EE 538 Integrated Circuits for Communications
Lecture 1 : Introduction
3/28/05

<u>Modulation:</u> A process by which an information-bearing signal is modified to a format suitable to communication over a <u>channel</u>. This course focuses on communication over wireless channels, although there are many similarities with wireline channels.

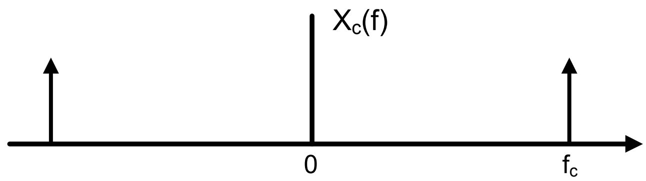
Why modulate?

1. Antenna size should be a significant fraction of the wavelength λ of the signal that it is used to transmit or receive. Recall $\lambda = \frac{c}{f}$ where c is the speed of light and f is the frequency.
2. FCC regulations: Spectrum usage is tightly regulated by the FCC in the US and similar agencies elsewhere. A particular device can operate only over its licensed band and must not interfere with other devices.
3. Possibly because detection may be easier in the presence of channel non-idealities.

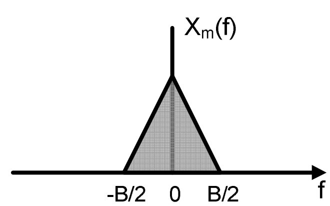
<u>Carrier Modulation:</u>

- Carrier → single-frequency sinusoid of frequency f_c.

$$x_c(t) = \cos(2\pi f_c t) \overset{F.T}{\Longleftrightarrow} X_c(f) = \frac{\delta(f - f_c) + \delta(f + f_c)}{2}$$



- Modulating signal
  - Analog or digital information carrying signal
  - usually a lowpass signal of narrow bandwidth B << f_c



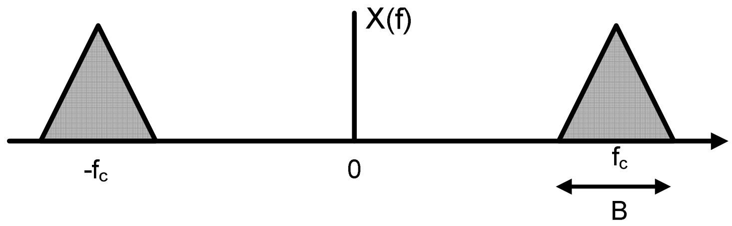
- A simple modulated signal

  → Double-sideband suppressed carrier (DSB-SC), a form of amplitude modulation

$$x(t) = x_m(t) \cdot x_c(t) = x_m(t)\cos(2\pi f_c t)$$

  → To find the spectrum of the transmitted signal, recall that time-domain multiplication corresponds to frequency-domain convolution:

$$X(f) = \frac{X_m(f - f_c) + X_m(f + f_c)}{2}$$



Representation of bandpass signals:

- In general, we can modulate either the amplitude or the phase (or both) of the carrier:

$$x(t) = a(t)\cos[2\pi f_c t + \phi(t)]$$

a(t) = amplitude modulation, ϕ(t) = phase modulation. This is called the *polar representation*.

- A second very important representation is the *Cartesian representation*:

$$x(t) = x_I(t)\cos(2\pi f_c t) - x_Q(t)\sin(2\pi f_c t)$$

which can be related to the polar form as

$a(t) = \sqrt{x_I^2(t) + x_Q^2(t)}$ and $\varphi(t) = \tan^{-1}\dfrac{x_Q(t)}{x_I(t)}$ (note that this is the 4-quadrant arc-tangent, atan2 in Matlab).

- *Complex signal representation:*

Define the complex envelope $\tilde{x}(t) = x_I(t) + jx_Q(t)$ which is a complex signal made up of two real signals referred to as the in-phase and quadrature components respectively.

Euler's identity: $e^{j2\pi f_c t} = \cos(2\pi f_c t) + j\sin(2\pi f_c t)$

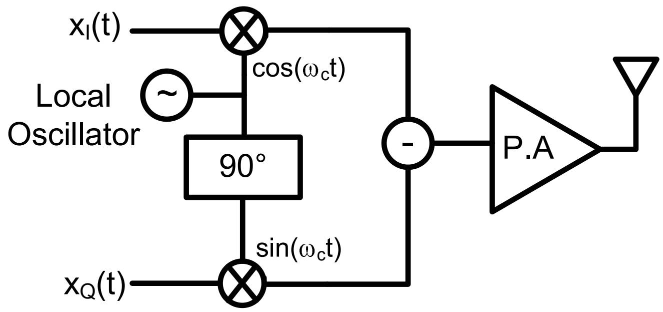
→ $x(t) = \mathrm{Re}\left[\tilde{x}(t)\cdot e^{j2\pi f_c t}\right] = \left[x_I(t)\cos(2\pi f_c t) - x_Q(t)\sin(2\pi f_c t)\right]$

- $\tilde{x}(t)$ is a lowpass complex signal of bandwidth B.
- This representation is similar to phasors commonly used in linear circuit analysis.
- It is especially useful in visualizing digital modulation schemes through I/Q signal constellations

Each of the above forms is useful in system-level analysis and design of modern transceiver architectures.

– we can represent any carrier modulated signals with these basic templates
– the polar form leads naturally to polar modulators based on phase-locked loops that are widely used in GSM cellphones
– the Cartesian form leads to I/Q multi-mode transmitters and image-reject receivers. It is also invaluable as an analysis tool both for transmitters and receivers
– the complex representation greatly simplifies the analysis of systems involving a mix bandpass and baseband signals and filtering, as is the case in all transceivers.

A simple general transmitter:

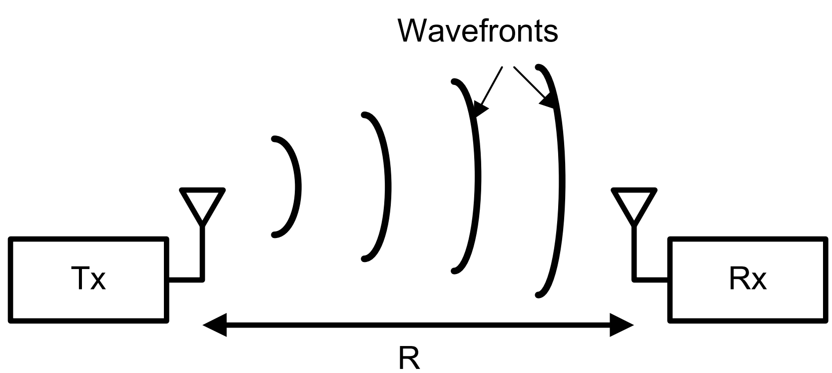


Key circuit blocks:

- Mixers
- Voltage controlled-oscillator & frequency synthesizer
- I/Q generation
- Power amplifiers

Wireless channels: The Friis transmission equation

If we transmit at a power level P_t and receive the signal a distance R away, what is the power received at the receive antenna? The Friis transmission equation offers an estimate which is useful although it is very optimistic in practical wireless channels.



An isotropic antenna radiates power equally in all directions i.e., power flows outward from the transmit antenna in spherical wavefronts. Thus, the power density at a distance R from the antenna is equal to $\frac{P_t}{4\pi R^2} W/m^2$, since the surface area of a sphere of radius R is $4\pi R^2$.

A directional antenna concentrates some of this power in a specific direction, and is characterized by a "gain" G which is defined as the amount over the isotropic power that is radiated in this direction[1].

[1] The units of antenna gain are dBi, or dB's over isotropic.

If we use a directional antenna with gain G_t at transmitter, the power density at the receiver is $\frac{P_t G_t}{4\pi R^2} W/m^2$. Next, assume that the receive antenna has an "effective aperture area" A_e. The total received power is then:

$$P_r = \frac{P_t G_t}{4\pi R^2} A_e \text{ W}.$$

The effective antenna aperture is related to the antenna gain and the wavelength through the relationship:

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

We then arrive at the Friis transmission equation, which expresses the received power as a function of the transmit power, the antenna gains and the wavelength:

$$\boxed{P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2} \text{ W}}.$$

Path loss is an associated measure of the attenuation in received power due to the channel:

$$PL = \frac{P_t}{P_r} = \frac{(4\pi)^2 R^2}{G_t G_r \lambda^2}$$

When expressed in dB's, the path loss is:

$$PL(dB) = 20\log_{10}\left(\frac{2\pi \mathrm{R}}{\lambda}\right) - \mathrm{G_r(dB)} - \mathrm{G_t(dB)}$$

Numerical example - IEEE 802.11a wireless LAN standard:

$P_t = 100\text{mW} \rightarrow 20\text{dBm}$ ($\text{dBm} = 10\log_{10}(P_t/1\text{mW})$)

$f_c = 5\text{GHz} \rightarrow \lambda = c/f = 0.06\text{m}$

Assume $G_t = G_r = 10\text{dBi}$, and R (distance between transmitter and receiver) = 100m.

→ PL = 60dB ⇒ Received power = P_t (dBm) – PL (dB) = -40dBm.

In practice, the path loss is much higher. For example, in one of the possible modes in the 802.11a standard, the received signal can be as low as -82dBm, which is 25μV across a 50Ω resistor!

A simple general receiver:

The received signal is a carrier modulated signal of the form:

$$x(t) = x_I(t)\cos(2\pi f_c t) - x_Q(t)\sin(2\pi f_c t)$$

Suppose we multiply x(t) by a locally generated carrier of the same frequency as the received signal:

$$x(t)\cos(2\pi f_c t) = x_I(t)\cos^2(2\pi f_c t) - x_Q(t)\sin(2\pi f_c t)\cos(2\pi f_c t)$$

$$= \frac{1}{2}x_I(t) + \frac{1}{2}x_I(t)\cos(2\cdot 2\pi f_c t) - \frac{1}{2}x_Q(t)\sin(2\cdot 2\pi f_c t)$$

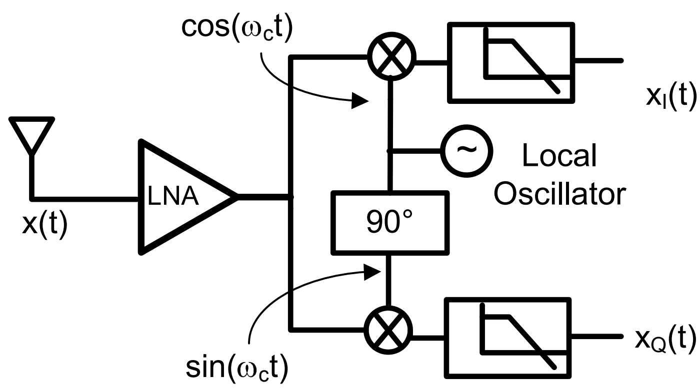
This contains the in-phase component of the received signal along with unwanted components at *twice* the carrier frequency. We can then extract the $x_I(t)$ by low-pass filtering.

Similarly, for $x_Q(t)$, we can multiply by the sin(.) phase of an LO:

$$\boldsymbol{x}(\boldsymbol{t})\sin(2\pi \boldsymbol{f}_c \boldsymbol{t}) = \boldsymbol{x}_I(\boldsymbol{t})\cos(2\pi \boldsymbol{f}_c \boldsymbol{t})\sin(2\pi \boldsymbol{f}_c \boldsymbol{t}) - \boldsymbol{x}_Q(\boldsymbol{t})\sin^2(2\pi \boldsymbol{f}_c \boldsymbol{t})$$

$$= \frac{1}{2}\boldsymbol{x}_I(\boldsymbol{t})\sin(2\cdot 2\pi \boldsymbol{f}_c \boldsymbol{t}) - \frac{1}{2}\boldsymbol{x}_Q(\boldsymbol{t}) + \frac{1}{2}\boldsymbol{x}_Q(\boldsymbol{t})\cos(2\cdot 2\pi \boldsymbol{f}_c \boldsymbol{t})$$

<u>A simple receiver</u>: (ignore the LNA for the present)



This is the direct conversion receiver, currently the dominant architecture in fully integrated WLAN chips.

<u>What are the requirements on the receiver?</u>

– must be able to detect extremely small signals (e.g. -104dBm for GSM)

→ cannot waste power that is available from the receive antenna

--- power matching networks

– must be able to boost up the received signal without degrading the SNR

--- low-noise amplifiers (LNA)

Key circuit blocks:

– matching networks
– low-noise amplifiers
– mixers
– VCO and frequency synthesizer
– I/Q generation circuits
– on-chip filters (this is beyond the scope of this class)