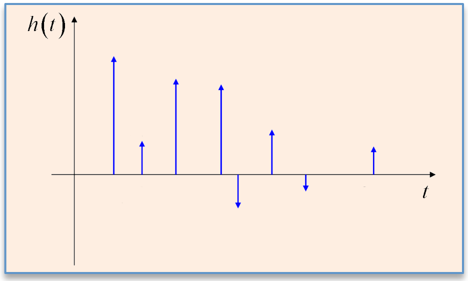
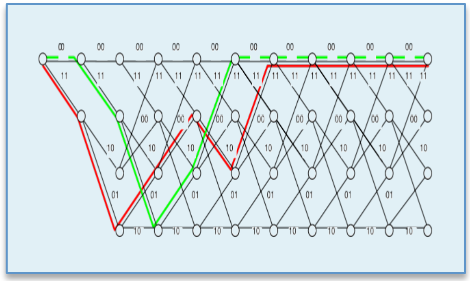
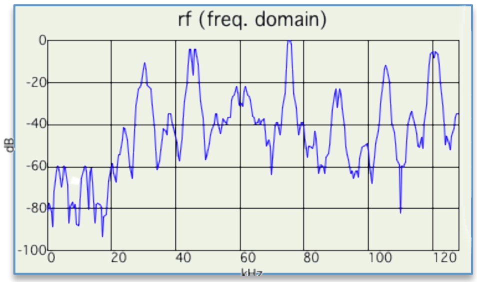
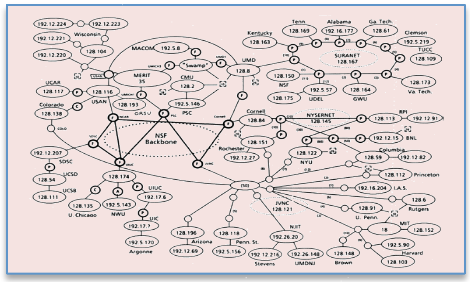




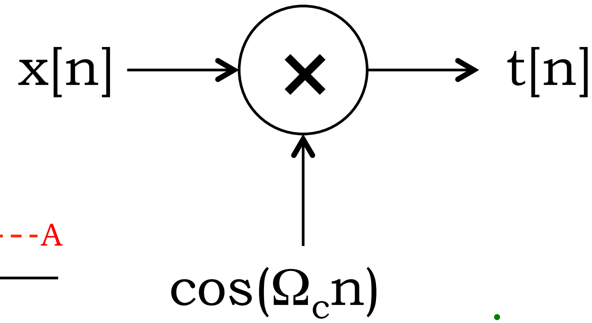
INTRODUCTION TO EECS II

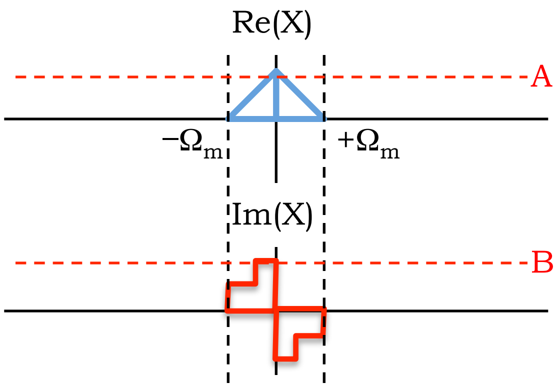
DIGITAL COMMUNICATION SYSTEMS

6.02 Fall 2013
Lecture #17

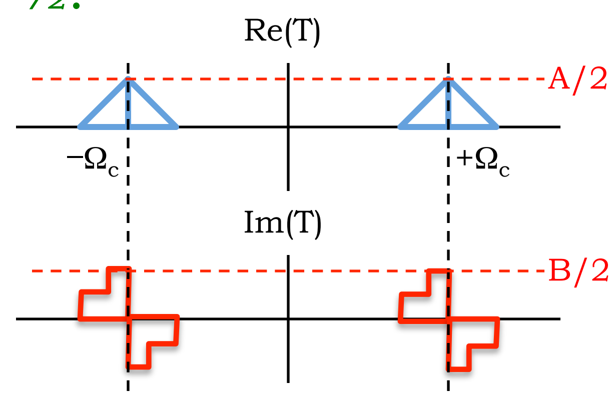
- Quadrature Modulation/Demodulation
- Frequency Division Multiplexing (FDM)

Modulation by Heterodyning** or Amplitude Modulation (AM)





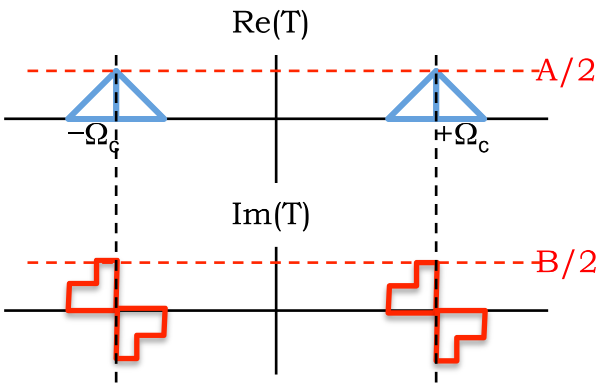
i.e., just replicate baseband signal at $\pm\Omega_c$, and scale by ½.



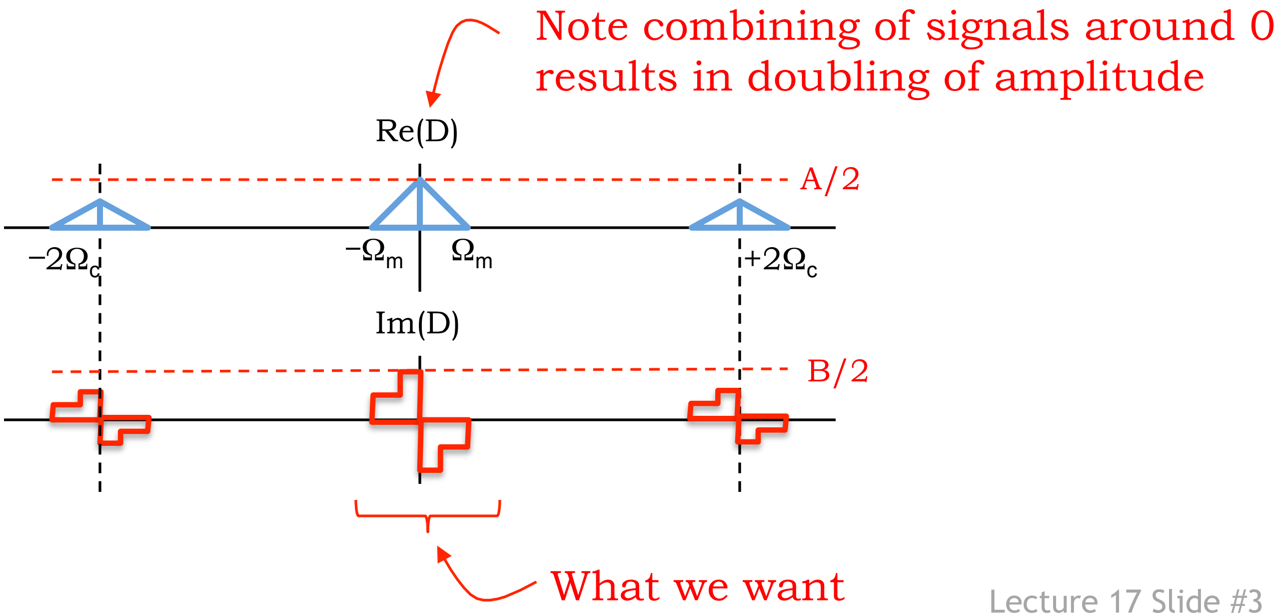
** Reginald Fessenden's invention:
http://www.ewh.ieee.org/reg/7/millennium/radio/radio_unsung.html

Demodulation Frequency Diagram

$R(\Omega)=T(\Omega)$



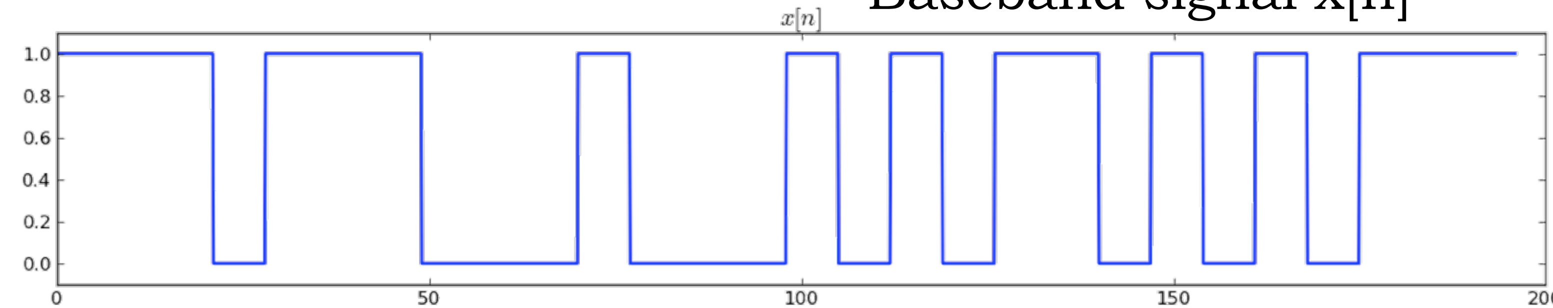
$D(\Omega)$



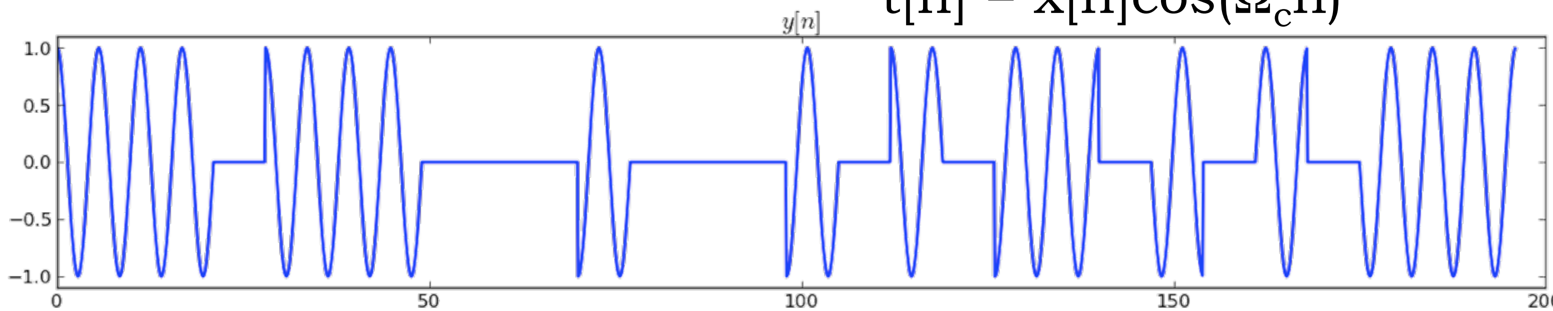
Example: Demodulation (time)

Showing idealized signals ---
no bandwidth limit on channel

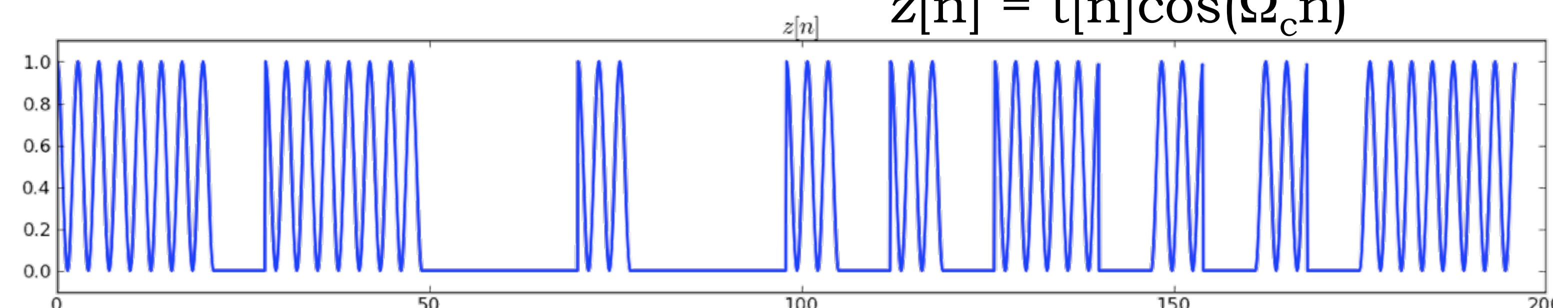
Baseband signal x[n]



$t[n] = x[n]\cos(\Omega_c n)$



$z[n] = t[n]\cos(\Omega_c n)$

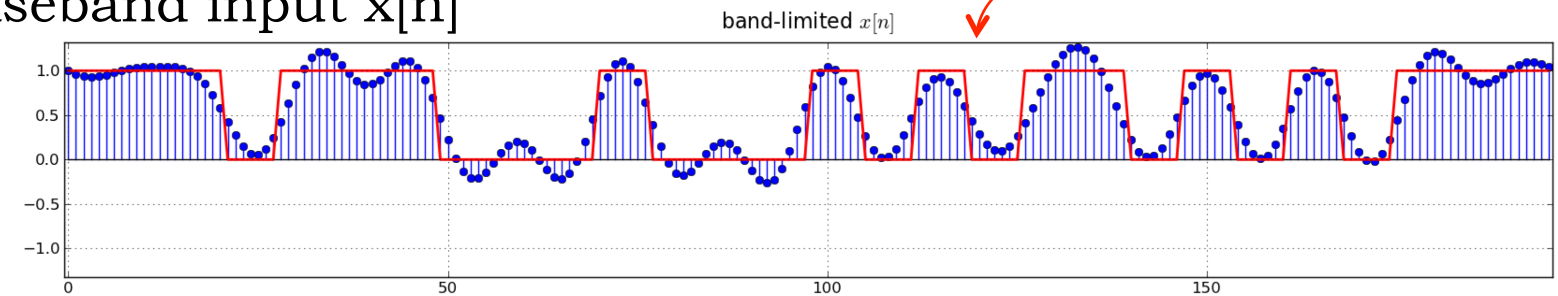


Note: lowpass filtering of this signal
will yield x[n]/2 !

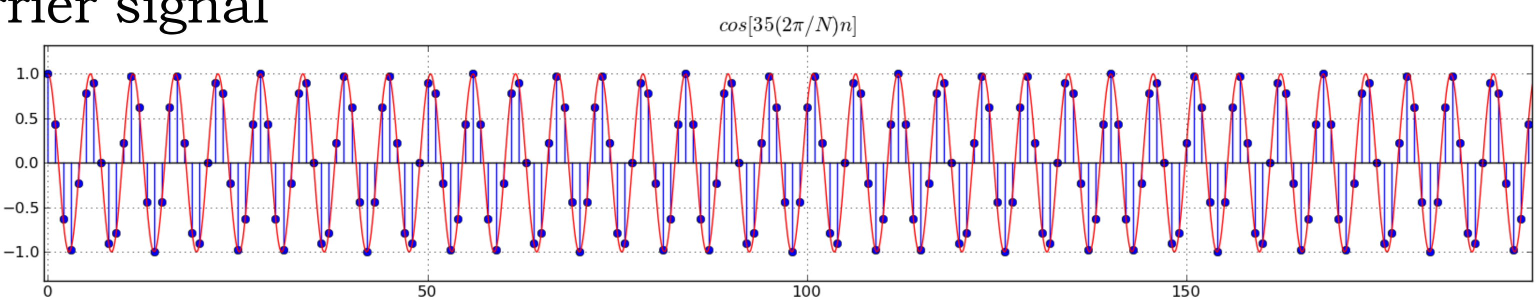
Example: Modulation (time)

Shaped pulses! Chosen because we know the channel is bandlimited

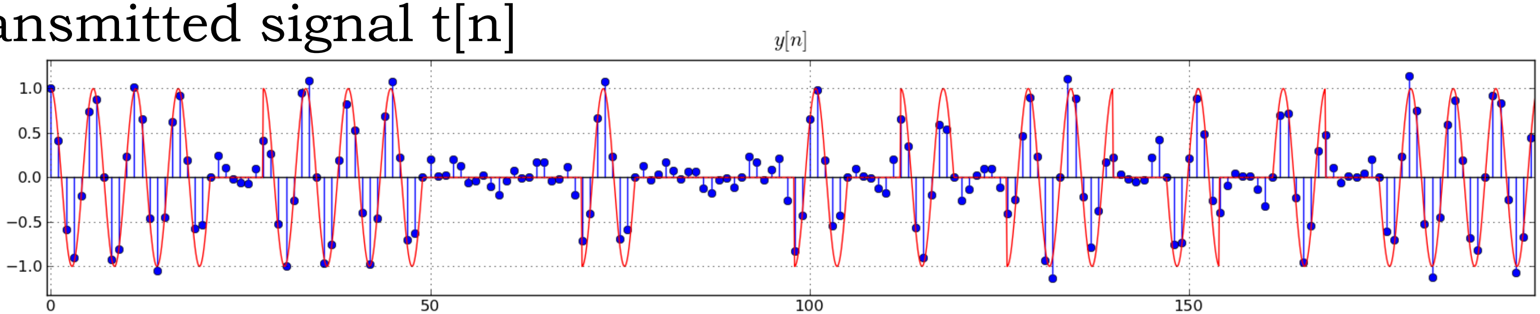
Baseband input x[n]



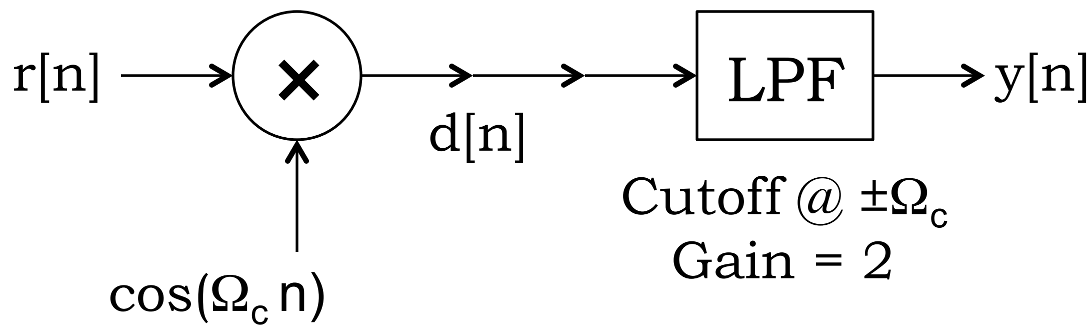
Carrier signal

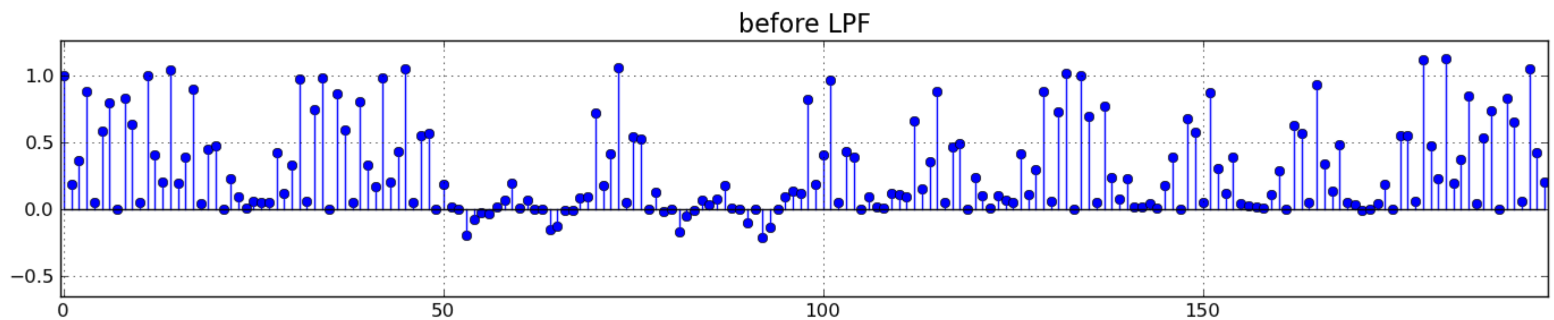


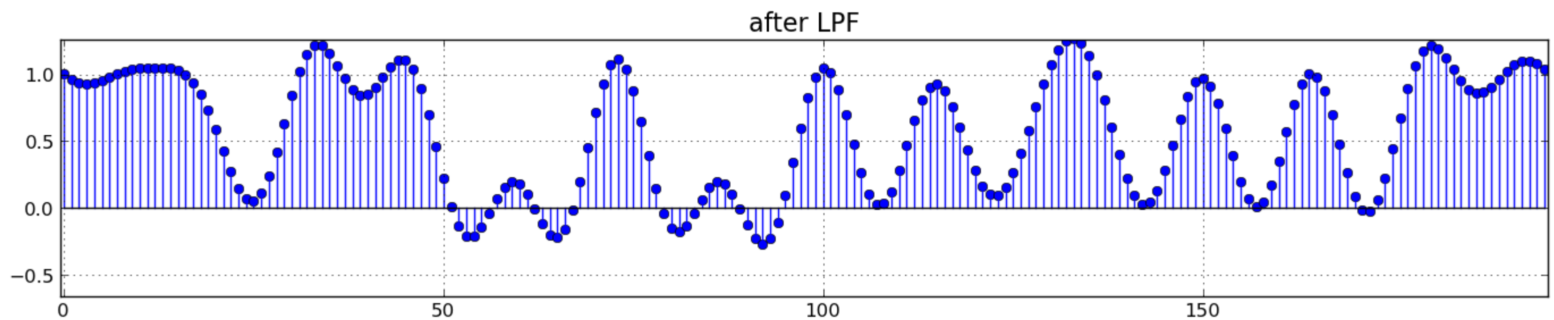
Transmitted signal t[n]



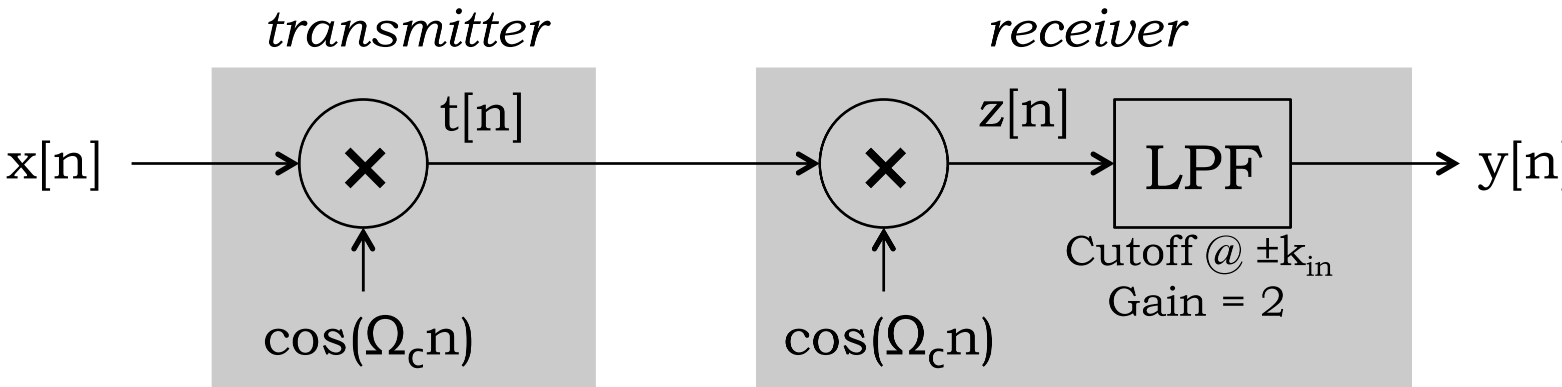
Demodulation

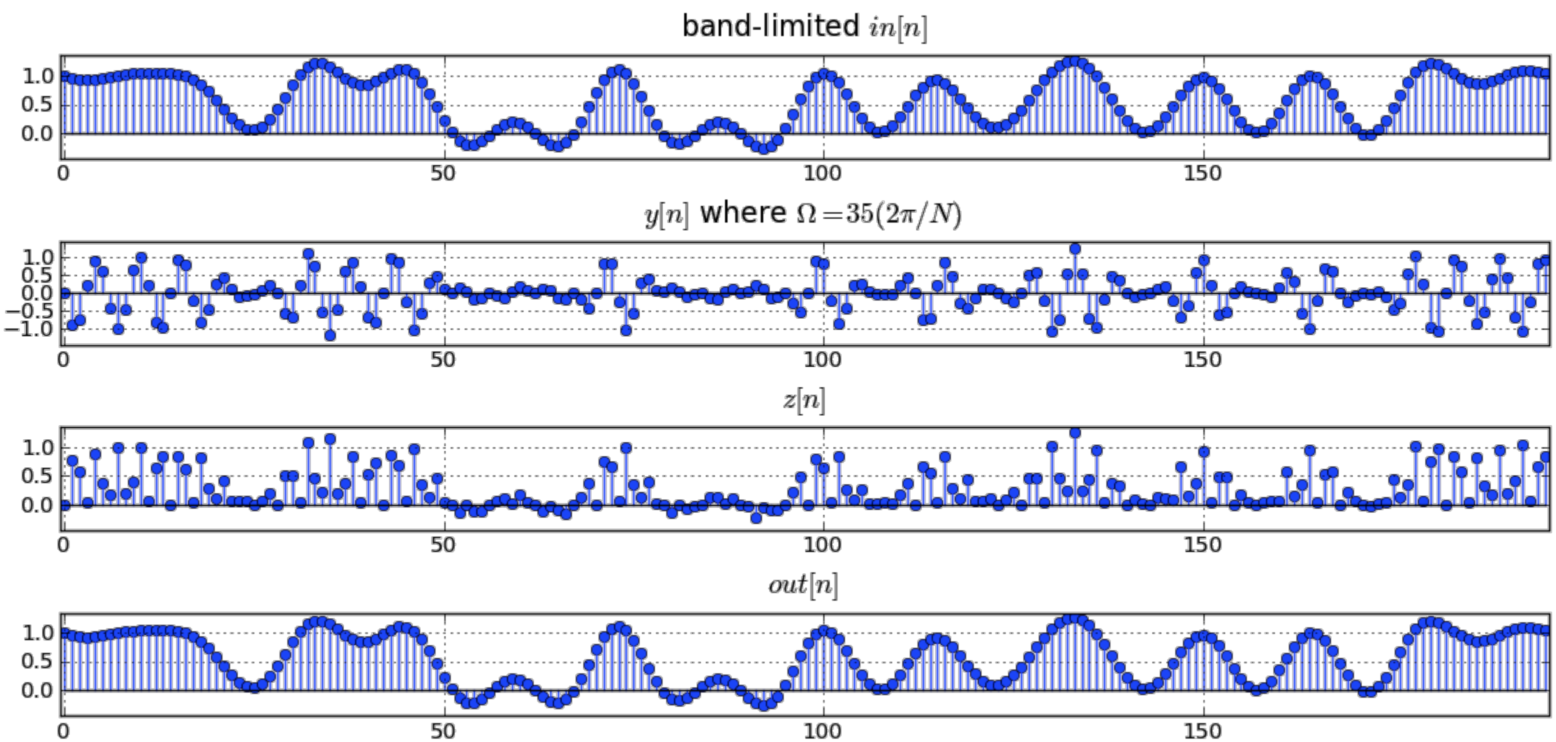






Ideal Modulation/Demodulation





Phase Error In Demodulation

When the receiver oscillator is out of phase with the transmitter:

$$d[n] = r[n] \cdot \cos(\Omega_c n - \varphi) = x[n] \cdot \cos(\Omega_c n) \cdot \cos(\Omega_c n - \varphi)$$

But

$$\cos(\Omega_c n).\cos(\Omega_c n - \varphi) = 0.5\{\cos(\varphi) + \cos(2\Omega_c n - \varphi)\}$$

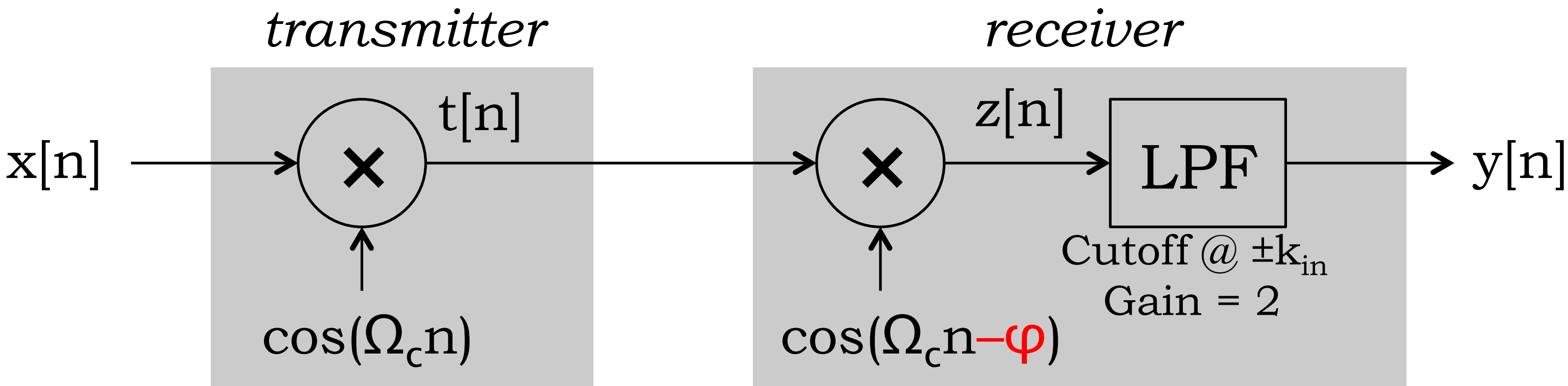
It follows that the demodulated output, after the LPF of gain 2, is

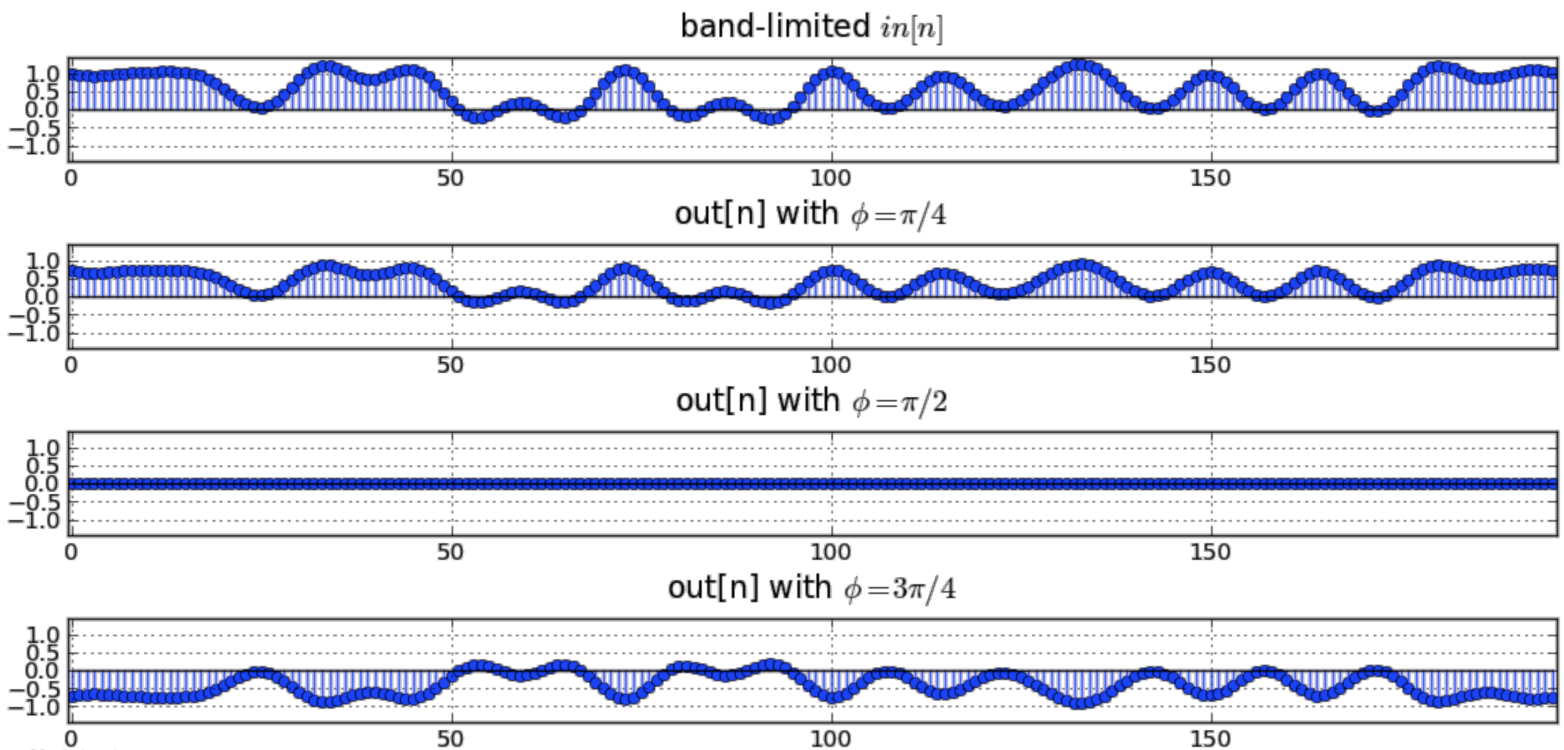
$$y[n] = x[n].\cos(\varphi)$$

So a phase error of φ results in amplitude scaling by cos(φ).

Note: in the extreme case where $\varphi=\pi/2$, we are demodulating by a sine rather than a cosine, and we get y[n]=0 .

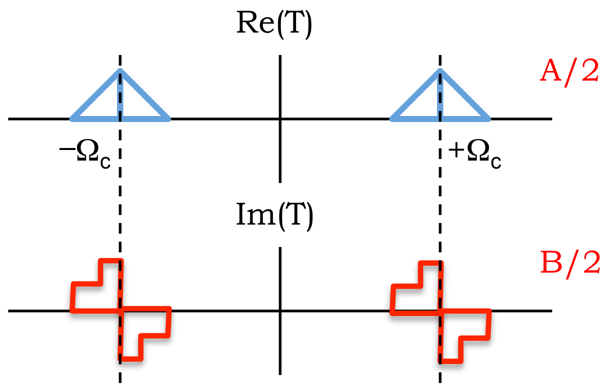
Phase Error in Demodulator



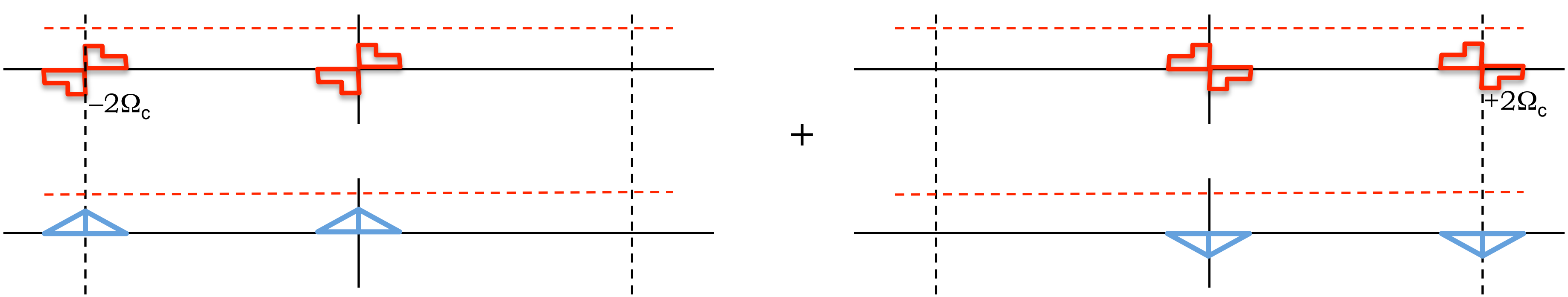


Demodulation with sin(Ω_cn)

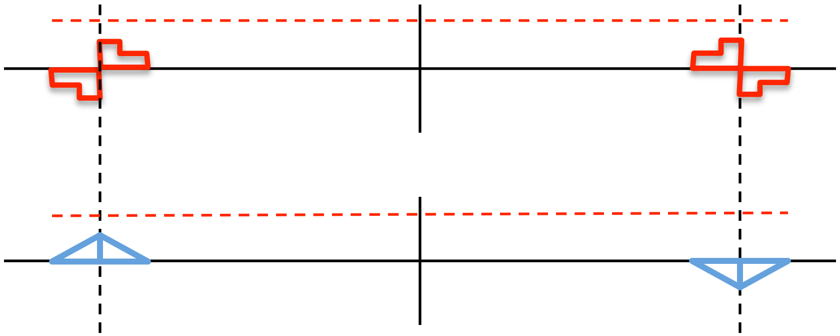
R(Ω)



D(Ω)

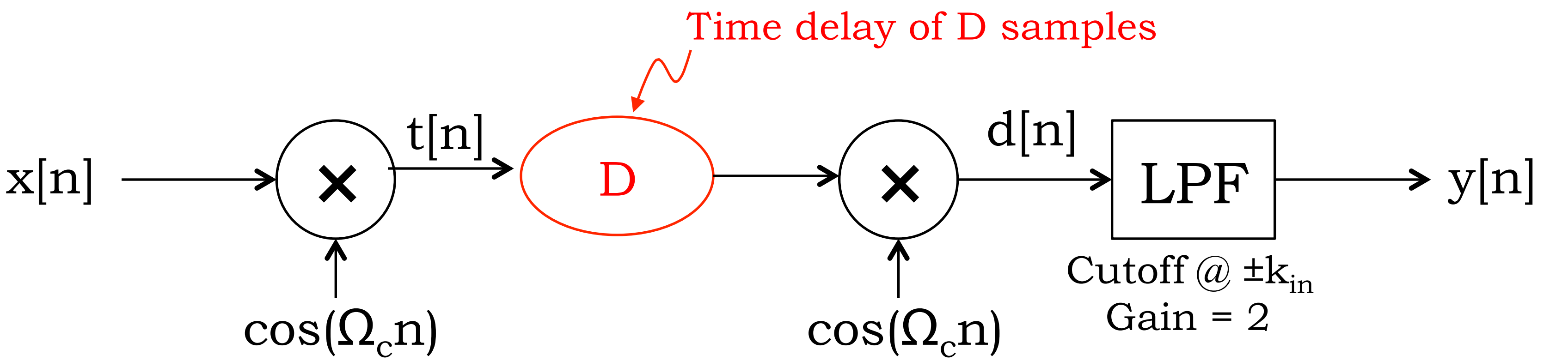


··· produces



Note combining of signals around 0
results in cancellation!

Channel Delay



Very similar math to the previous "phase error" case:

$$d[n] = t[n-D] \cdot \cos(\Omega_c n)$$
$$= x[n-D] \cdot \cos[\Omega_c (n-D)] \cdot \cos(\Omega_c n)$$

Passing this through the LPF:

Looks like a phase error of $\Omega_c D$

$$y[n] = x[n-D] \cdot \cos(\Omega_c D)$$

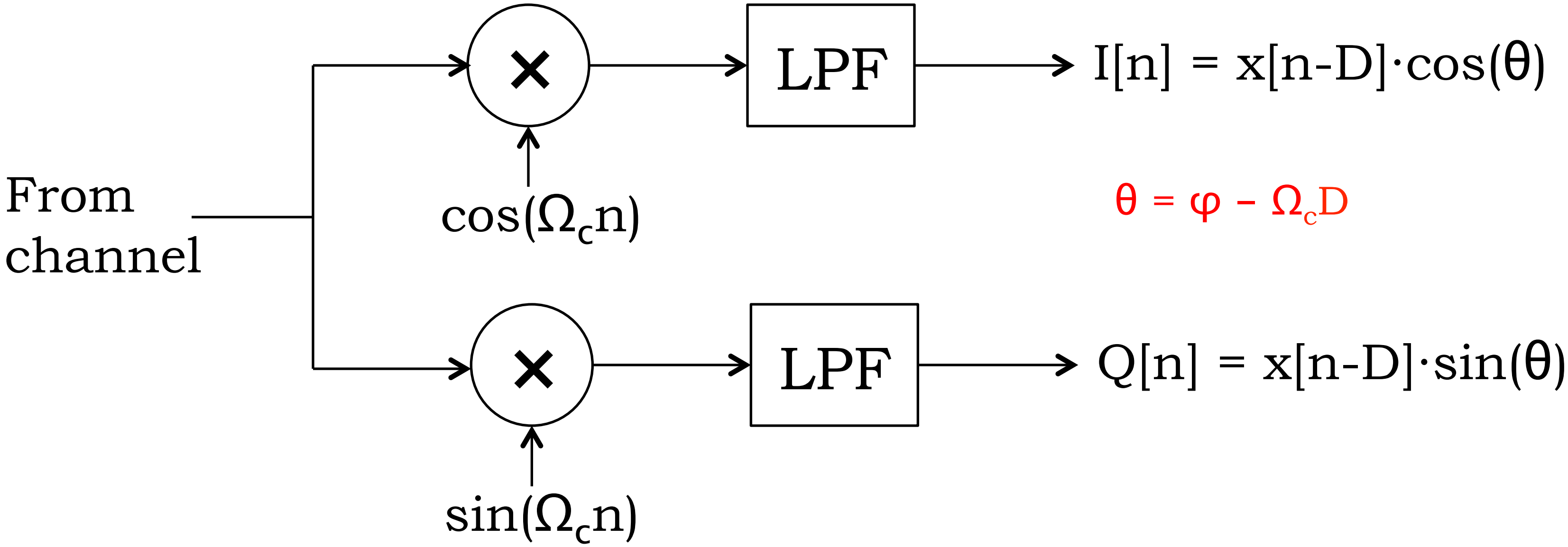
If $\Omega_c D$ is an odd multiple of $\pi/2$, then y[n]=0 !!

Fixing Phase Problems in the Receiver

So phase errors and channel delay both result in a scaling of the output amplitude, where the magnitude of the scaling can't necessarily be determined at system design time:

- channel delay varies on mobile devices
- phase difference between transmitter and receiver is arbitrary

One solution: *quadrature demodulation*



Quadrature Demodulation

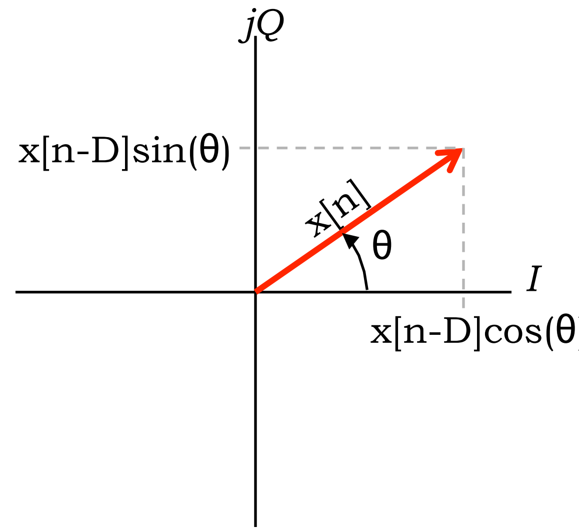
If we let

$$w[n] = I[n] + jQ[n]$$

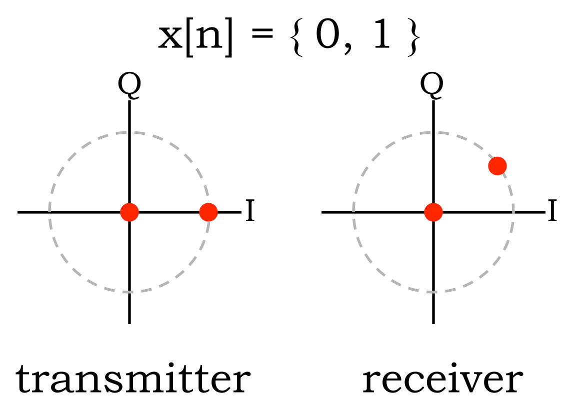
then

$$|w[n]| = \sqrt{I[n]^2 + Q[n]^2}$$
$$= |x[n-D]|\sqrt{\cos^2\theta + \sin^2\theta}$$
$$= |x[n-D]|$$

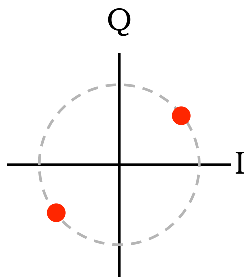
OK for recovering x[n] if it never goes negative, as in on-off keying



Constellation diagrams:



Dealing With Phase Ambiguity in Bipolar Modulation



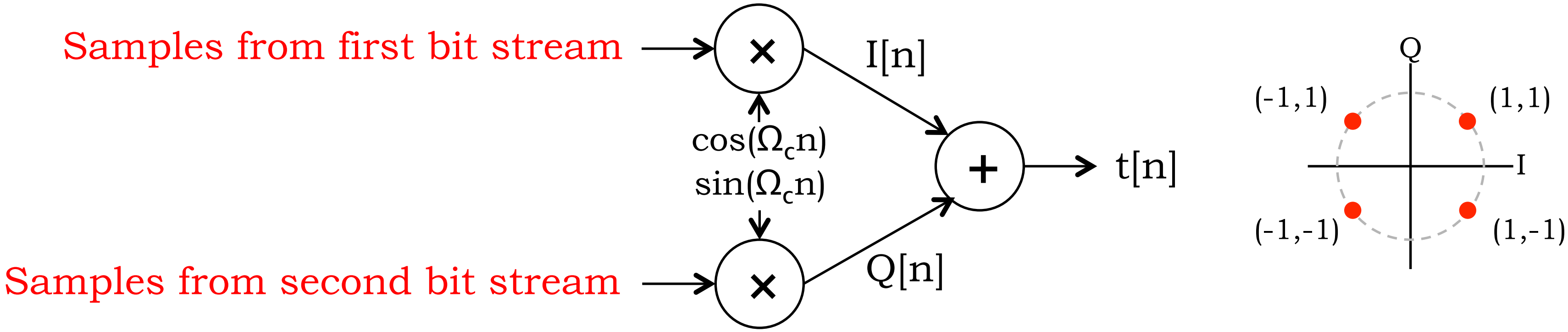
In bipolar modulation ($x[n]=\pm 1$), also called Binary Phase Shift Keying (BPSK) since the modulated carrier changes phase by $\pi/2$ when x[n] switches levels, the received constellation will be rotated with respect to the transmitter's constellation. Which phase corresponds to which bit?

Different fixes:

1. Send an agreed-on sign-definite preamble
2. Transmit differentially encoded bits, e.g., transmit a "1" by stepping the phase by π, transmit a "0" by not changing the phase. (Agreed starting symbol, say "0".)

QPSK Modulation

We can use the quadrature scheme at the transmitter too:

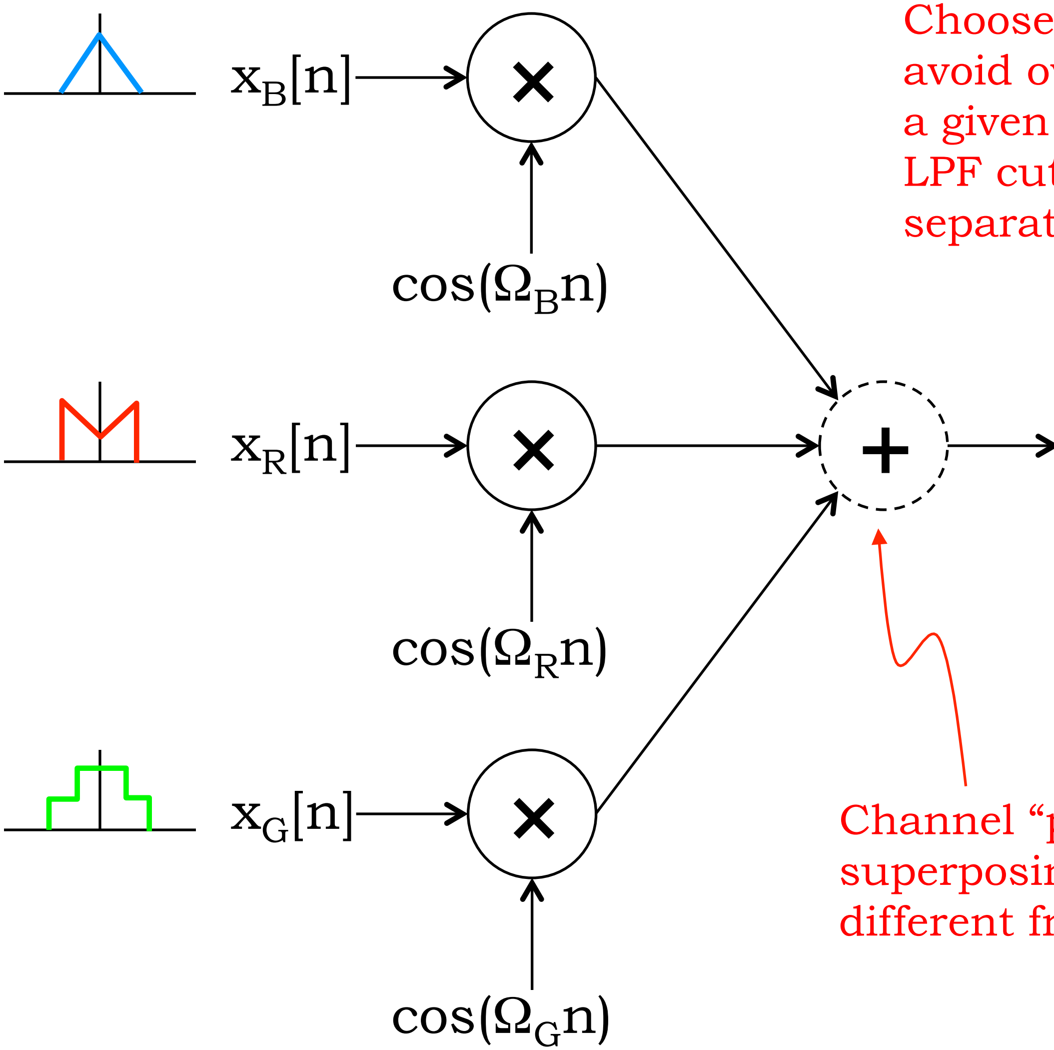


Phase Shift Keying underlies many familiar modulation schemes

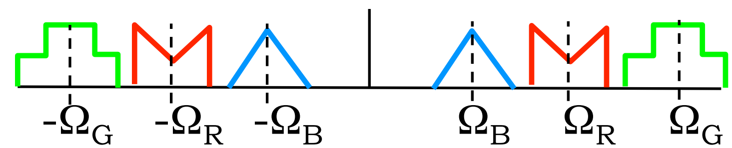
The wireless LAN standard, IEEE 802.11b-1999,[1][2] uses a variety of different PSKs depending on the data-rate required. At the basic-rate of 1 Mbit/s, it uses DBPSK (differential BPSK). To provide the extended-rate of 2 Mbit/s, DQPSK is used. In reaching 5.5 Mbit/s and the full-rate of 11 Mbit/s, QPSK is employed, but has to be coupled with complementary code keying. The higher-speed wireless LAN standard, IEEE 802.11g-2003[1][3] has eight data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbit/s. The 6 and 9 Mbit/s modes use OFDM modulation where each sub-carrier is BPSK modulated. The 12 and 18 Mbit/s modes use OFDM with QPSK. The fastest four modes use OFDM with forms of quadrature amplitude modulation.
Because of its simplicity BPSK is appropriate for low-cost passive transmitters, and is used in RFID standards such as ISO/IEC 14443 which has been adopted for biometric passports, credit cards such as American Express's ExpressPay, and many other applications.[4]
Bluetooth 2 will use (p/4)-DQPSK at its lower rate (2 Mbit/s) and 8-DPSK at its higher rate (3 Mbit/s) when the link between the two devices is sufficiently robust. Bluetooth 1 modulates with Gaussian minimum-shift keying, a binary scheme, so either modulation choice in version 2 will yield a higher data-rate. A similar technology, IEEE 802.15.4 (the wireless standard used by ZigBee) also relies on PSK. IEEE 802.15.4 allows the use of two frequency bands: 868–915 MHz using BPSK and at 2.4 GHz using OQPSK.

http://en.wikipedia.org/wiki/Phase-shift_keying

Multiple Transmitters:
Frequency Division Multiplexing (FDM)



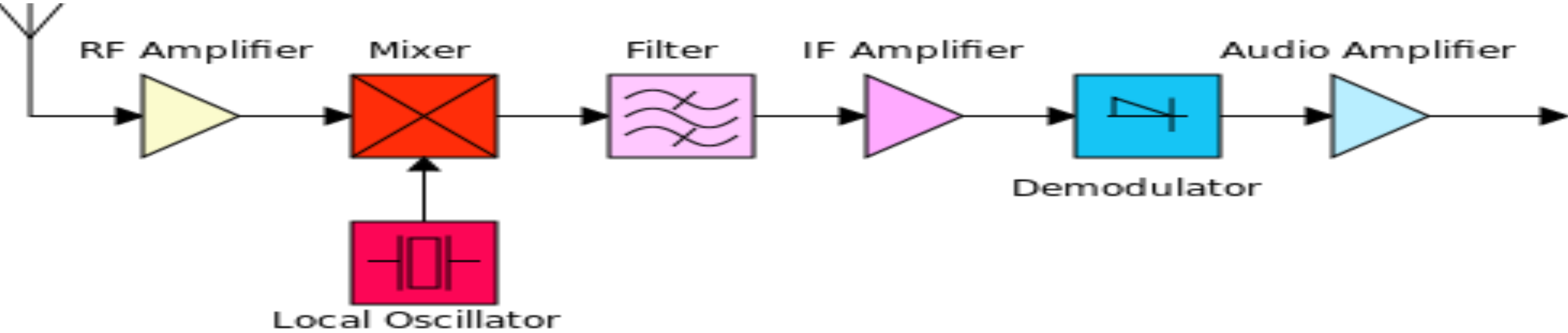
Choose bandwidths and Ω_c's so as to avoid overlap! Once signals combine at a given frequency, can't be undone… LPF cutoff needs to be half the minimum separation between carriers



Channel "performs addition" by superposing signals ("voltages") from different frequency bands.

Edwin Howard Armstrong** (1890-1954)

Invented and patented first positive feedback ("regenerative") electronic oscillator and tuned amplifier while undergrad at Columbia (1914); superheterodyne reception for FDM (1918, see block diagram below); frequency modulation (FM, 1930's); … (42 patents)



**http://en.wikipedia.org/wiki/Edwin_Armstrong

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

Superhet Reception: AM and FM Radio

AM radio receivers span 510 – 1655 kHz in the US, with carrier frequencies of different stations spaced 10 kHz apart.
The usual IF frequency is 455 kHz.

FM radio receivers span 88 – 108 MHz, with carrier frequencies spaced 200 kHz apart.
The usual IF frequency is 10.7 MHz.