ELEN 665

RF Communications : Systems & Circuits

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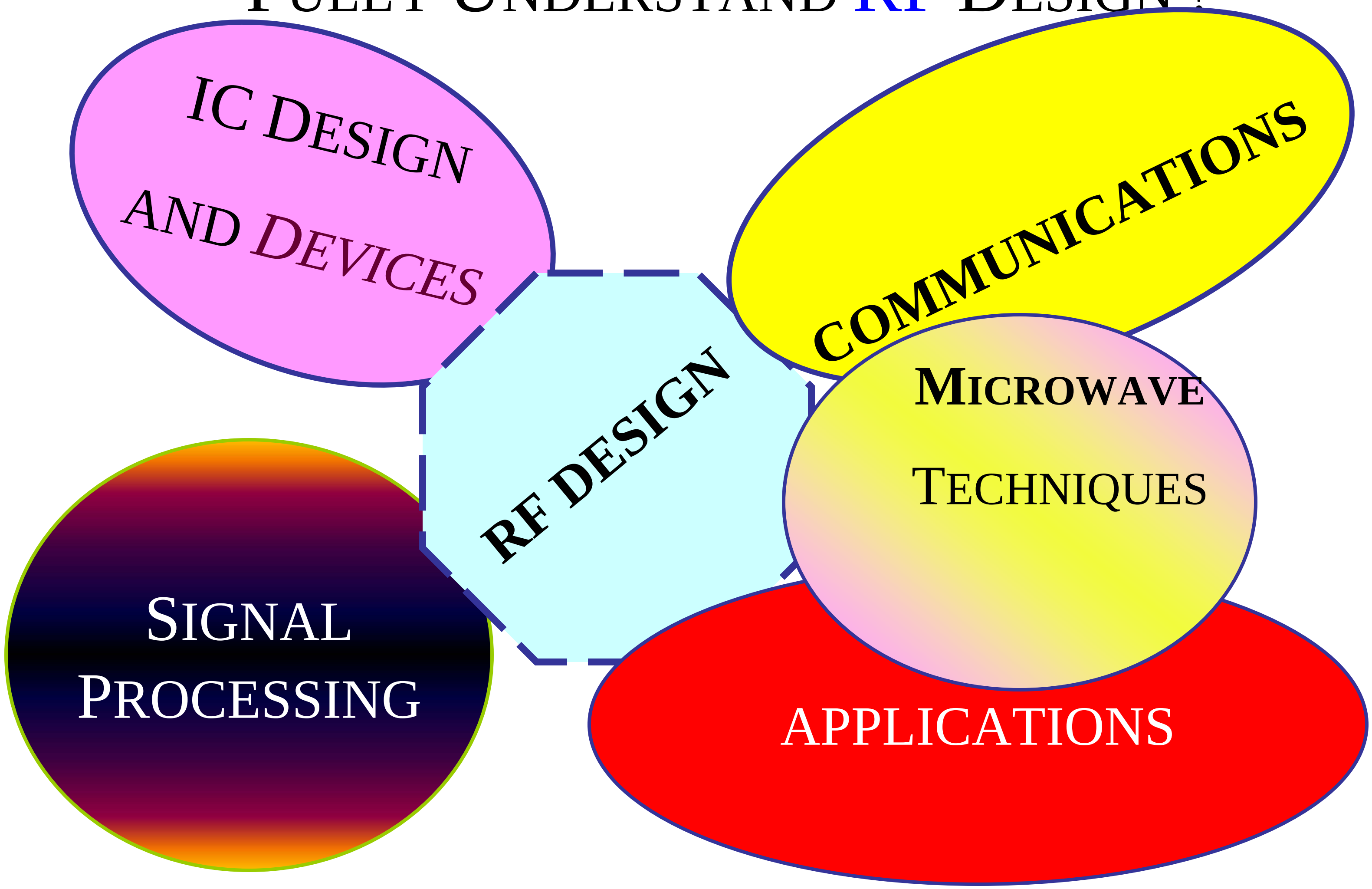
Fall 2009

What Are the Main Topics Involved to Fully Understand RF Design ?



INTRODUCTION AND MOTIVATION

- HOW DO LIVING BEINGS COMMUNICATE ?
- HOW CAN WE MIMIC HUMAN COMMUNICATIONS ?
- WHAT ARE THE FUNDAMENTAL ARCHITECTURES OF WIRELESS RECEIVERS AND TRANSMITTERS ?
- WHAT ARE THE FUNDAMENTAL PROBLEMS IN A RECEIVER? How does non-linearity play a role?

How do living beings communicate?

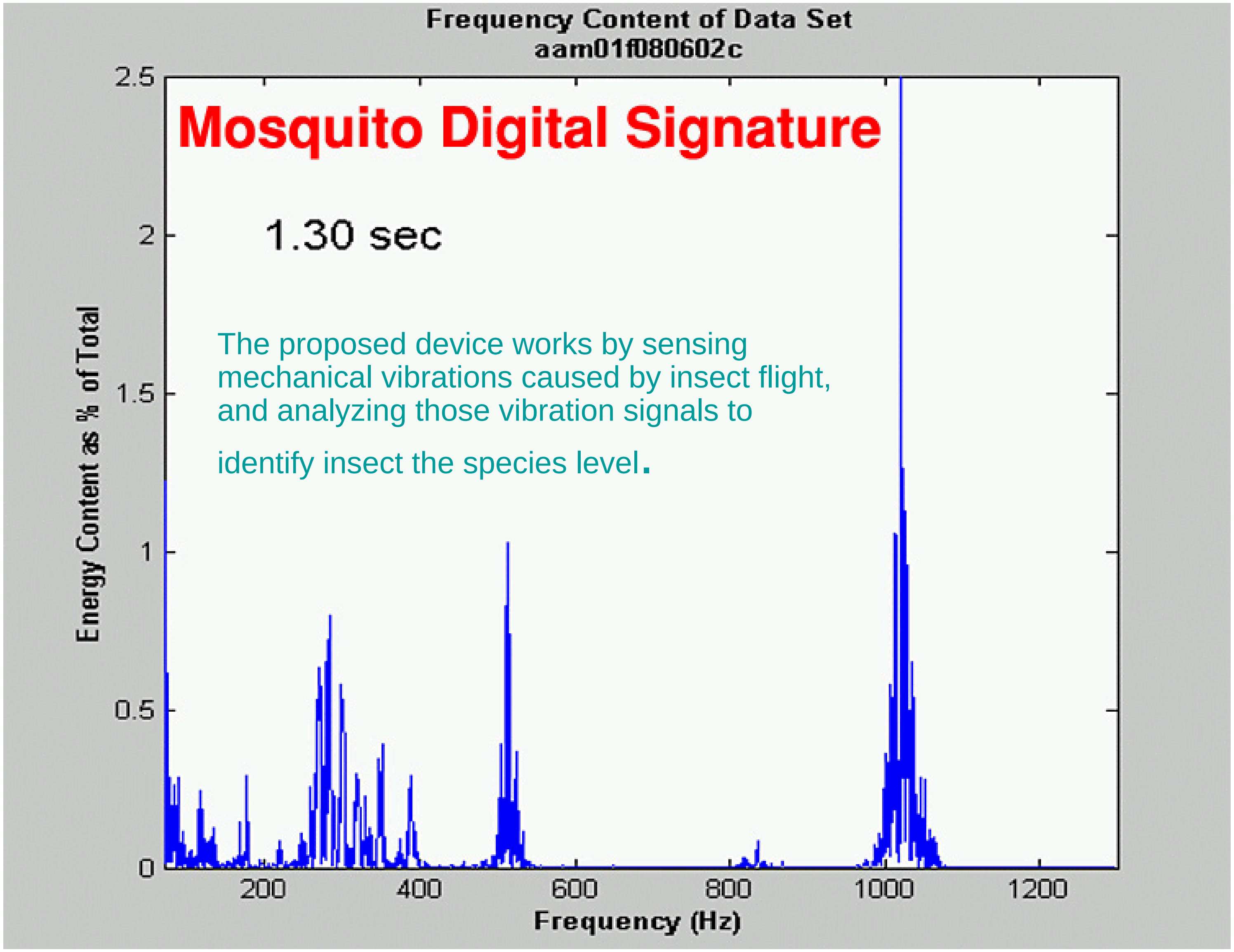
- Communicating is something that all animals, including humans, do. It could be a dog barking a warning, a cat arching its back, or crickets chirping, animals are always sending messages to each other.
- Animals and plants react to stimuli which might come from other living things or from the environment. A stimulus usually causes the organism which receives it to respond to it. Animals use all their senses to communicate.
  - For example, some male birds develop colorful plumage so that the females will be attracted by a visual stimulus as well as by sound.
  - Bees (dogs) communicate by means smelling (sniffing).
  - Dolphins communicate through sounds.

• The signals which an organism uses can be visual (sight), sensual (touch), auditory (sound) or chemical

Marine mammals establish contact with specific individuals using short-range vocalizations. The most singular example of marine mammals using sound to make or maintain contact is between mother and offspring.

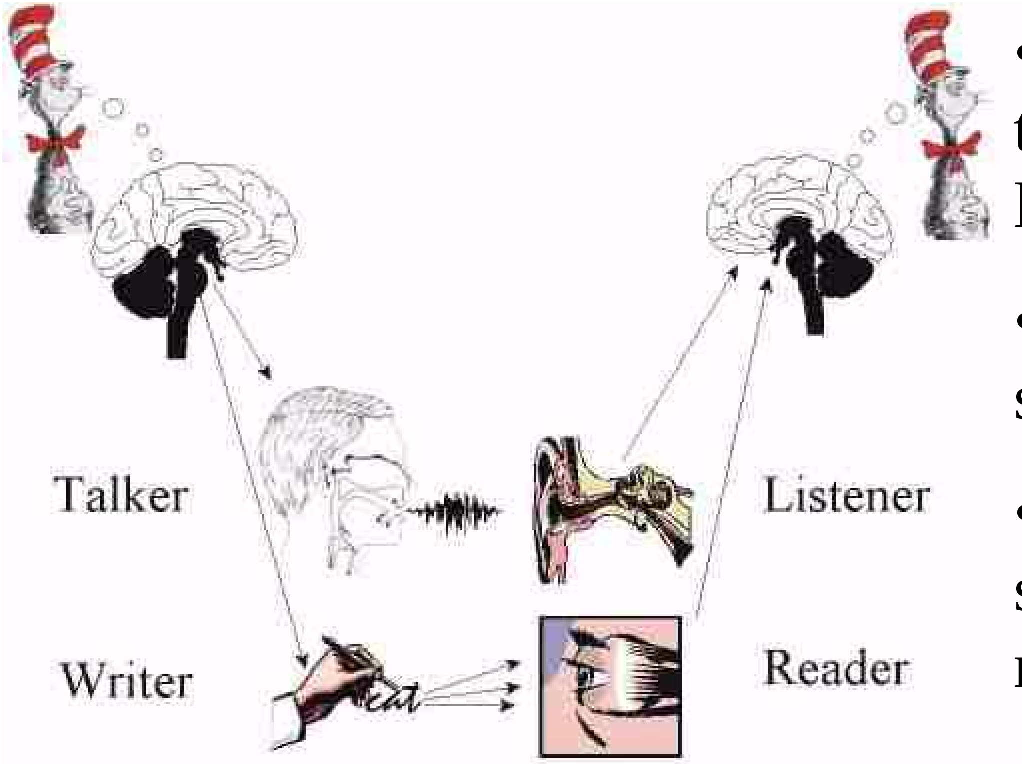
• Basic communications among living beings are not complex. For instance anger, hungry and sensuality are some examples of this type of communications.

More elaborated communications impose certain rules:



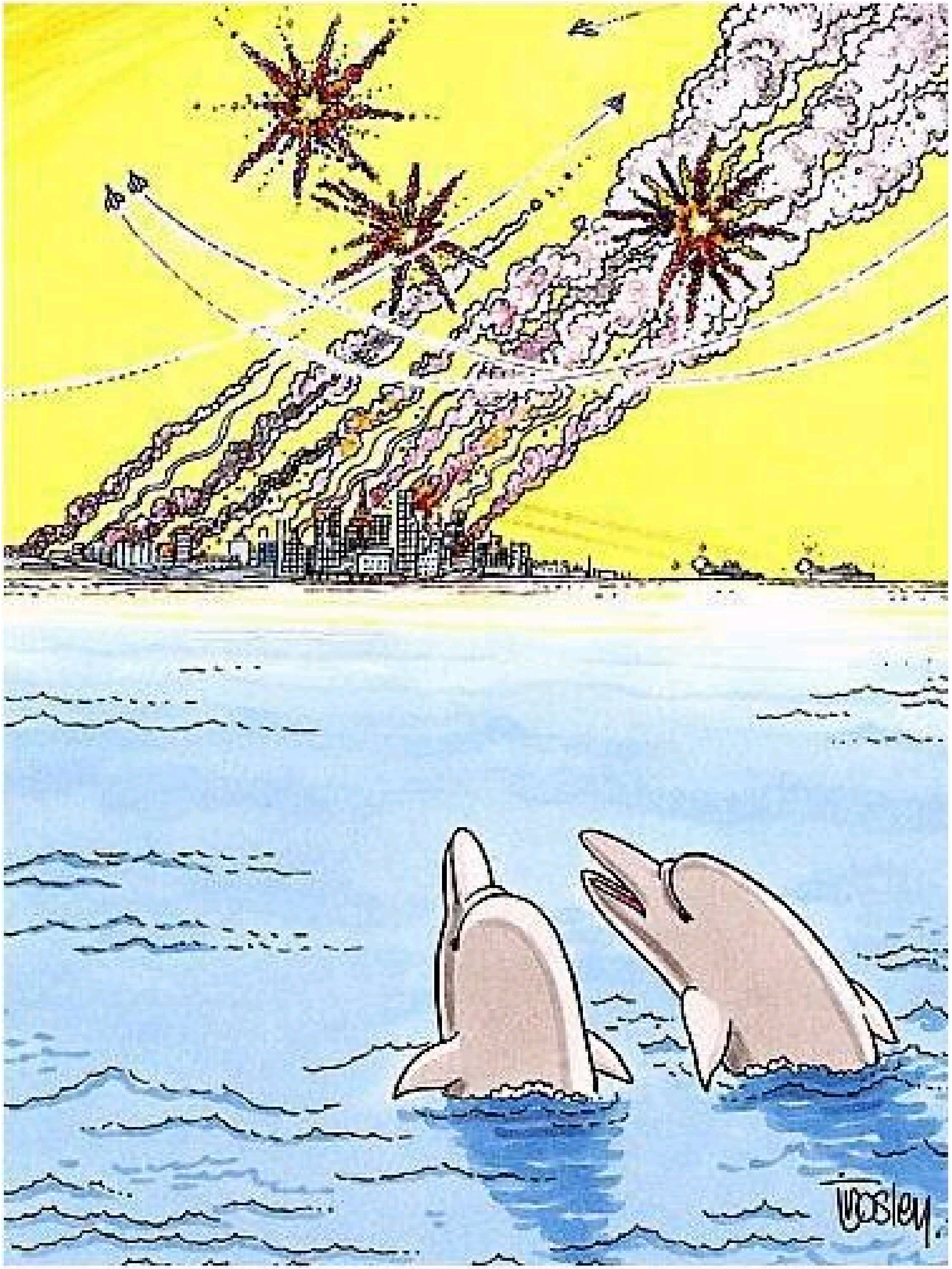
This is the image in its **original context**

on the page: sensors.ag.utk.edu/ Projects/IPM_Monitoring.html



- Language should be the same for talker (transmitter) and (receiver) listener
- Speed of the communication should be compatible
- The level of the transmitted signal should be adequate for the receiver to understand it.

- How about distractions for the listener such as “ noise”, can the receiver understand transmitted signal in spite of noise? Trying to understand while a train is passing by or an ambulance or someone is screaming is difficult.
- Thus the desired signal should be larger than the noise to allow the listener to understand.



"It's a shame human beings can't communicate with each other."

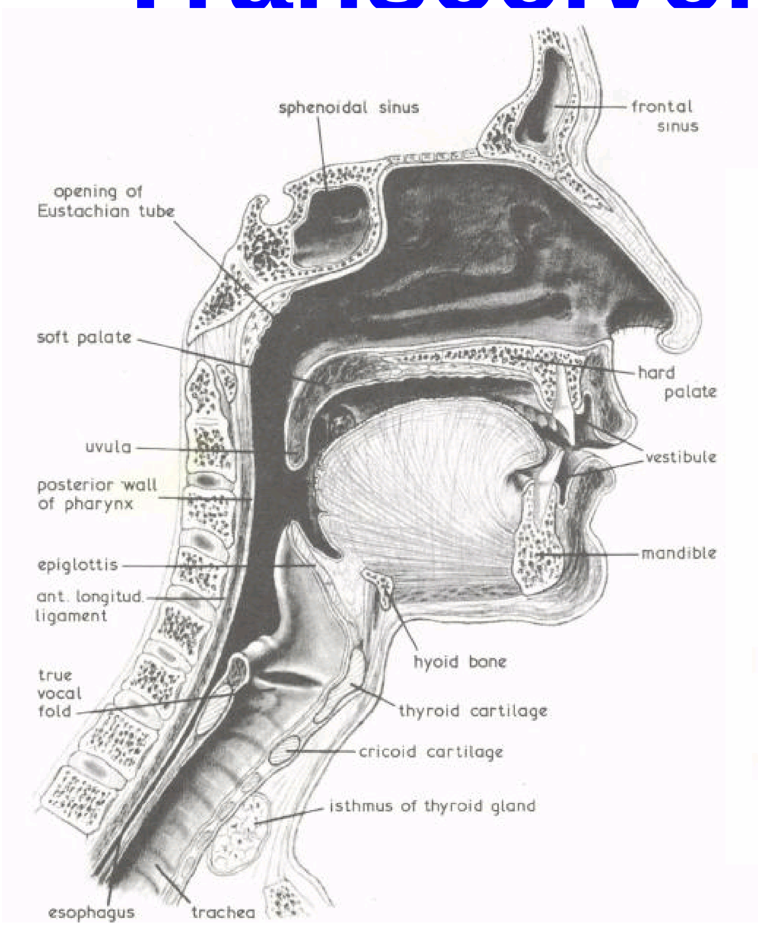
- **Communication Problems**

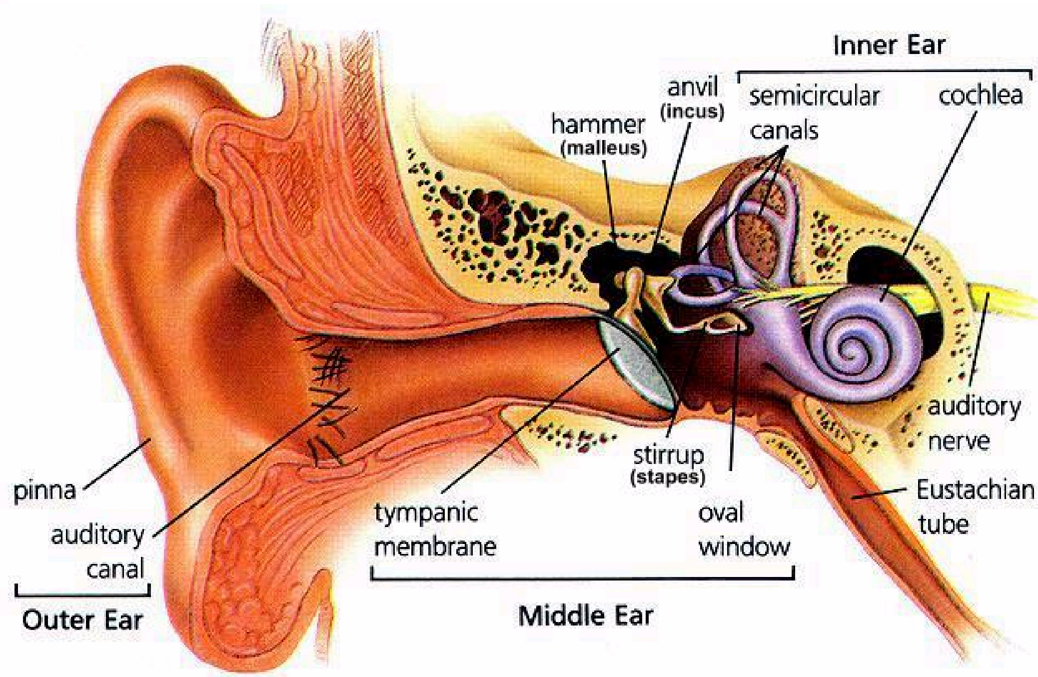
- Very large or very small transmitted signals.
- Receiver not capable to interpret signals, *no common language;* say a cow and a rabbit, a French and a Swedish.
- Language of a spy (or slang) and a common citizen, that is “encoded signals”.
- Too much noise in the environment to understand the desired signal

Next we discuss electrical transceivers

Transceiver Architectures

Receiver



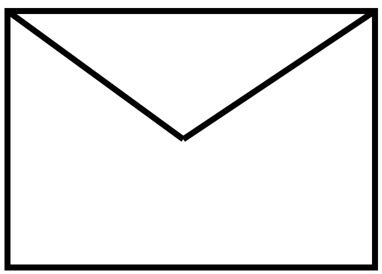


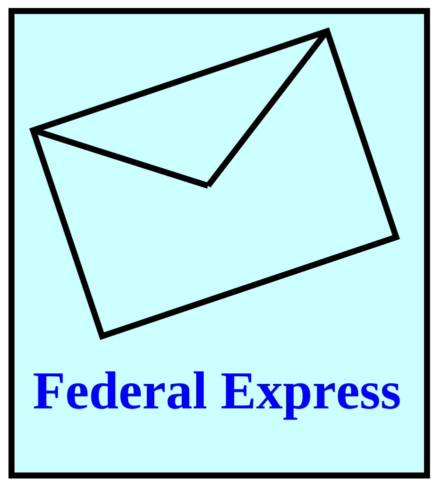
How to mimic these living beings communications ?

COMMUNICATIONS ANALOGY

- Input signal Carrier Modulation Encoding

- Letter Envelope Letter inside the envelope

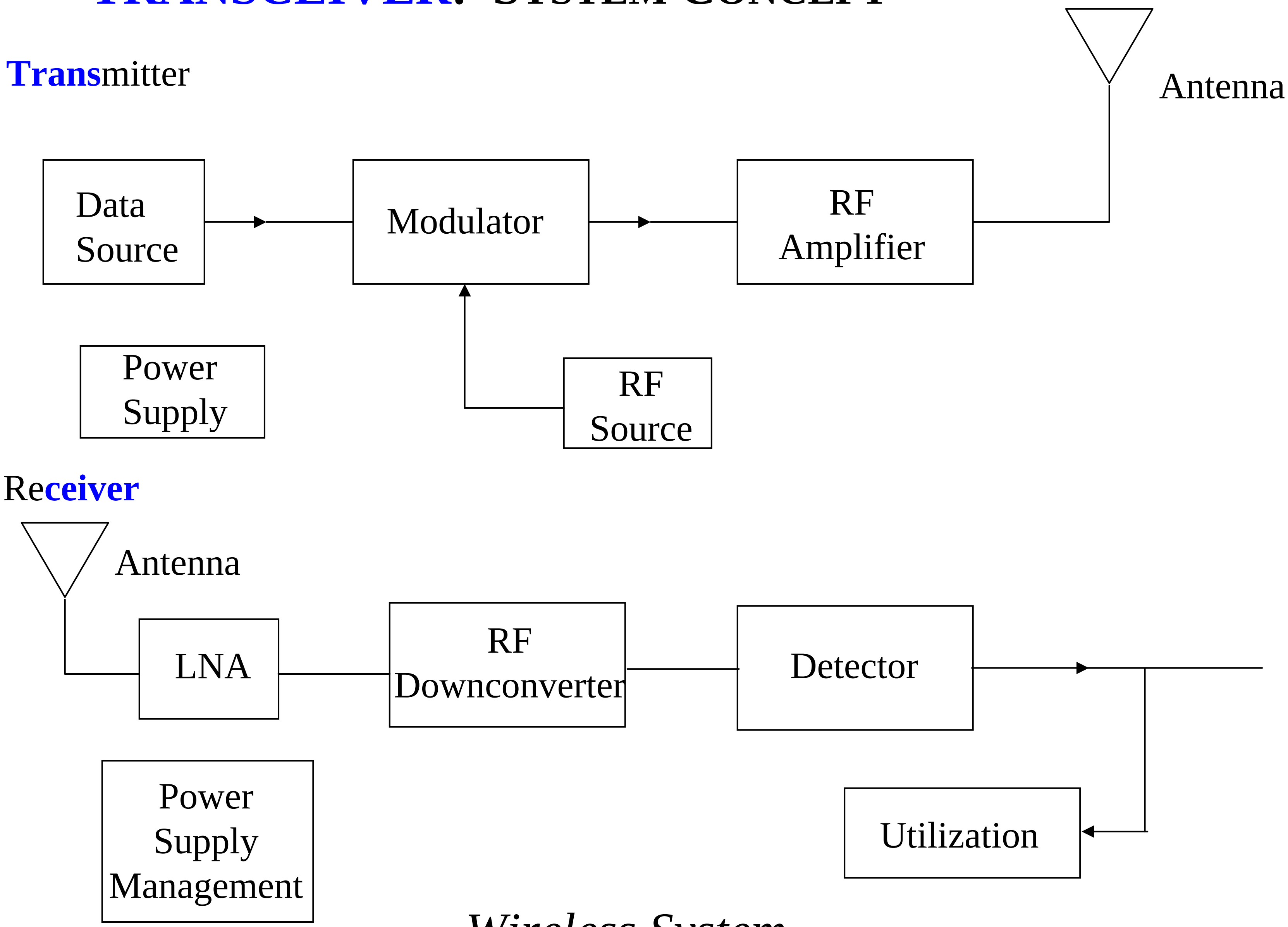




- Different letter folding
- Information that can be interpreted unless you know how. i.e.,

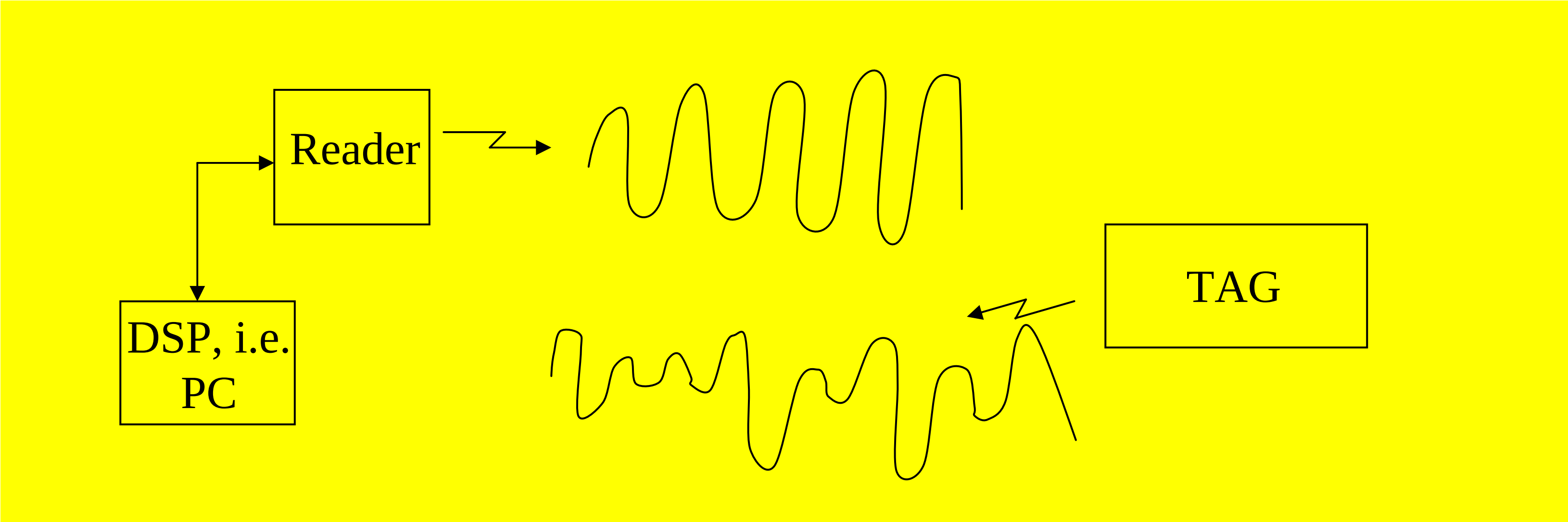
PRICE= ESS.IP
Code
12 3456 7 890
HIPOCRATES

TRANSCEIVER: SYSTEM CONCEPT



Wireless System

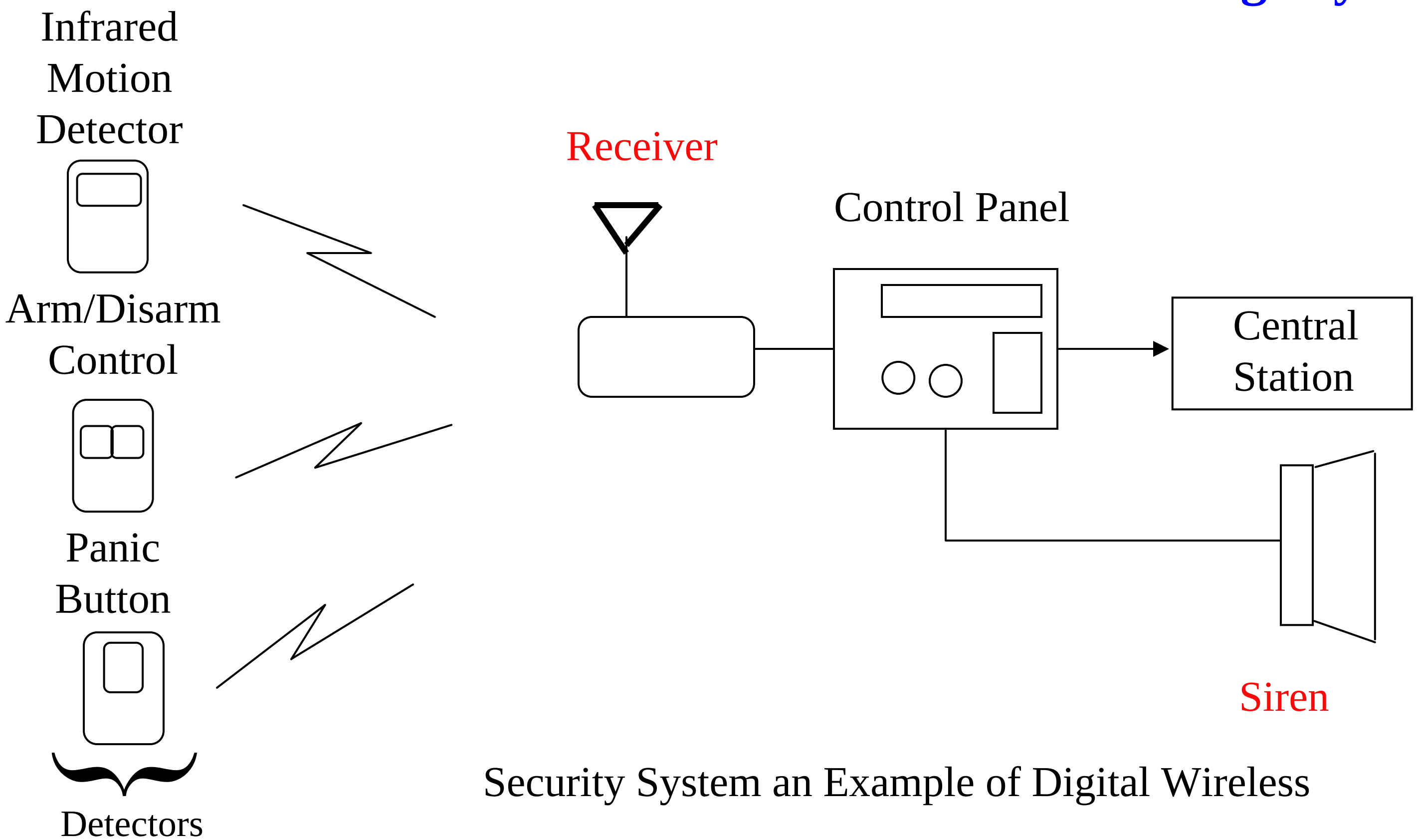
A particular Transceiver: An RFID



Radio Frequency Identification

- The data are not available in the transmitter.
- Data are added to the RF signal in a receptor denominated receptor or TAG.
- TAG can be active or passive.
- The original transmitted signal is modified by the transducer (TAG)

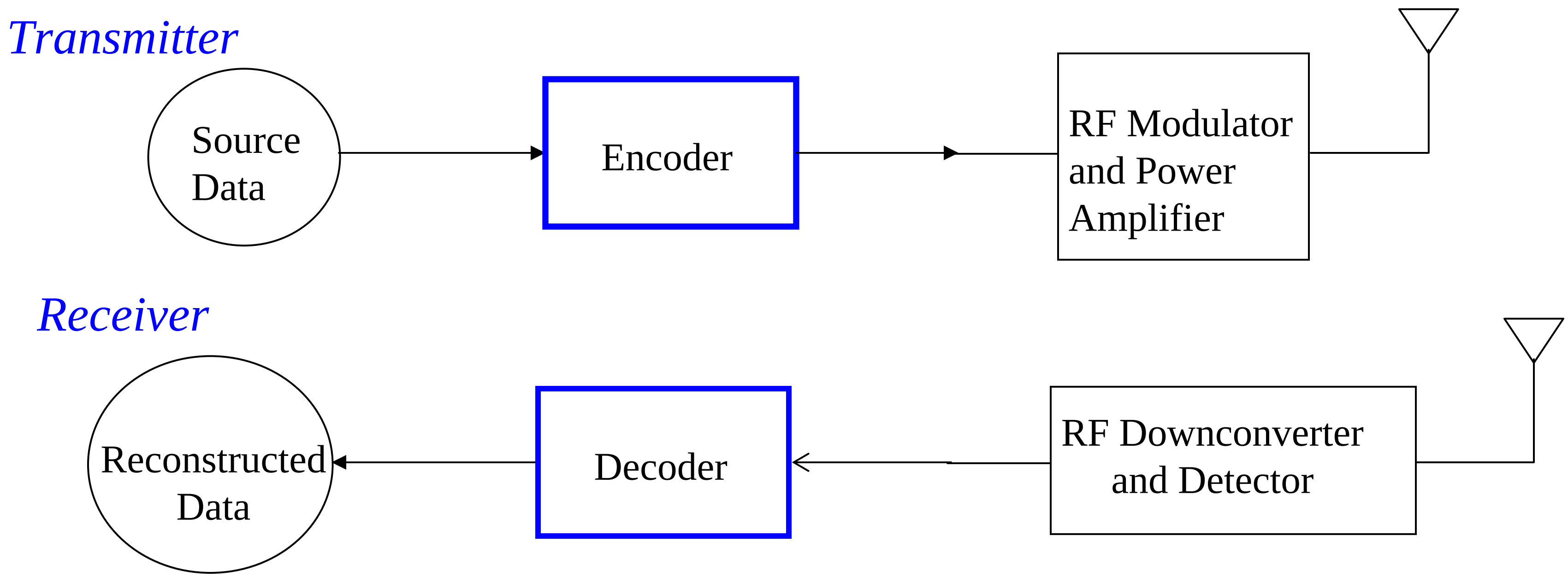
Wireless Communication Link: Short-Range System



Security System an Example of Digital Wireless

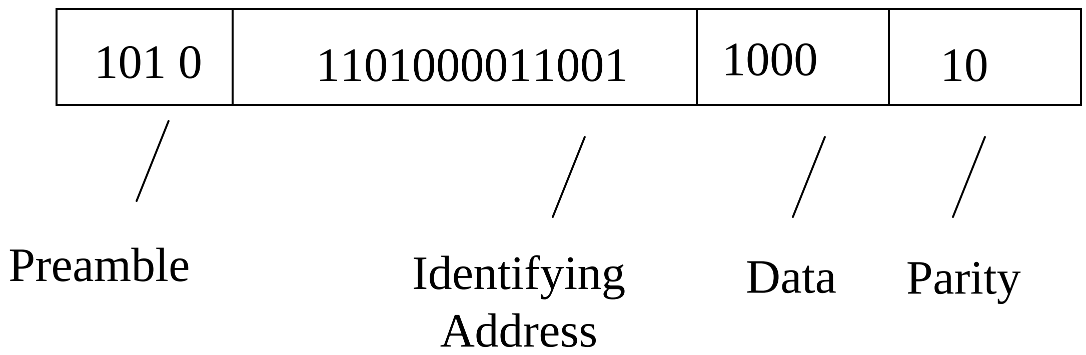
- Information originated in one location (source data)
- Information transmitted to another location (reconstructed data)
- Detector besides the ones illustrated above are the "Technical" alarms i.e., gas detector, water level detectors, high of low temperature sensors (detectors).

Radio Communication Link Block Diagram



- Very low-bandwidth information sources (i.e., few Hertz)
- Simple on/off information of the transmitter must be coded. This is the purpose of the encoder.

The encoder creates a group of bits, assembled into a frame. An example of a message frame follows:



Message Frame with Four Fields

- Preamble with start bit indicates when the message begins.

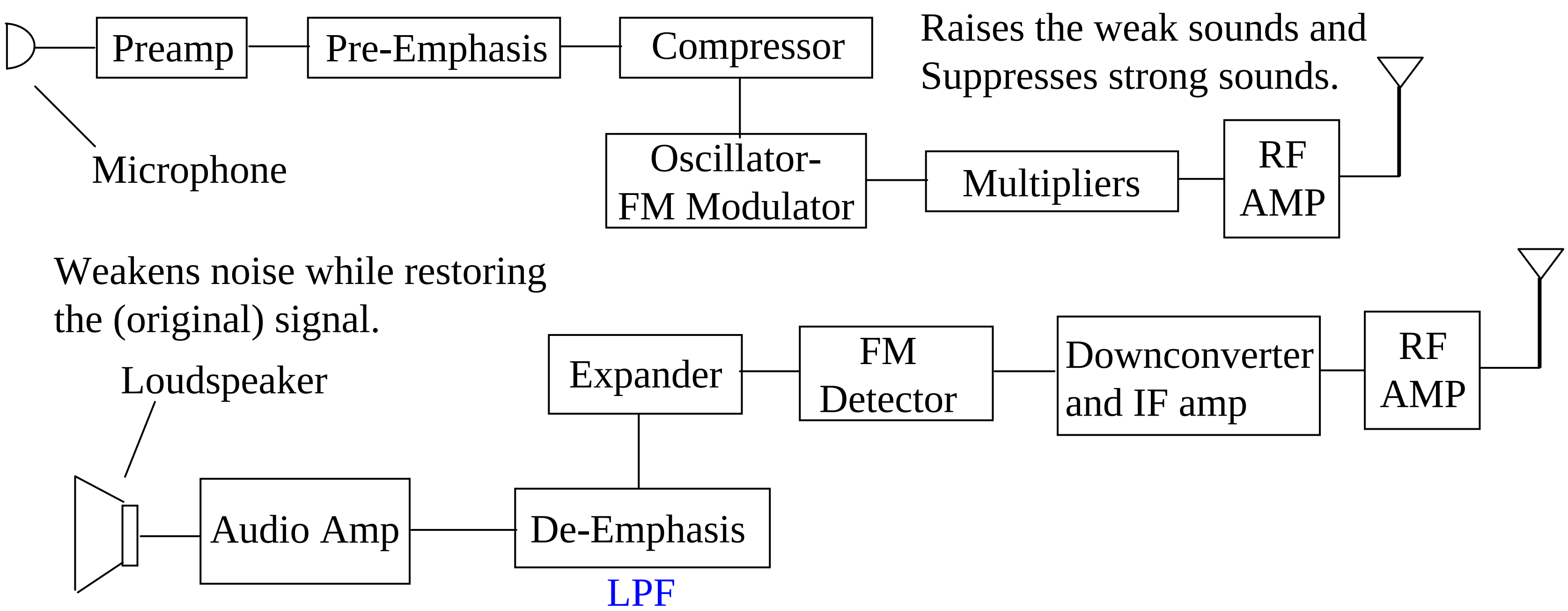
- Identifying address is unique and notifies the receiver from what unit (or from where) the message is coming.

- Data field indicates what type of event is signaled.

- In some protocols, parity bit(s) allows receiver to determine if the message was received correctly.

SHORT-RANGE COMMUNICATION SYSTEMS.

Examples: *Wireless Microphones and Headsets*



Wireless Microphone System

- These systems must maintain High Audio Quality (HAQ) while varying indoor environments and path lengths.

- An approach to maintain HAQ is by means of a signal conditioning element in their baseband path before modulation.

  - Pre-emphasis/De-emphasis
  - Compression/Expansion

RECEIVERS

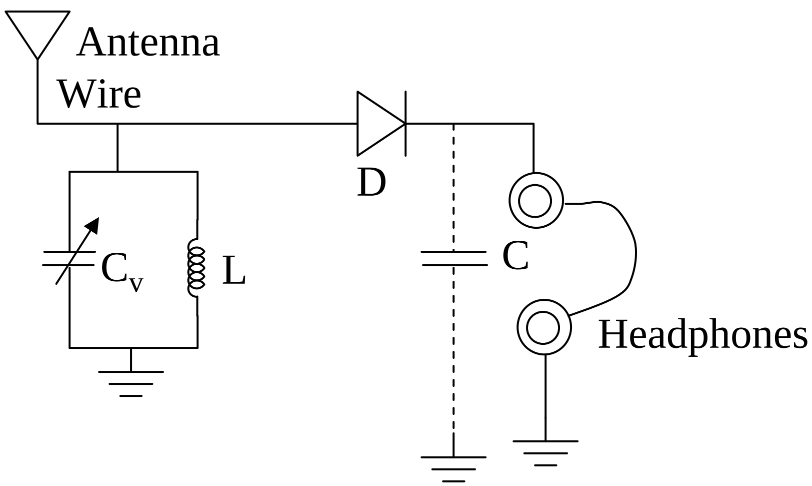
What is the signal to be received?

- Voice
- Data
- Short Range Control Device

What is the distance range between the transmitter and the receiver?

- Several Meters
- Few Centimeters
- Km or any distance

Example of a simple crystal radio



AM i.e. $L \sim 250\,\mu H$

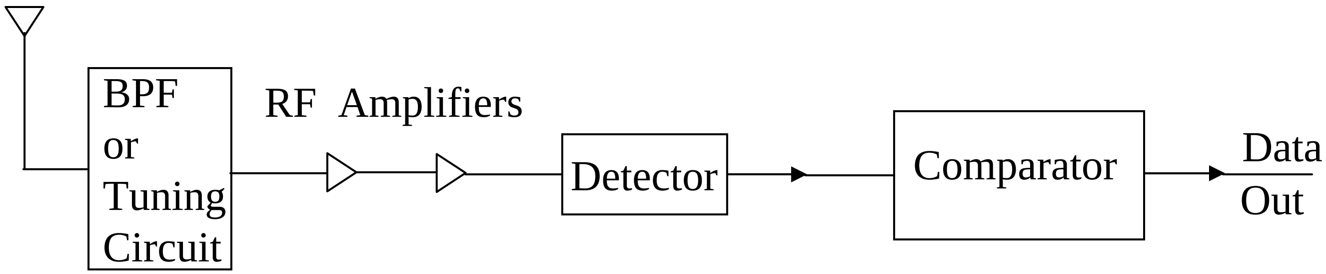
$40\,pF < C < 400\,pF$

$Z_H > 20k\Omega\,//(1-5nF)$

Wire > Long

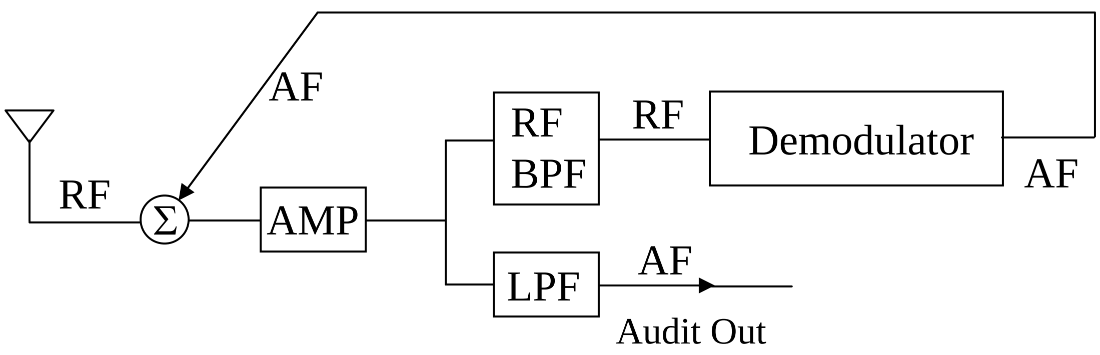
D: 1N334A Ge

- **TUNED RADIO FREQUENCY (TRF) RECEIVER**

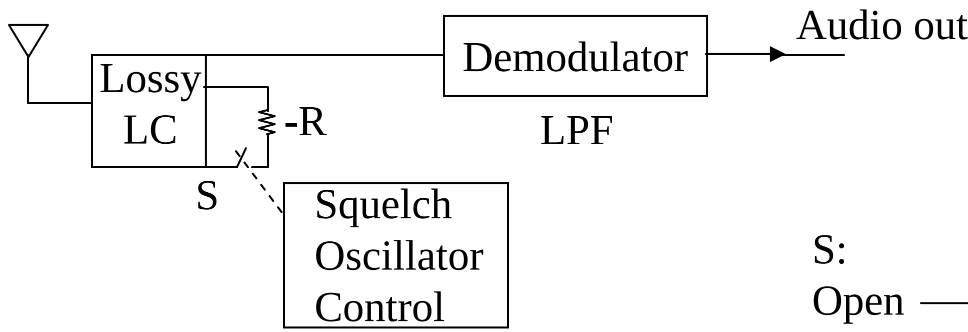


- Suitable (using ASK) for a few meters, i.e. computer mouse

- **REFLEX RECEIVER**



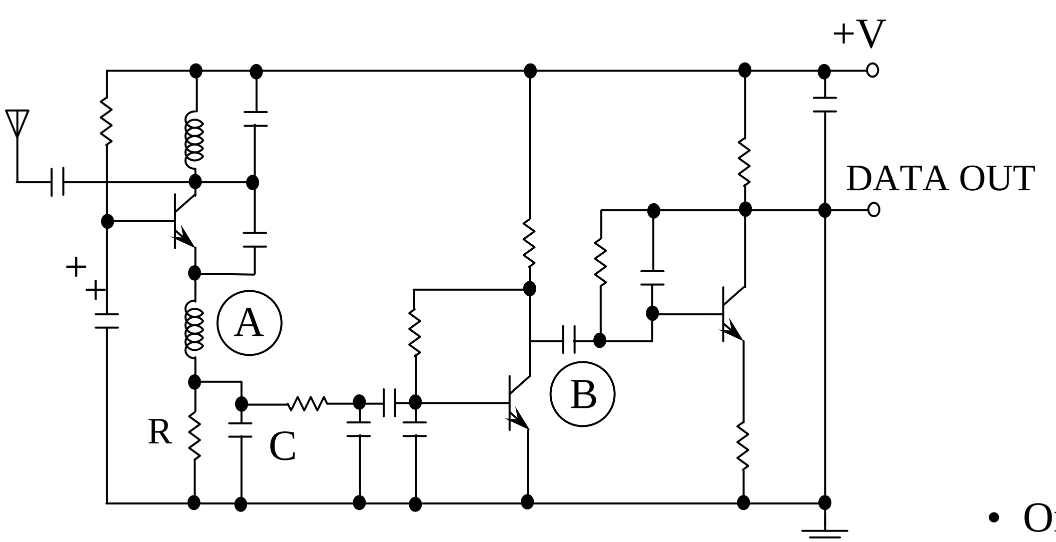
SUPERREGENERATIVE RECEIVER



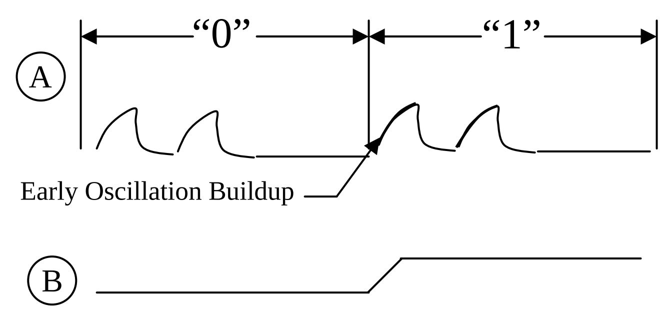
S:
Open ⟶ suppress oscillation
Closed ⟶ initiate oscillation (regenerative)

Conceptual Block Diagram

$$100k\ Hz < f_{o,tuning} < 500\,kHz$$



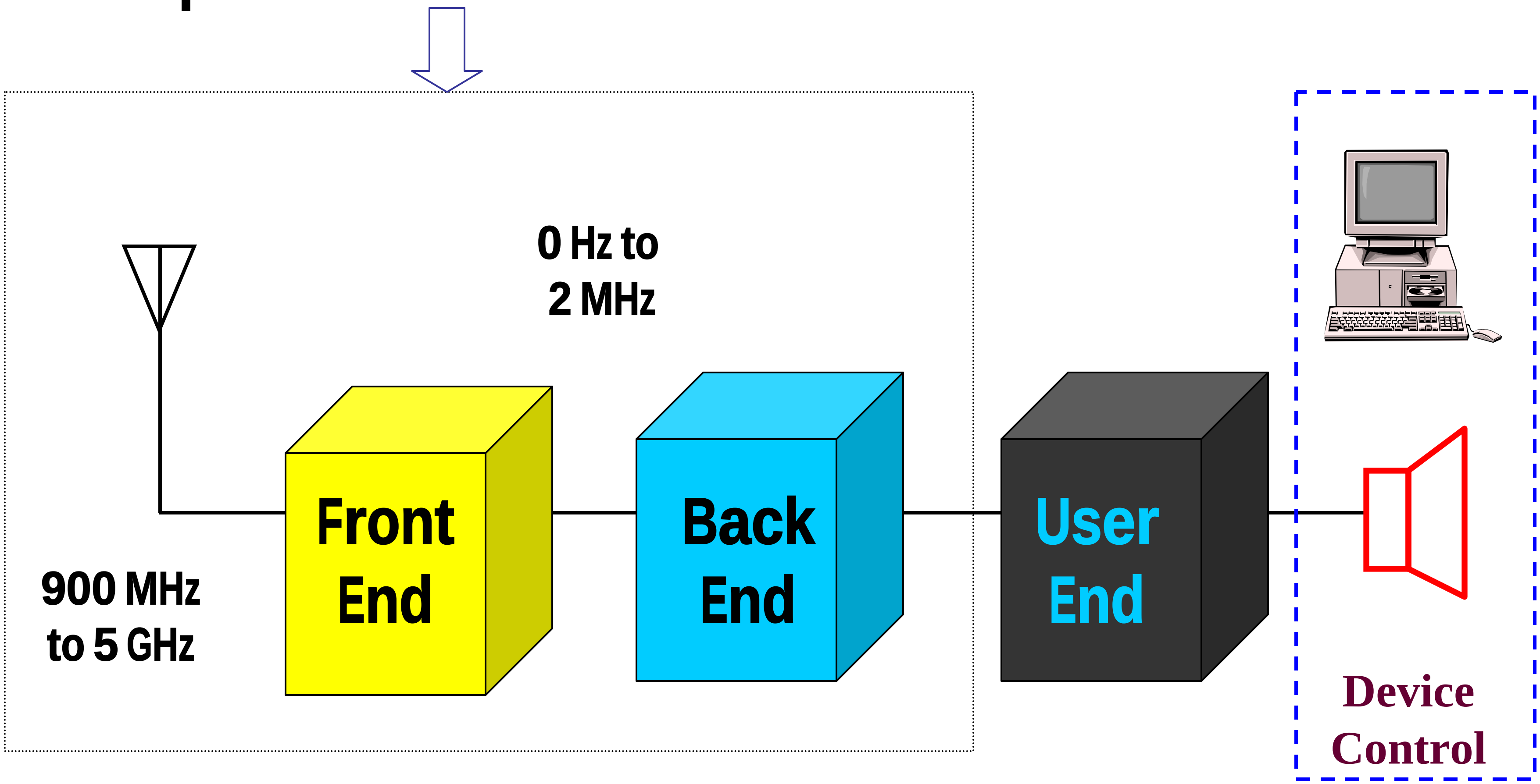
A Simple Implementation



Superregenerative Receiver Operation

- Only usable with ASK modulation.

Conceptual Receiver for Wireless Communications



- The Front End converts the antenna signal in a signal that can be demodulated by the back-end. Front End performs the frequency downconversion.
- Back End does the actual demodulation, decoding and decompression.
- User End converts information into a suitable form for user.

Important issues on Receivers:

- How small (and large) can be the signal coming from the antenna ?
  Minimum signal is determined by the ***sensitivity,*** *this also determines the gain requirement, and linearity.For example the smallest signal is -70 dBm needs to be amplified to 0.5 Vp-p at the A/D input*

- How large is the input referred noise at the input?
  The noise amount should be such that the Signal to Noise Ratio (SNR) at the output of the receiver is acceptable. The inband noise is given by the phase noise times interferer

- What is the shape of the input signal?
  This is determined by the standard and the modulation used.

Important issues on Receivers:

- How big are the interferes reaching the receiver, and at what frequencies ?

  The presence of an interferer must not deteriorate the SNR by more than 3 dB.

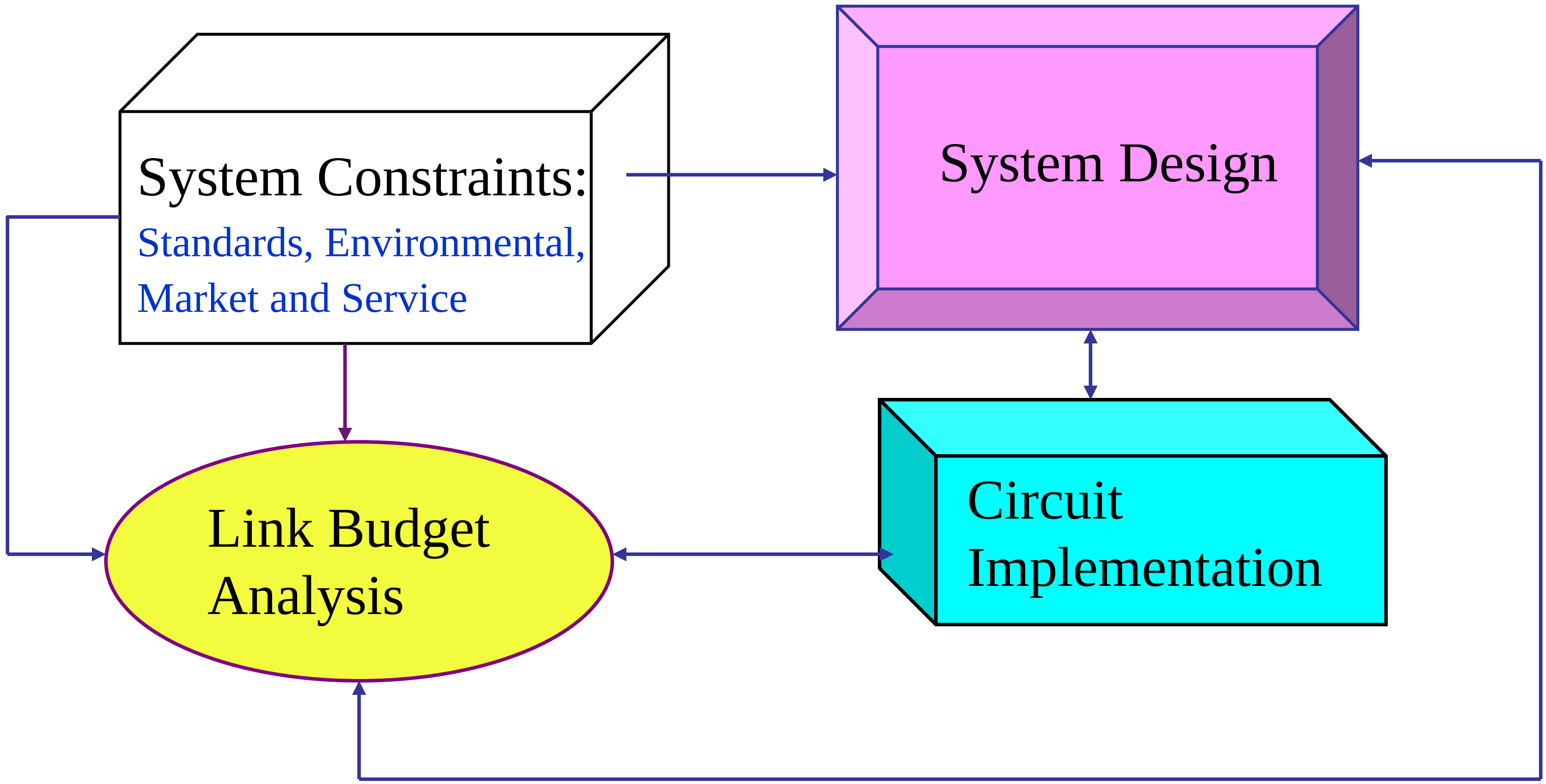
  In a Bluetooth standard , sensitivity is -70 dBm. With out of band interferer, the signal allowed is x? dBm.

- What is the bandwidth of the input signals?

- What are the frequencies at the antenna and at internal nodes?

  Highest frequency at the receiver antenna and lower inside receiver

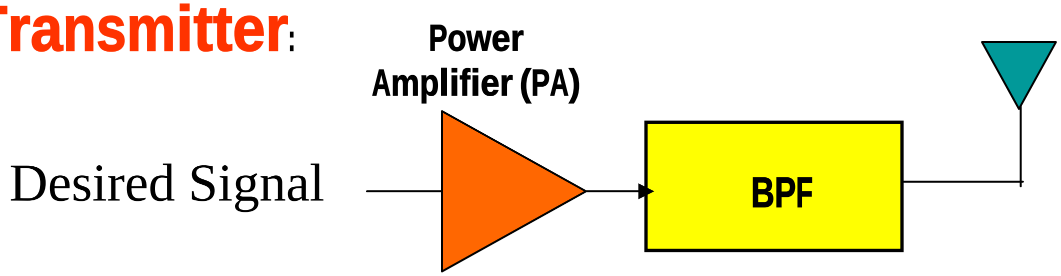
- Why do we have to change the frequency at the internal nodes?

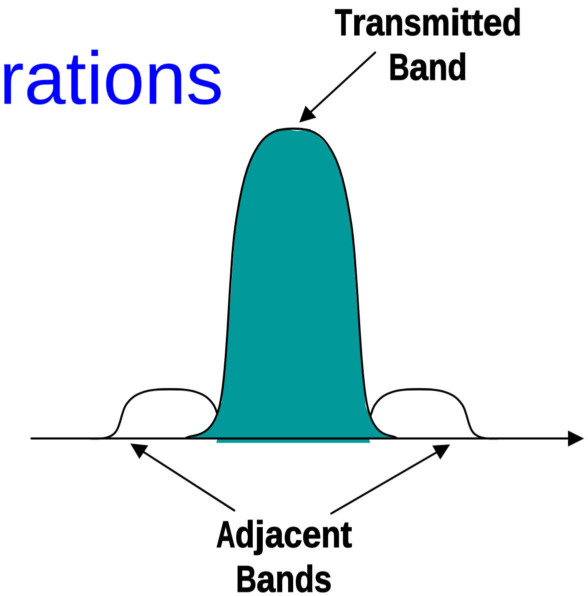


Transceiver Design Process

Simple RF Front End Considerations

Transmitter:

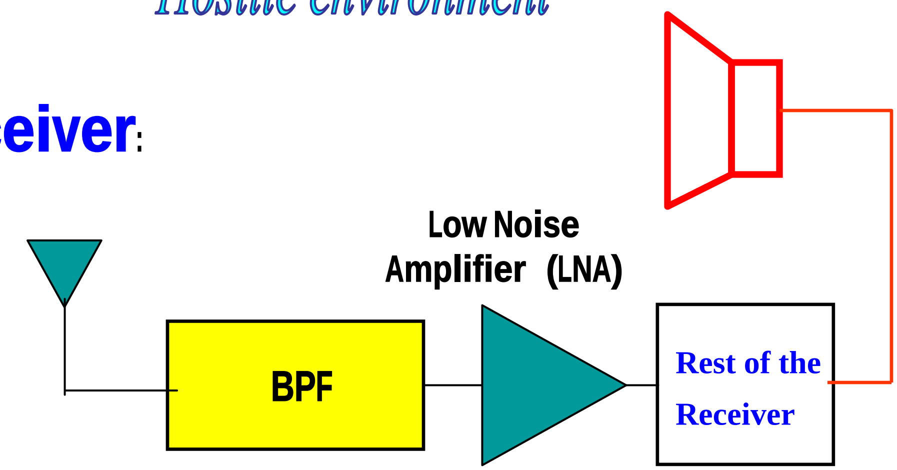


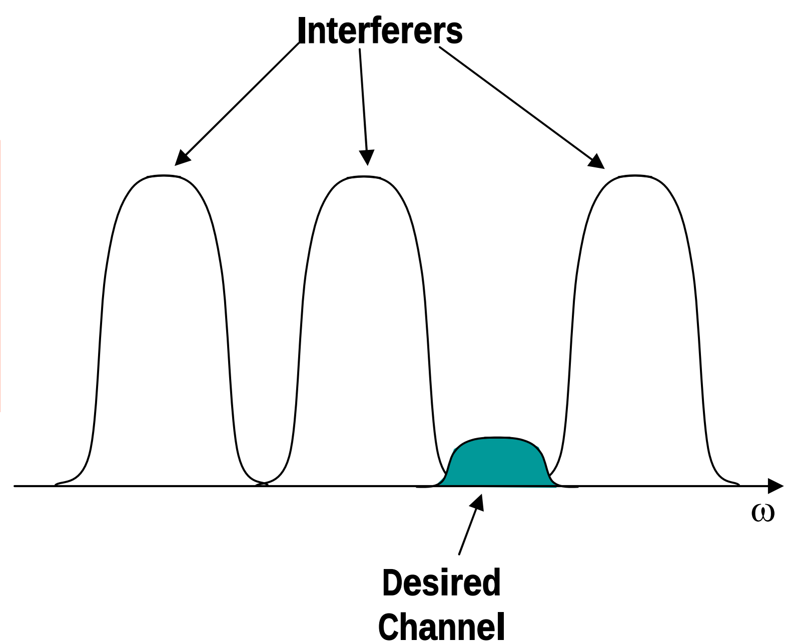


Hostile environment

Hostile environment

Receiver:





Limited Spectrum(signal bandwidth) for User, i.e., 30 KHz in IS-54 and 200 KHz in GSM(935Mz-960MHz) The US government limits companies to 45 MHz of mobile wireless capacity in any market.

INTERFERERS

- Interference comes from adjacent channel interferences.
  - Electromagnetic signal generators such as microwave ovens.
  - Signals coming from transmitters in other standards such as WCDMA and GSM

- The interferers are part of the FCC standards, thus they are specified for the wireless standards.

- Interferers model usually the worst-case of the undesired power level at the antenna.

What is the most popular and used receiver topology?

- The ***Superheterodyne*** or ***Heterodyne*** receiver was invented by Edwin Howard Armstrong (Patented in 1917). Its key feature is the use of an intermediate frequency (IF frequency). This receiver is also known as ***IF Receiver*** or as ***Superhet*** for short

- Sarnoff from RCA bought the "Superhet" rights and they dominated the radio market in 1930.

- Armstrong also developed (wideband) frequency Modulation

What are the principles and basic operation of a“Superhet” receiver ?

- Transfer all received channels to an intermediate frequency band where the weak input signal is amplified before being applied to the detector.

- High performance of the receiver is due to the filtering and amplification done at (one) several frequencies that do not change the input tuning of receiver .

- The generated intermediate frequency together with greater amplification is used without creating instability problems.

Receiver Front-End Architectures

- **Heterodyne (Superheterodyne) :**
  - *The Single-Stage IF Receiver*
  - *Multi-Stage IF Receivers*
- **Homodyne or Zero - IF Receivers**

- **Mixed Architecture Receivers**

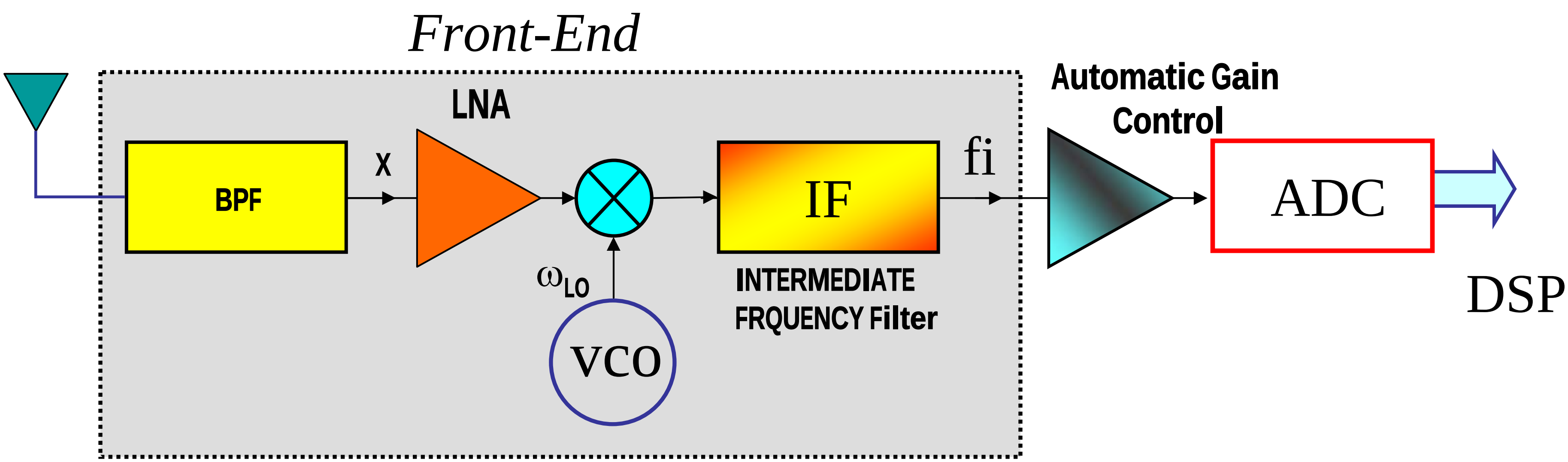
- **Integrated Heterodyne**
  - *Hartley Architecture*
  - *Weaver Architecture*
- **Sub - Sampling Architectures**

What is the nature of the building blocks in a transceiver?

- **Low Noise Amplifiers**
- **Mixer**
- **Filters**
- **Power Amplifiers**

If the building blocks are non-linear, what are the implications?

Heterodyne or IF Receivers:
- *The Single-Stage IF Receiver*



- The wanted signal is downconverted from its carrier fc to the intermediate fi by multiplying with a single sinusoidal flo

- The main weakness of this architecture is the appearance of a mirror frequency that is converted to the IF

What Devices Perform Frequency Translation in an single stage IF receiver ?

- Linear, time-invariant systems can not generate spectral component not present in the input.
- Mixer must be non-linear or time-variant system.
- Historically, a lot of devices are being tried as mixers: electrolytic cells, magnetic ribbons, brain tissues, rusty scissors, vacuum tubes and transistors.

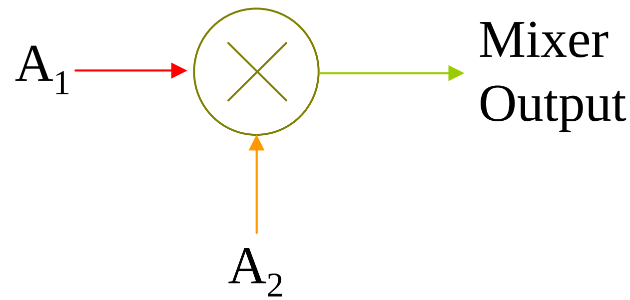
Virtually any nonlinear elements can be used as mixer. Some nonlinearities work better and more practical.

How to translate frequency?

Most mixer implementations use some kind of multiplication of two signals in time domain:

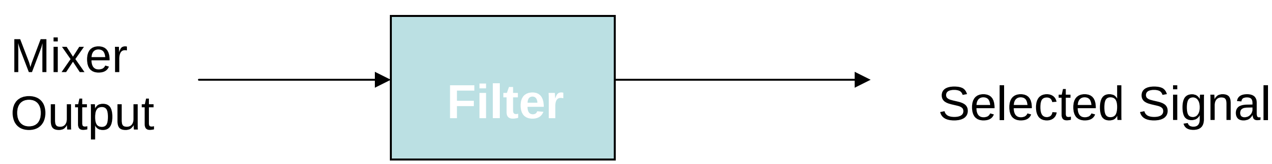
RF×LO→ IF (down conversion)

IF×LO → RF (up conversion)

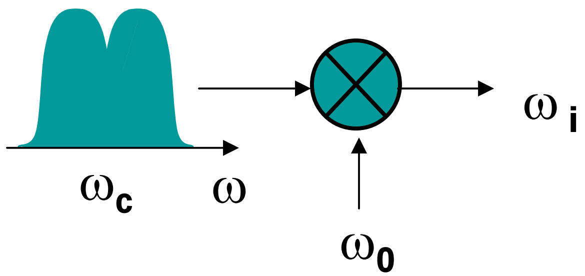


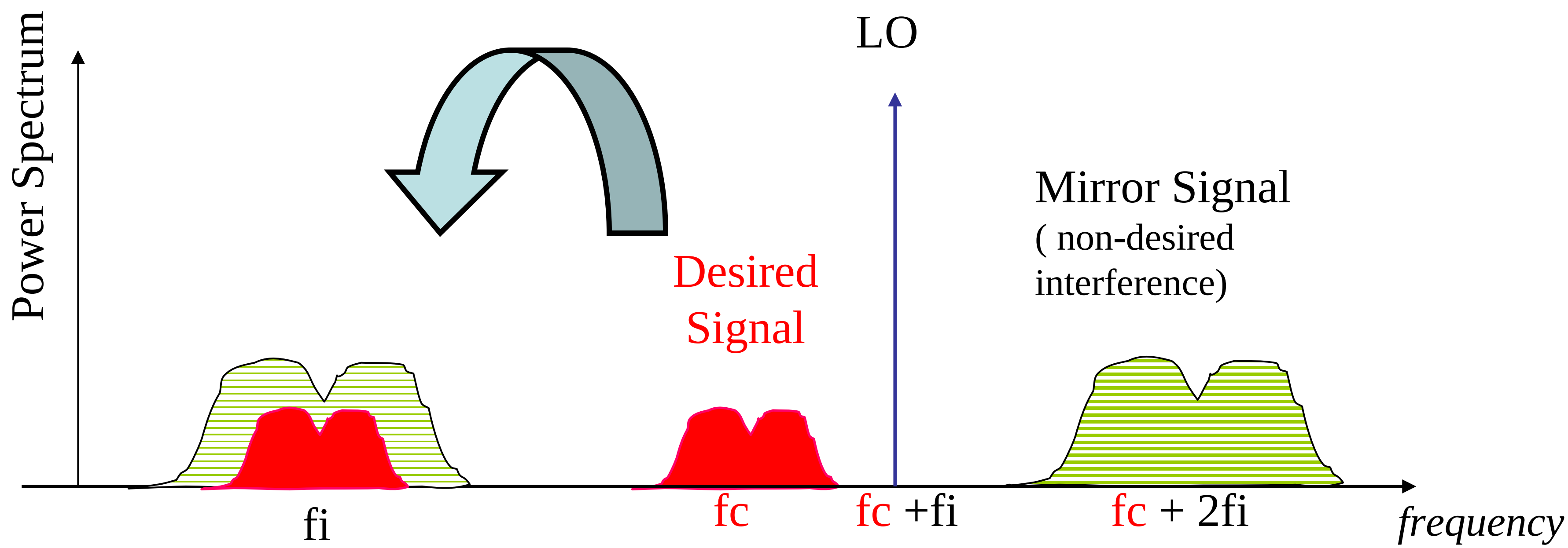
$$(A_1 \cos \omega_1 t)\times(A_2 \cos \omega_2 t)=\frac{A_1A_2}{2}\cos(\omega_1-\omega_2)t+\frac{A_1A_2}{2}\cos(\omega_1+\omega_2)t$$

- Up conversion filters out $\omega_1 - \omega_2$ component.
- Down conversion filter out $\omega_1 + \omega_2$ component.



How does the frequency translation occur in an single stage IF receiver ?





$fi = -fc + f_{o},$

$fc + 2fi = 2fo - fc = fo + fi$

$fc = fo - fi$

How to separate the desired and mirror signals ?

What are the practical issues in the implementation of this single-stage IF architecture?

- The mirror frequency (unwanted) is located at fc+2fi=fo+fi
- This mirror frequency has to be suppressed (filter out) before it is mixed down to the IF.
- The required filter is a high-frequency with narrow bandwidth, the effective Q must be higher than 20. This has to be done with an off-chip filter.
- Furthermore the regular IF must also have large selectivity of the order of 50 and the filter order is usually equal or greater than 8.
- Modern applications require higher RF frequencies (0.9, 1.8, 2.4) GHz while keeping the same BW (200KHz to 2MHz).
- The ratio of RF frequencies and the desired BW makes useless and impractical the use of a single stage IF receiver.

Mathematical Analysis of Image Problem in a Single-IF Receiver

$$V_{if}(t) = A_{RF}\cos\omega_{RF}t \cdot A_{LO}\cos\omega_{LO}t$$

$$V_{if}(t) = A\cos\omega_{RF}t \cdot A\cos\omega_{LO}t$$

$$V_{if}(t) = \frac{1}{2}A^2[\cos(\omega_{RF}+\omega_{LO})t + \cos(\omega_{RF}-\omega_{LO})t]$$

$$V_{if}(t) = \frac{1}{2}A^2[\cos(\omega_{RF}+\omega_{LO})t + \cos\omega_{IF}t]$$

The two components of the IF signal has one undesirable component at $(\omega_{RF}+\omega_{LO})$

Let us analyze the situation when the receiver consists not only of the RF signal but also of an interferer at the image frequency ω_{IMAGE}

The image problem occurs by the fact that two input frequencies can produce an IF of a given frequency.

Let us consider a numerical example.
RF=800 MHz, LO=870 MHz, yield a 70 MHZ and a 940 MHz.
An RF signal at 940 MHz would also produce an IF signal at 70 MHz.
This undesirable signal is known as ***image signal.***

Under this interferer situation besides the two $V_{if}(t)$ components obtained before, we will have an additional component:

$$a_{if}(t) = A\cos\omega_{IMAGE}t \cdot A\cos\omega_{LO}t$$

The image signal is spaced at two times the intermediate from the RF signal, that is:

$$\omega_{IMAGE} = \omega_{LO} - \omega_{IF} = \omega_{RF} + 2\omega_{IF}$$

Thus, we can determine the location of the new frequency components:

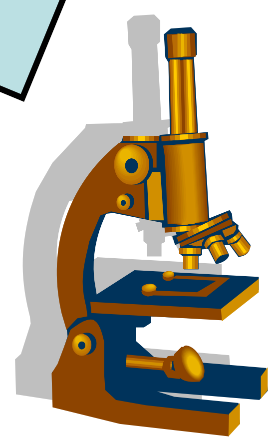
IMAGE REJECTION SIGNAL

$$\frac{1}{2}A^2[\cos(\omega_{LO}-\omega_{IF}+\omega_{LO})+\cos(\omega_{LO}-\omega_{IF}-\omega_{LO})t]$$

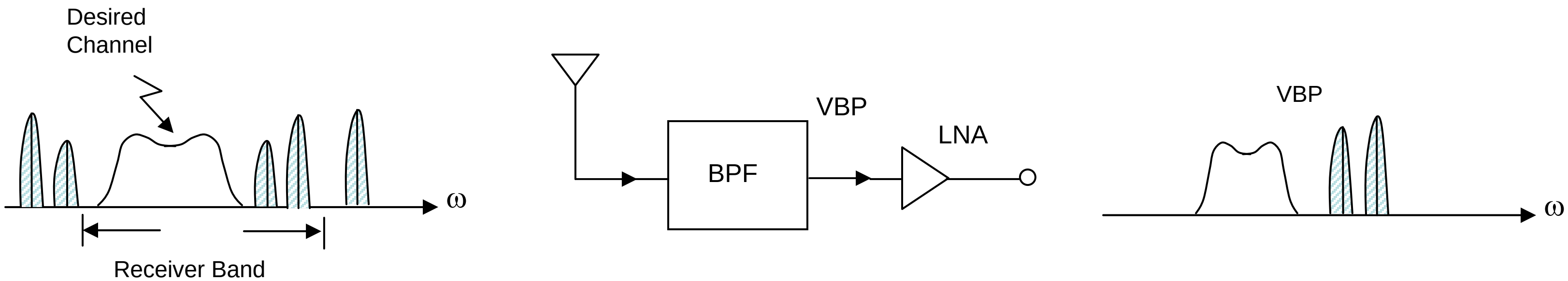
$$=A^2[\cos(2\omega_{LO}-\omega_{IF})t+\cos(\omega_{IF})t]$$

$$=0.5A^2\cos(2\omega_{LO}-\omega_{IF})t+0.5A^2\cos(\omega_{IF})t]$$

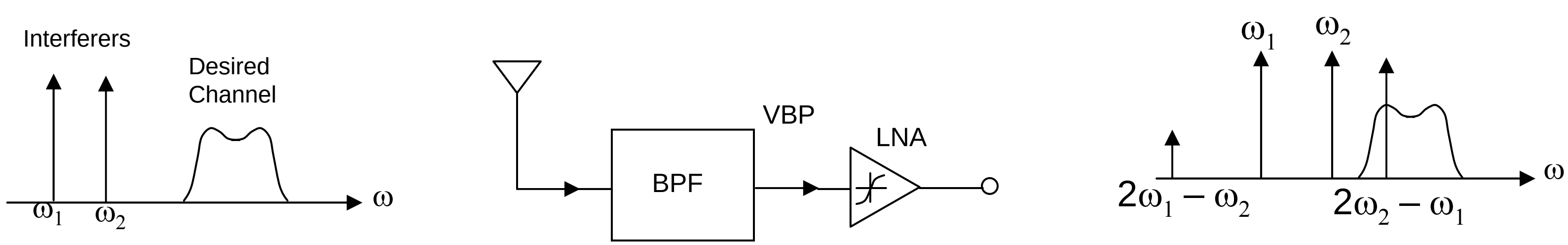
There is a strong interference at the image frequency, then at the IF there will be a strong interference sitting on Top of the desired signal. A solution is placing a BPF in front of the mixer center around LO, the BW is standard dependent.



Remarks on Interferers and Image Signal

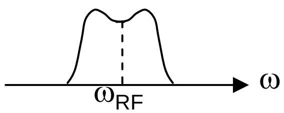


If the input besides the desired channel contains interferers, and taking into account the nonlinearities of the LNA, a number of undesirable components appear at the output of the LNA.

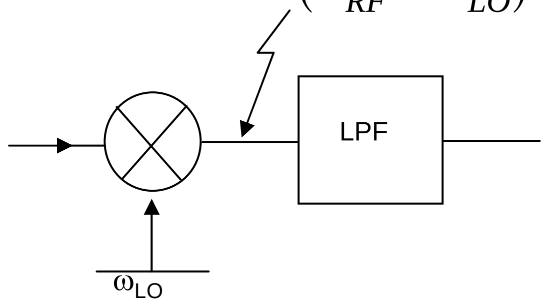


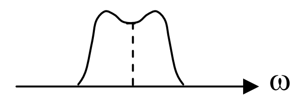
Downconversion Mixing

Ideal Situation



$$(\omega_{RF} - \omega_{LO}) \text{ and}$$
$$(\omega_{RF} + \omega_{LO}) = 2\omega_{RF} - \omega_{IF}$$



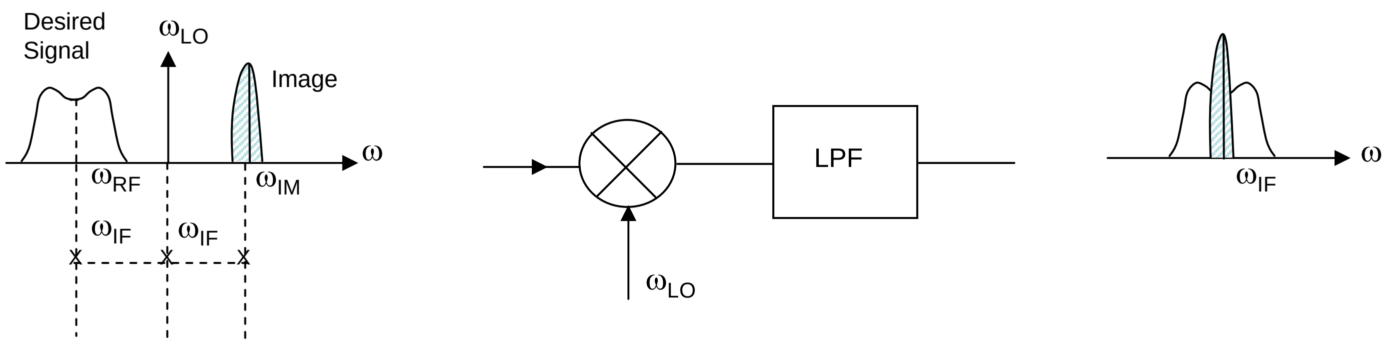


$$\omega_{IF} = \omega_{RF} - \omega_{LO}$$

- Adding a LNA before the mixer lower the overall noise.

- What happens if $\omega_{IF} = \omega_{LO} - \omega_{RF}$?
  The image signal is around
  $2\omega_{LO} - \omega_{RF} = \omega_{LO} + \omega_{IF}$

- The bands symmetrically located below and above ω_{LO} are downconverted to the same center frequency. See next illustration.



How to tackle this image problem?

• Insert an image reject filter between the LNA and the mixer. Fix the intermediate frequency at

$$\omega_{RF} - \omega_{IMAGE} = 2\omega_{IF}$$

• Consider tradeoffs between ω_{IF} and the selectivity of the IR filter as well as noise.