TAIPEI TECH

國立臺北科技大學

High-Frequency Electronic Circuits

Lecture 1

Overview of High-Frequency Electronic Circuits

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Spring 2025

Electronic Engineering, Taipei Tech.

Course Information

345899 Spring 2025 (Prof. Yen-Sheng Chen)

High-Frequency Electronic Circuits

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Office hours: Wed. 13:00-16:00

Course materials: Lecture notes available for download from *I-Learning* (北科I學園$^+$)

Overview of This Course

Content

1. Overview of High-Frequency Electronic Circuits
2. Transmission Line Theory
3. Impedance Matching Networks
4. Microwave Network Analysis (if time allows)

References

1. D. M. Pozar, Microwave Engineering, 4th ed., Wiley.
2. Kai Chang, RF and Microwave Wireless Systems, Wiley.
3. Simon Saunders and Alejandro Aragón-Zavala, Antennas and Propagation for Wireless Communication Systems: 2nd Edition, McGraw-Hill.

Grading Policy

Dynamic Grading System (DGS)

1. **Flipped Classroom and Quizzes** 40 points
2. **Midterm Exam** 40 points
3. **Unscheduled In-class Activities** Variable points
4. **Final Exam Weight**

(100 – Total Points Earned Above)%

Examples

Example 1:

- Flipped Classroom and Quizzes: 25 points (15 + 10)
- Midterm Exam: 30 points
- In-class Activities: 10 points
- Total Before Final Exam: 25 + 30 + 10 = 65 points

Final Exam Weight: 100 – 65 = 35%

Final Exam Score: 85
Final Grade Calculation:

$$(65) + (85 \times 35\%) = 95$$

Examples

Example 2:

- Flipped Classroom and Quizzes: 0 points (0 + 0)
- Midterm Exam: 5 points
- In-class Activities: 0 points
- Total Before Final Exam: 0 + 5 + 0 = 5 points

Final Exam Weight: 100 – 5 = 95%

Final Exam Score: ____
Final Grade Calculation: ____

Important Policy of DGS

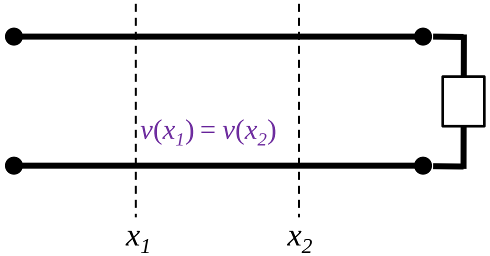
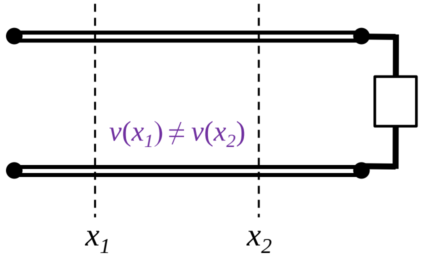
- **Track Your Score**: Follow your progress online at https://docs.google.com/spreadsheets/d/1jbQpiGCEWX-NlJUyEt-TkvtbAAKxkL4n93zAQPnZB8Y/edit?usp=sharing

- **No Make-up Activities**: If you miss a flipped classroom participation or even the midterm exam, there is no make-up opportunity directly associated to that event

- **No Grade Curving**: Your final grade is solely based on the points you accumulate and your final exam performance

Positioning of HFEC (1/2)

1. Compared with the course of *Circuit Theory*:

Circuit Theory	**HFEC**
	
• Lumped-parameter system	• Distributed-parameter system
• The electrical signals are transmitted through the circuit without time delay	• The electrical signals are transmitted through the circuit with time delay
• Circuit variables: $v(t)$, $i(t)$	• Circuit variables: $v(x, t)$, $i(x, t)$
• Ordinary differential equations (Kirchhoff's laws)	• Partial differential equations (Maxwell equations)
• No electromagnetic radiation happens	• Electrical components might radiate power

The KCL and KVL **CANNOT** be applied to microwave engineering directly

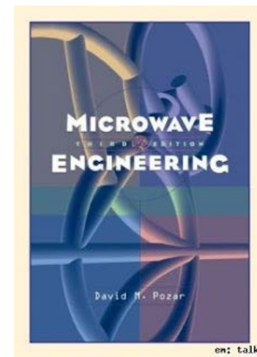
Positioning of HFEC (2/2)

2. Compared with the course of *Electromagnetics*:

Electromagnetics

- Solve Maxwell's equations
- Full-wave analysis by field theory
- Provide a complete description of the EM field at every point in space

HFEC



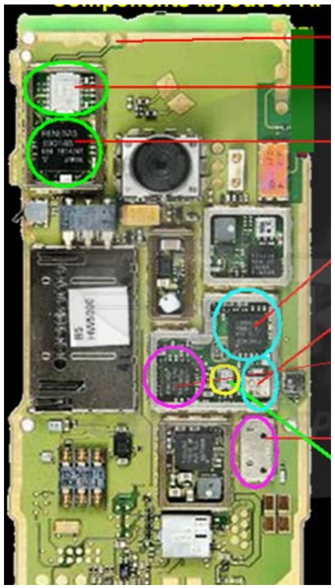
- Begin with Maxwell's equations
- Reduce the complexity of a field theory solution and express the solution in terms of simpler circuit theories
- Interested in terminal quantities such as power, impedance, voltage, and current

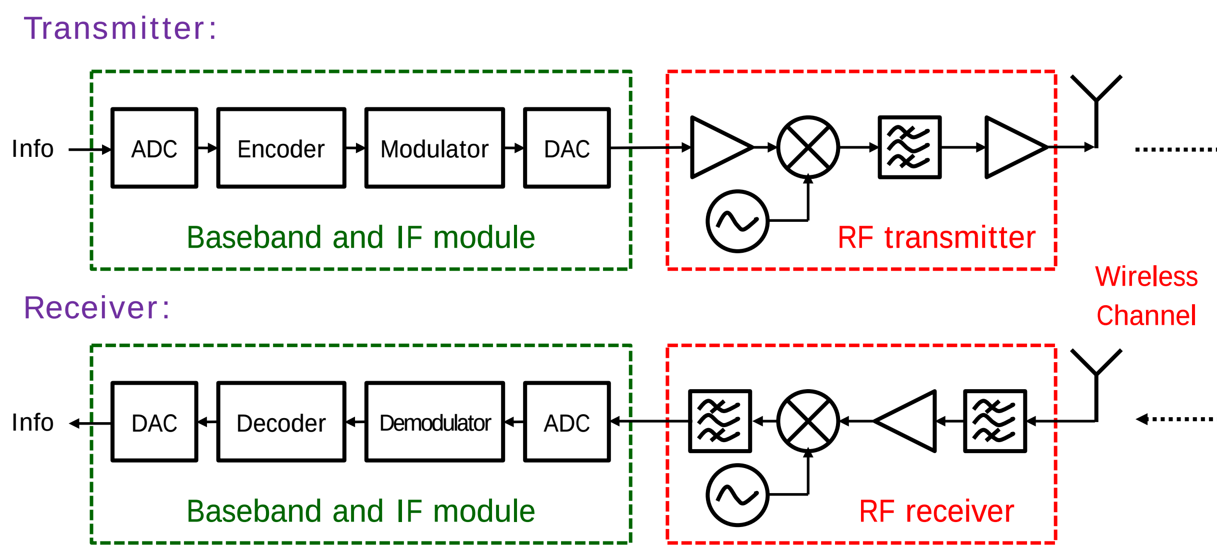
Less complicated than EM theory

Agenda

Week	Topic	Detailed Lecture
1	Opening	Introduction to This Course
2	Lecture 1	One Class Cancellation Due to a Meeting
3		System Components of Microwave Communications
4		Link Budget
5	Lecture 2	Circuit-Model
6		Frequency-Domain Analysis
7		Frequency-Domain Analysis
8		Smith Chart
9		Smith Chart
10	Midterm Exam	Midterm Exam
11	Lecture 2	Physical Guided Structures
12	Lecture 3	Matching with Lumped Elements
13		Single-Stub and Double-Stub Matching
14		Bandwidth and the Q Value
15		Practical Issues in Matching Networks
16	Lecture 4	Basic Definitions of Single Network Parameters
17	Final Exam	Final Exam (6/10)

Overview of High-Frequency Electronic Circuits

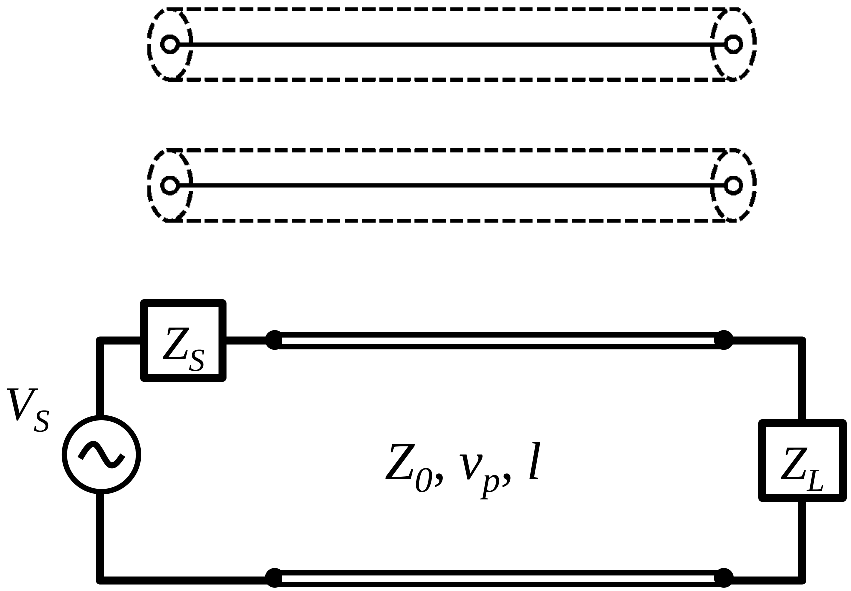


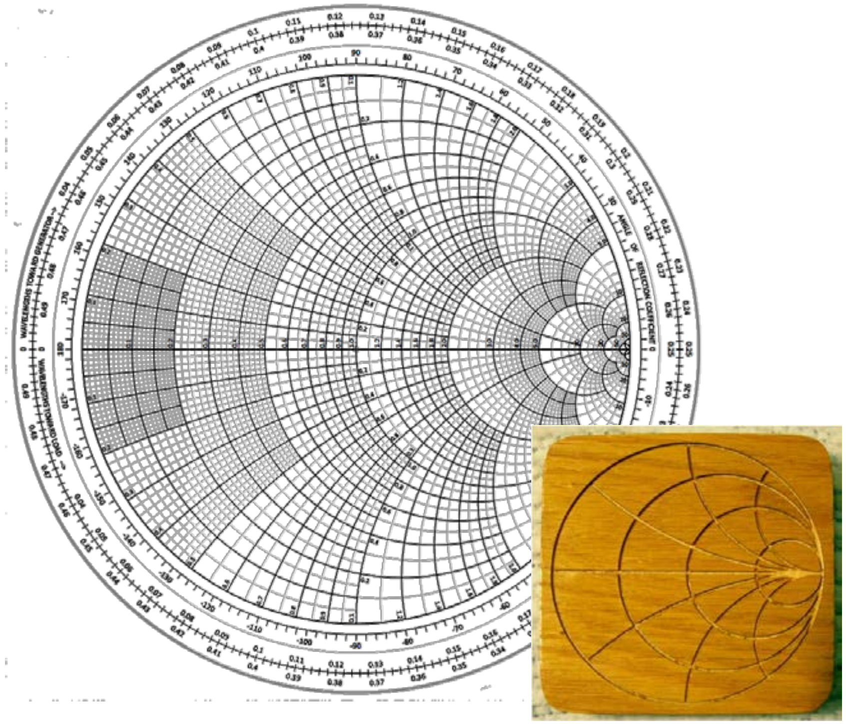


1. What is the function of the components in transceiver structures?
2. How do we compute the required transmitting power for microwave wireless communication systems?

Understanding how RF circuit works on cell phone [on-line]. Available: http://cellphonerepairtutorials.blogspot.tw/2010/08/understanding-how-rf-circuit-works-on.html

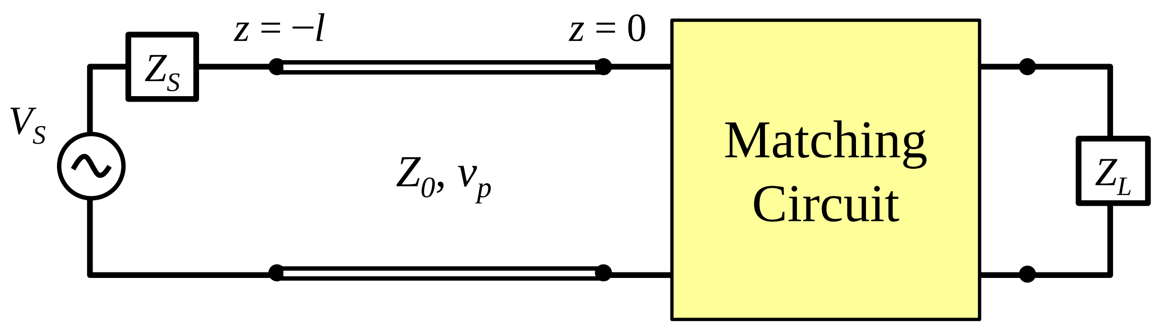
Transmission Line Theory

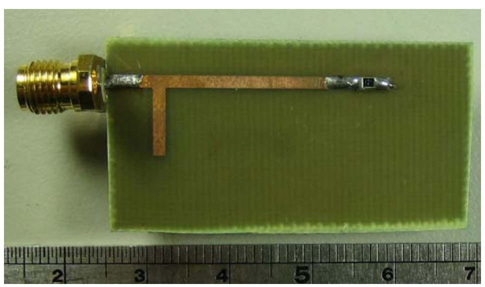


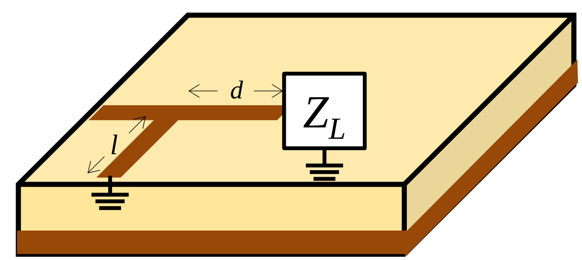


1. How do signals and waves transmit in guided structures?
2. How to use the Smith chart to do the higher-frequency circuit analysis?

Impedance Matching Networks

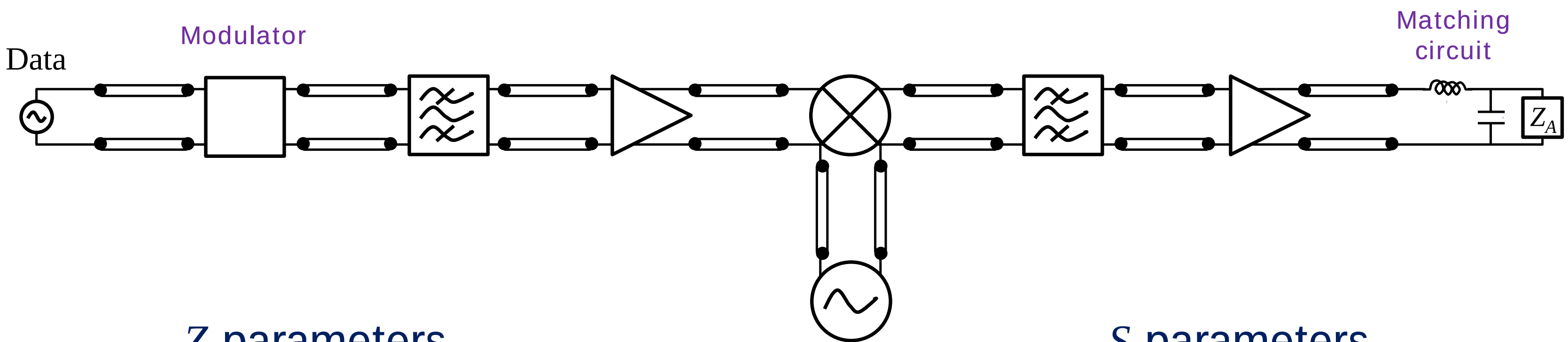






1. How does a RF component receive the maximum power?
2. How to do impedance matching via the Smith chart?

Microwave Network Analysis (if time allows)



Z parameters

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

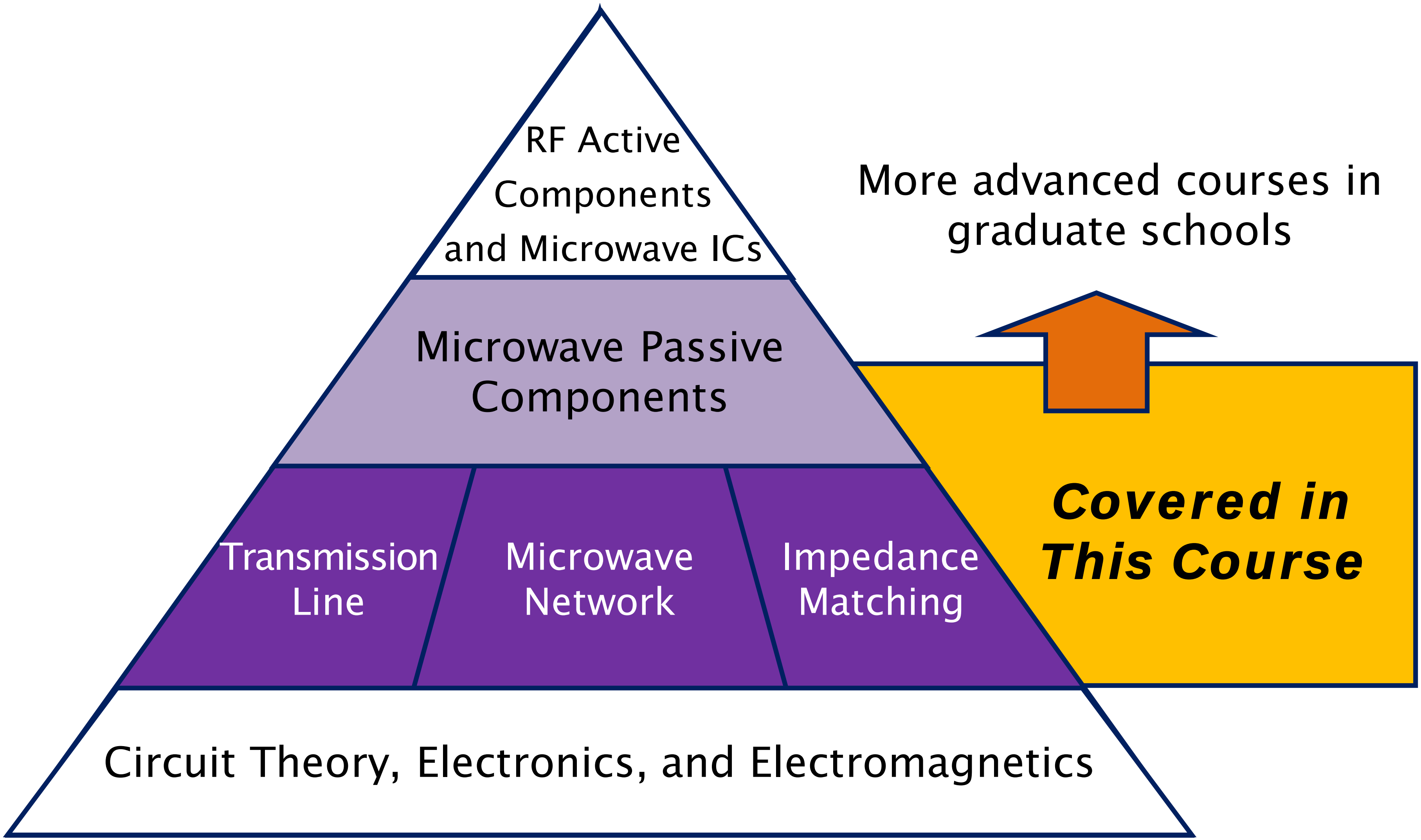
$\Longrightarrow$

S parameters

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

1. How to analyze inter-connected RF components efficiently?
2. How to calculate the S parameter for a given circuit?

EM Engineering Background Build-Up



Contents

Lecture 1: Overview of High-Frequency Electronic Circuits

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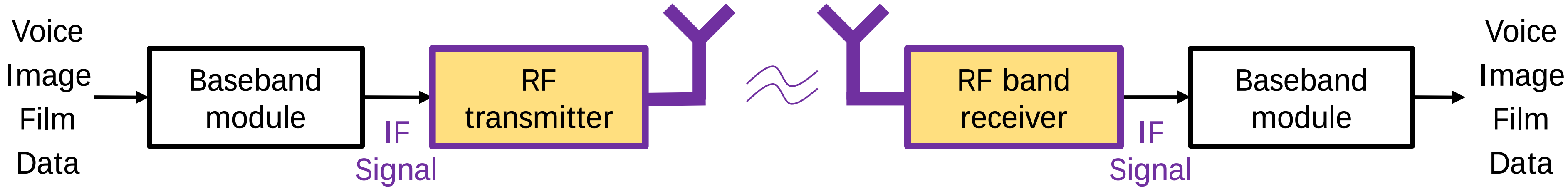
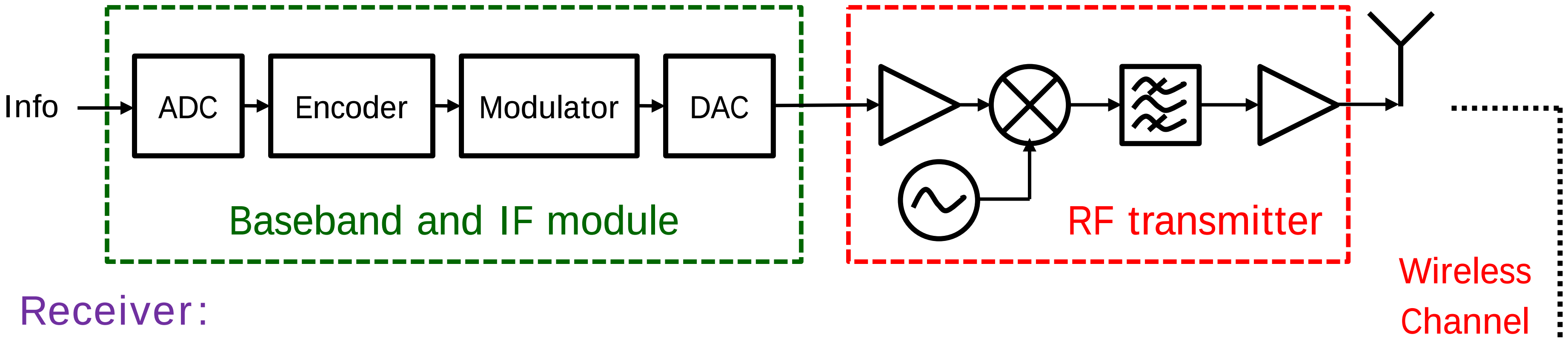
1.1 Transceiver Architecture

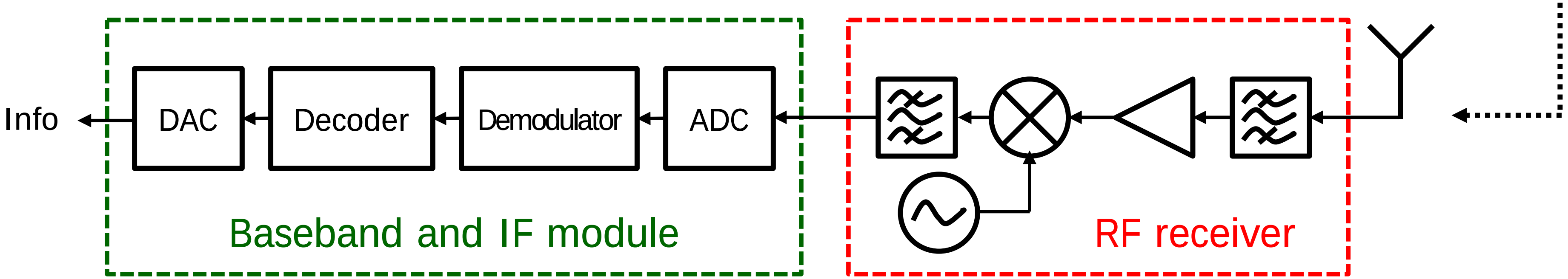
Typical Microwave Communication System



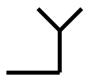
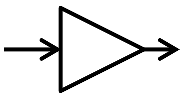
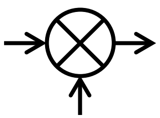
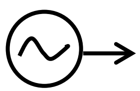
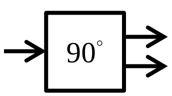
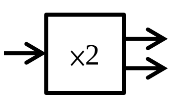
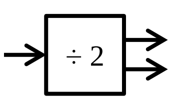
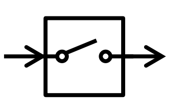
Transmitter:

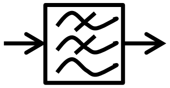
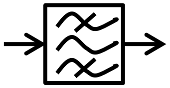
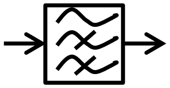


Receiver:

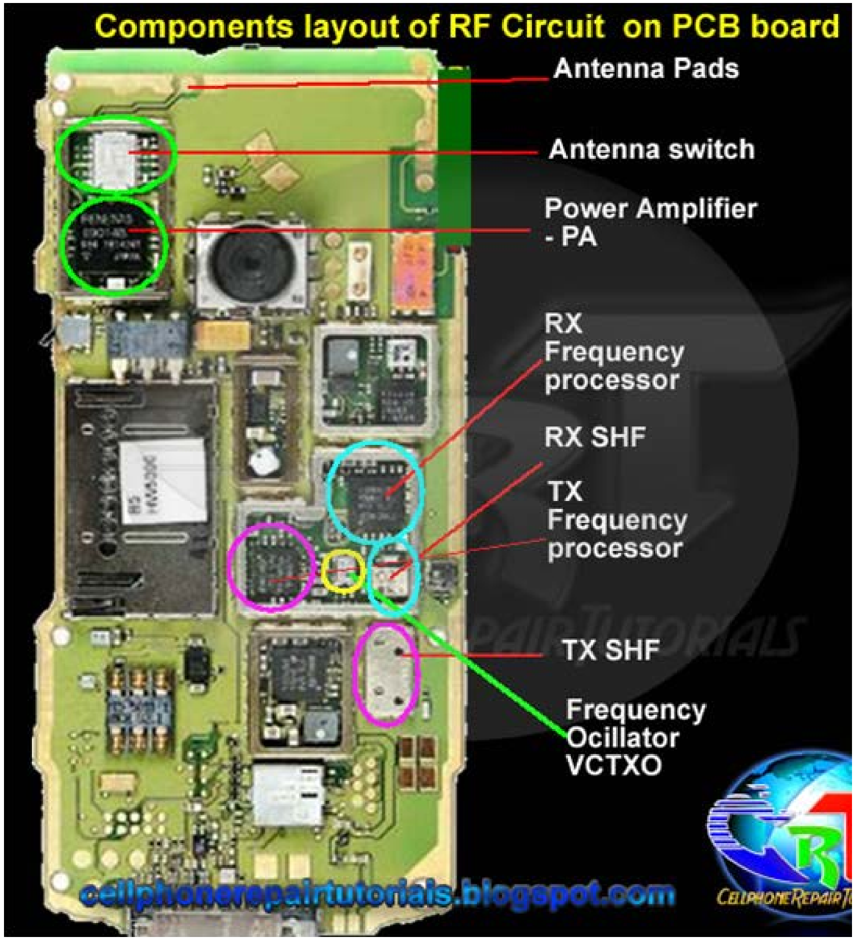


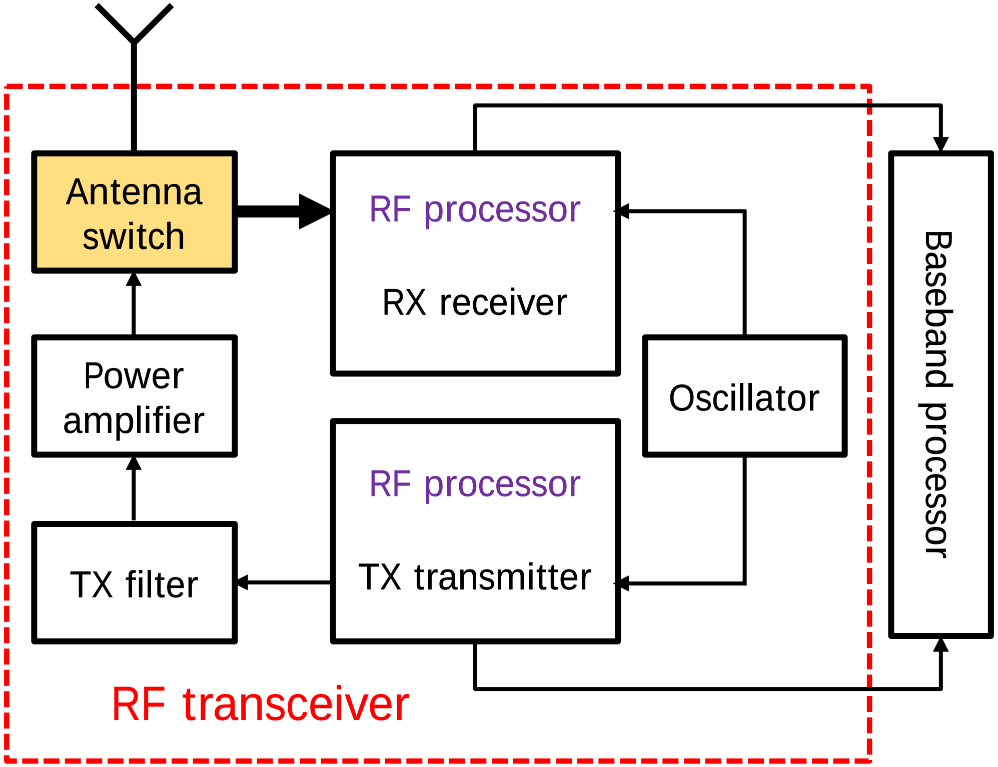
Block Diagram Symbols

Symbol	Component name
	Antenna
	Amplifier
	Mixer
	Oscillator
	90° power divider
	Frequency multiplier
	Frequency divider
	Switch

Symbol	Component name
	Low-pass filter
	Band-pass filter
	High-pass filter

Bilateral Transceiver Structure

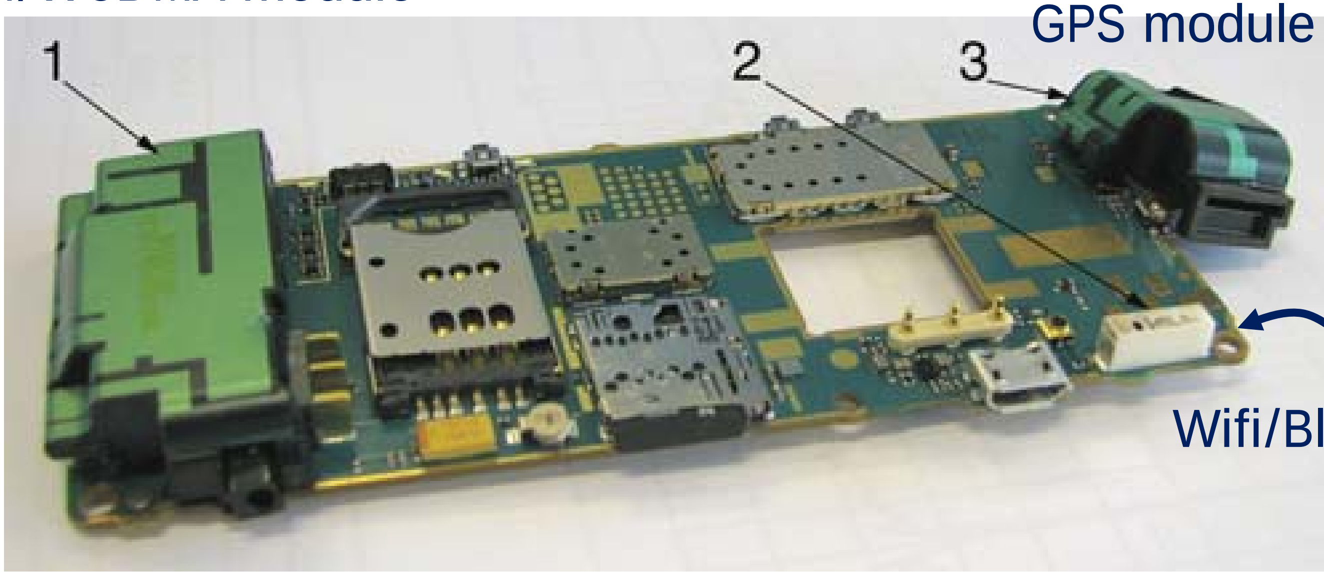




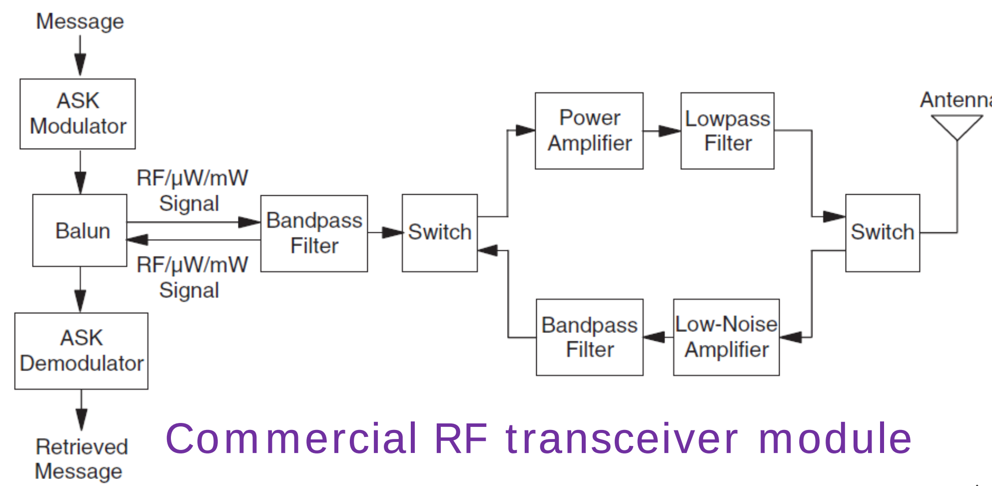
- Most of the time, the antenna switch connects its gateway to the RX circuit
- Except for the antenna, all the components in a transceiver can be made easily on a single chip

Understanding how RF circuit works on cell phone [online]. Available: http://cellphonerepairtutorials.blogspot.tw/2010/08/understanding-how-rf-circuit-works-on.html

Modules in Your Smart Phone



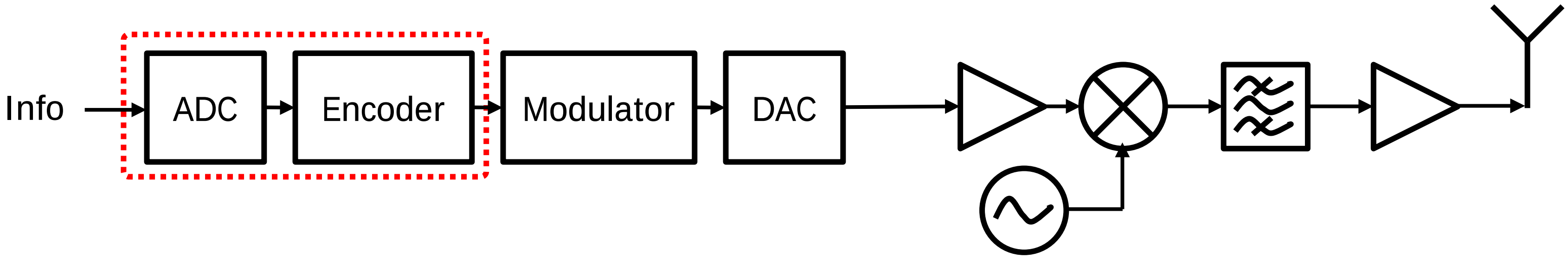
- In modern applications, the RF transmitter and receiver are combined with a modulator and demodulator to form a single-module transceiver
- There are 3 modules in this handset device



Commercial RF transceiver module

R. B. Langley, “Innovation: mobile phone GPS antennas,” *GPS World*, [on-line]. Available: http://gpsworld.com/professional-oemcomponent-technologiesinnovation-mobile-phone-gps-antennas-9457/
K. Feher, *Wireless Digital Communications: Modulation and Spread Spectrum Applications*. Upper Saddle River, NJ: Prentice Hall, 1995.

Encoding the Input Information (1/3)



Objective:

- ADC: Converting analog data to digital formats
- Coding process:
    1. Source encoder: Eliminating the redundancy in the information bits
    2. Channel encoder: Incorporating error control to minimize the probability of error in transmission

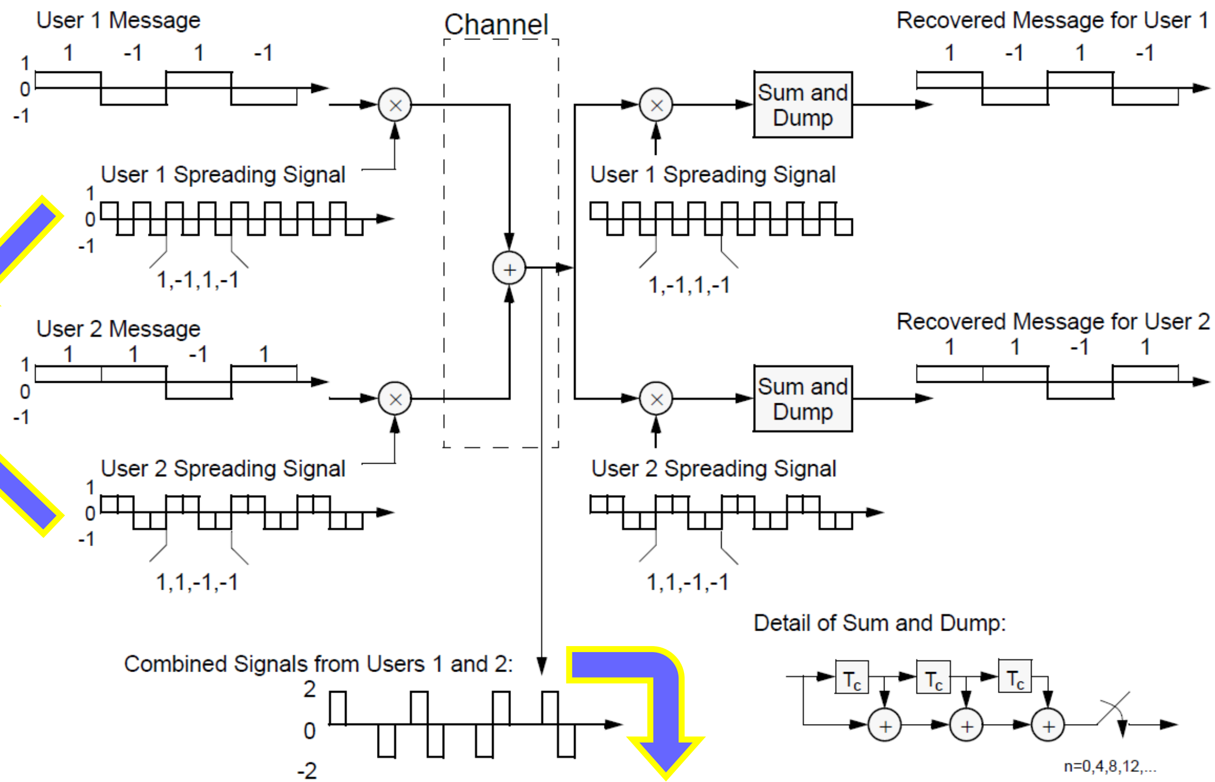
Characteristic:

- The encoder can be a circuit, a software program, or firmware (an algorithm burned into programmable hardware) that converts the source bits to channel bits
- The DSP units allow multiple access schemes

Encoding the Input Information (2/3)

The encoding procedure in CDMA systems:

Signals from different users are assigned unique spreading codes

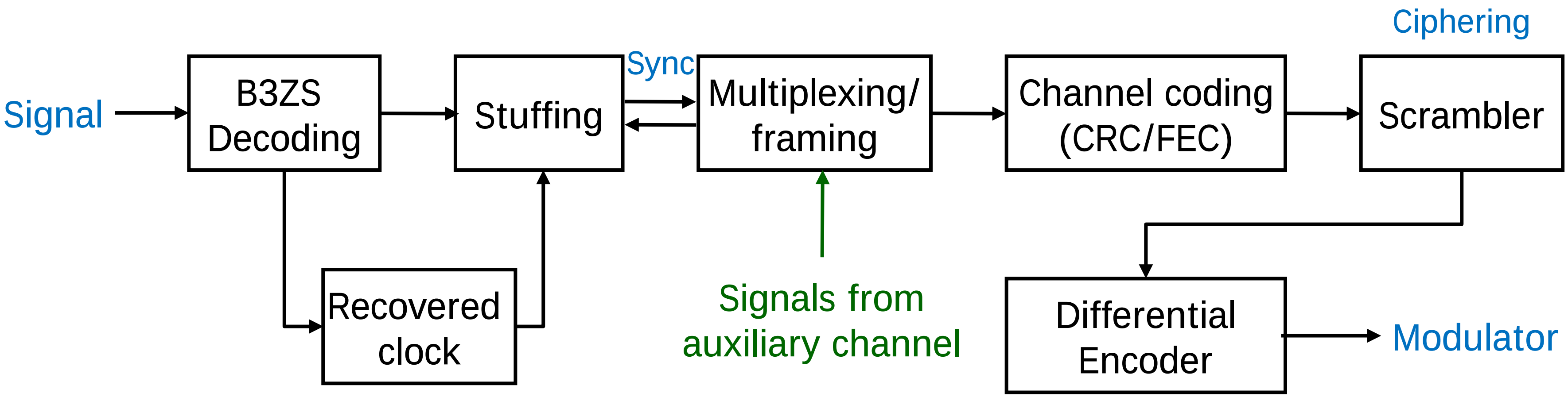


Signals from different users occupy the same spectrum at the same time

J. Liberti and T. S. Rappaport, *Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications*, Prentice Hall, 1999.

Encoding the Input Information (3/3)

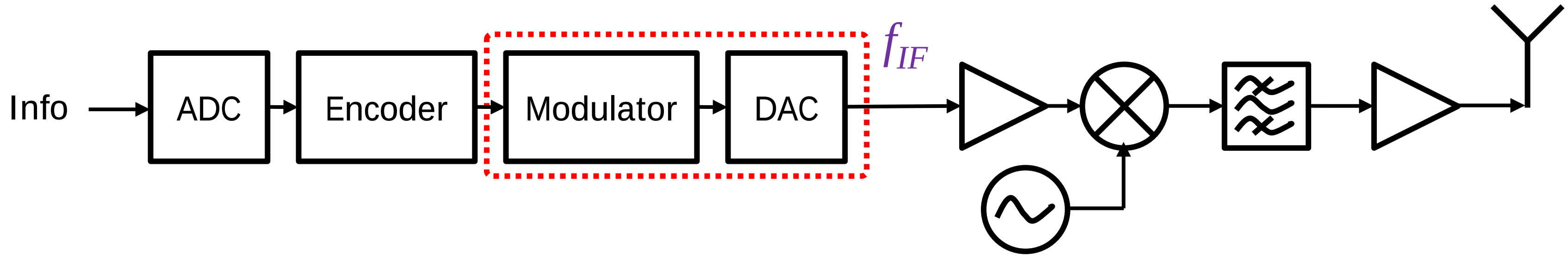
An example of encoder:



Related course:

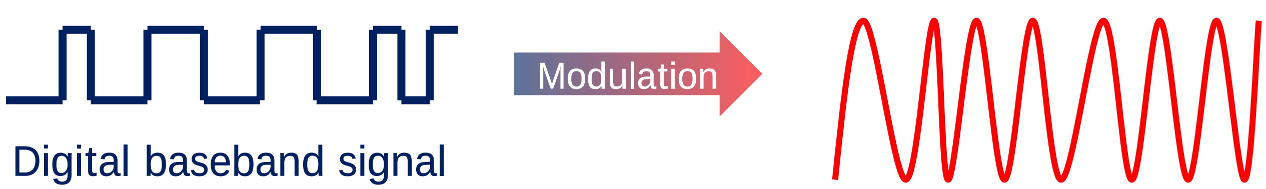
- Digital Signal Processing
- Digital Communication System
- Error Control Coding
- Baseband Communication System and Circuit Design
- Etc.

Modulation: Basic Ideas (1/2)



Objective:

- Transforming the spectrum of the baseband signal to a higher frequency, called the intermediate frequency (IF)



Characteristic:

- IF range: several KHz to hundreds of MHz
- The most important issue: trade-off between bit error rate (BER) and data transmission rate

Modulation: Basic Ideas (2/2)

- Modulation process of digital baseband signal can be expressed as:

$$v_c(t) = \underbrace{A}_{\text{Amplitude}} \cdot \cos\left(\underbrace{\omega_c}_{\text{Frequency}} \times t + \underbrace{\phi}_{\text{Phase}}\right)$$

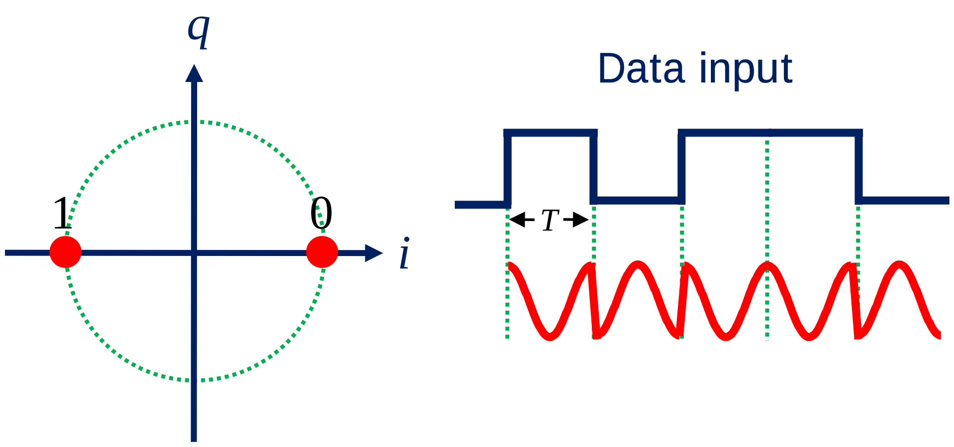
- Basic methods of digital modulation:
  1. **Amplitude shift keying (ASK)**: mapping digital baseband signals to analog IF sinusoidal functions where A are distinct while ω_c and φ are constant
  2. **Phase shift keying (PSK)**: mapping digital baseband signals to analog IF sinusoidal functions where φ are distinct while A and ω_c are constant
  3. **Frequency shift keying (FSK)**: mapping digital baseband signals to analog IF sinusoidal functions where ω_c are distinct while A and φ are constant
- Advanced methods of digital modulation:
  4. **Quadrature amplitude modulation (QAM)**: mapping digital baseband signals to analog IF sinusoidal functions where A and φ are distinct while ω_c are constant
- The greater the modulation modes, the higher the data throughput is; but, the required signal-to-noise ratio (SNR) increases

Modulation: PSK

BPSK:

- The modulated carrier $v_c(t)$:

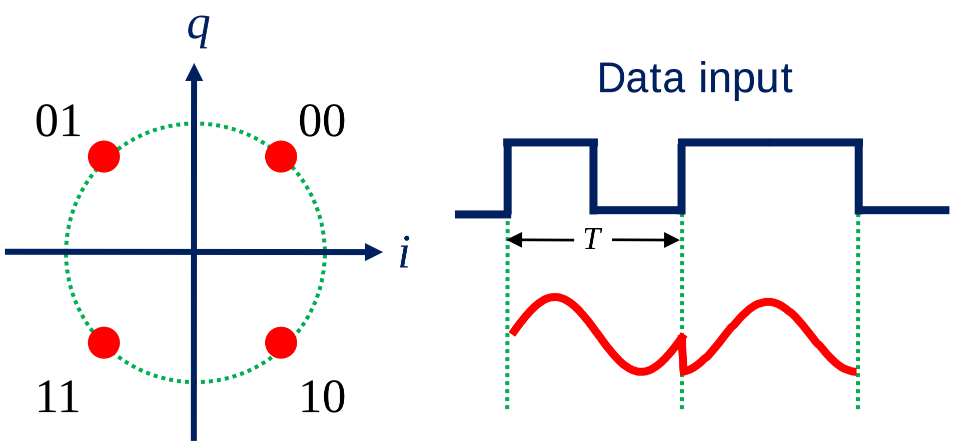
Digital signal	Modulated carrier
0	$A\cos(\omega_c t + 0°)$
1	$A\cos(\omega_c t + 180°)$



QPSK:

- The modulated carrier $v_c(t)$:

Digital signal	Modulated carrier
00	$A\cos(\omega_c t + 45°)$
01	$A\cos(\omega_c t + 135°)$
11	$A\cos(\omega_c t - 135°)$
10	$A\cos(\omega_c t - 45°)$

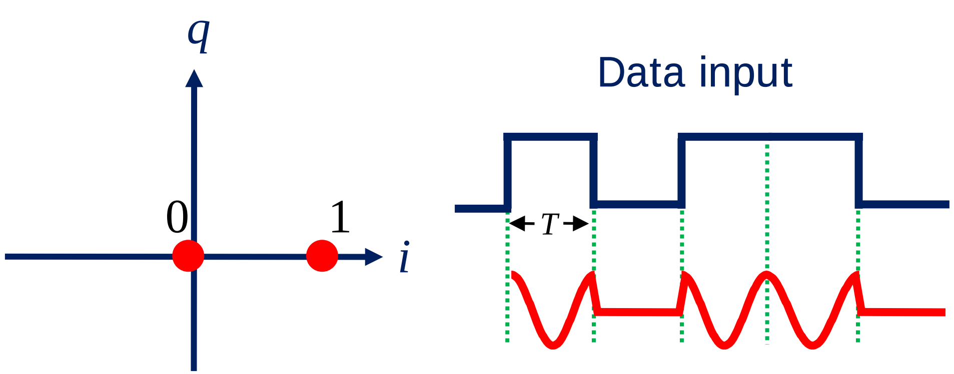


Modulation: ASK

ASK:

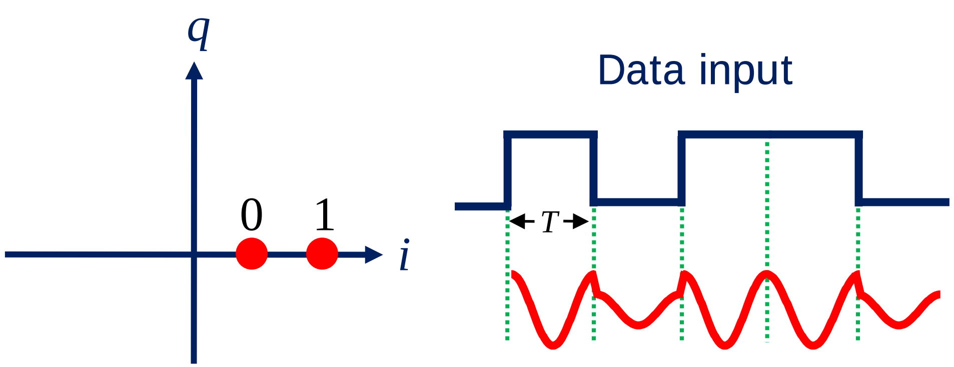
- Usually, we don't use this method in microwave communication because of the significant variation in received signal strength and the associated difficulty of fixing a decision threshold
- The modulated carrier $v_c(t)$:

Digital signal	Modulated carrier
0	$0\cdot\cos(\omega_c t + 0°)$
1	$A\cdot\cos(\omega_c t + 0°)$



- A bad method to define states:

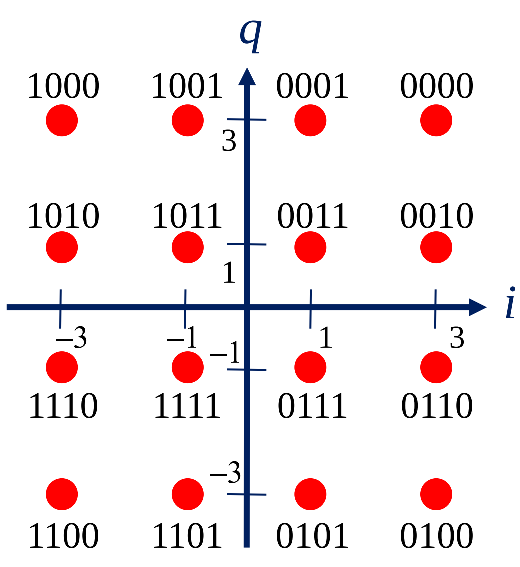
Digital signal	Modulated carrier
0	$A/2\cdot\cos(\omega_c t + 0°)$
1	$A\cdot\cos(\omega_c t + 0°)$



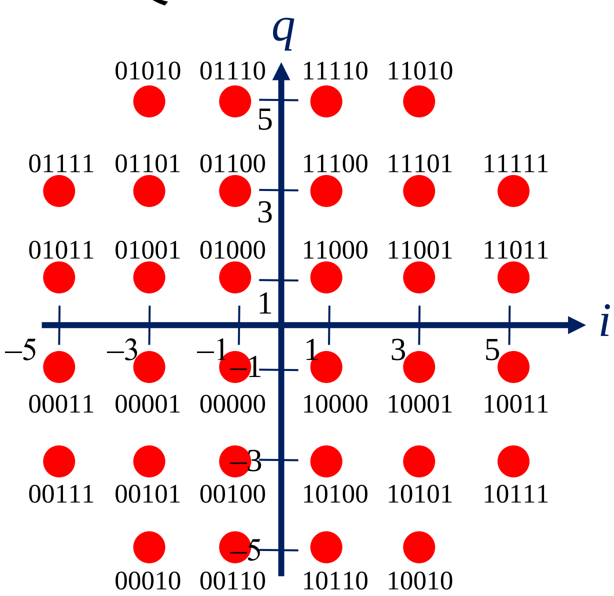
Modulation: QAM

QAM:

- Both the amplitude and phase are used for mapping purpose
- M-QAM is a carrier keying mode largely used in high capacity digital radio communication systems
- This mode has higher frequency spectrum utilization and when the modulation is of more than binary, the signal vector set is reasonably allocated and the mode can be easily carried out
- The most popular constellations are the QAM and the PSK

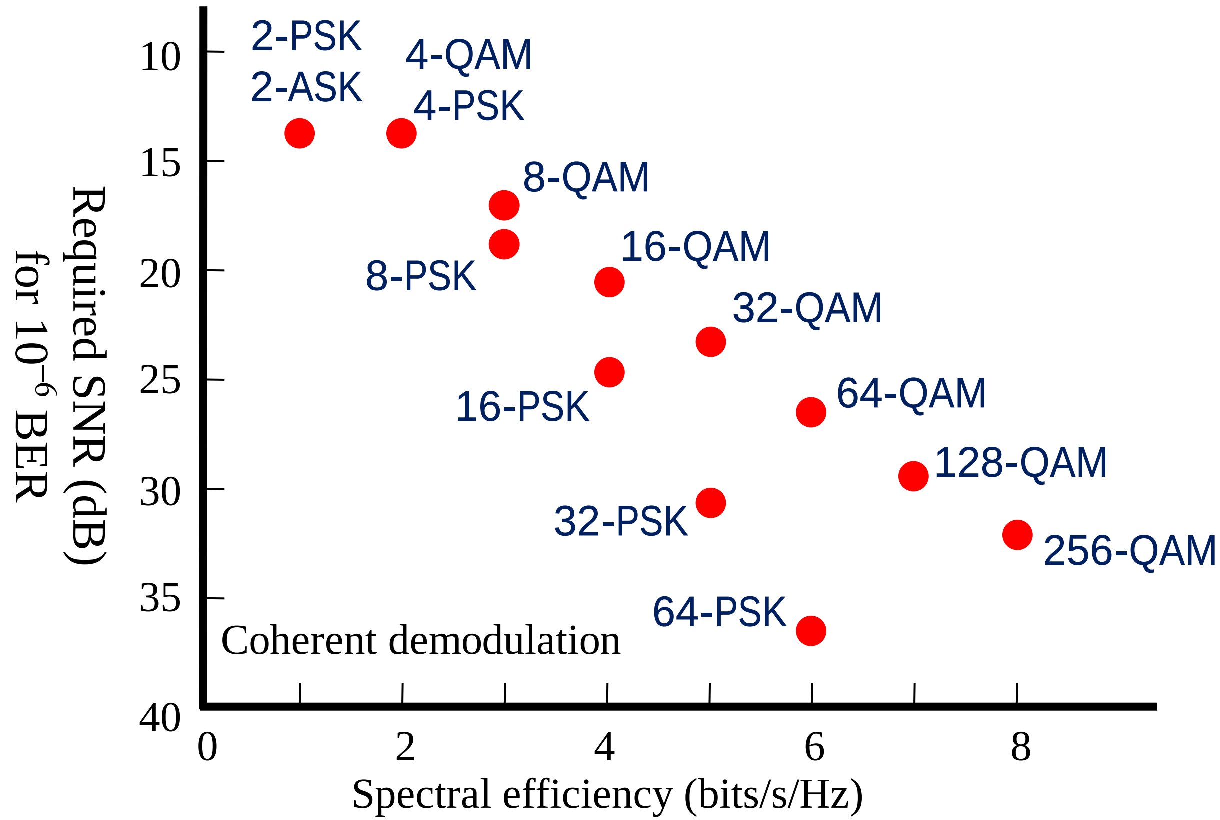


16-QAM



32-QAM

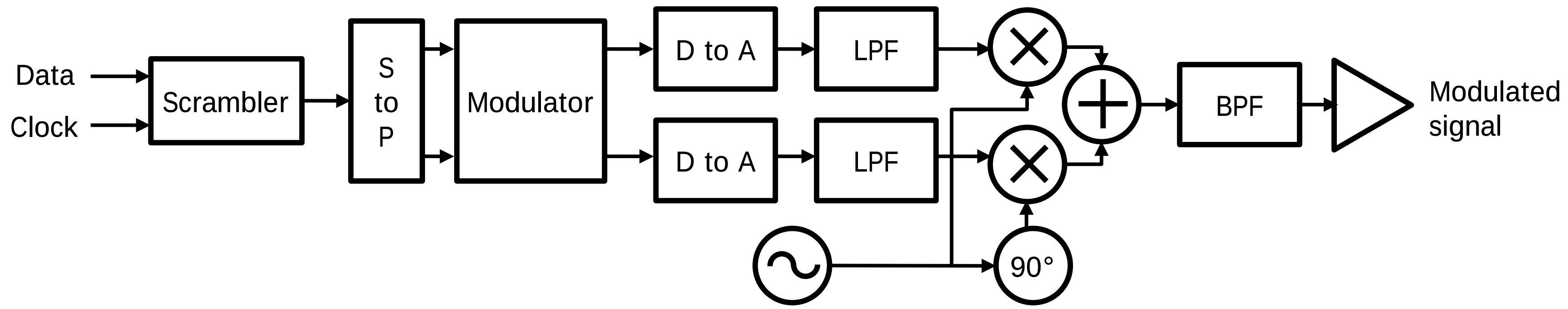
Modulation: How to Select One from Them?



- The higher levels of modulation give better bandwidth efficiency but would require higher values of SNR to achieve a given BER
- The lower the SNR, the higher the BER and the more difficult it is to reconstruct the desired data information

Modulation: How to Implement Them?

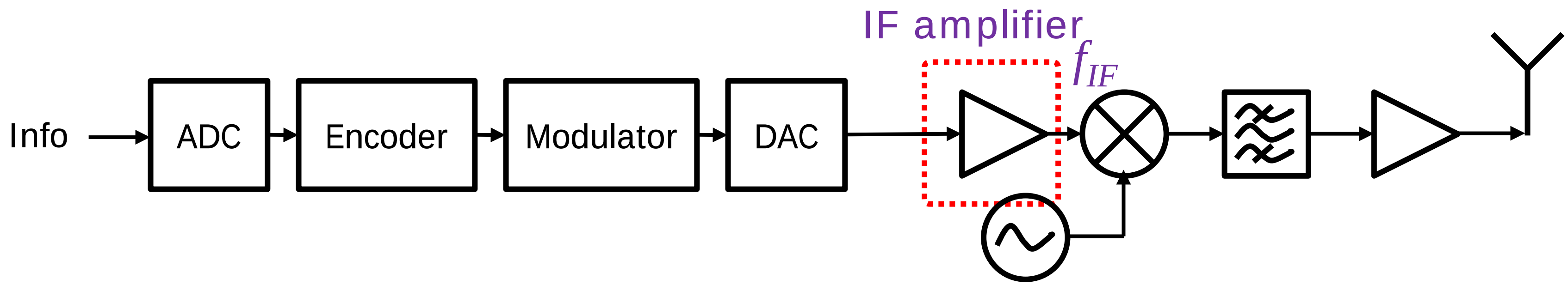
- Example: a typical QAM transmitter



- These circuits are implemented in relatively lower frequencies
- The design of circuitry is performed by *Circuitry Theory* and *IC Design Approach*
- The frequency range of IF: several kHz to hundreds of MHz
- Why need IF? Why not convert to RF in the first place?

➡ In this frequency range, circuits and systems can be designed simply using lumped components without involving transmission-line theories

IF Amplifier



Objective:

- Enhancing the signal level because the modulator produces some insertion loss

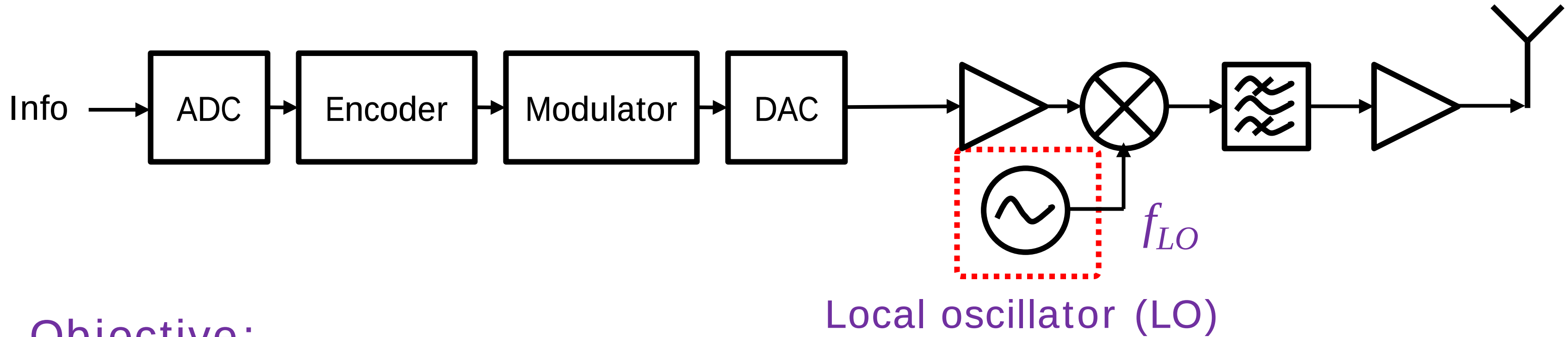
Characteristic:

- A three-terminal active device such as GaAs or Si field effect transistors (FETs), bipolar transistors, heterojunction bipolar transistors (HBTs), and high electron mobility transistors (HEMTs)

Specification:

- Power gain
- Noise figure
- Intercept points

Oscillator (1/2)



Objective:

- Generating a precise, controlled carrier frequency f_{LO}

Characteristic:

- A nonlinear circuit that converts DC power to an AC waveform
- An active component with DC bias, consisting of a transistor which generates a negative resistance under proper-biased conditions

Specification:

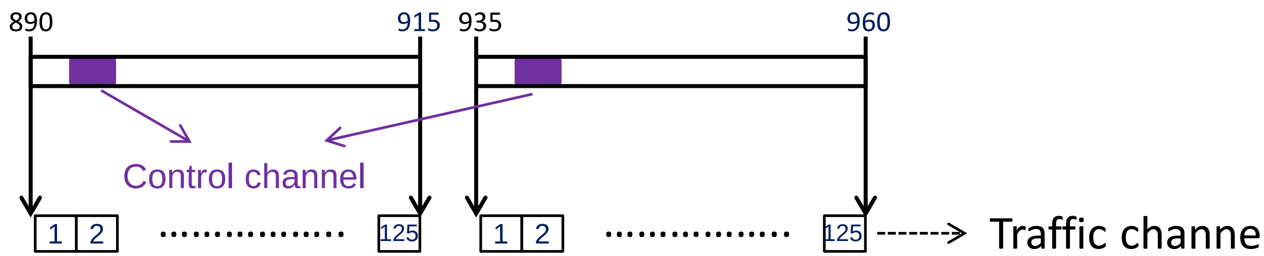
- Tuning range
- Frequency resolution
- Phase noise
- Frequency stability
- Power consumption

Oscillator (2/2)

Example: GSM900 (890-960 MHz)

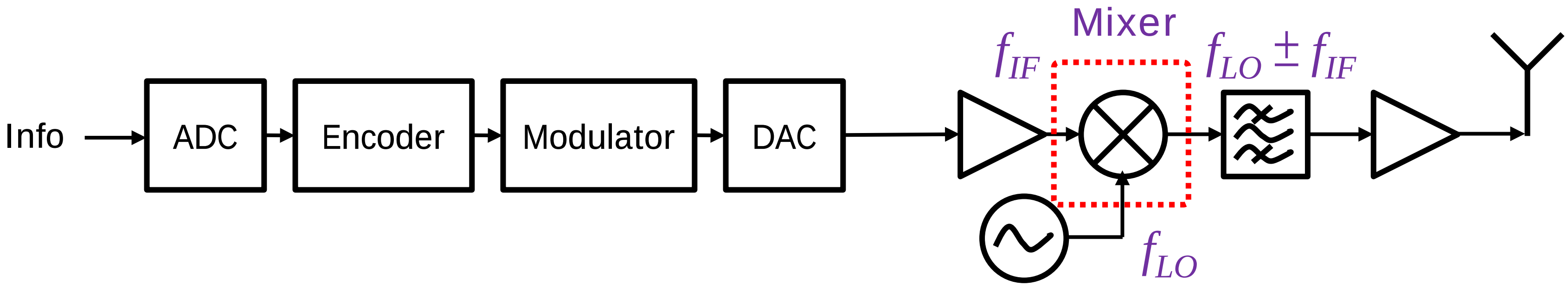
Channel number	Uplink (MHz)	Downlink (MHz)
1	890.2	935.2
2	890.4	935.4
3	890.6	935.5
4	890.8	935.6
…		
124	914.8	959.8
125	915.0	960.0

200 KHz



- Distinct users occupy different frequencies
- LO must be tunable over a set of frequency range

Mixer



Objective:

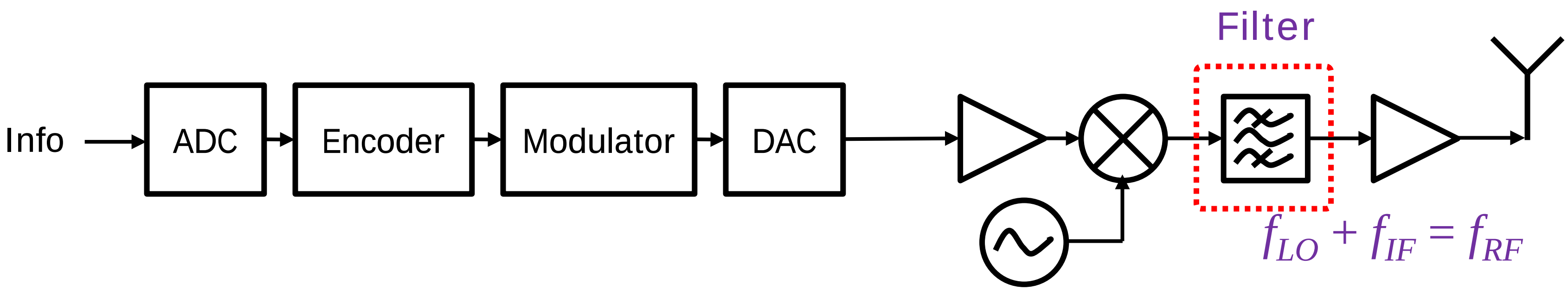
- Up-converting the intermediate signal to RF

Characteristic:

- A three-port active device that uses a nonlinear element (diodes and transistors) or time-varying element (switches) to achieve frequency conversion
- The output of the idealized mixer:

$$v_{RF}(t) = K \cdot v_{LO}(t) v_{IF}(t) = K \cdot \cos(2\pi f_{LO} t)\cos(2\pi f_{IF} t)$$
$$= \frac{K}{2}\left[\cos 2\pi (f_{LO} + f_{IF})t + \cos 2\pi (f_{LO} - f_{IF})t\right]$$

RF Filter (1/2)



Objective:

- Ensuring only the desired frequency component is left

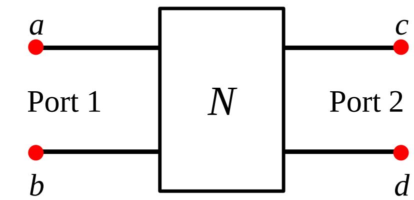
Characteristic:

- The frequency conversion results from the nonlinearity of transistor or diode
- A nonlinear component can generate a wide variety of harmonics and other products of f_{LO} and f_{IF}, including $f_{LO} + f_{IF}$ and $f_{LO} - f_{IF}$
- We need an RF filter and make it select only $f_{LO} + f_{IF} = f_{RF}$

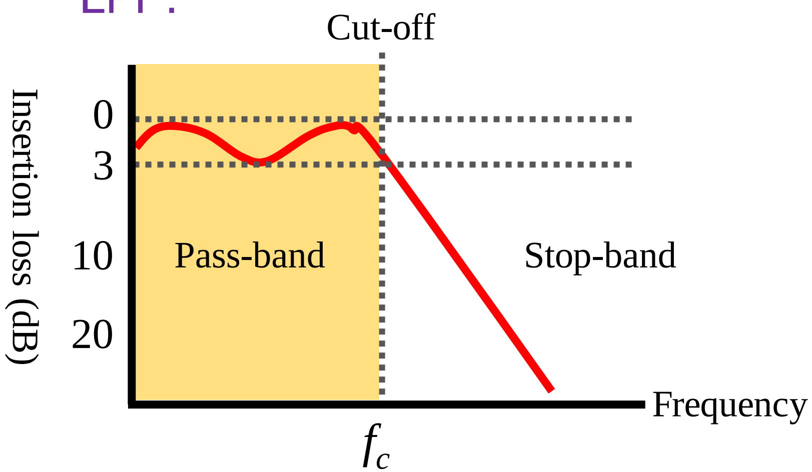
Specification:

- Insertion loss
- Cut-off frequency
- Group delay
- Out-of-band attenuation rate

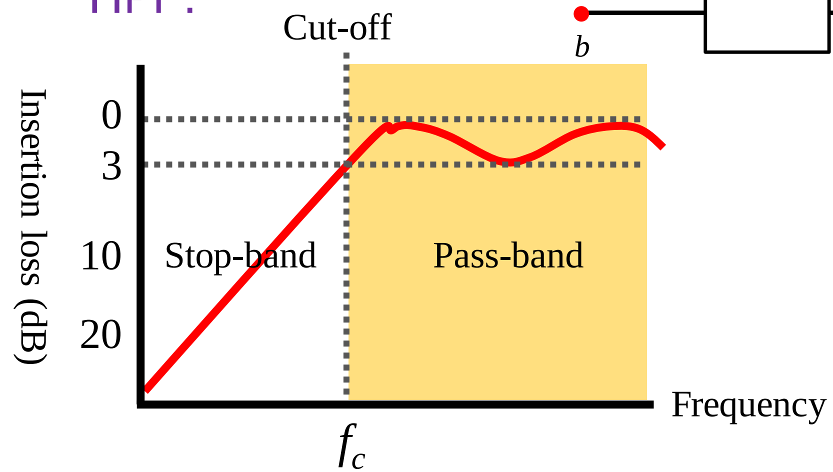
RF Filter (2/2)



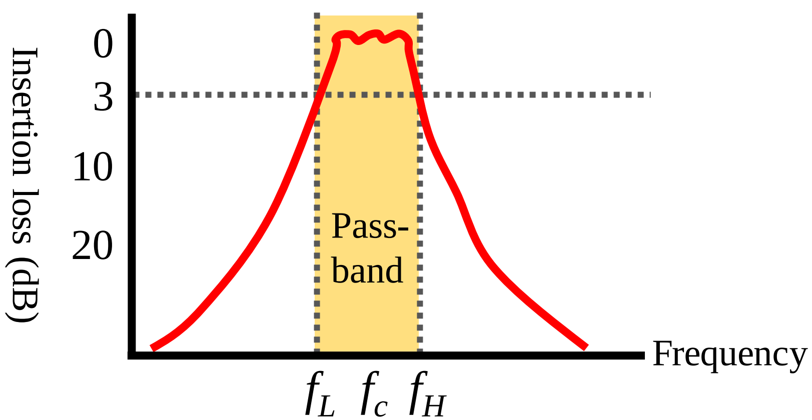
LPF:



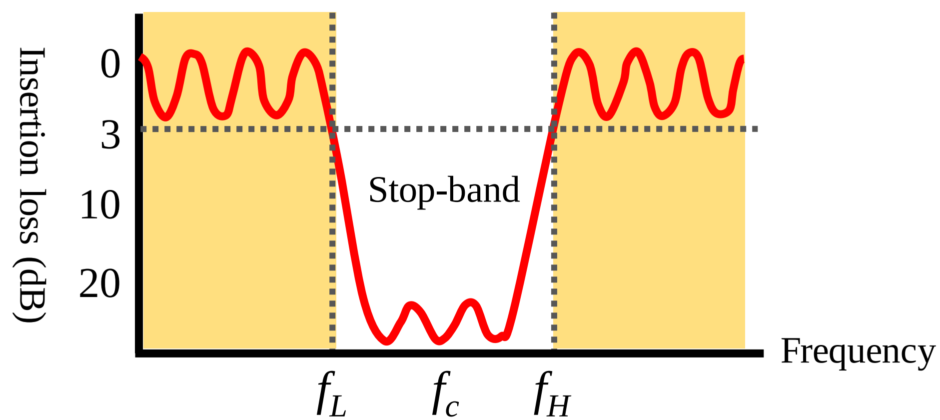
HPF:



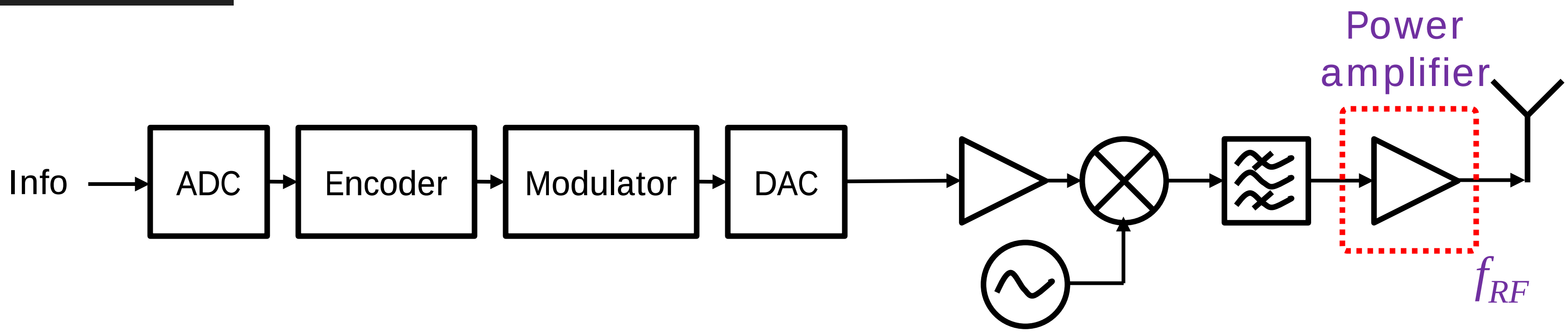
BPF:



BSF:



Power Amplifier



Objective:

- Increasing the output power of the transmitter

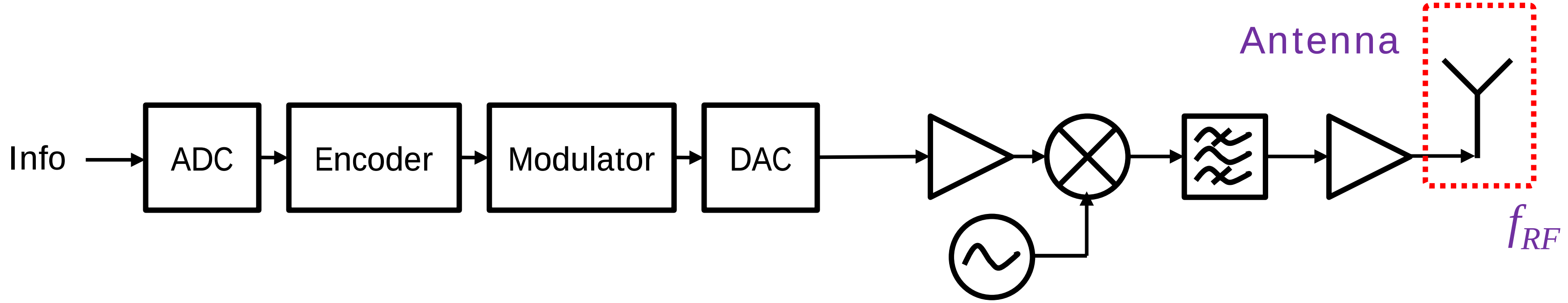
Characteristic:

- Current Silicon-based devices are commonly used up to 2 GHz
- Above 4 GHz, GaAs devices are preferred for better performance
- Microwave transistor amplifiers can be easily integrated in IC with mixers, oscillators, switches, and related components

Specification:

- Power added efficiency
- Compressed gain (1-dB compression point)

TX Antenna



Objective:

- Converting the modulated carrier signal from the transmitter to a propagating EM plane wave

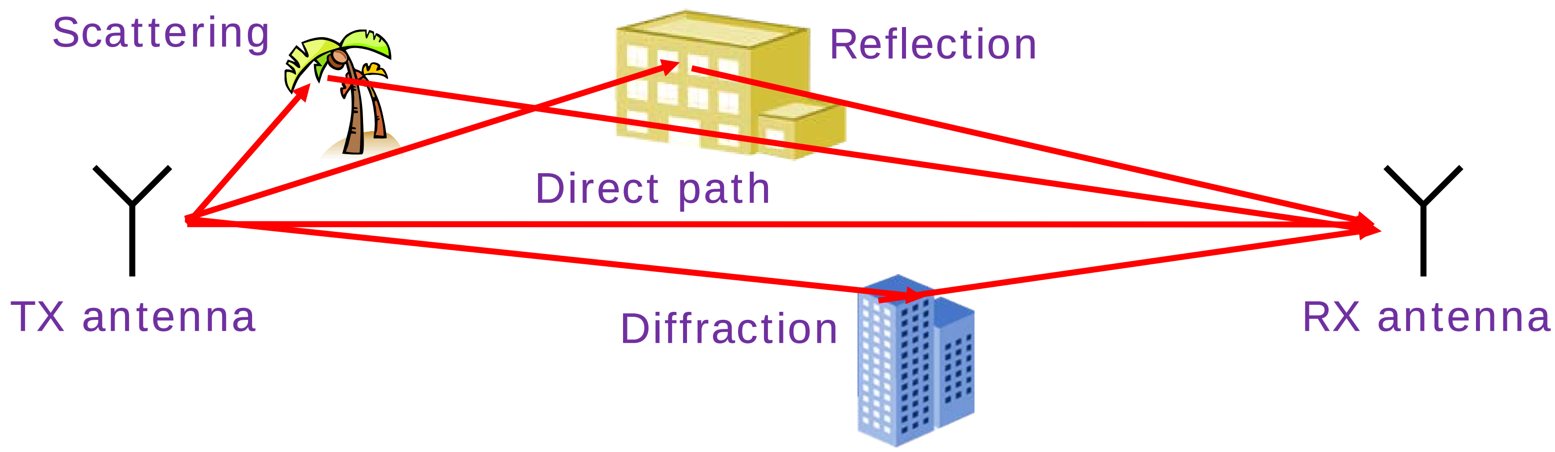
Characteristic:

- Point-to-point communication: a high directivity pattern is required
- Multipoint-to-multipoint communication: omnidirectional patterns are preferred
- Broadcast: an omnidirectional pattern is required

Specification:

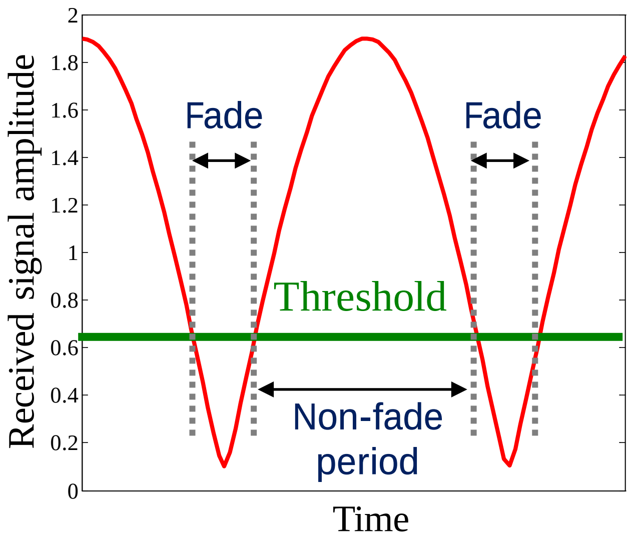
- Radiation pattern
- Radiation efficiency
- Peak gain
- Return loss
- Bandwidth
- Size

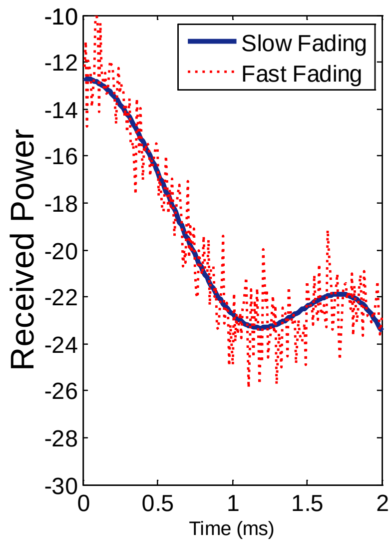
Wireless Propagation



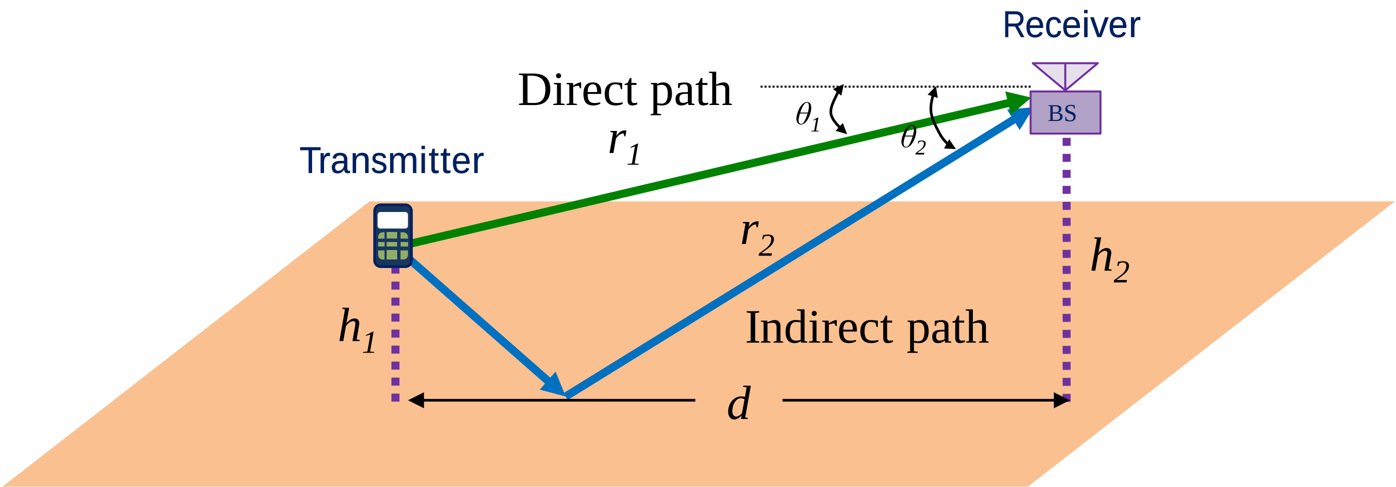
The most important issues of wireless propagation:

- Multipath effects: fading, intersymbol interference, path loss, etc.
- Fading: The amplitudes of the received signal fluctuate severely





An Example of Fading (1/4)



- Two paths exist in our formulation:
  - Direct path: length r_1

$$r_1 = \sqrt{d^2 + (h_2 - h_1)^2} \approx d + \frac{(h_2 - h_1)^2}{2d}$$

  - Indirect path due to the reflection: length r_2

$$r_2 = \sqrt{d^2 + (h_2 + h_1)^2} \approx d + \frac{(h_2 + h_1)^2}{2d}$$

An Example of Fading (2/4)

- Assuming the reflection coefficient of the ground is $R = |R|e^{j\varphi}$
- The total received field **in phasor domain**: (phasor)

$$E_r = \frac{E_0 e^{-jkr_1}}{r_1} + \frac{E_0 R e^{-jkr_2}}{r_2}$$

- Assuming $r_1 \approx r_2$. The total field can be written as

$$E_r = \frac{E_0 e^{-jkr_1}}{r_1} + \frac{E_0 R e^{-jkr_2}}{r_2} = \frac{E_0 e^{-jkr_1}}{r_1}\left[1 + Re^{-jk(r_2 - r_1)}\right]$$

$$= \frac{E_0 e^{-jkr_1}}{r_1}\left[1 + |R| e^{-j\left(k\frac{2h_1h_2}{d} - \phi\right)}\right]$$

$$= \frac{E_0 e^{-jkr_1}}{r_1}\left[1 + |R|\left(\cos\left(k\frac{2h_1h_2}{d} - \phi\right) - j\sin\left(k\frac{2h_1h_2}{d} - \phi\right)\right)\right]$$

An Example of Fading (3/4)

- The received signal in time domain:

$$e_r(t) = \mathrm{Re}\left\{E_r e^{j\omega t}\right\}$$

$$= \underbrace{\frac{E_0}{r_1}\left(1 + |R|\cos\left(k\frac{2h_1h_2}{d} - \phi\right)\right)}_{X}\cos(\omega t - kr_1) + \underbrace{\frac{E_0}{r_1}|R|\sin\left(k\frac{2h_1h_2}{d} - \phi\right)}_{Y}\sin(\omega t - kr_1)$$

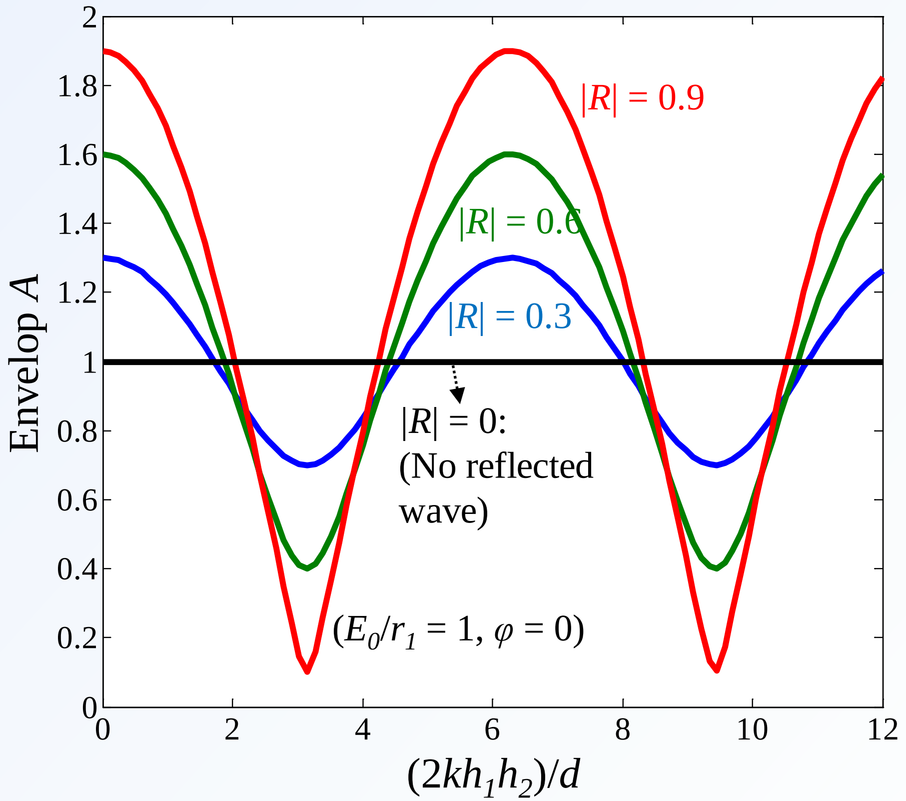
$$= A\cos(\omega t - kr_1 + \Psi)$$

- Note that if $R = 0$, the formulation reverts to the direct path solution
- This formulation depicts that the signal envelop and phase change are the function of the movement of the MS (d, h_1)
  - The envelop of the received signal (A): $A = \sqrt{X^2 + Y^2}$
  - The phase of the received signal (Ψ): $\psi = \tan^{-1}\left(\frac{Y}{X}\right)$

An Example of Fading (4/4)

The envelop of the received signal

$$A=\frac{E_0}{r_1}\sqrt{\left(1+|R|\cos\left(k\frac{2h_1h_2}{d}-\phi\right)\right)^2+\left(|R|\sin\left(k\frac{2h_1h_2}{d}-\phi\right)\right)^2}$$



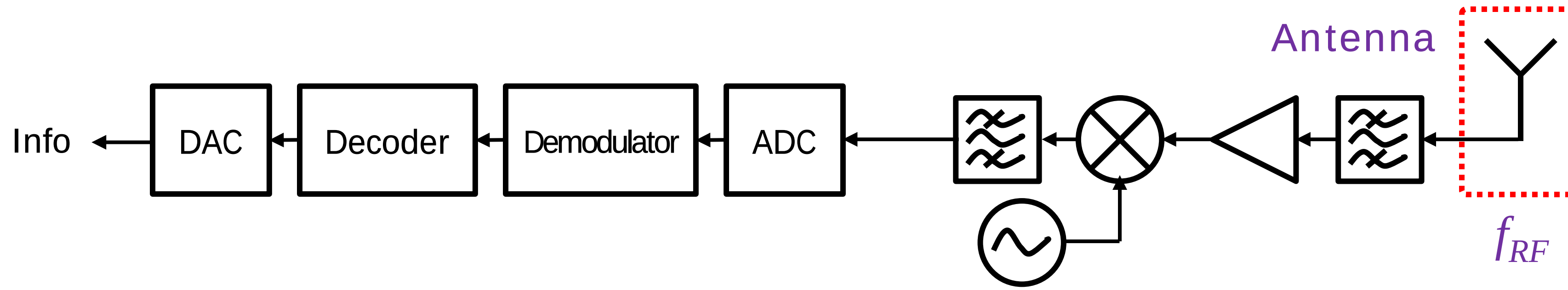
Fading:

- The amplitude of the total received signal can fluctuate between zero and up to twice the amplitude of the direct path component
- It causes periodic attenuation of received signals

This model is far from reality:

- In typical channel scenarios, the distribution of large numbers of reflecting, diffracting, refracting, and scattering objects becomes random
- The fading becomes more severe

RX Antenna



Objective:

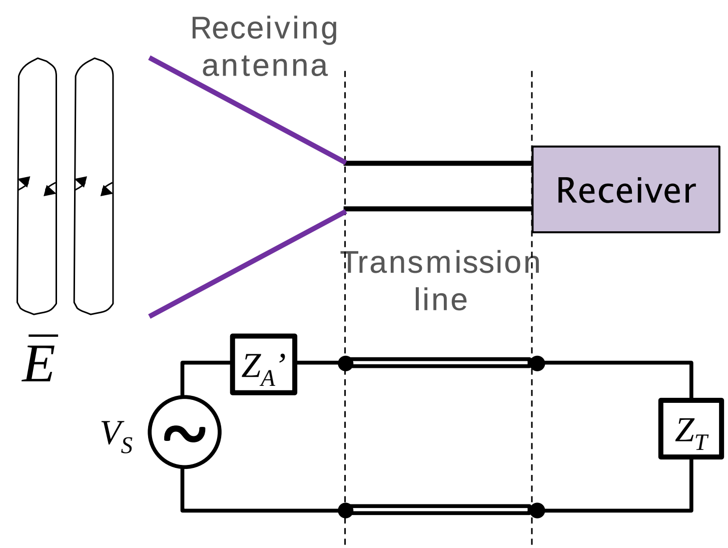
- The antenna receives EM waves which come from multipath propagation over a very broad frequency range

Characteristic:

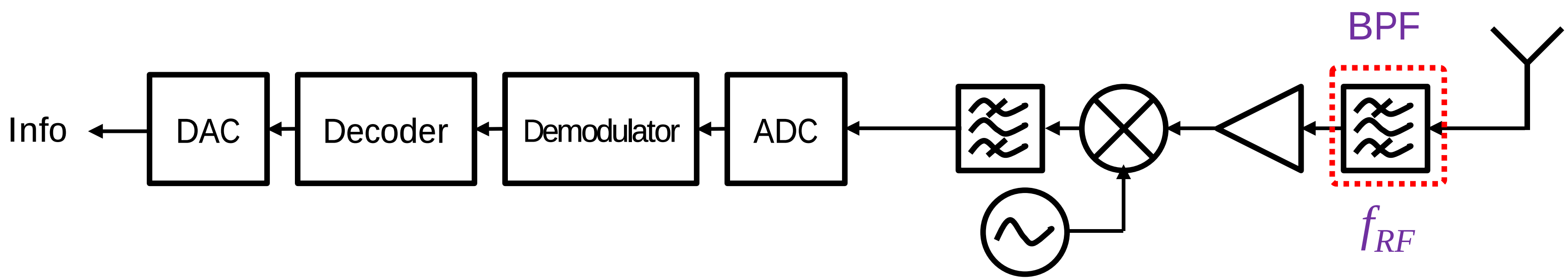
- Voltage source in the equivalent circuit:

$$V_S = \int_L \overline{E} \cdot d\overline{l} \qquad (L\text{: antenna length})$$

- The larger the antenna size, the better the receiving capability is



Band-Pass Filter



Objective:

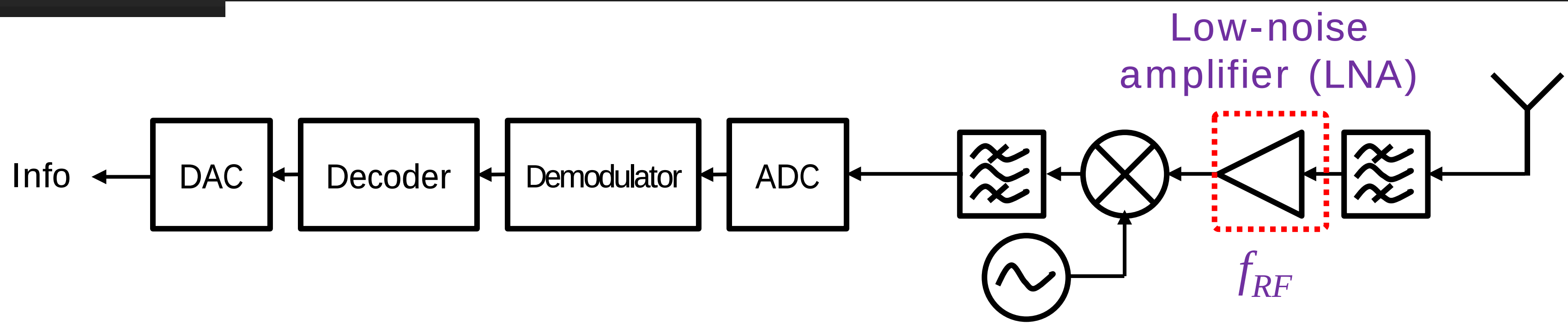
- An input BPF rejects interfering signals at undesired frequencies

Characteristic:

- BPF removes the unwanted signals and noise picked up by the RF signal from the channel medium
- Since an antenna already has frequency-selective characteristics, why do we still need a BPF to reject it?

1. The antenna enables various resonant modes to transfer into RX
2. Placing a BPF before the LNA reduces the possibility that a sensitive amplifier will be overloaded by interfering signals of high power

Low-Noise Amplifier



Objective:

- Magnifying the signal received, which is usually weak and noisy after traveling a long distance in the channel

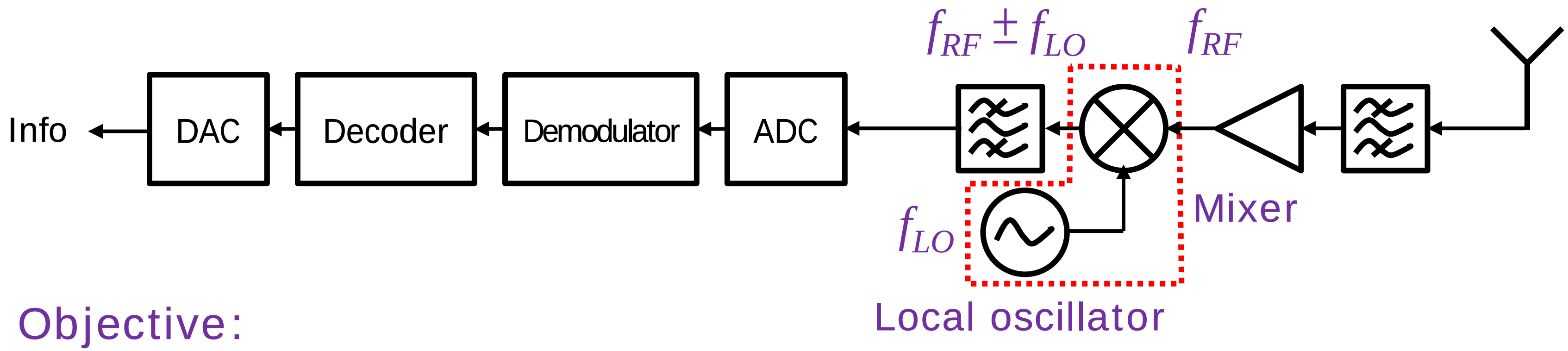
Characteristic:

- Greatly reducing the noise power added to the received signal
- The noise power in a receiver is affected more by the first few components than by later components
- If the received signal has enough power, the LNA can be omitted

Specification:

- Noise figure
- Maximum gain

Mixer and Oscillator



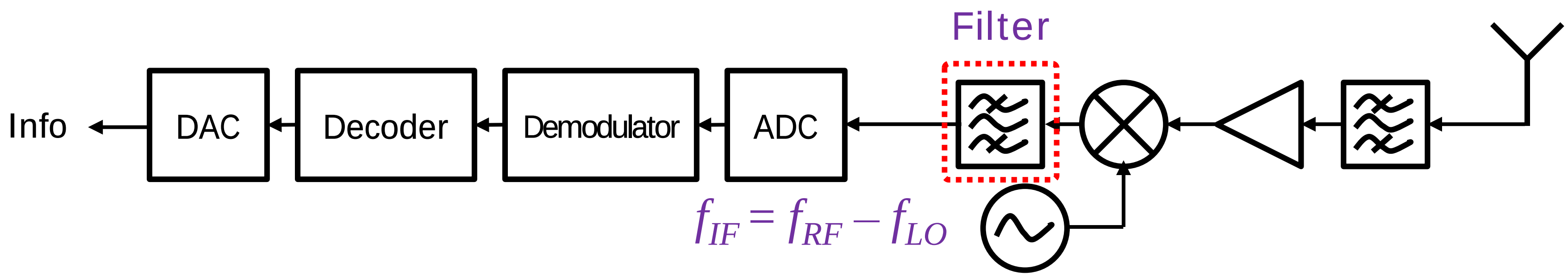
Objective:

- A local carrier is used to down-convert the RF signal back to IF so that it can be processed by the baseband module

Characteristic:

- In practice, the RF and LO frequencies are relatively close together, so the sum frequency is approximately twice the RF frequency, while the difference is much smaller than f_{RF}
- Usually, we cascade multiple stages to achieve better performance
- If we don't use a LNA in a receiver, noise and loss characteristics of the mixer will dominate the performance of the receiver
- LO-to-RF isolation of the mixers: The power of LO leaks backward and re-radiates from the receiving antenna

IF Filter



Objective:

- Removing any undesired harmonic and spurious products resulting from the mixing process

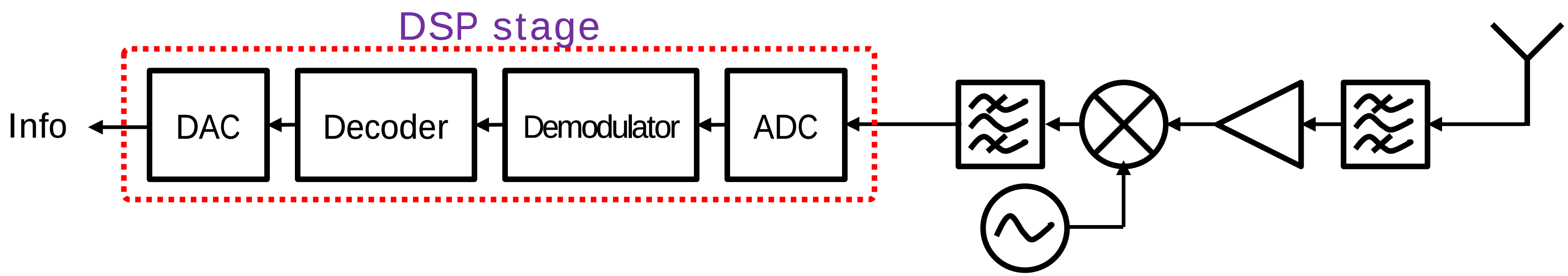
Characteristic:

- f_{IF} is chosen to be much lower than f_{LO} (typically less than 100 MHz)
- In a realistic mixer many more products of f_{RF} and f_{LO} will be generated due to the more involved nonlinearity of the diode or transistor

Summary of the RF end:

- The RF front ends are required to be low loss, low cost, light weight, high performance, power efficient, and small in size
- All the components can be integrated in an IC except for the antenna

Baseband and IF Module



Objective:

- Demodulator: Retrieving the message from the IF signal received
- Decoder: Retrieving the original message from the channel bits received

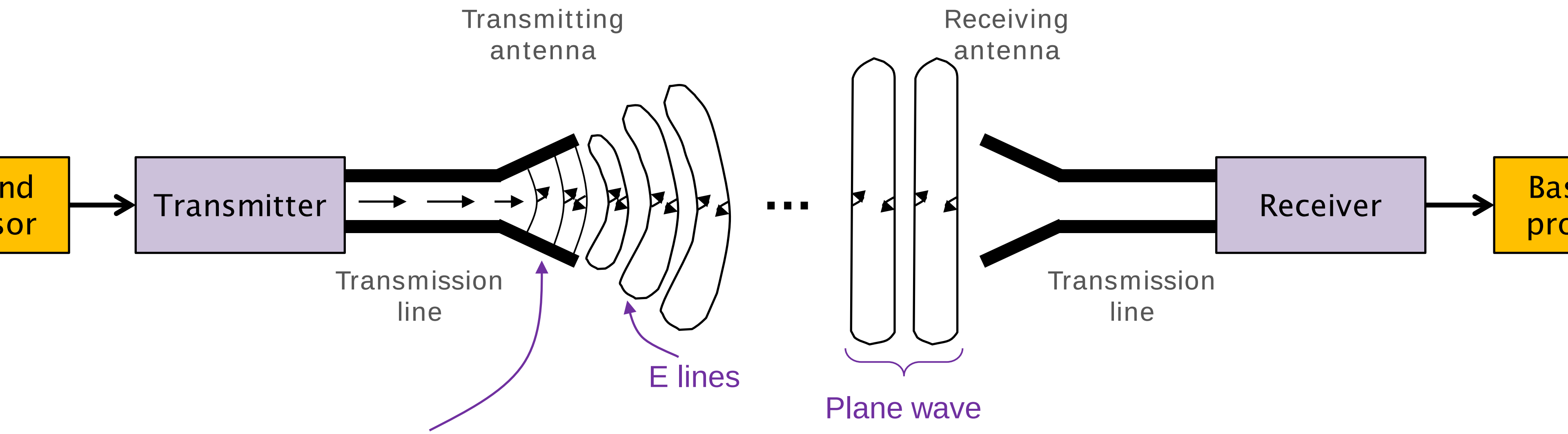
Characteristic:

- The received signal is demodulated by a coherent detector followed by a decision circuit
- Powerful digital-signal-processing chips allow *carrier acquisition* and *carrier synchronization* to be performed easily and inexpensively

Contents

1.2 How Does an Antenna Work?

Why Do We Need Antennas?



An antenna is a transitional structure between free space and transmission line

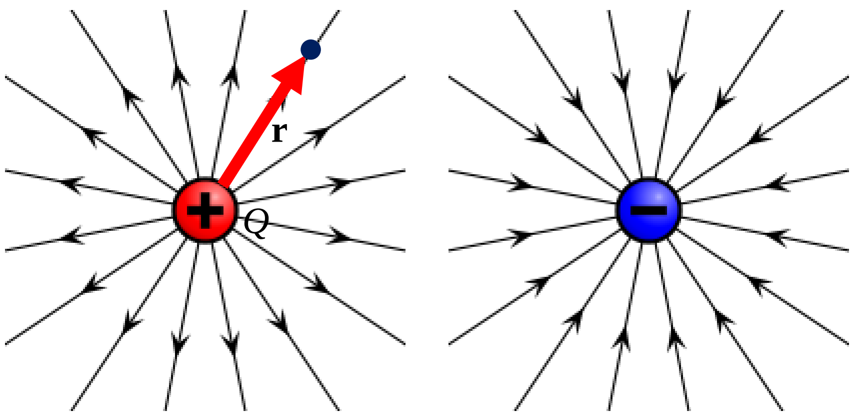
Operational principles of antennas:

1. Receiving input power that comes from a transmitter
   - Parameters: impedance matching, return loss, operational bandwidth
2. Radiating input power toward desired direction(s)
   - Parameters: patterns, directivity, beamwidth, radiation efficiency

Static Electric and Magnetic Fields

The scenarios that **DO NOT** produce radiation:

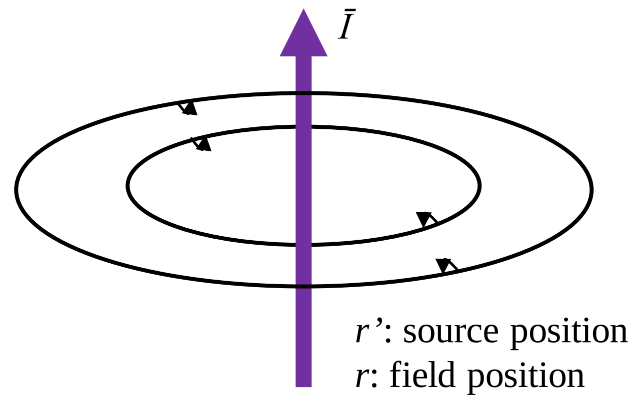
Charges are not moving



- Only producing static E-field

$$\mathbf{E}(r) = \frac{1}{4\pi\varepsilon_0}\frac{Q}{|r|^2}\hat{r}$$

Charges are moving with constant velocity

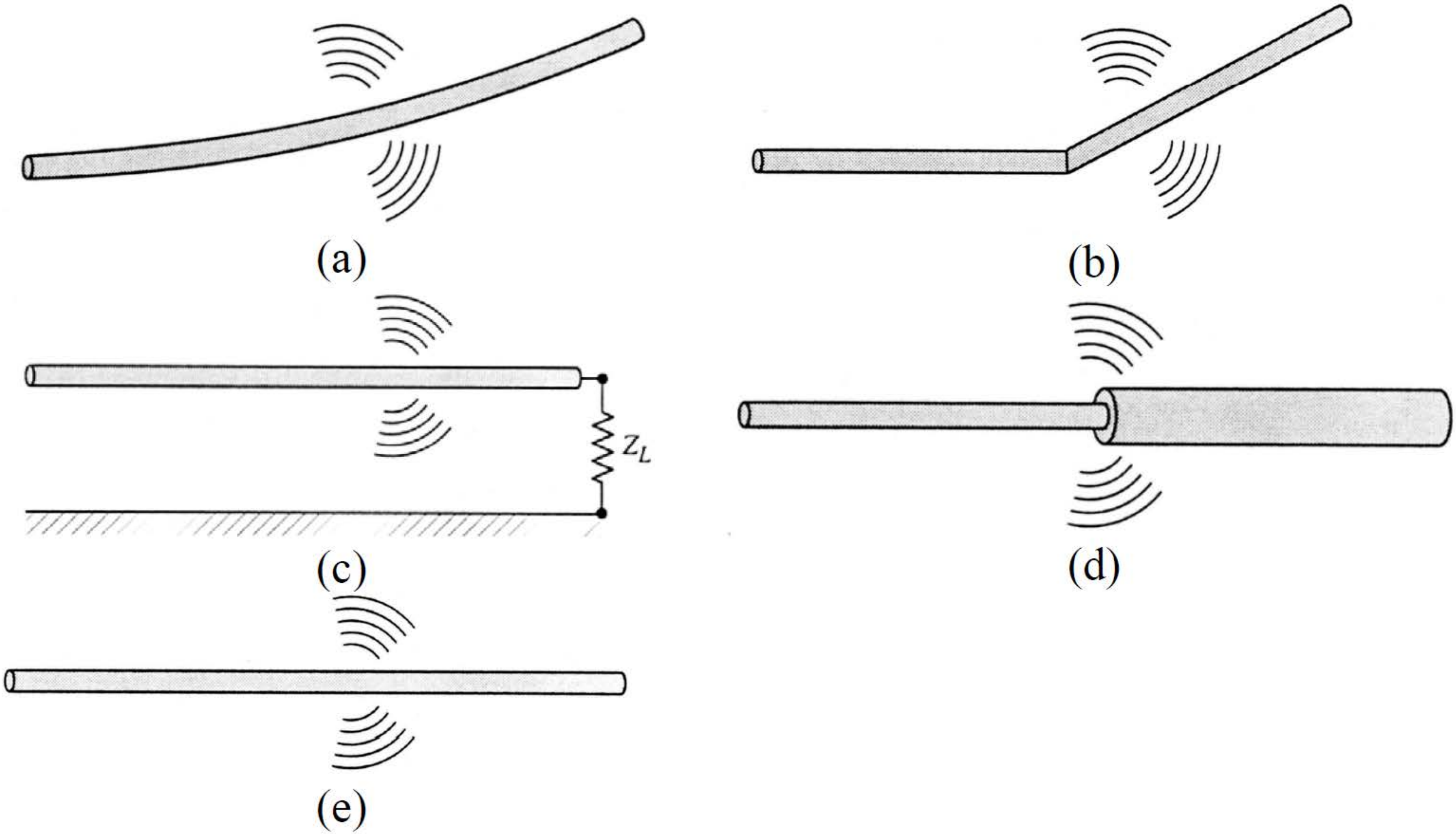


- Only producing static magnetic field

$$\mathbf{B}(r) = \frac{\mu_0 \bar{I}}{4\pi}\int \frac{r-r'}{|r-r'|^3}dl'$$

Wikipedia. [Online] Available: http://en.wikipedia.org/wiki/Electric_charge

Radiation from Simple Sources

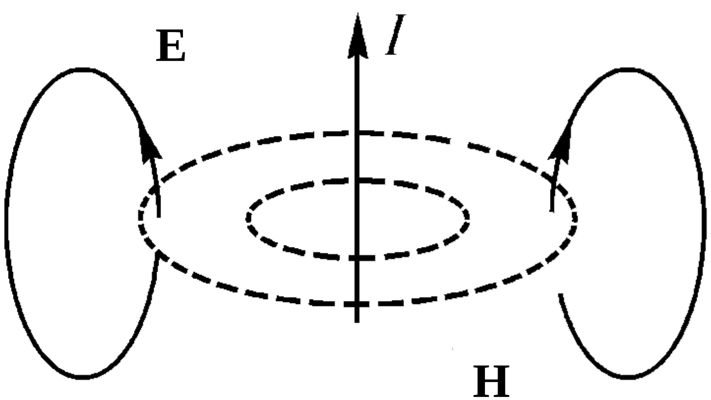


Dynamic Electromagnetic Wave

The scenarios that **DO** produce radiation:

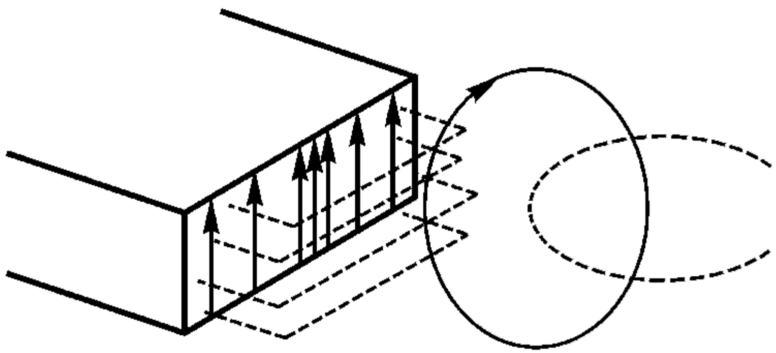
- Time-varying current
- Acceleration and deceleration of charge

Time-varying current



(Wire antenna)

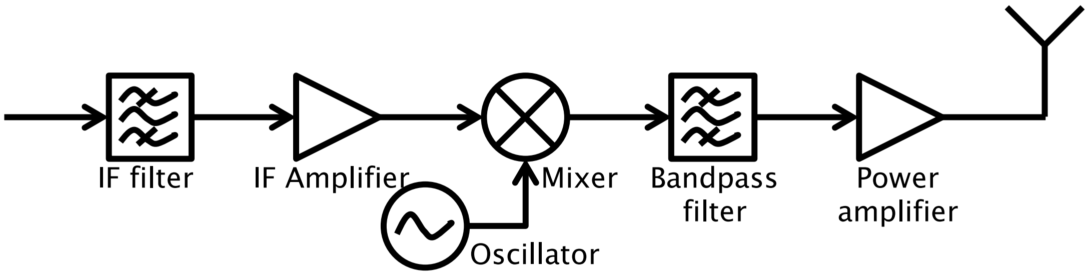
Truncated waveguide

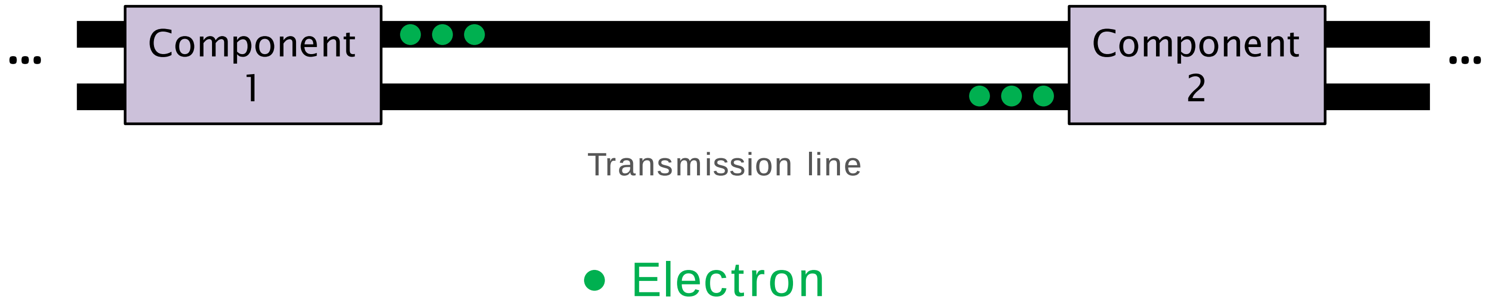


(Aperture antenna)

How Does an Antenna Work? (1/4)

Considering a transmission line which carries signals:

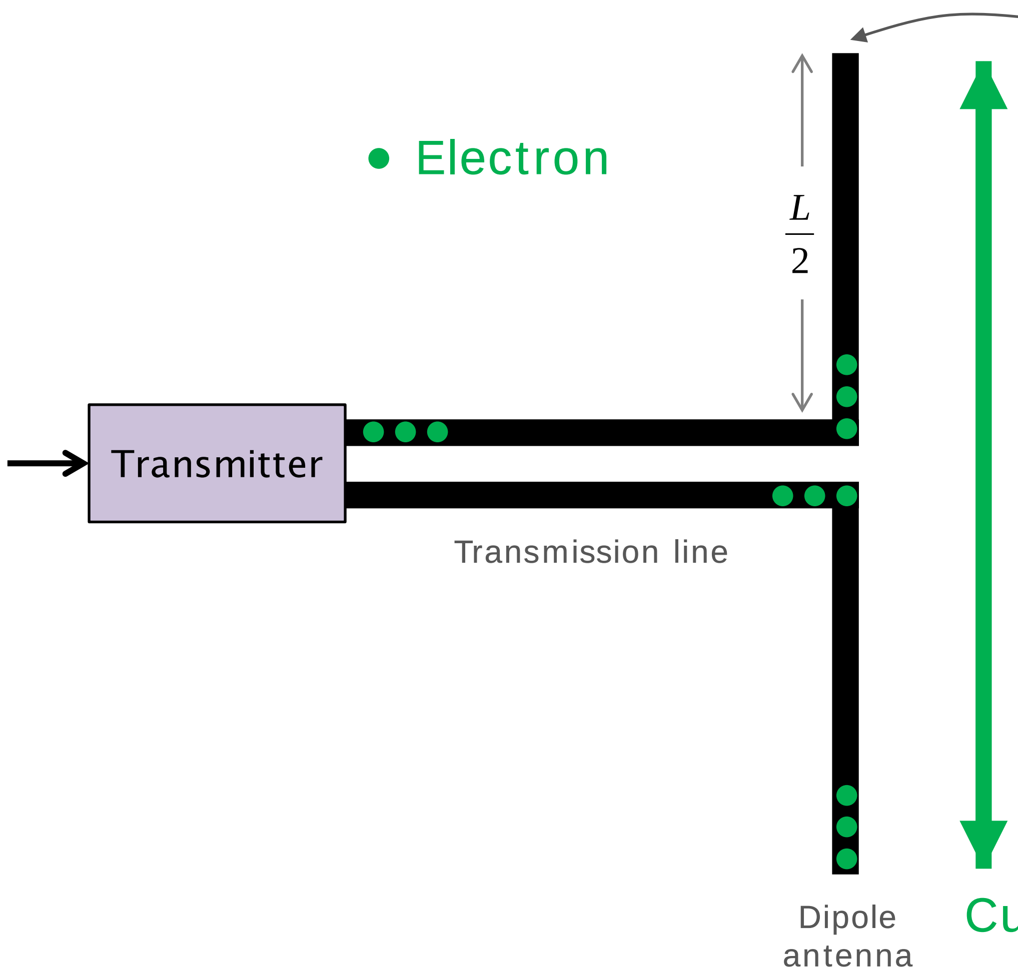




- The currents on two conductors have opposite directions
- The resultant magnetic fields cancel out

How Does an Antenna Work? (2/4)

Changing the scenario into a dipole antenna:



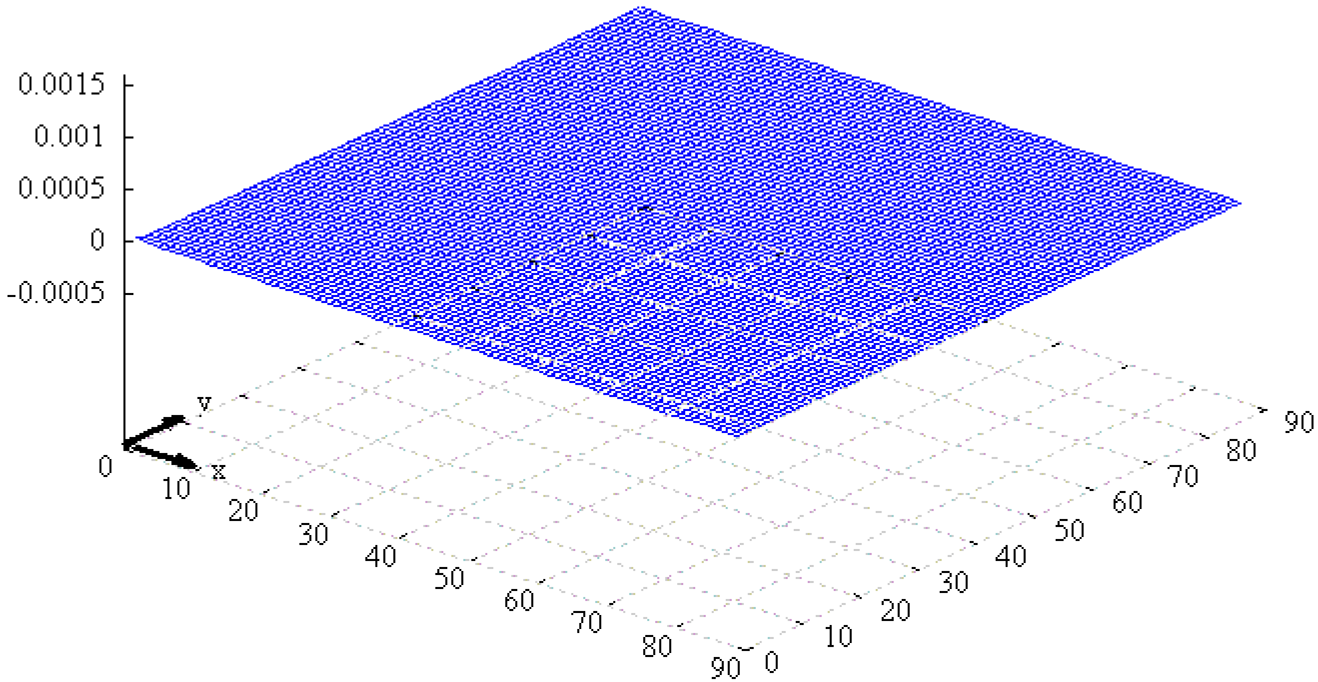
- **Transmission line:** The resultant fields cancel out
- **Antenna:** Radiated fields are produced at each end and along the remaining of the wire

The accelerating charges form an AC current

Current distribution $\mathbf{I}(\mathbf{r}', t)$

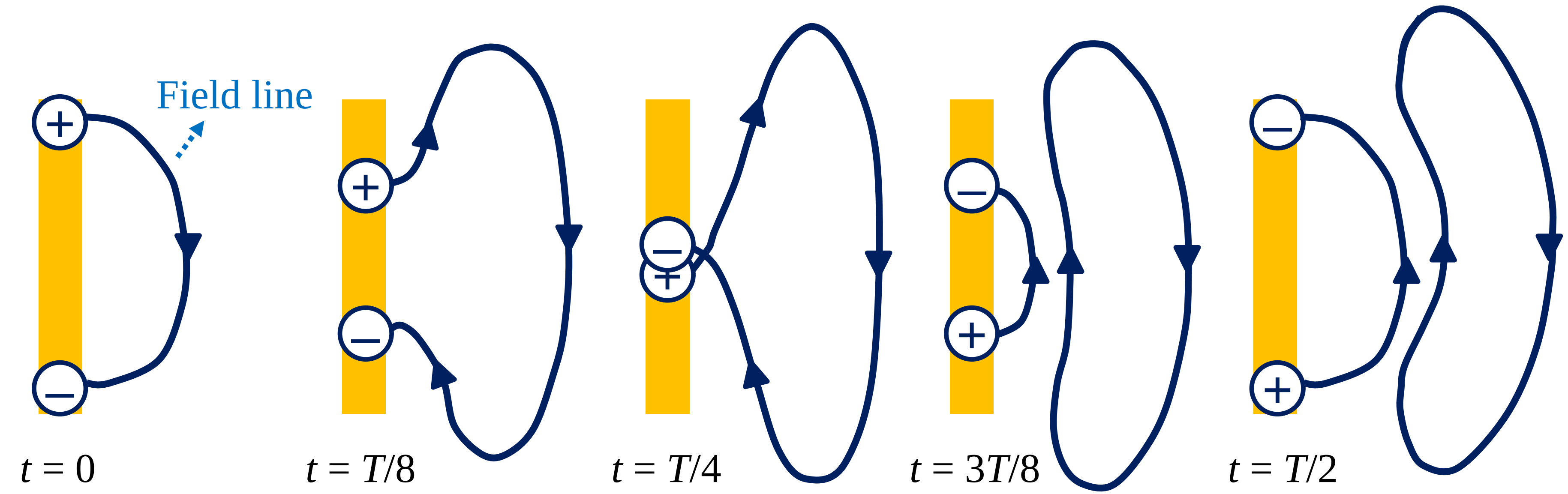
[On-line]. Available: http://reviseomatic.org/help/2-antenna/Antenna.php

Oscillation for Only One Time



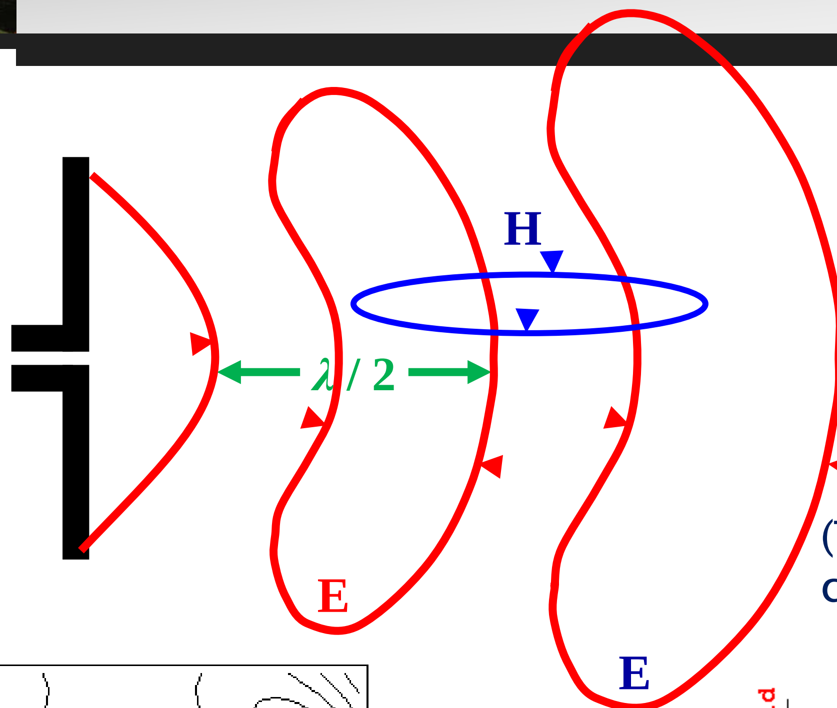
How Does an Antenna Work? (3/4)

A closer look to the radiation mechanism:

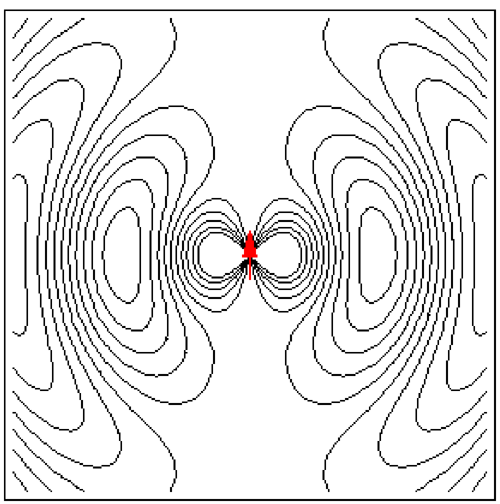


E filed line (wave front) at the ends of dipoles	Wave front moves out as charges go in	As charges pass the midpoint, the field line cuts loose	Wave fronts move out	Wave fronts move out

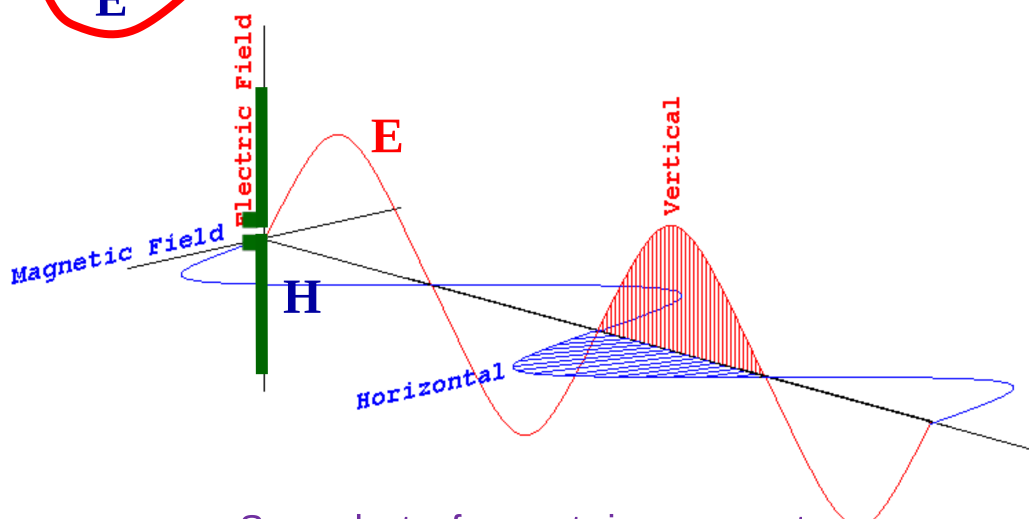
How Does an Antenna Work? (4/4)



(That’s why the radiated field is called “ELECTROMAGNETIC WAVE”)



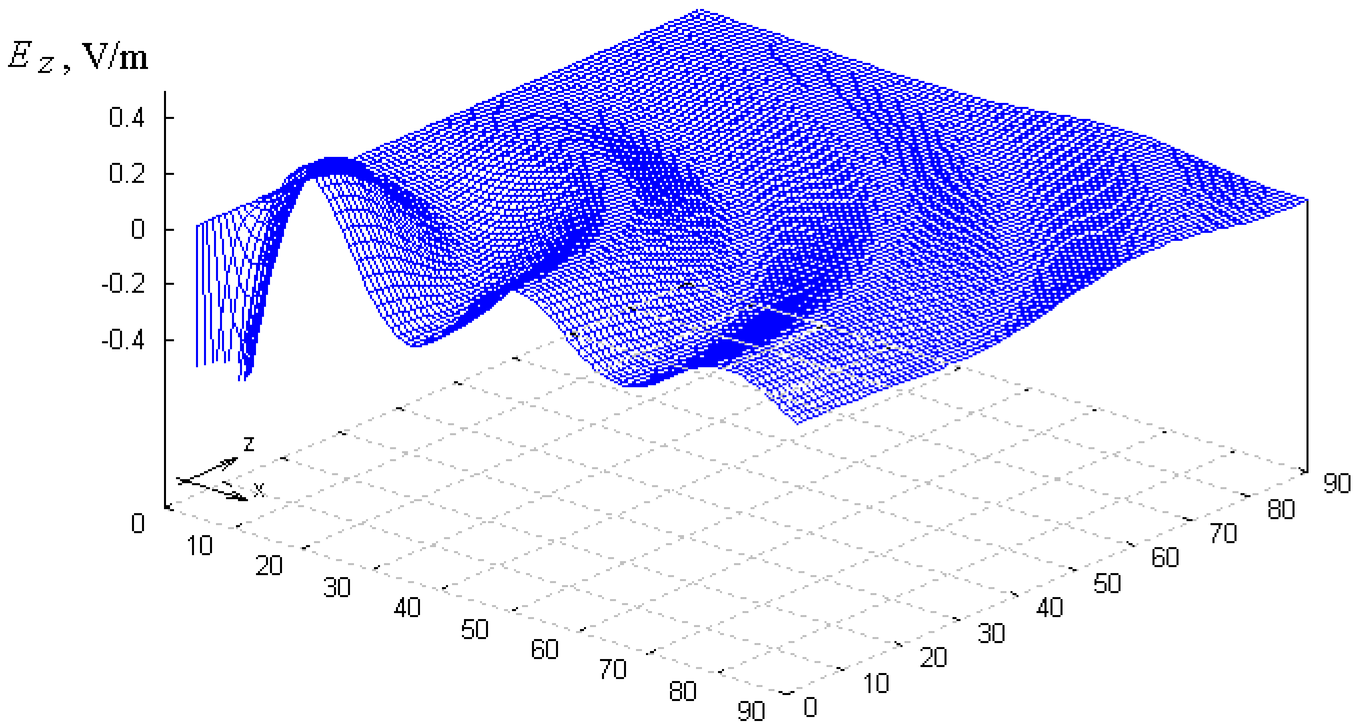
Radiation animation (E lines only)



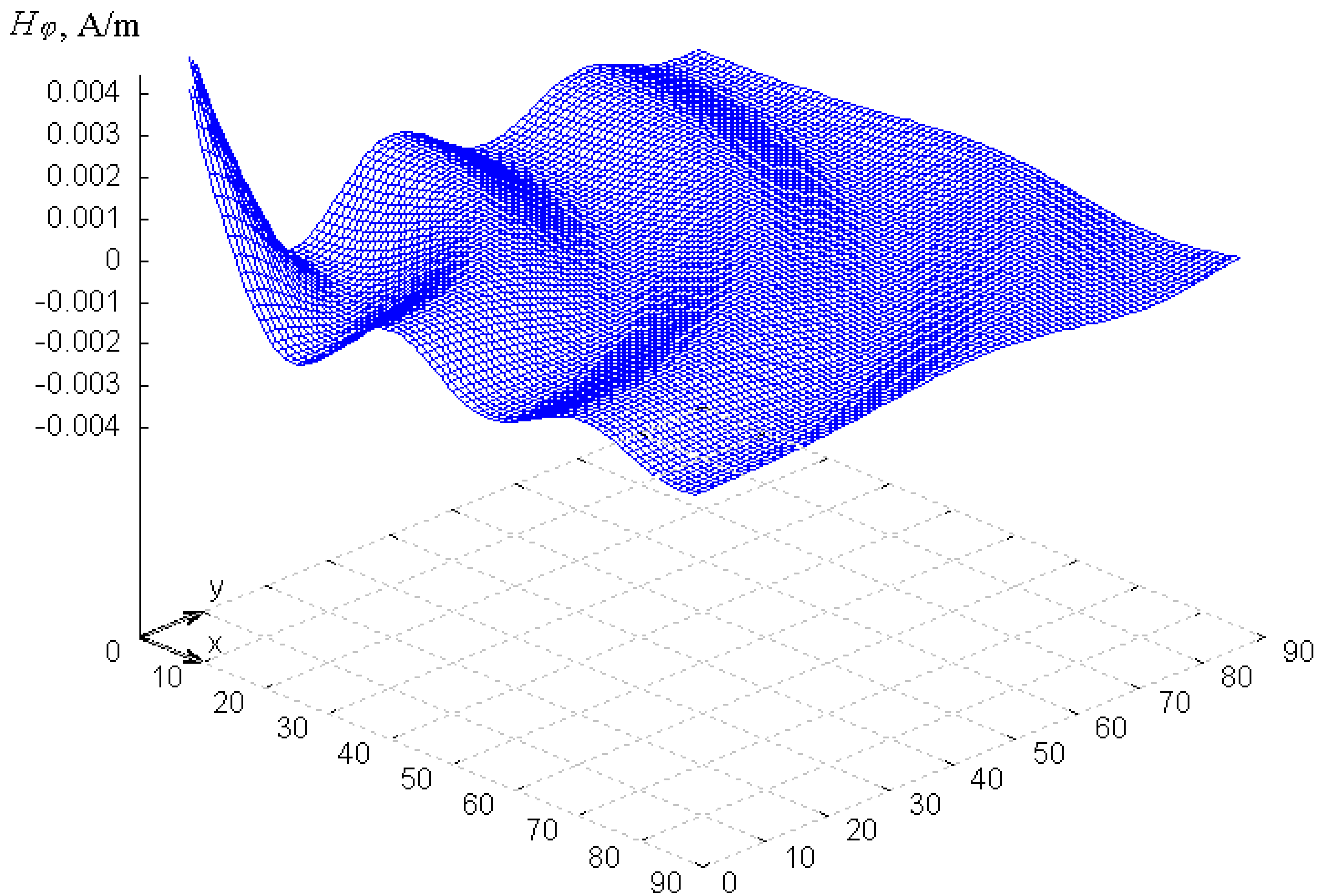
Snapshot of a certain moment

[On-line]. Available: http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/smalldipole/smalldipole.html
[On-line]. Available: http://reviseomatic.org/help/2-antenna/Antenna.php

Radiation of Short Dipole (E_z)

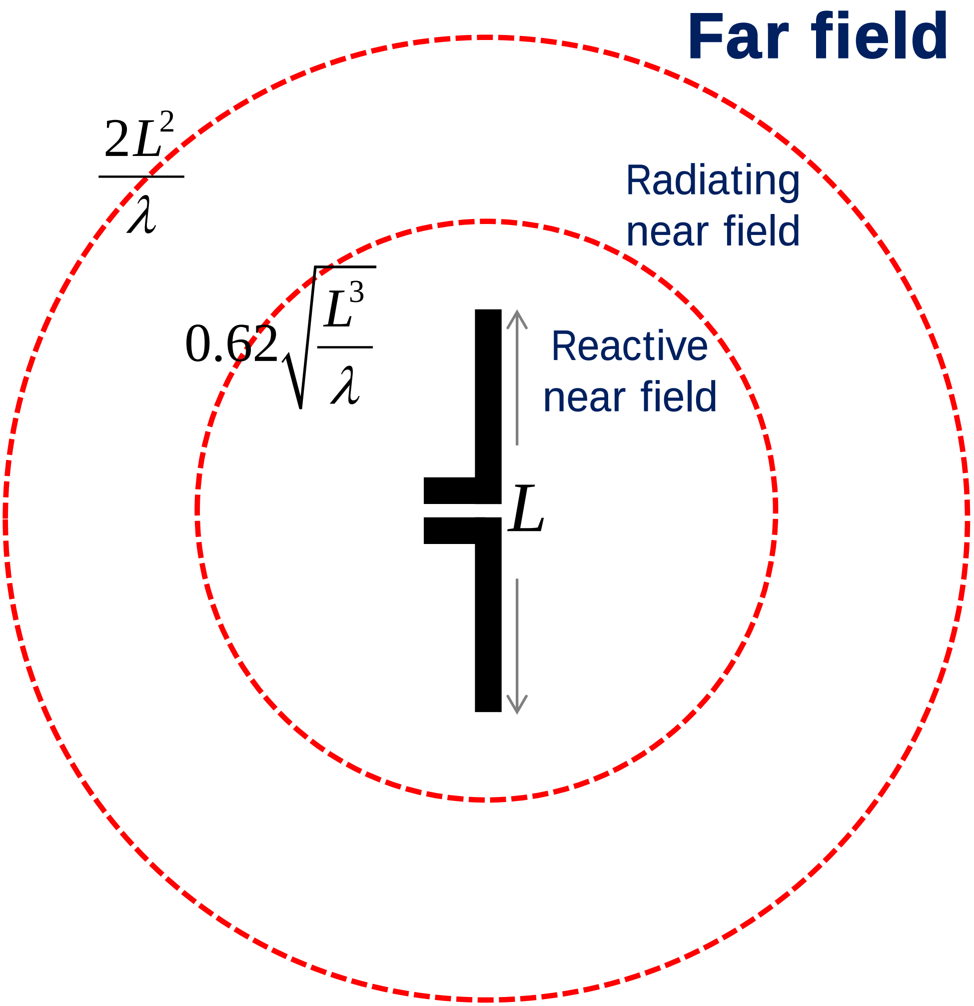


Radiation of Short Dipole (H_φ)



Antenna Field Regions

Antennas produce EM fields both near to and far from the antennas:



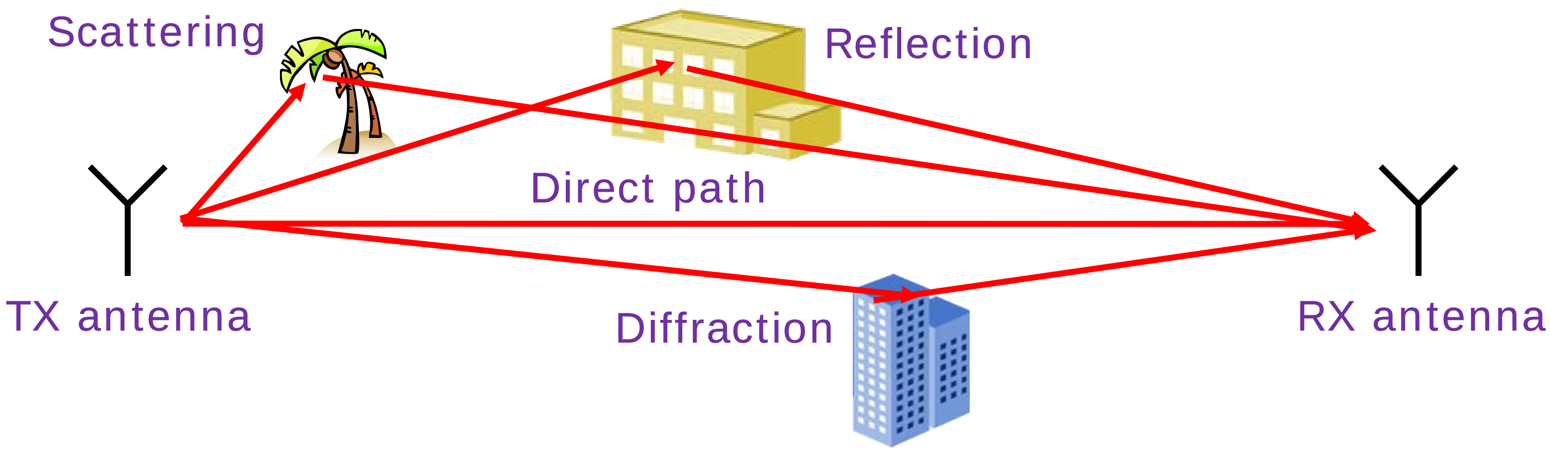
1. Reactive near field
   - It represents energy stored in the vicinity of the antenna
   - The energy does not radiate
   - The energy is seen in the imaginary part of the antenna terminal impedance
2. Radiating near field
   - The antenna field radiates but the radiation pattern changes with distance
3. Far field
   - The radiation pattern is unchanging over distance

$$R \geq \frac{2L^2}{\lambda}$$

Contents

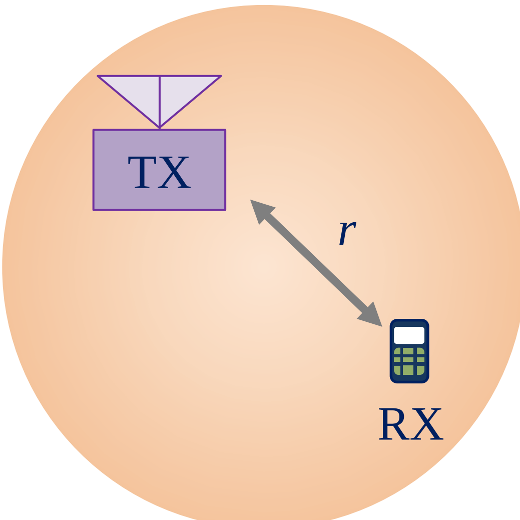
1.3 Link Budget

Recall Wireless Propagation



- There are multiple propagation paths
- How do we estimate the attenuation in the channel?

Friis Transmission Formula (1/4)



Transmitting antenna

- Transmitting power: P_t
- Antenna gain: G_t

Receiving antenna

- Receiving power: P_r
- Antenna gain: G_r

Propagation

- Free space
- Distance: r
- Frequency: f_0

- It's important to know the receiving power level when the transmit conditions are given:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda_0}{4\pi r} \right)^2$$

λ_0: the associated wavelength of f_0

- Harald T. Friis developed this formula In 1946

Friis Transmission Formula (2/4)

Example: Consider a GSM-900 base station with an antenna of 10-dBi gain and a cell phone with an antenna of 1.76-dBi. They are separated by 100 m away. Calculate the uplink receiving power of the base station if the cell phone uses a 33-dBm power to transmit.

(1) Linear scale:

$$P_r = \left(\frac{\lambda_0}{4\pi r}\right)^2 P_t G_t G_r = \left(\frac{0.33}{4\pi \times 100}\right)^2 2\times 10\times 1.5 = 2.11\, uW$$

(2) Log scale:

$$P_r(dBm) = 20\log\left(\frac{\lambda_0}{4\pi r}\right) + 10\log P_t + 10\log G_t + 10\log G_r$$

$$= -71.61(dB) + 33 + 10 + 1.76 = -26.85(dBm)$$

Friis Transmission Formula (3/4)

If polarizations have mismatch:

- The polarization mismatch effect can be quantified by multiplying the formula by the **polarization loss factor** e_{pol}

$$e_{pol} = \left|\hat{e}_t \cdot \hat{e}_r\right|^2$$

$\hat{e}_t,\ \hat{e}_r$: The polarizations of transmitting and receiving antennas, respectively

The overall Friis equation becomes:

$$P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2 \left|\hat{e}_t \cdot \hat{e}_r\right|^2$$

- If the transmitting antenna is LP in x-axis and the receiving antenna is LP in y-axis $\Longrightarrow P_r = 0\ \mathrm{W}$
- If the transmitting antenna is LP in x-axis, and the receiving antenna is CP $\Longrightarrow P_r = 50\%$ of those of perfectly-matched case

Friis Transmission Formula (4/4)

If impedances have mismatch:

- The impedance mismatch effect can be quantified by multiplying the formula by the impedance mismatch factor e_{imp}

$$e_{imp} = \left(1 - \left|\Gamma_t\right|^2\right)\left(1 - \left|\Gamma_r\right|^2\right)$$

Γ_t, Γ_r : The reflection coefficient at the transmitter and the receiver, respectively

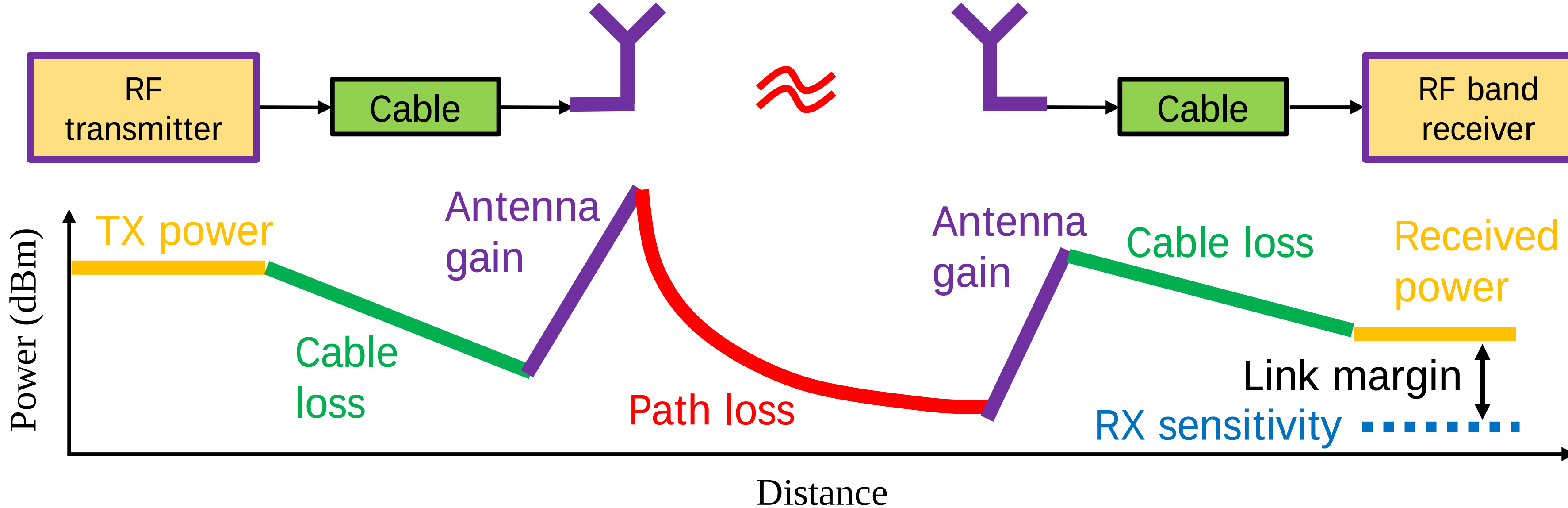
The overall Friis equation becomes:

$$P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2 \left|\hat{e}_t \cdot \hat{e}_r\right|^2 \left(1 - \left|\Gamma_t\right|^2\right)\left(1 - \left|\Gamma_r\right|^2\right)$$

If the orientation is considered:

$$P_r = P_t G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r) \left(\frac{\lambda_0}{4\pi r}\right)^2 \left|\hat{e}_t \cdot \hat{e}_r\right|^2 \left(1 - \left|\Gamma_t\right|^2\right)\left(1 - \left|\Gamma_r\right|^2\right)$$

Objective of Link Budget Calculation



Objective:

- To calculate how far we can go with an equipment we have
- To compute required transmitting power
- To know the required sensitivity of receiver's chip

Limitation of link budget analysis:

- It gives only an approximation—most often a worst case estimate—for the total SNR
- The power calculated is only an average; we have to add a "fading margin"

Power in Log Scale

- We usually measure power in watt (W) and milliwatt (mW)
- The corresponding dB notations are dBW and dBm

	Linear scale	Log scale (dB)
Watt	$P\vert_{W}$	$P\vert_{dBW} = 10\log\left(\frac{P\vert_{W}}{1\vert_{W}}\right) = 10\log\left(P\vert_{W}\right)$
milliwatt	$P\vert_{mW}$	$P\vert_{dBm} = 10\log\left(\frac{P\vert_{mW}}{1\vert_{mW}}\right) = 10\log\left(P\vert_{mW}\right)$
Relation	$P\vert_{dBm} = 10\log\left(\frac{P\vert_{W}}{0.001\vert_{W}}\right) = 10\log\left(P\vert_{mW}\right) + 30\vert_{dB} = P\vert_{dBW} + 30\vert_{dB}$	

Example:

- Sensitivity level of a GSM RX: 6.3×10^{-14} W = −132 dBW or −102 dBm
- Bluetooth TX: 10 mW = −20 dBW or 10 dBm
- Vacuum cleaner: 1600 W = 32 dBW or 62 dBm
- GSM base station TX: 40 W = 16 dBW or 46 dBm

Path Loss Estimation

The most convenient way to estimate the path loss:

- By Friis transmission formula:

$$\text{Path Loss} = \left(\frac{\lambda}{4\pi R}\right)^2$$

- The $1/R^2$ rule
- The higher the frequency, the larger the path loss is

More realistic path loss:

- By the "breakpoint" model:
  - For distance $d < d_{break}$:

$$\text{Path Loss} = \left(\frac{\lambda}{4\pi d}\right)^2$$

  - For distance $d > d_{break}$:

$$\text{Path Loss} = \left(\frac{\lambda}{4\pi d_{break}}\right)^2 \left(\frac{d_{break}}{d}\right)^n$$

Environment	Path loss exponent n
Free space	2
Urban	2.7–3.5
Shadowed urban	3–5
In-building LOS	1.6–1.8
In-building shadowed	4–6
Factory shadowed	2–3
Retail store	2.2
Office-soft partitions	2.4

EX 4.1

Link Budget Calculation (1/3)

Scenario

- Consider a 5-km link with one access point (AP) and one client radio
- The AP is connected to an antenna with 10 dBi gain, with a transmitting power of 20 dBm and a receive sensitivity of -89 dBm
- The client is connected to an antenna with 14 dBi gain, with a transmitting power of 15 dBm and a receive sensitivity of -82 dBm
- The cables in both systems are short, with a loss of 2 dB at each side at the 2.4 GHz frequency of operation
- The fading margin is 5 dB

1. Calculate the path loss by the free-space estimation
2. Calculate the link margin for the AP-to-client link
3. Calculate the link margin for the client-to-AP link

EX 4.1 Link Budget Calculation (2/3)

AP-to-client link:

- Path loss in the free-space environment:

$$\text{Path Loss} = \left(\frac{\lambda}{4\pi R}\right)^2 = \left(\frac{0.125}{4\pi \times 5000}\right)^2 = 3.96\times 10^{-12} = -114\ \text{dB}$$

- From the link budget diagram:

TX side	Value
TX power	20 dBm
Losses (cable)	−2 dB
Antenna gain	10 dBi
Total	28 dBm

Channel	Value
Path loss	−114 dB
Fading margin	−5 dB
Total	−119 dB

RX side	Value
Antenna gain	14 dBi
Losses (cable)	−2 dB
Received power	
Sensitivity	−82 dBm

Link Budget Calculation (3/3)

Client-to-AP link:

- Path loss in the free-space environment:

$$\text{Path Loss} = \left(\frac{\lambda}{4\pi R}\right)^2 = \left(\frac{0.125}{4\pi \times 5000}\right)^2 = 3.96 \times 10^{-12} = -114\ \text{dB}$$

- From the link budget diagram:

TX side	Value
TX power	15 dBm
Losses (cable)	−2 dB
Antenna gain	14 dBi
Total	27 dBm

Channel	Value
Path loss	−114 dB
Fading margin	−5 dB
Total	−119 dB

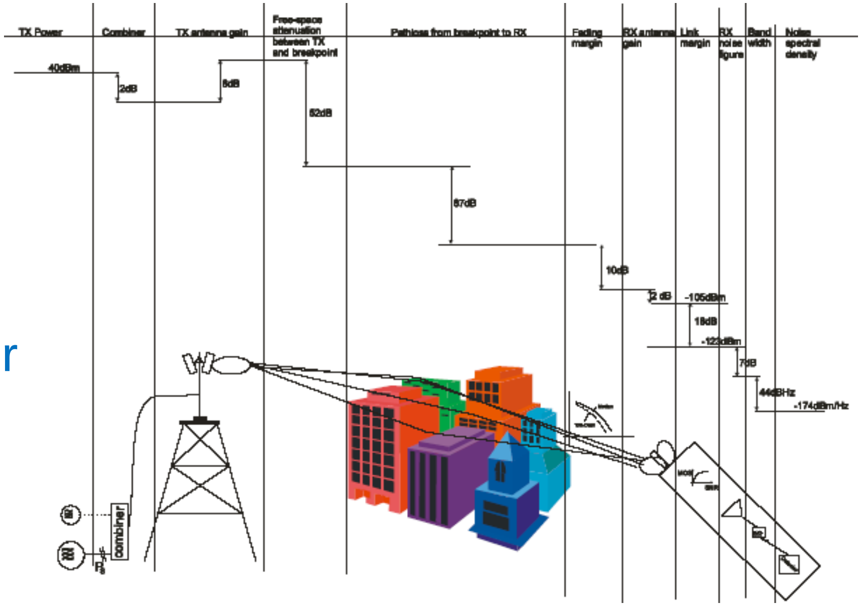
RX side	Value
Antenna gain	10 dBi
Losses (cable)	−2 dB
Received power	
Sensitivity	−89 dBm

Calculation of the Required TX Power

Scenario

- Consider a mobile radio system at 900-MHz
- Antenna gains at TX and RX sides are 8 dBi and −2 dBi, respectively
- Losses in cables, combiners, etc. at the TX are 2 dB
- The noise level at the RX side is −123 dBm, and the required operating SNR is 18 dB
- The IF gain in the receiver is 30 dB
- The desired range of coverage is 2 km, and the breakpoint is at 10-m distance; beyond the point, the pathloss exponent is 3.8, and the fading margin is 10 dB

Calculate the minimum TX power



A. F. Molisch, *Wireless Communications*, John Wiley & Sons, NJ, 2005.

A Closer Look to the Receiver Structure

The power level at consecutive stages of a receiver: