_r = \frac{P_t \cdot G_t}{4\pi \cdot d^2} \times A_{er} = \frac{EIRP}{4\pi \cdot d^2} \times A_{er}$$

Let’s discuss G, Ae, and EIRP!

Antenna Gain & Effective Area

- Power gain is expressed relative to isotropic (assume ohmic loss very small η=1; note: η>=1)

Antenna Gain and Effective Area

Antenna	Power Gain	Effective Area
Isotropic	1	$\lambda^2/(4\pi)$
Small Dipole or Loop **Also known as Hertzian Dipole**	1.5	$(1.5\lambda^2)/(4\pi)$
Half-Wave Dipole	1.64	$(1.64\lambda^2)/(4\pi)$
Horn, mouth area *A*	$(10A)/\lambda^2$	$0.81A$
Parabola, face area *A*	$(7A)/\lambda^2$	$0.56A$
Turnstile	1.15	$(1.15\lambda^2)/(4\pi)$

$$P_r = \frac{P_t \cdot G_t}{4\pi \cdot d^2} \times A_{er} = \frac{EIRP}{4\pi \cdot d^2} \times A_{er}$$

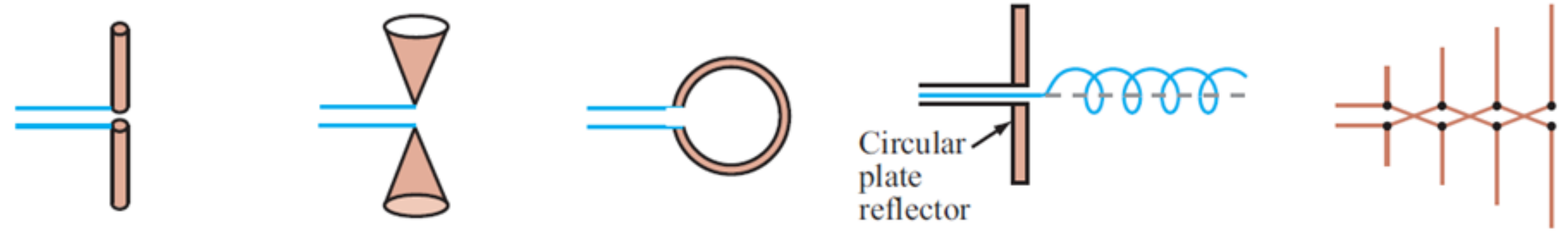
For Isotropic

$$G = \frac{4\pi \cdot \eta}{\lambda^2} \cdot A_e = \frac{4\pi f^2 \cdot \eta}{c^2} \cdot A_e$$

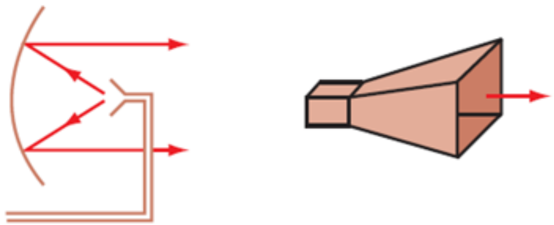
$$Ae = \frac{G \cdot \lambda^2}{4\pi \cdot \eta}$$

η is efficiency of the system (later)

Different Antenna Types



(a) Thin dipole (b) Biconical dipole (c) Loop (d) Helix (e) Log-periodic



(f) Parabolic dish reflector (g) Horn

Receiver Effective Area

- On the receiver side the larger the antenna the more of the radiated power can be captured (intercepted)
  - Pr = P_{den} . Aer (in Watt)
  - Aer is the physical effective area of the receiver antenna

$$P_r = \frac{P_t}{4\pi \cdot d^2} \cdot A_{er}$$

$$= P_t \cdot G_t \cdot G_r \cdot \frac{\lambda^2}{4\pi \cdot d^2}$$

$$= P_t \cdot G_t \cdot G_r \cdot \frac{1}{4\pi \cdot (d^2 / \lambda^2)}$$

Also known as Range Eqn.
Or Friis Or Free Space Eqn.

Antenna Gain & Effective Area

$$P_r = \frac{P_t \cdot G_t}{4\pi \cdot d^2} \cdot A_{er}$$

- Both TX and RX antennas can have gains
- The receiver gain is directly related to its effective area
  - Note that larger Aeff → more gain → more power TX and RX

Remember:

$$G_r = \eta \frac{4\pi A_{er}}{\lambda^2}$$

$$G_t = \eta \frac{4\pi A_{et}}{\lambda^2}$$

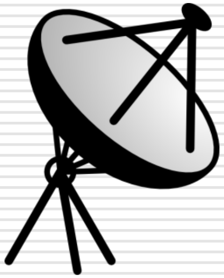
η is efficiency of the system (later)

Equivalent Isotropic Radiated Power

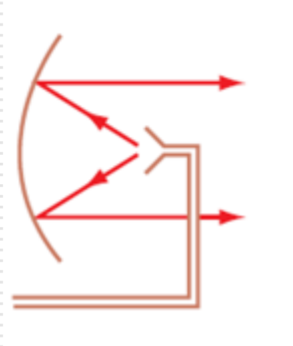
- EIRP= Pt.Gt
  - Indicates signal strength radiated
  - Can be expressed in dBi or dBd
    - dBi represents the power density with respect to an isotropic antenna
    - dBd represents the power density with respect to a dipole antenna
  - Note: dBi = dBd + 2.15dB
- For example:
  - Calculate EIRP if a 12 dBi gain antenna is fed with 15 dBm of power

12 dBi + 15dBm = 27 dBm (500 mW)

Example: Antenna Gain



- Given a parabolic antenna with radius of 1 meter used to send WiFi (802.11b) channel 2; Assume the effective area of the parabolic is 0.56A(Face Area) and $\eta=1$:
  - Find the gain and its effective area.
  - What is the gain in dB?



MATLAB CODE:

```
Face_Area=0.56*pi*r*r;
f=2.417*10^9;
c=3*10^8;
l=c/f

Gain=(4*pi*Face_Area*f*f)/(c*c)
Gain_in_db=10*log10(Gain)
```

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

See next slide for freq. bands in 802.11 b

Example: Antenna Gain

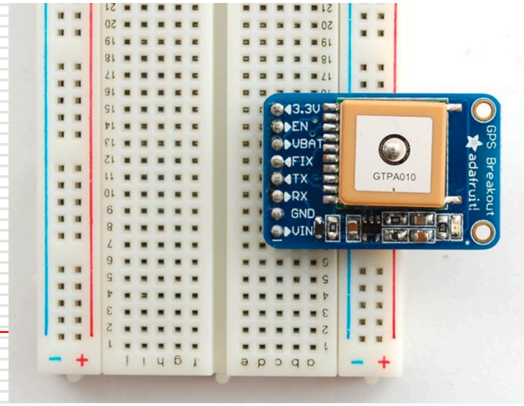
802.11b Frequency Band (GHz)

- In the United States and Canada there are 11 channels available for use in the 802.11b 2.4GHz WiFi Frequency range. This standard is defined by the IEEE.

		Average	
1	2.401	2.412	2.423
2	2.404	2.417	2.428
3	2.411	2.422	2.433
4	2.416	2.427	2.438
5	2.421	2.432	2.443
6	2.426	2.437	2.448
7	2.431	2.442	2.453
8	2.436	2.447	2.458
9	2.441	2.452	2.463
10	2.446	2.457	2.468
11	2.451	2.462	2.473

http://www.moonblinkwifi.com/2point4freq.cfm

Receiver Sensitivity



GPS Receiver

- What is the minimum level of signal power the receiver can receive and still process it properly?

$$P_r(\min) = \frac{P_t \cdot G_t}{4\pi d^2} \cdot A_{er} \rightarrow P_r(\min) = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{\eta (4\pi d)^2}$$

- In this case, given d → we find Pr(min)

Maximum Distance Covered

- Using sensitivity:

$$P_r = \frac{P_t \cdot G_t}{4\pi d^2} \cdot A_r \rightarrow P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{\eta (4\pi d)^2}$$

$$\Rightarrow d_{\max} = \sqrt{\frac{P_t \cdot G_t \cdot G_t \cdot \lambda^2}{\eta (4\pi)^2 \cdot P_r^{\min}}}$$

η=1 if no ohmic loss!

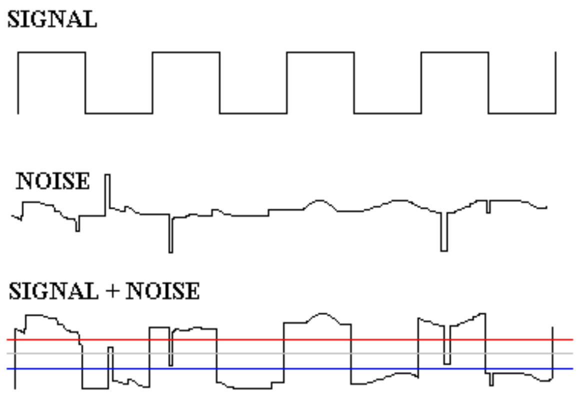
Sensitivity and RSSI

- Remember: EIRP → signal strength radiated
- Power strength can be adjusted in the routers/wireless devices
- There are two well-known values for **link quality** estimation:
  - Received Signal Strength Indicator (RSSI)
    - Determines the total energy of the signal
    - Higher RSSI → more signal energy
    - Higher RSSI → less packet error ratio (PER)
  - Link Quality Indicator (LQI)
    - Measurement is performed per packet
- No standard as to how to implement RSSI
  - Difficult to compare performances of difference devices to one another

Example:
Power Transmission in XBEE

- XBEE has a threshold sensitivity of -44dBm and it can transmit with maximum of 10 dBm. What is the maximum distance two XBEE transceivers can be separated from one another? (assume: free space, Gt=Gr=1; no ohmic loss, f=2.417GHz)

$$d_{max} = \sqrt{\frac{P^{max}{}_t \cdot G_t \cdot G_r \cdot \lambda^2}{\eta (4\pi)^2 \cdot P_r^{min}}}$$



Signal Distortion

- Received signal conditions
  - must have sufficient strength so that circuitry in the receiver can interpret the signal
  - must maintain a level sufficiently higher than noise to be received without error
- Signal can be distorted: (1) High Noise; (2) Low Signal Strength
- Low Signal Strength is due to Attenuation (loss of energy)
- There are many sources contributing to signal attenuation
- Strength of signal falls off with distance over transmission medium (free space) → Free Space Loss (signal spreading)
- Ohmic loss – converting to heat
- Note: Equalizing attenuation improves distortion
- By equalizing we can ensure that the signal performs the same over the entire frequency band

Loss in Free Space Model

- Note that Lpath is the loss due to signal spreading as it travels (not due to converting to heat or ohmic loss)
- Note:
  - as wave length increases more loss occurs
  - the impact of distance and wavelength are very drastic

$$P_r = EIRP \cdot G_r \cdot \frac{1}{(4\pi)^2 \cdot (d^2 / \lambda^2)}$$

$$L_{path} = (4\pi)^2 \cdot (d^2 / \lambda^2)$$

How does loss changes as the frequency increases?

Free Space Loss

- The signal disperses with distance
- Free space loss, for ideal isotropic antenna

$$L_{path} = \frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

- P_t = signal power at transmitting antenna
- P_r = signal power at receiving antenna
- λ = carrier wavelength
- d = propagation distance between antennas
- c = speed of light (» 3 × 10^8 m/s)

where d and λ are in the same units (e.g., meters)

When there is loss (dB)→ we have to subtract!

Free Space Loss (in dB)

- Free space loss equation can be represented as

$$L_{path\_dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right); P_t \leq P_r$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\,\text{dB}$$

Attenuation (loss) is greater at higher frequencies, causing distortion

Other Factors Impacting Attenuation

- Mismatch between the source and antenna
- Propagation loss (passing though walls)
- Absorption (due to hitting building)
- Antenna ohmic loss (converting to heat)

$$P_r = EIRP \cdot G_r \cdot (1/L_{path}) \cdot (1/L_{sys})$$

$$L_{sys} = L_1 \times L_2 \times L_3 + ... = \prod_{i}^{n} L_i$$

$$L_{sys\_dB} = 10\log(L_1) + 10\log(L_2) + 10\log(L_2) + ...$$

Free Space Loss:
A different view

$$P_r = EIRP \cdot G_r \cdot \frac{1}{(4\pi)^2 \cdot (d^2/\lambda^2)}$$

- Free space loss <u>accounting</u> for gain of other antennas

$$L_{end-to-end} = \frac{P_t}{P_r} = \eta \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \eta \frac{(\lambda d)^2}{A_{er} A_{et}} = \eta \frac{(cd)^2}{f^2 A_{er} A_{et}}$$

- G_t = gain of transmitting antenna
- G_r = gain of receiving antenna
- A_{et} = effective area of transmitting antenna
- A_{er} = effective area of receiving antenna

$$G_r = \frac{4\pi A_{er}}{\lambda^2}$$

$$G_t = \frac{4\pi A_{et}}{\lambda^2}$$

…..Free Space Loss

- Free space loss accounting for gain of other antennas can be recast as

$$L_{end-to-end} = \frac{P_t}{P_r} = \eta \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \eta \frac{(\lambda d)^2}{A_r A_t} = \eta \frac{(cd)^2}{f^2 A_r A_t}$$

$$L_{end-to-end\_dB} = 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r)$$

$$= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\text{dB}$$

Note that as λ increases frequency decreases and Hence, the total attenuation increases!

Free Space Loss and Frequency

Note that, ASSUMING THERE IS NO GAIN CHANGE, as f increases the loss increases!

$$L_{end-to-end\_dB} = L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi f d}{c}\right)$$

$$L_{end-to-end\_dB} = 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r)$$

Two approaches

$$= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\text{dB}$$

Note that, IF WE ACCOUNT FOR GAIN, as frequency increases total attenuation decreases!

Frequency impacts gain!

Efficiency

- We define the efficiency of antenna (system) using η_{eff}
  - Note the total power transmitted: $P_r + P_{loss} = P_{total}$

$$\eta_{eff} = P_r / P_{total} = P_r / (P_r + P_{loss})$$

Electromagnetic Energy

Example: Find the received power in a cell phone

- Notes

Refer to Notes Example A

Example: Compare the received power for different antennas

- Notes

Refer to Notes Example B

References

- Stallings, William. *Wireless Communications & Networks, 2/E*. Pearson Education India, 2009.Stallings, William. *Wireless Communications & Networks, 2/E*. Pearson Education India, 2009.
- Black, Bruce A., et al. *Introduction to wireless systems*. Prentice Hall PTR, 2008.
- Rappaport, Theodore S. *Wireless communications: principles and practice*. Vol. 2. New Jersey: Prentice Hall PTR, 1996.