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EECE5155: Wireless Sensor Networks and the Internet of Things

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Module T4: Data Communication

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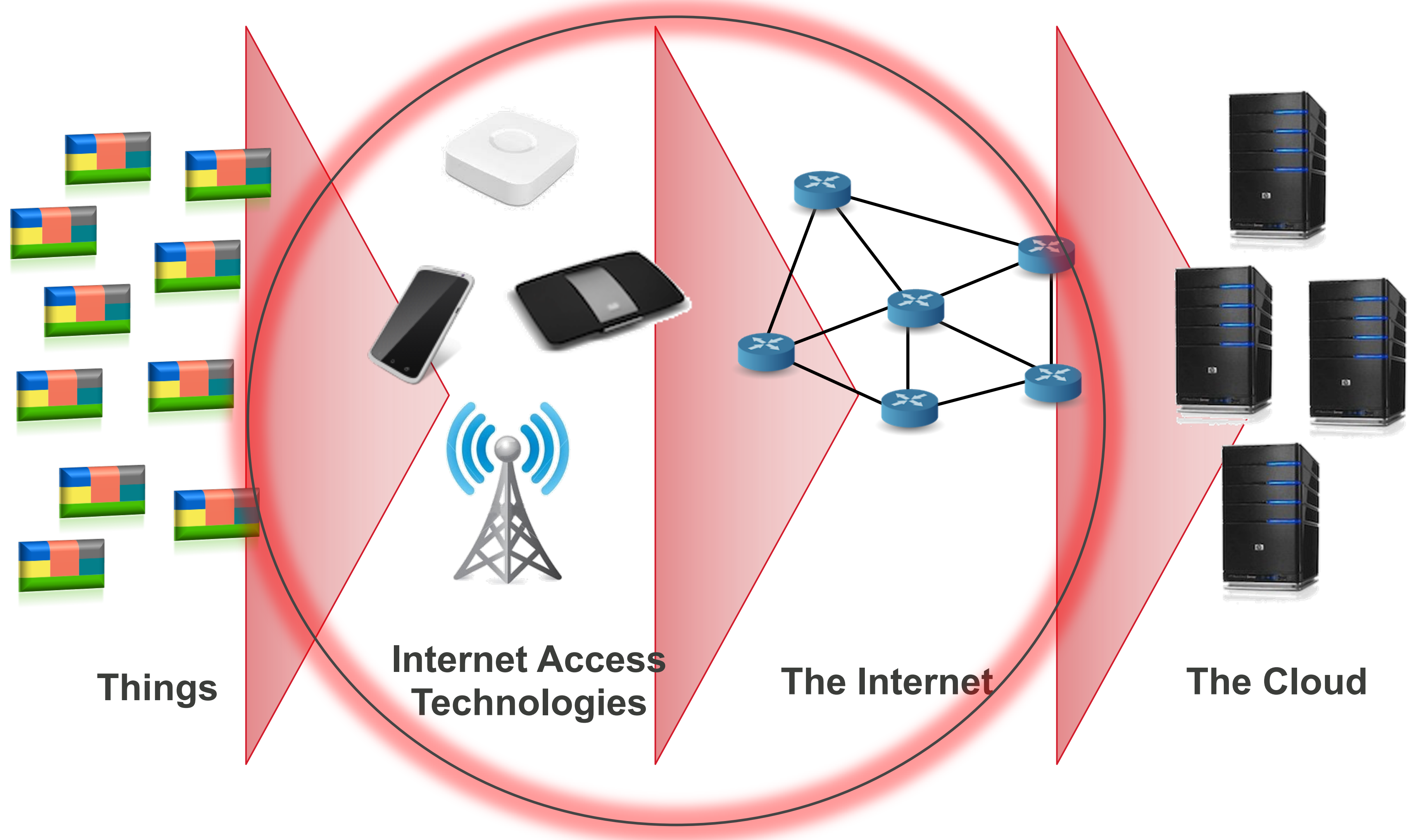
Part 2: Protocols and Standards

Part 2


Things
Internet Access Technologies
The Internet
The Cloud

Outline

- The Protocol Stack

- The Physical Layer
- The Link Layer
- The Network Layer
- The Transport Layer

- IoT Standards

The Protocol Stack

- To reduce their design complexity, most networks are organized as a **stack of layers**, each one built upon the one below it:
  - Each layer offers certain **<u>services</u>** to the higher layers…
  - … which are accessed by means of **<u>interfaces</u>** …
  - … **without actually showing the details** of their implementation

- **Different types of networks** might have different:
  - Number of layers
  - Name of each layer
  - Contents of each layer
  - Function of each layer

- Layer *n* of a node interacts with layer *n* of another node by following a **layer *n* <u>protocol</u>**

The Protocol Stack

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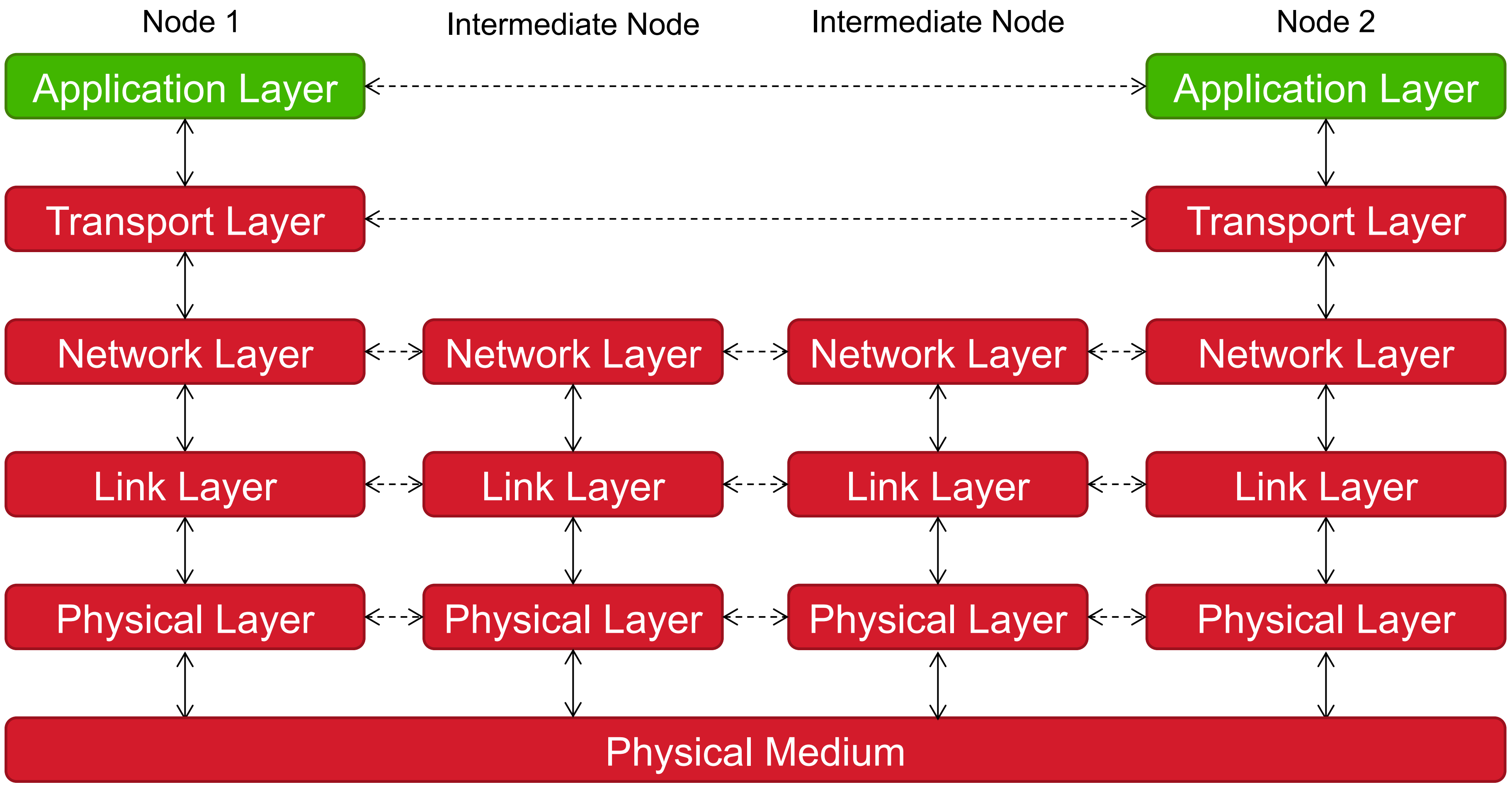

The Physical Layer

The Physical Layer

The Physical Layer

- Defines the way in which bits (0s and 1s) are transmitted as **signals** over a **communication channel**:
  - **Signal:** *“A function that conveys information about the behavior or attributes of some phenomenon”*
    - **E.g., electric, magnetic, electromagnetic, acoustic, molecular, etc.**
  - **Channel:** *“The medium that carries the signal to be transmitted”*
    - **E.g., twisted pair, coaxial cable, optical fiber, air, water, etc.**

Some Basic Concepts

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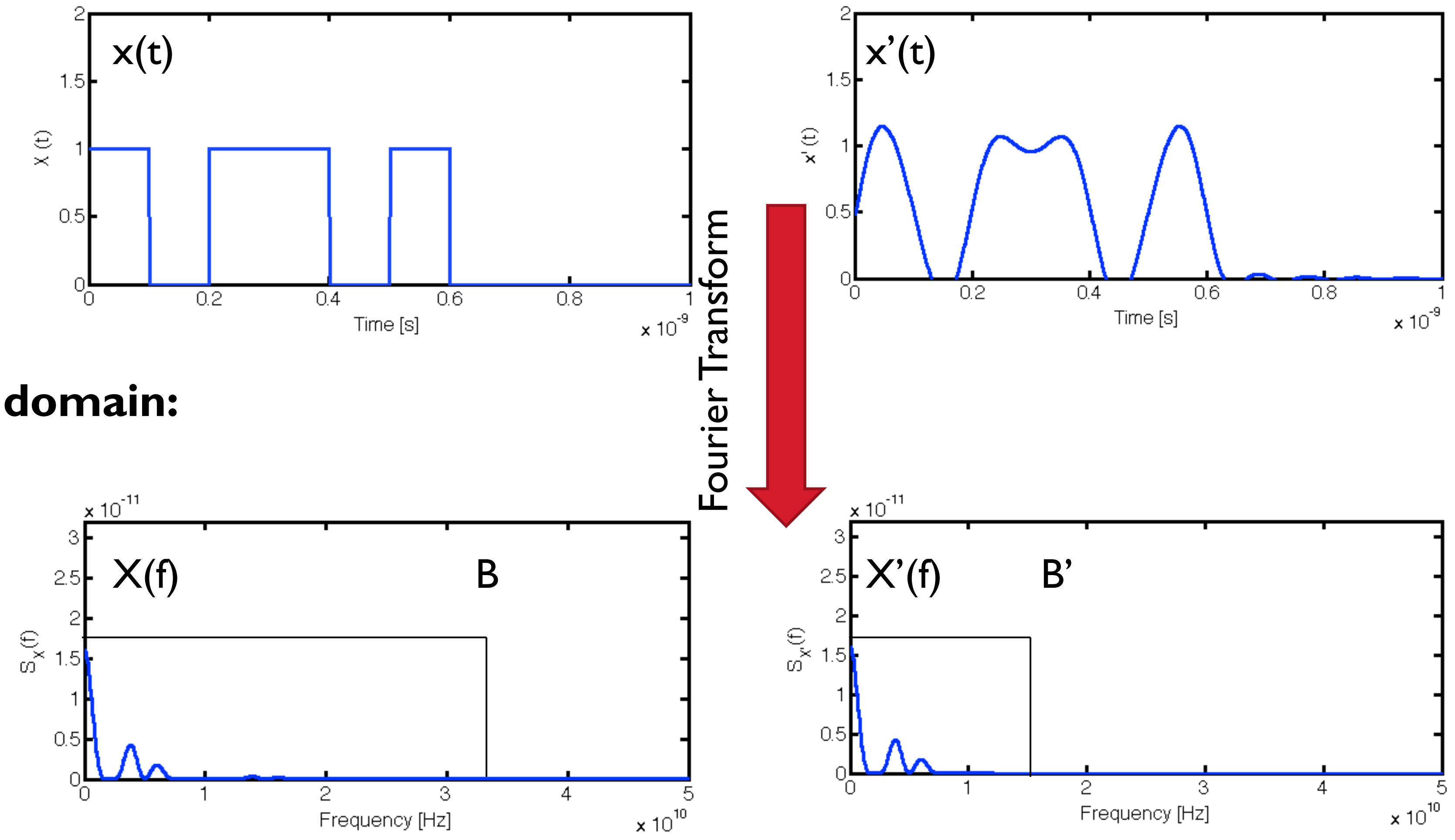
- **Baseband Signal**: a signal whose range of frequencies expands from 0 Hz (or very close) up to a certain cut-off frequency
  - Used for example in some of the wired networking standards (e.g., Ethernet 10BASE5, 10BASET, etc.)

- **Passband Signal:** a signal whose range of frequencies is away from 0 Hz
  - Used for example in Radio Frequency (RF) communications, Digital Subscriber Line (DSL) systems, etc.

- **Bandwidth:**
  - **For baseband signals:** the highest frequency of the signal
  - **For passband signals:** the difference between the upper and the lower frequency of the signal

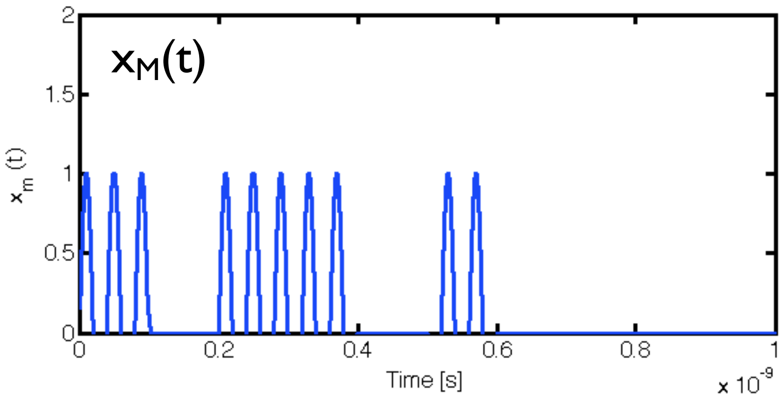
Representation of **Baseband** Signals

- **Time domain:**
- **Frequency domain:**



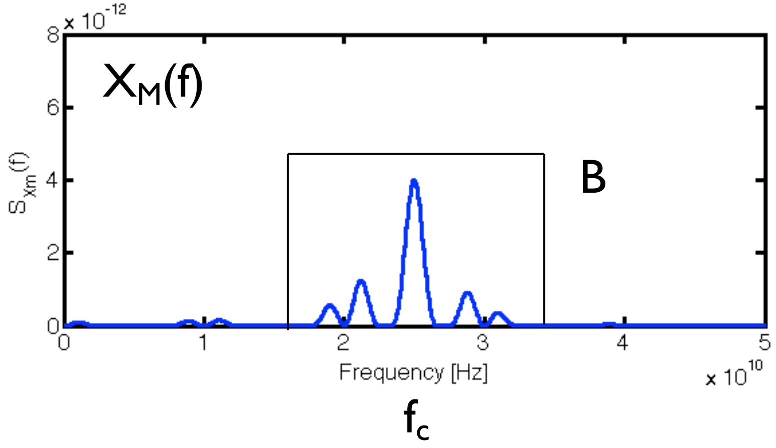
Representation of Passband Signals

- **Time domain:**



$$x_m(t) = x(t)\sin(2\pi f_c t)$$

- **Frequency domain:**



Digital Modulation (at the Transmitter)

- Mechanism by which a binary sequence is converted in a signal suited for transmission in the physical medium
  - **Baseband:** commonly used in wired communication
  - **Passband:** commonly used in wireless and optical communication

Baseband Modulations

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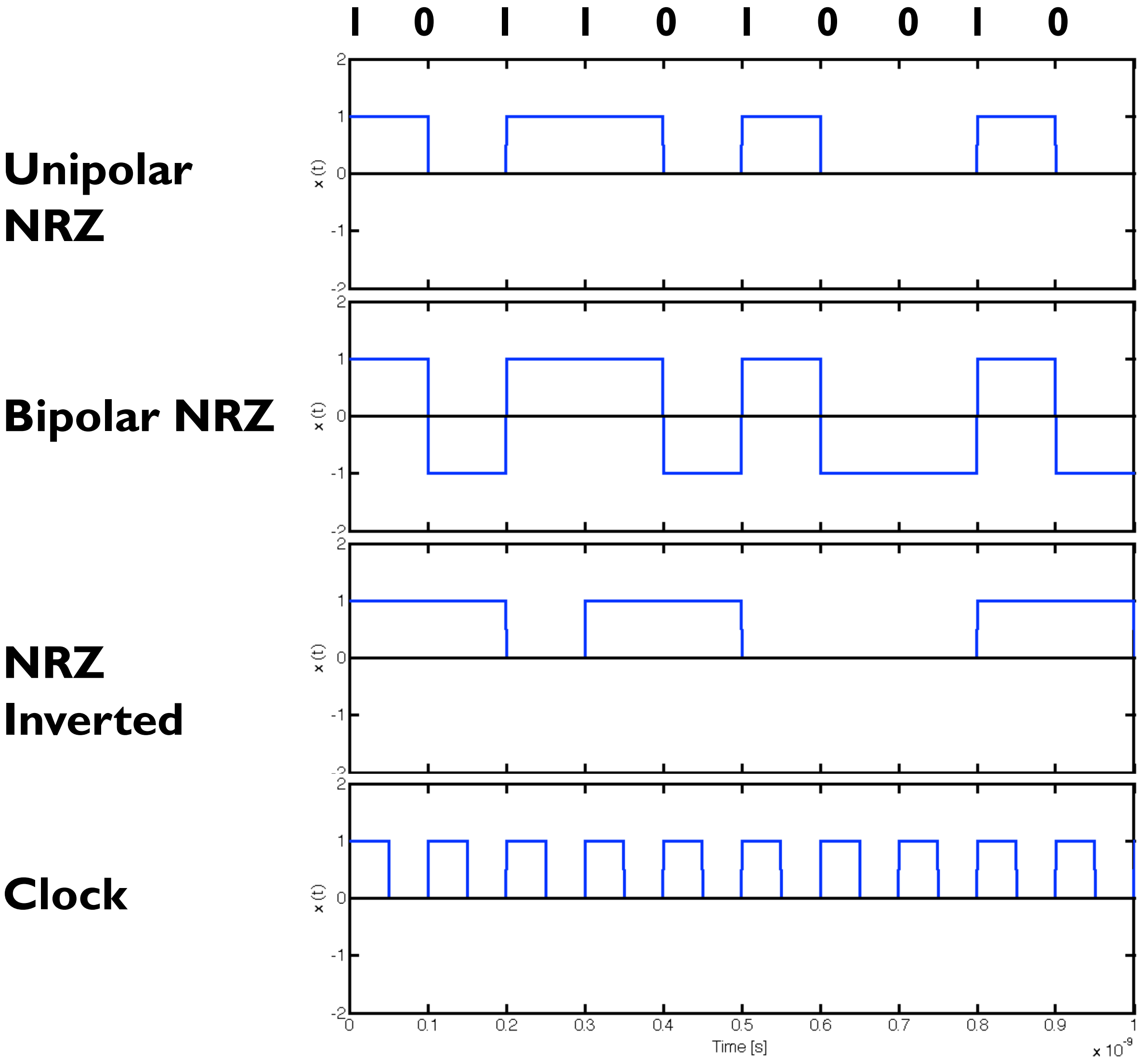
- **Unipolar Non-Return-to-Zero:**
  - A binary 1 is transmitted as a positive voltage
  - A binary 0 is transmitted as a null voltage
- **Bipolar Non-Return-to-Zero:**
  - A binary 1 is transmitted as a positive voltage
  - A binary 0 is transmitted as a negative voltage
- **Non-Return-to-Zero Inverted:**
  - A binary 1 is transmitted as a transition in the signal level
  - A binary 0 is transmitted as a no transition

Examples



(e.g., USB)

Passband Modulations

- **Single Carrier Modulations:** the properties of a single tone or carrier frequency are changed according to the data to be transmitted:
  - **Amplitude Shift Keying (ASK):**
    - Two amplitude levels are used to transmit a binary 1 and a binary 0
    - More amplitude levels can be used to transmit more symbols, e.g., 00, 01, 10, 11
  - **Frequency Shift Keying (FSK):**
    - Two different frequency tones are used to transmit a binary 1 and a binary 0
    - More frequency tones can be used to transmit more symbols
  - **Phase Shift Keying (PSK):**
    - The phase of the carrier signal is shifted by a certain phase at each symbol transition:
      - **Binary Phase Shift Keying (BPSK):** phase is shifted by 0 or 180 degrees
      - More phases can be used to transmit more symbols, e.g., QPSK
  - **Quadrature Amplitude Modulation:** combination of amplitude and phase modulations
    - E.g., 16QAM (4 bits per symbol), 64QAM (6 bits per symbol)

Examples

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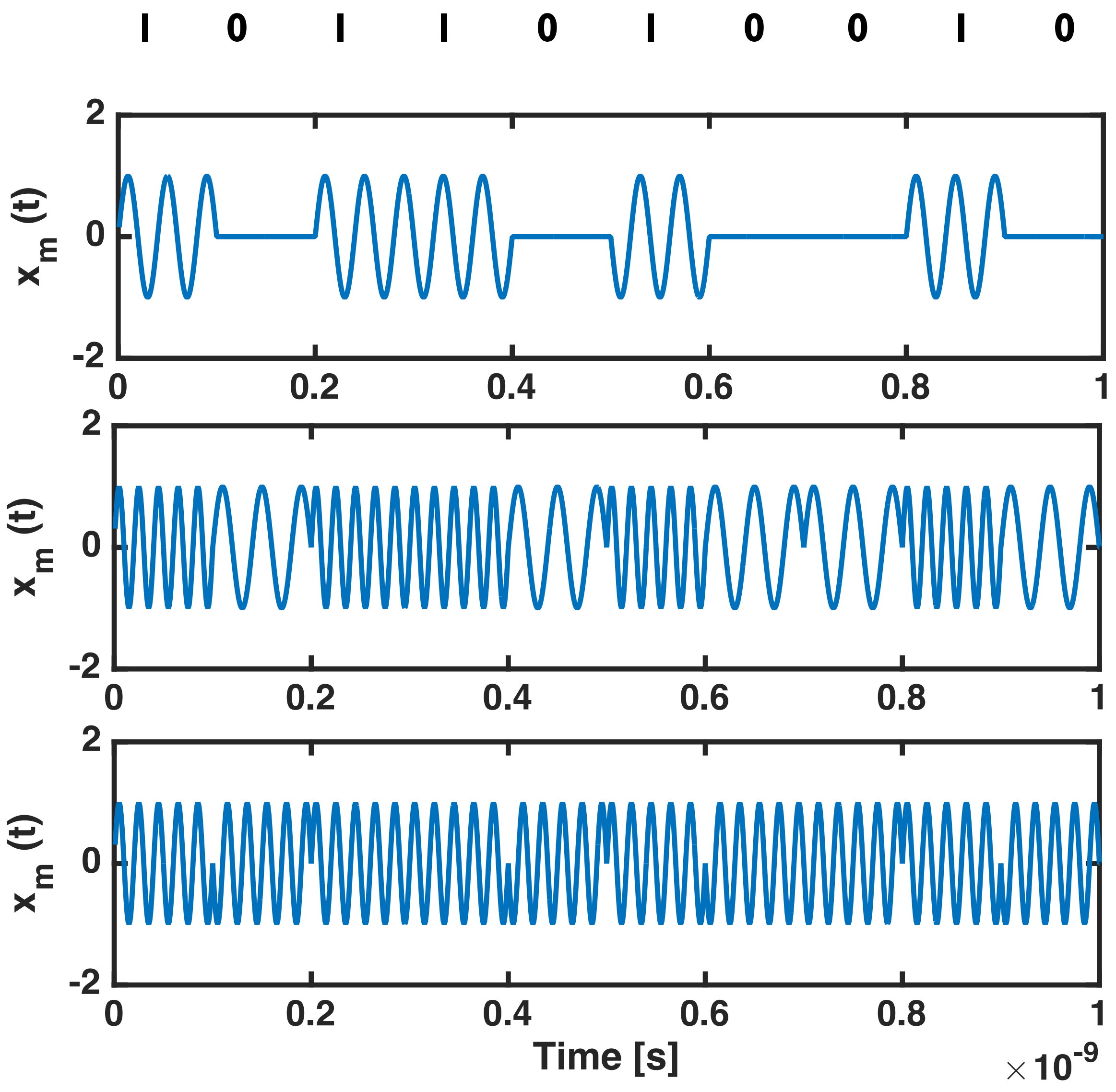
Binary ASK

Binary FSK

Binary PSK



Important: In-phase and Quadrature Data

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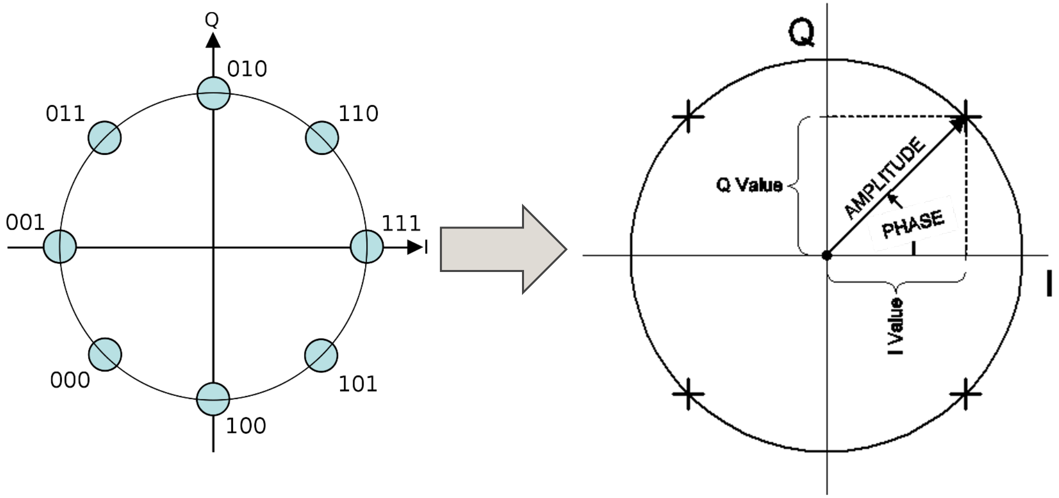
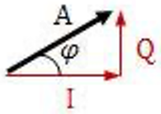
- Precisely varying the phase of a high-frequency carrier sine wave in a hardware circuit according to an input message signal is difficult
  - Circuit would be expensive and difficult to design/build!
- Instead, the concept of in-phase and quadrature components is introduced to manipulate the signal in baseband before being up-converted (at the transmitter) or after being down-converted (at the receiver)



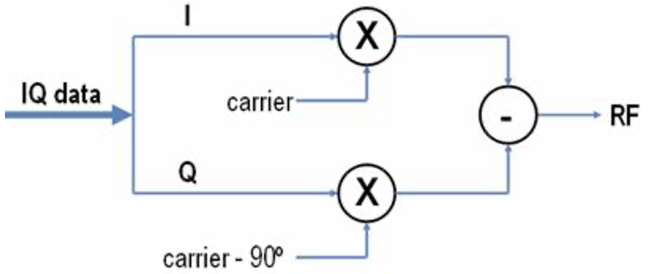
$$\cos(\alpha+\beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta)$$

$$A\cos(2\pi f_c t + \varphi) = A\cos(2\pi f_c t)\cos(\varphi) - A\sin(2\pi f_c t)\sin(\varphi)$$



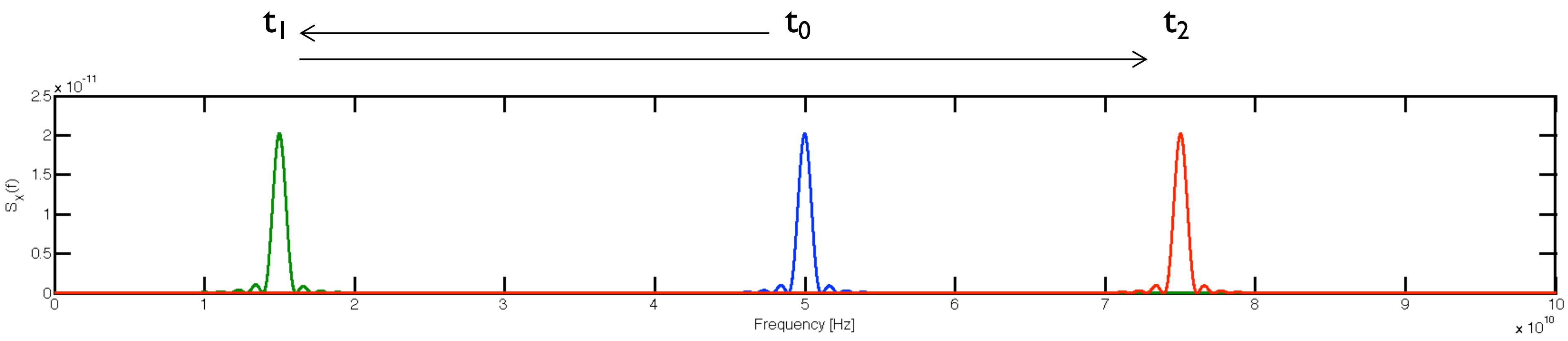
$$I = A\cos(\varphi)$$
$$Q = A\sin(\varphi)$$

$$A\cos(2\pi f_c t + \varphi) = I\cos(2\pi f_c t) - Q\sin(2\pi f_c t)$$



Frequency Hopping

- The transmitter hops among frequencies many times per second
  - Enhanced security, low interference, high spectral reuse
  - E.g., military communications, Bluetooth



This is at the basis of Bluetooth!

Chirp Spread Spectrum

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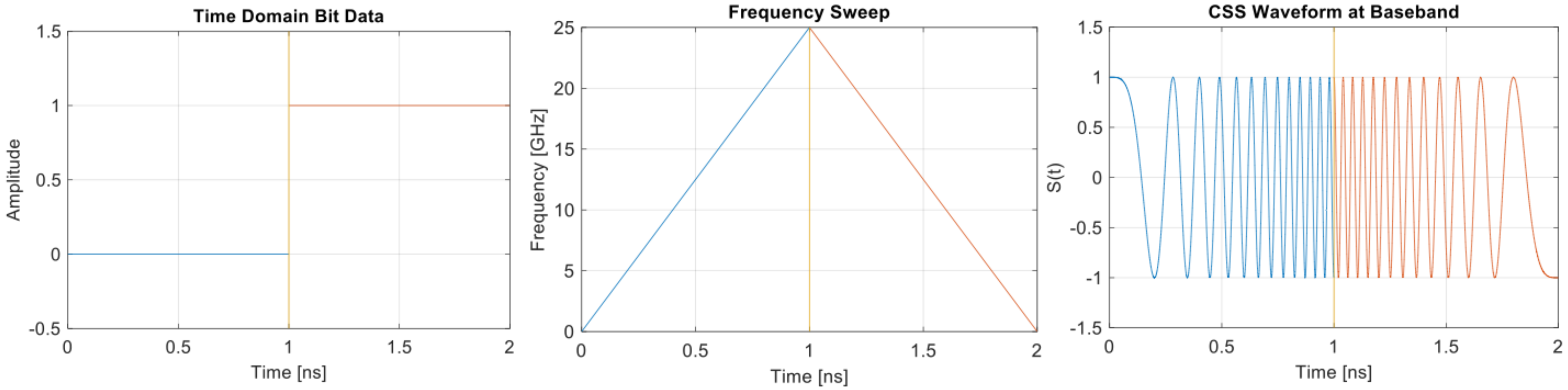
- Information is encoded in the changes in carrier frequency across a large bandwidth
- Signal occupies a wideband spectrum at all times

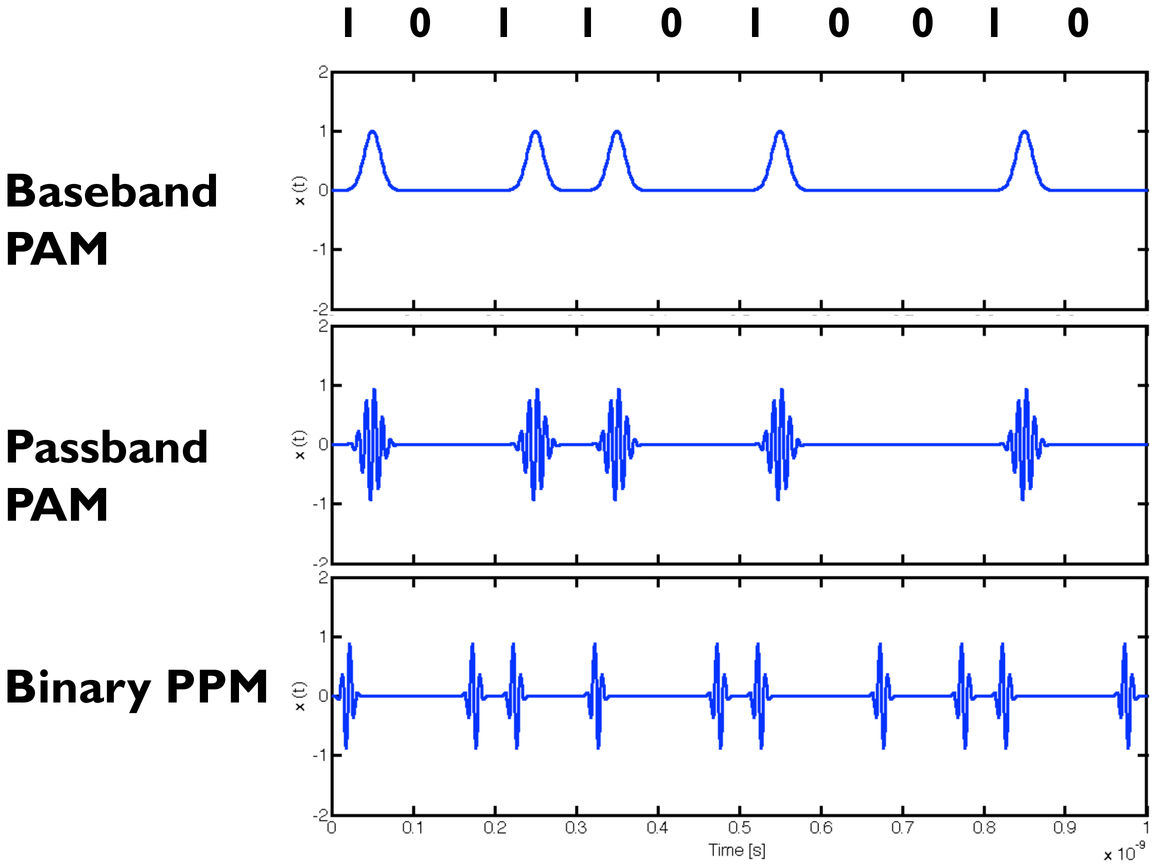


We will talk more about this modulation when covering LoRaWAN, one of the major IoT standards!

Pulse-based Modulations

- Make use of pulse-shape signals
  - **Pulse Amplitude Modulation (PAM):** two different pulse amplitudes are used to transmit either 0 or 1
    - Unipolar (On/Off), Bipolar, and multi-level variations exist
  - **Pulse Position Modulation (PPM):** the relative temporal position of a pulse within a slot is used transmit either 0 or 1
    - Multi-level PPM modulations are also common

Examples



1 0 1 1 0 1 0 0 1 0
Baseband PAM
Passband PAM
Binary PPM
x (t)
Time [s]
x 10^-9

Multiplexing

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- To combine **multiple signals over the same physical medium**
  - Either to enable one user to transmit more information at the same time
  - Or to enable multiple users to share the physical medium without interfering → We will see more about this at the link layer

- Common techniques:
  - **Frequency Division Multiplexing (FDM)**
  - **Time Division Multiplexing (TDM)**
  - **Code Division Multiplexing (CDM)**

Frequency Division Multiplexing

- To utilize different bandpass signals at different frequencies over the same medium simultaneously

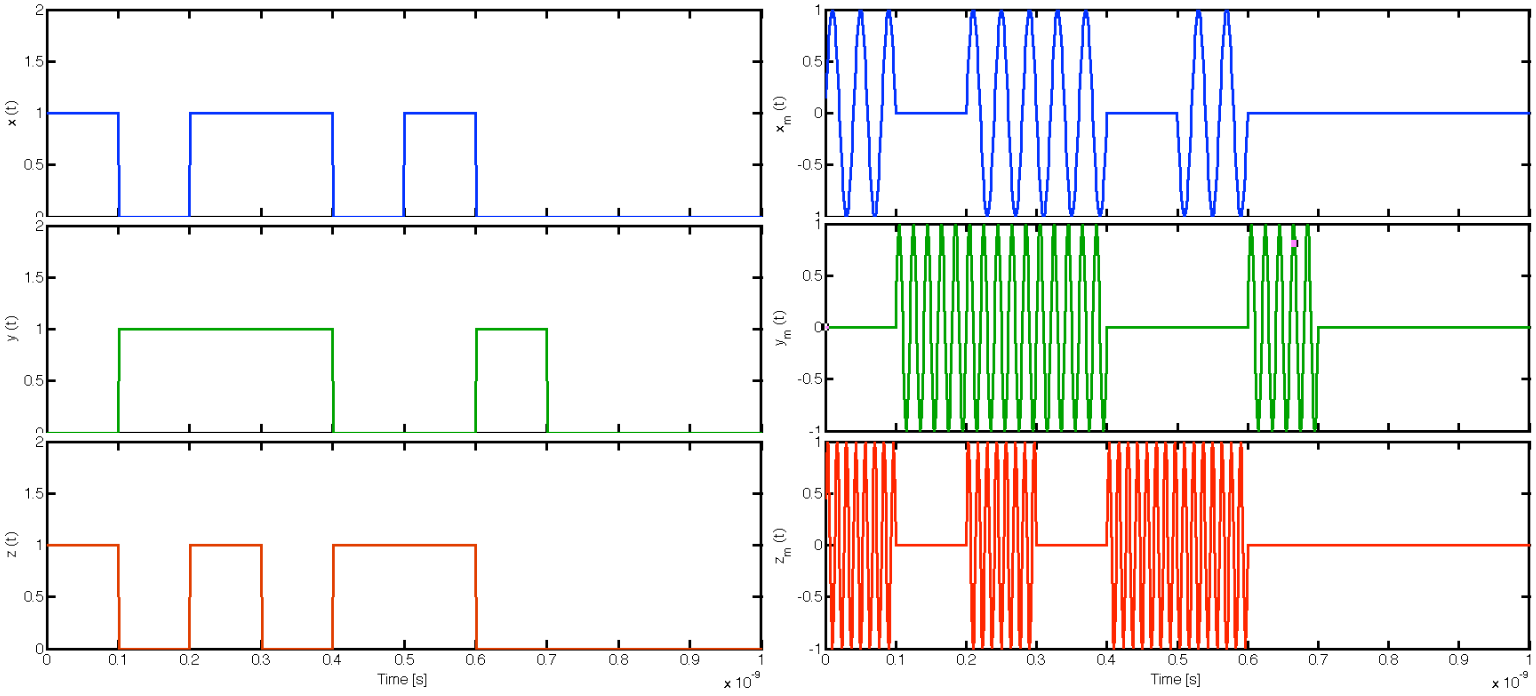
- In classical FDM,
  - The separation between frequencies needs to be larger than twice the baseband signal bandwidth

Example

$x(t), f_{c1}$

$y(t), f_{c2}$

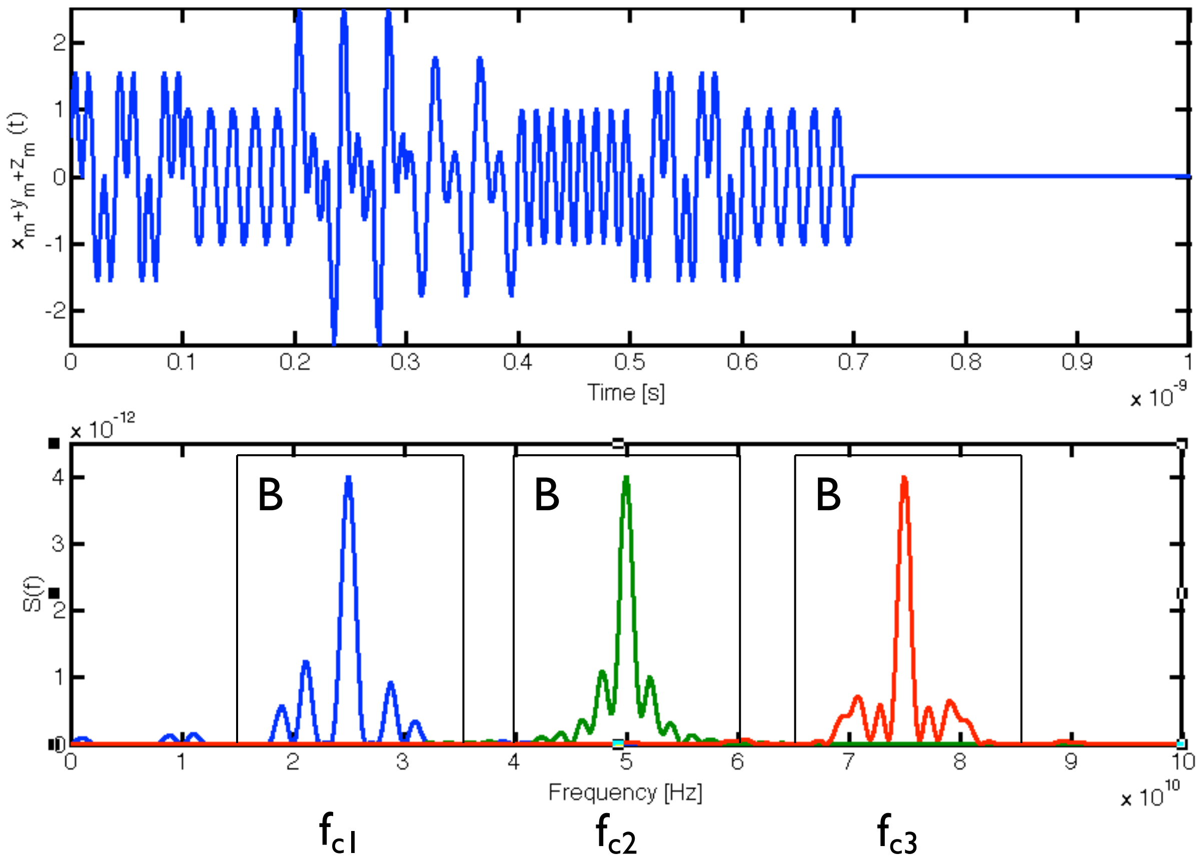
$z(t), f_{c3}$



Example

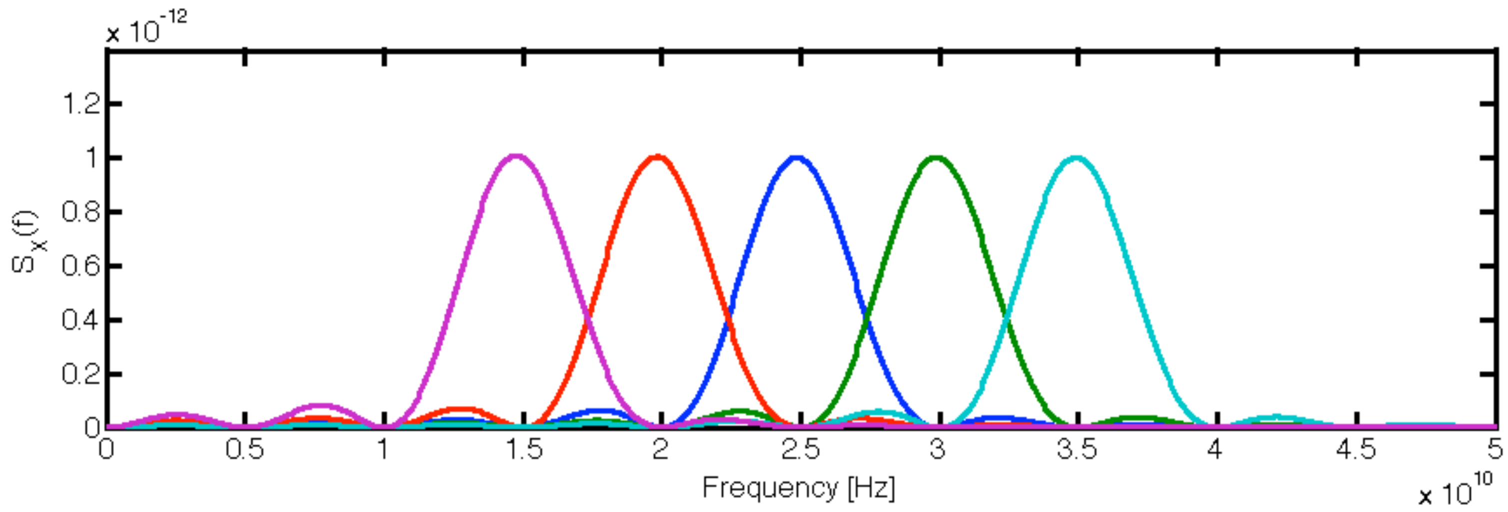
x(t)+y(t)+z(t)

$S_X(f)+S_Y(f)+S_Z(f)$



Orthogonal Frequency Division Multiplexing

- Multiple sub-bands can be used without any actual band guard, by properly designing their position and shape:
  - Each "sub-band" is very narrow → Very low data-rate per carrier
  - But many parallel "sub-bands" can be used simultaneously → **High aggregated data-rate**



Time Division Multiplexing

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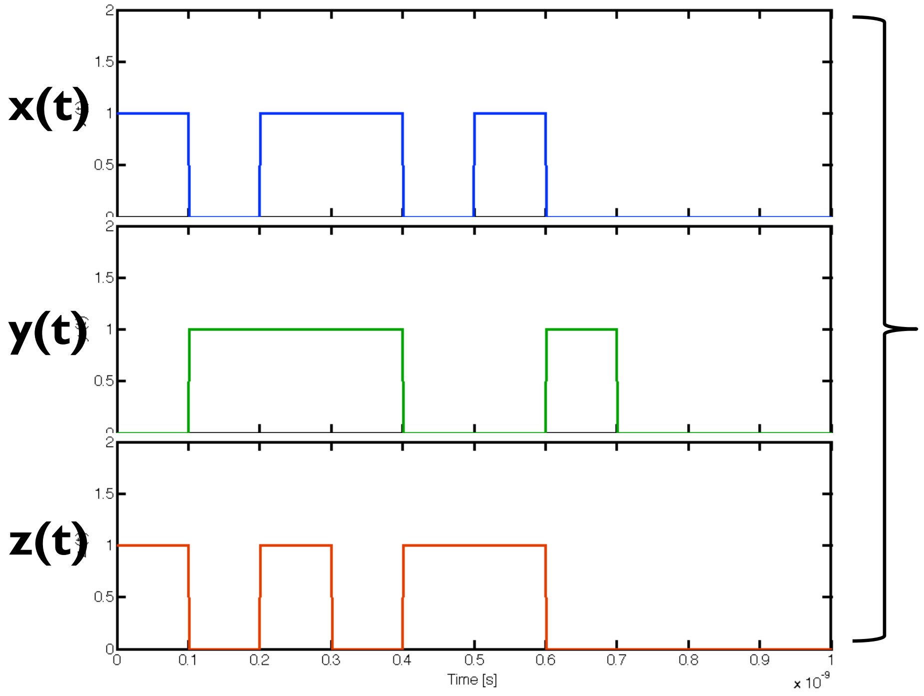
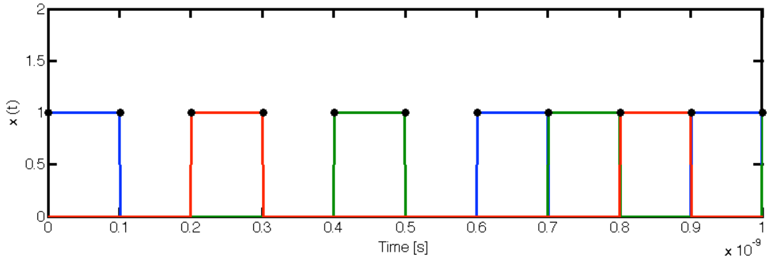
- Different signals take different times or slots to utilize the physical medium
  - Tight synchronization is needed!





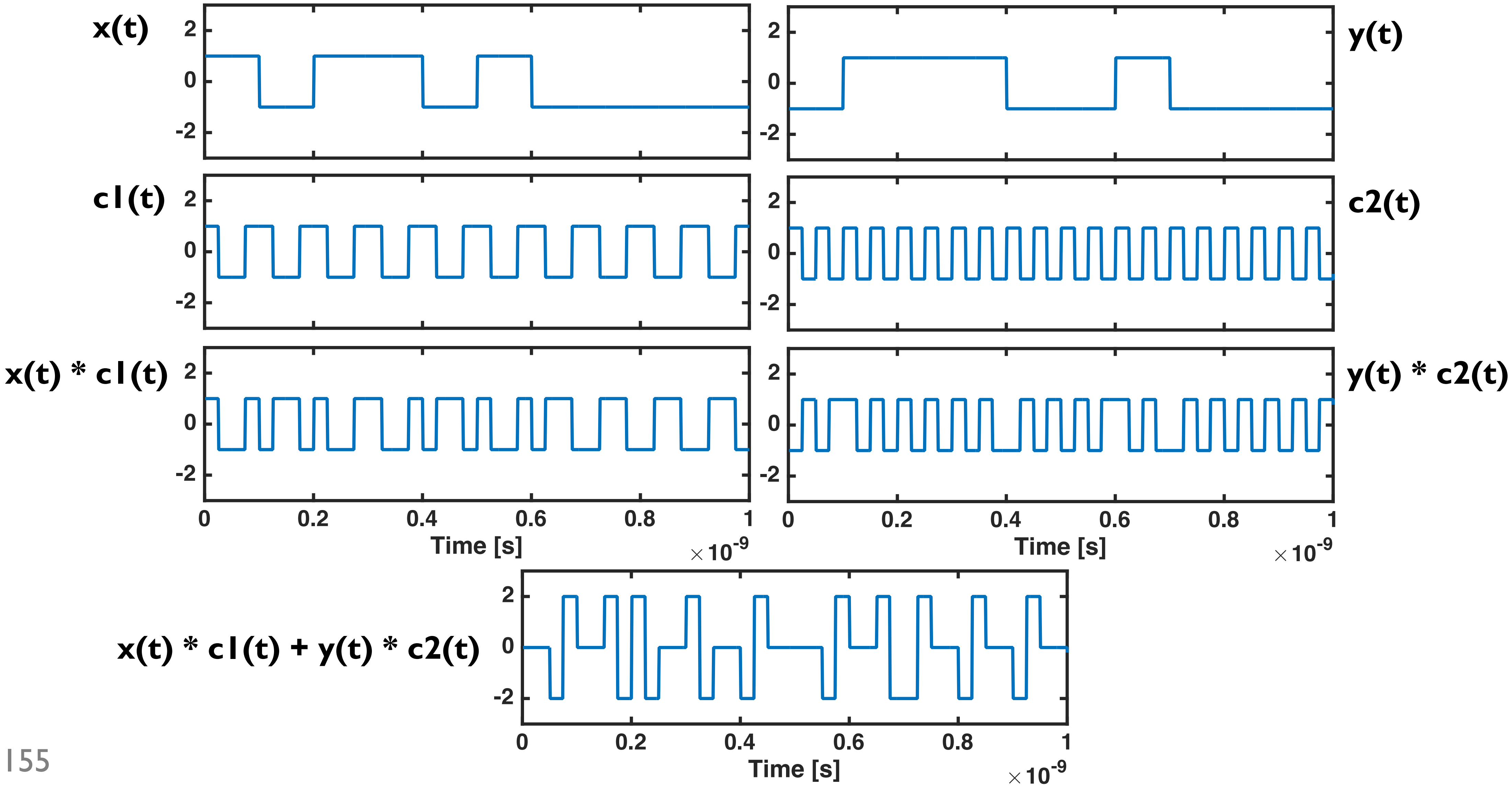
Code Division Multiplexing

- To spread a narrow band signal over a wider frequency band:
  - Multiple signals can occupy the same frequency band without altering each other…
  - … as long as they use different orthogonal codes
    - Code: a binary signal whose bits, usually called chips, are much shorter than the data bits

- To encode the data,
  - the transmitted signal is multiplied by a specific code

- To decode the data,
  - the received signal is multiplied by the same code

Example


x(t)
y(t)
c1(t)
c2(t)
x(t) * c1(t)
y(t) * c2(t)
x(t) * c1(t) + y(t) * c2(t)
2
0
-2
0
0.2
0.4
0.6
0.8
1
Time [s]
×10^-9

Demodulation (at the receiver)

- The receiver looks at the received waveform and matches it with the data bit that caused the transmitter to generate this waveform
  - Necessary: one-to-one mapping between data and waveform
  - Because of channel imperfections, this is at best possible for digital signals, but not for analog signals
- Problems caused by
  - **Carrier synchronization:** frequency can vary between sender and receiver (drift, temperature changes, aging, …)
  - **Symbol synchronization:** When does symbol representing a certain bit start/end?
  - **Frame synchronization:** When does a packet start/end?

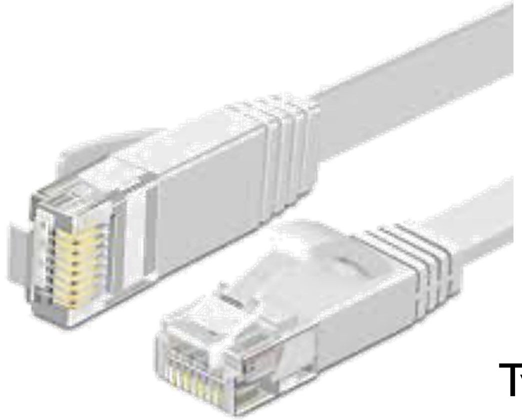
  - **Biggest problem:** Received signal is not the transmitted signal!
    - Why? Because of the **channel**!

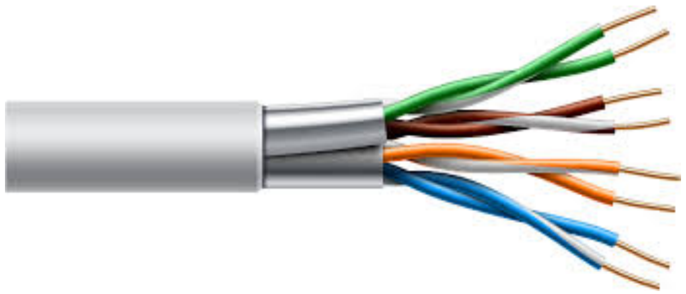
Channel Response

- **Channel Response:**
  - When a signal propagates through a channel, it usually suffers from **attenuation** (i.e., its power decreases) and it experiences a certain **delay**
  - In addition, the channel might affect the different frequency components of a signal in a different way, which results in **distortion**
  - Moreover, there might be:
    - **Noise:** any undesired random fluctuation of the signal
      - E.g., thermal noise, shot noise, etc.
    - **Interference:** generated by other users or phenomena, not necessarily random
      - E.g., multi-user interference, microwave ovens, etc.

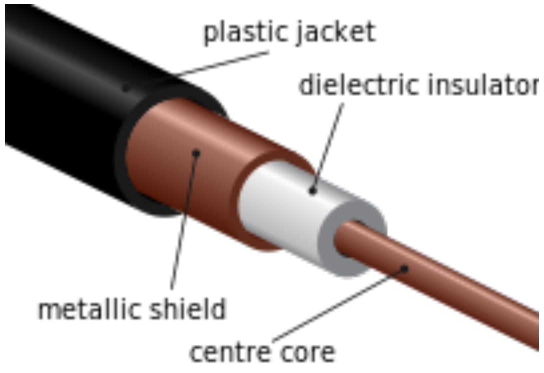
All these depend on the type of channel!

Wired Channels

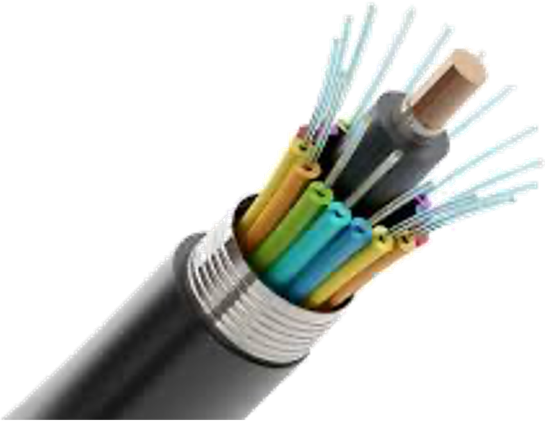




Twisted pairs



Coaxial cables



Optical fibers

Wireless Channels

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- Electromagnetic Communication
- Acoustic Communication
- Molecular Communication
- …

The Electromagnetic Spectrum

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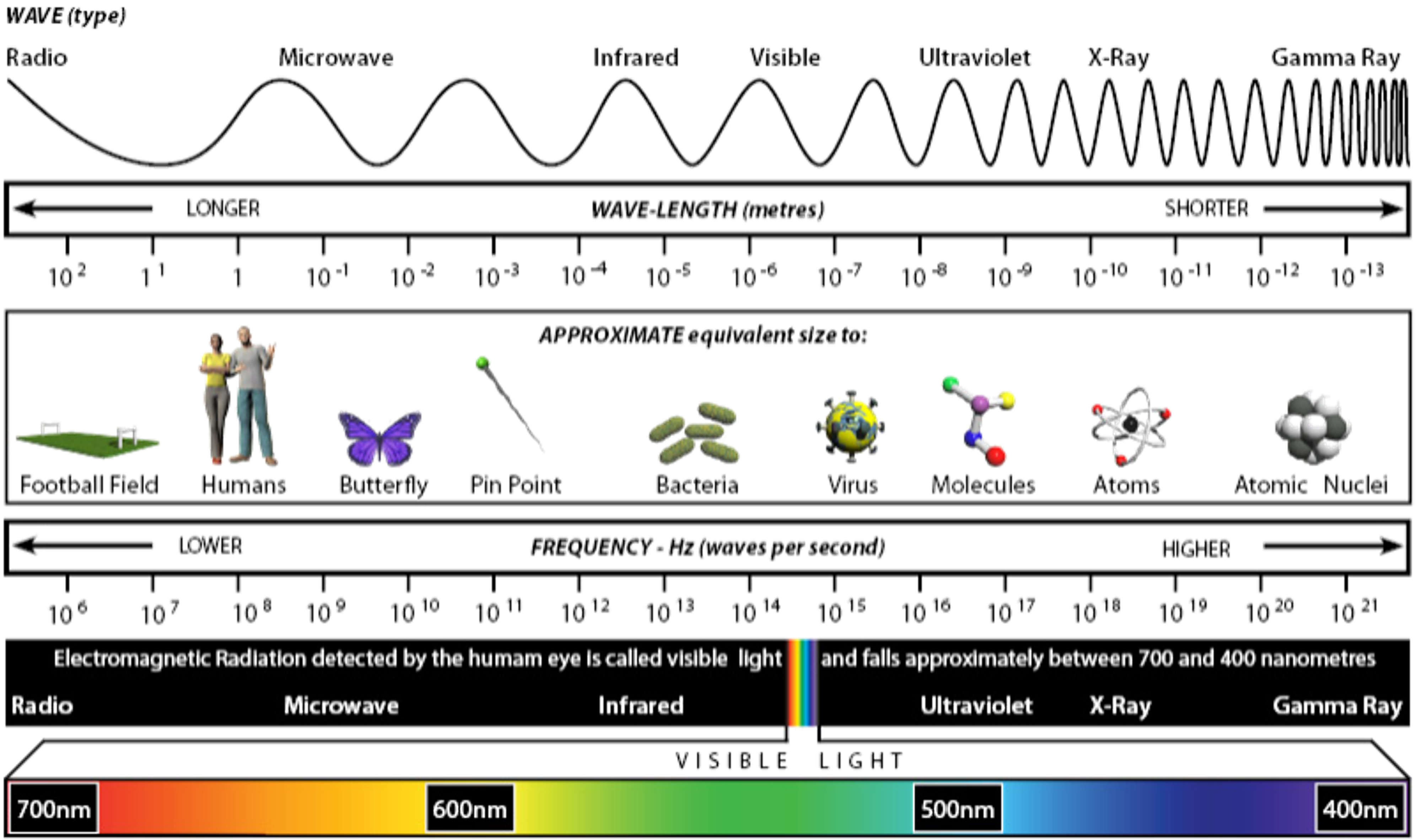

Electromagnetic Communication

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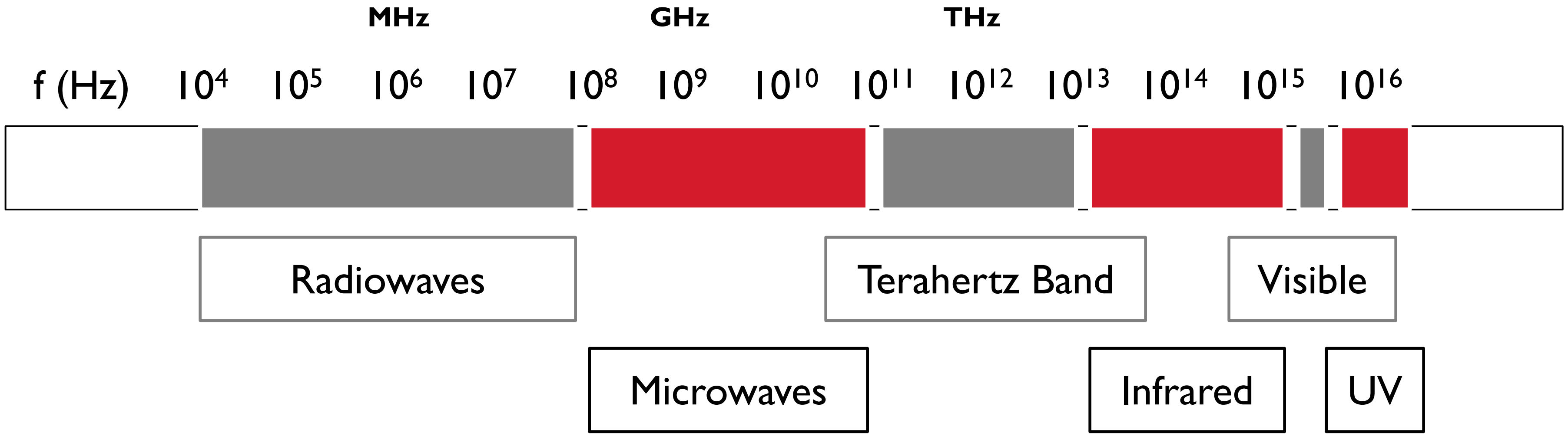
- Based on the transmission of electromagnetic (EM) waves, which propagate in the free space at close to the speed of light in the vacuum ($c \approx 3 \cdot 10^8$ m/s)



Radiowaves

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- **From 3 kHz to 300 MHz**
- **Properties:**
  - Easy to generate
  - Omnidirectional propagation
  - Transmission distance up to hundreds of km
  - Can penetrate buildings
- **Applications:**
  - AM radio broadcasting
    - f_c=[153-279 kHz, 531-1611 kHz, 2.3-26.1 MHz], B=10 kHz, Spacing=20 kHz
  - FM radio broadcasting
    - f_c=[87.5-108 MHz], B=20 kHz, Spacing=200 kHz
  - TV broadcasting
    - f_c=[54-806 MHz], B=[5-8 MHz]
  - Marine communication, air traffic control
  - …

Microwaves

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- **From 300 MHz to 30 GHz**
- **Properties:**
  - Easy to generate
  - Omnidirectional or directional propagation
  - Transmission distances decreases fast with distance (from hundreds of m up to few km)
  - Cannot easily penetrate buildings
- **Applications:**
  - Cellular telephony (1G, 2G, 3G, 4G and 5G New Radio Frequency-Range 1)
    - f_c=[806-960 MHz, 1710-2025 MHz, 2110-2200 MHz, 2600-2690, …], B=depends on standard=[200kHz, 20 MHz]
  - Cordless phones
    - f_c=[1.9, 2.4, 5.8 GHz], B=3.6 kHz
  - WiFi, Bluetooth, ZigBee
    - f_c=[2.4, 5 GHz}, B=depends on the standard

Millimeter Waves

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- **From 30 GHz to 300 GHz**
- **Properties:**
  - Harder to generate
  - Mostly directional propagation
  - Transmission distances decreases very fast with distance (from hundreds of m up to few km)
  - Cannot penetrate buildings
- **Applications:**
  - 5G New Radio Frequency Range 2
    - f_c=[24-250 GHz], B=up to 800 MHz
  - WiFi (IEEE 802.11ad and ay)
    - f_c=60 GHz, up to B=14 GHz (57-71 GHz)
  - …

Terahertz Band

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- **From 300 GHz to 10 THz (not yet regulated!)**
- **Properties:**
  - Not so easy to generate (becoming easier…)
  - Mainly directional propagation
  - Transmission distance below ten meters, unless ultra-directional systems are used
  - Cannot penetrate buildings, objects, etc.
- **Applications:**
  - Very high bandwidth applications (multi Gbps and Tbps links):
    - Next generation WLAN/WPAN
    - Next generation small cell systems
  - Electromagnetic Nanonetworks
  - …

Optical Wireless Communications

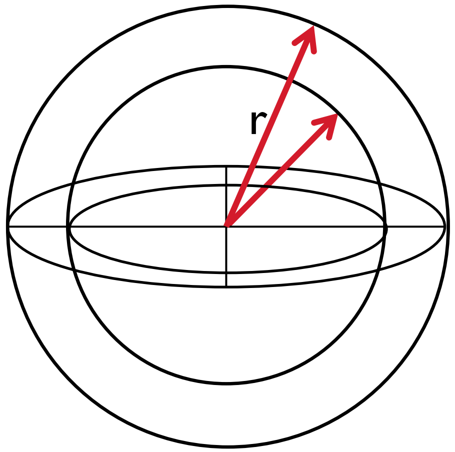
- **From 10 THz to 790 THz (infrared, visible, ultra-violet)**
- **Properties:**
  - Different technologies with different complexity and performance exists:
    - E.g., LEDs for low-cost OWC systems over short distances or more expensive lasers for LAN interconnection across buildings
  - Directional propagation only
  - Transmission distance changes drastically with application and technology (from few m up to km)
  - Cannot penetrate buildings, objects, etc.
- **Applications:**
  - Remote control for TV, DVD, etc.
  - LiFi: Indoor LAN with LEDs
  - Temporary network installation (e.g., fairs, conferences)
  - …

Wireless Propagation

- A wirelessly propagating signal might experience
  - **Delay:** The signals propagate at the speed of light, not instantaneously
  - **Attenuation**: The energy of the transmitted signal is distributed over larger areas as it propagates
  - **Distortion:** The waveform (shape) of the received signal is different from the transmitted one

Attenuation: Path Loss

- Measures how much power is lost as the signal propagates over longer distances
- The simplest model for the free space path-loss: the **Friis transmission equation**



$$P_{rx}(d) = P_{tx}G_{tx}\frac{1}{4\pi d^2}\frac{\lambda^2}{4\pi}G_{rx}$$

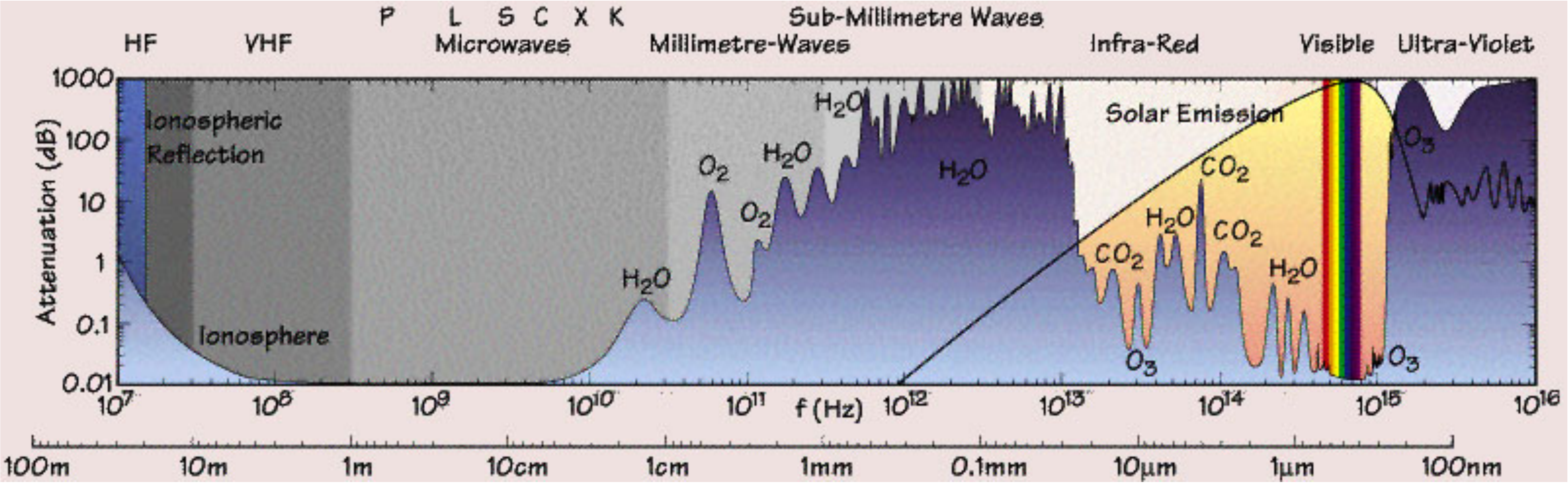
$$P_{rx}(d) = P_{tx}G_{tx}G_{rx}\left(\frac{\lambda}{4\pi d}\right)^2$$

$$P_{rx}(d) = P_{rx}(d_0)\left(\frac{\mathrm{d}_0}{d}\right)^2$$

- P_{rx} = Power at the receiver
- P_{tx} = Power at the transmitter
- d = distance
- G_{tx}= Antenna gain at the transmitter
- G_{rx}= Antenna gain at the receiver
- λ = c/f = Signal wavelength
- c = signal propagation speed
- f = signal frequency
- d_0= reference distance

Attenuation: Frequency Selectivity

- Attenuation might be different at different frequencies, because of different phenomena
  - For example, absorption by different molecules lead to frequency-selective behavior



Distortion Effects

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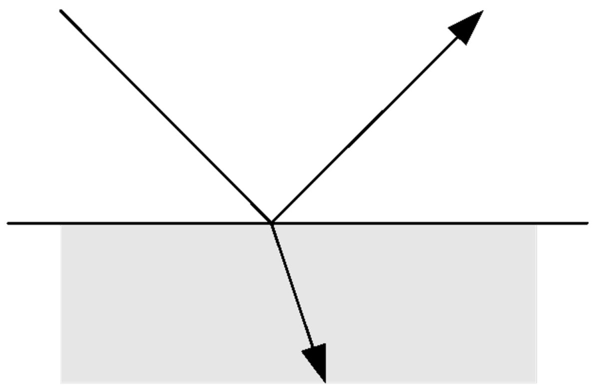
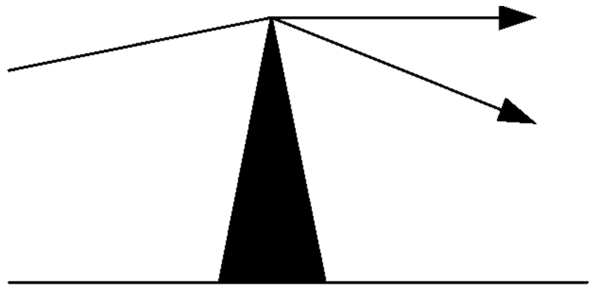
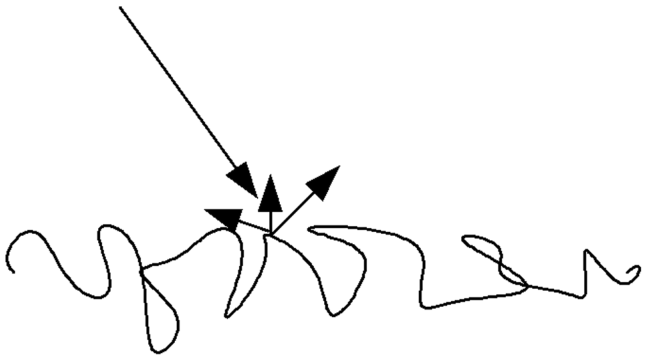
- Sources of distortion
  - **Reflection/refraction:** bounce of a surface; enter material
  - **Diffraction:** start "new wave" from a sharp edge
  - **Scattering:** multiple reflections at rough surfaces (e.g., tree leaves)
  - **Doppler fading:** shift in frequencies (loss of center)

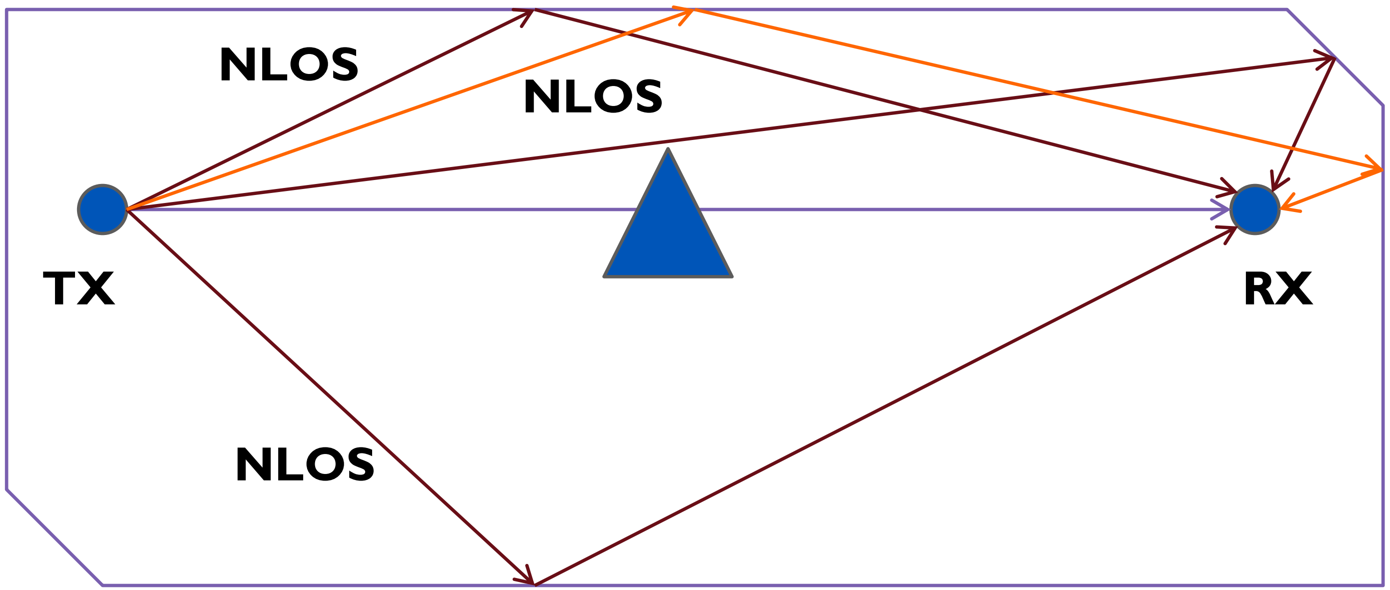


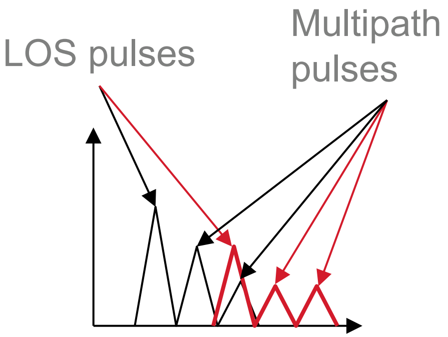




Distortion Effects: Non-line of Sight Paths

- Because of reflection, scattering, …, radio communication is not limited to the direct line of sight communication
  - Effects depend strongly on frequency, thus different behavior at higher frequencies

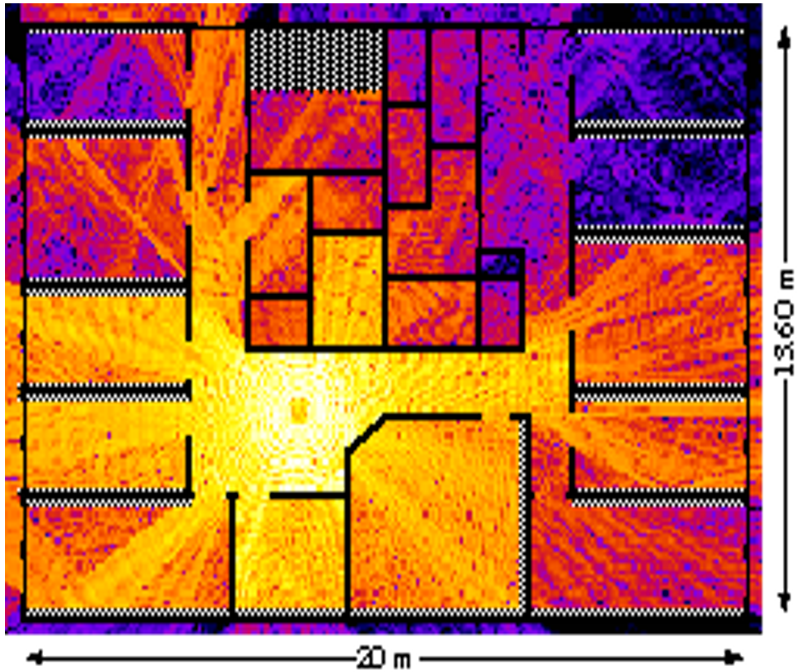


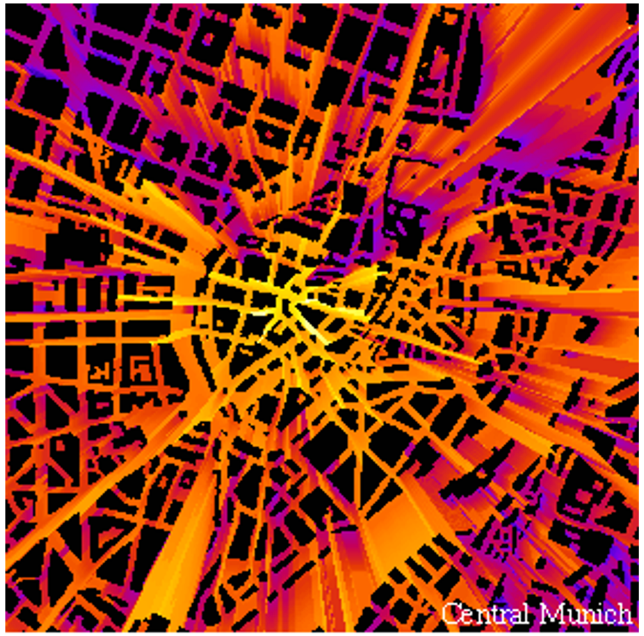


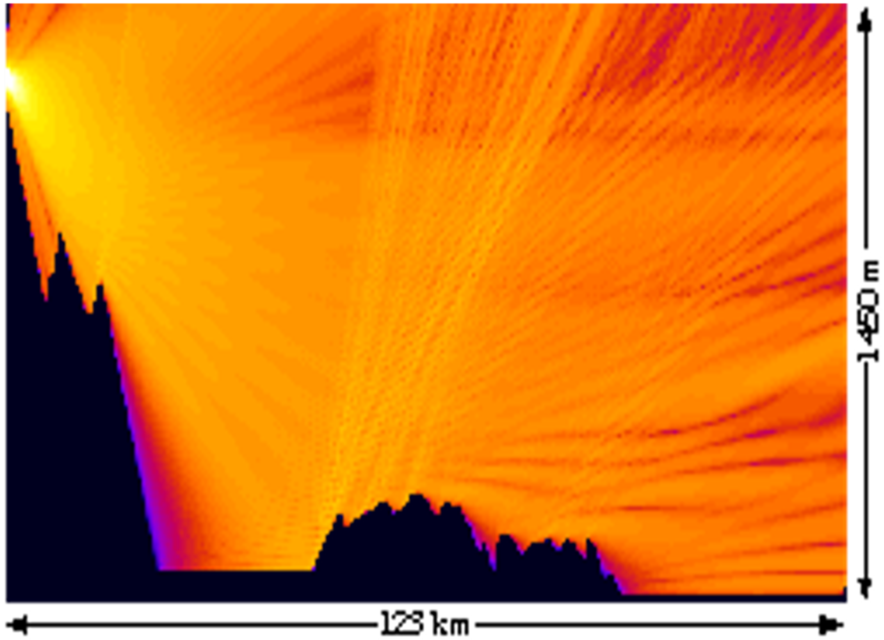
- Different paths have different lengths = propagation time
  - Results in **delay spread** of the wireless channel
  - Closely related to **frequency-selective fading** properties of the channel
  - With movement: **fast fading**

Wireless Signal Strength in Multi-path Environments

- Brighter color = stronger signal
- Obviously, simple (quadratic) free space attenuation formula is not sufficient to capture these effects







Path-loss in Multi-path Scenarios

- To take into account the stronger attenuation resulting from the presence of obstacles and multi-path propagation, a modified path-loss equation is used

$$P_{rx}(d) = P_{rx}(d_0)\left(\frac{\mathrm{d}_0}{d}\right)^{\gamma}$$

  - where γ is the path-loss exponent and, generally, $2 < \gamma < 5$
- This can also be rewritten in logarithmic form (in dBW):

$$P_{rx}(d)[dB] = P_{rx}(d_0)[dB] + 10\gamma \log_{10}\left(\frac{d_0}{d}\right)$$

- To take into account the random locations of the obstacles and their role, a Gaussian random variable with 0 mean and σ^2 variance can be added to the pathloss in dB

$$P_{rx}(d)[dB] = P_{rx}(d_0)[dB] + 10\gamma \log_{10}\left(\frac{d_0}{d}\right) + X_{\sigma}[dB]$$

  - This is equivalent to multiplying with a lognormal distributed r.v. in metric units
    - This is why we refer to this as lognormal fading

Noise and Interference

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- The received signal is further affected by
  - **Noise**
    - Temperature-dependent effects in the receiver electronics
    - Common model: **Additive White Gaussian Noise (AWGN)**
      - Noise is modeled as an additional random signal that appears at the receiver, independent of what is being received, and follows a Gaussian distribution with zero mean and the same power at all frequencies (that is what white means)
  - **Interference**
    - Co-channel interference: another sender uses the same spectrum
    - Adjacent-channel interference: another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it

- Conclusion: The received signal is distorted by the channel and corrupted by noise and interference
  - What is the result on the received bits?

Symbols and Bit Errors

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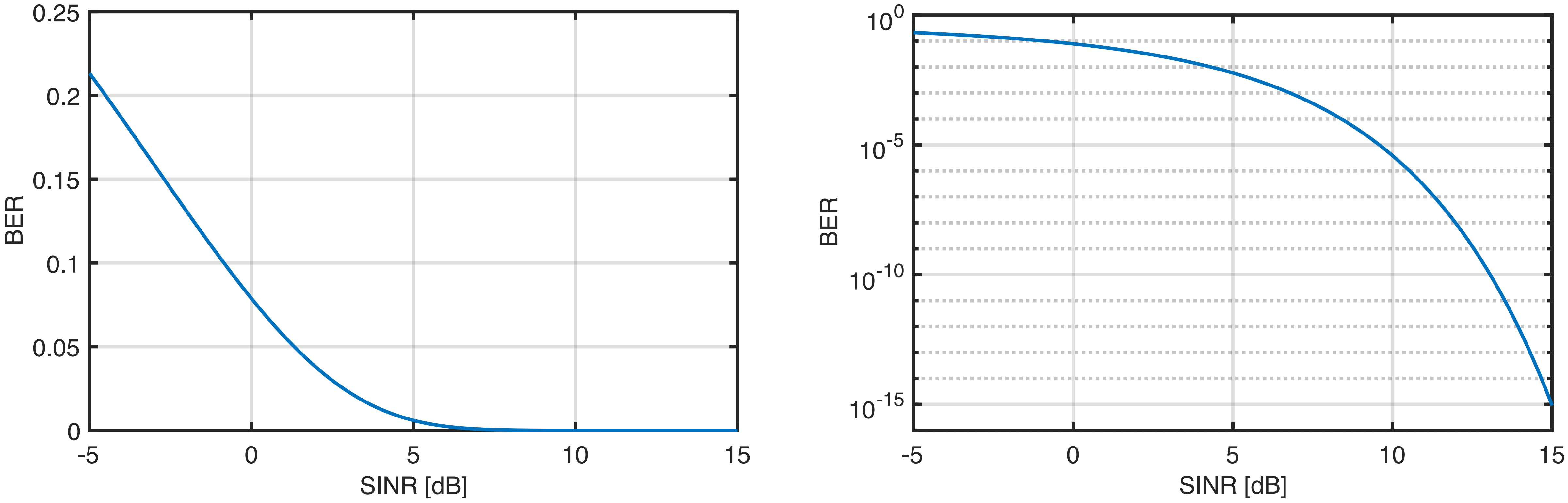
- Extracting symbols out of a distorted/corrupted waveform causes errors
- The number of errors depends on strength of the received signal compared to the corruption
  - This is measured by the **Signal to Interference plus Noise Ratio (SINR)**

$$SINR = 10\log_{10}\left(\frac{P_{rx}}{N_0 + \sum_{i=1}^{k} I_i}\right)$$

- The SINR allows to compute **Bit Error Rate (BER)** for a given modulation
  - Also depends on data rate (# bits/symbol) of modulation
  - E.g., for a Binary Phase Shift Keying modulation:

$$BER(SINR) = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \; with \; \frac{E_b}{N_0} = SINR \; (only\ for\ BPSK)$$

BER vs SINR



Notes: when plotting the BER, please use a logarithmic axis!
For a communication system to work properly, you should aim for BER=10^{-4} or lower!

(Analog) Channel Models

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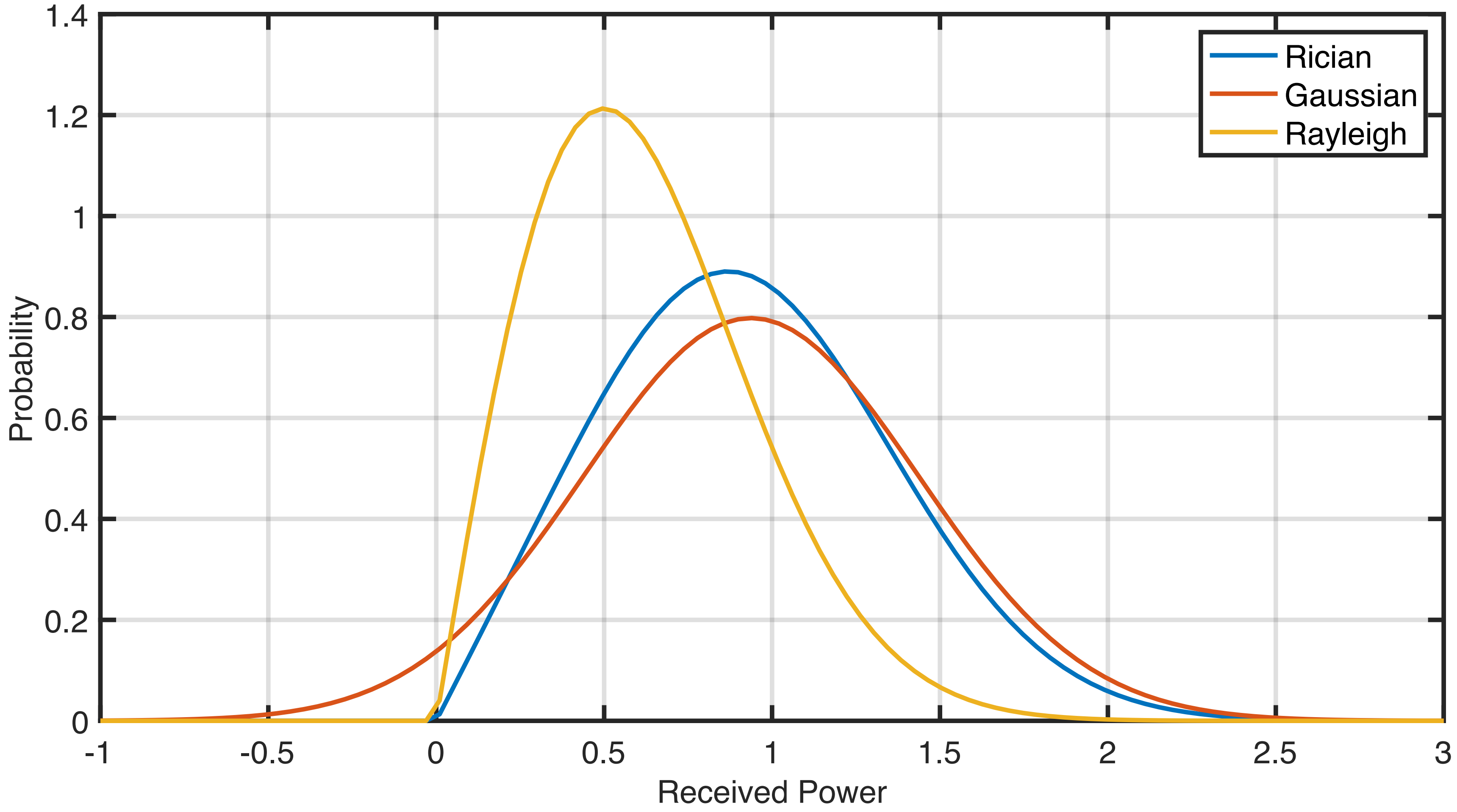
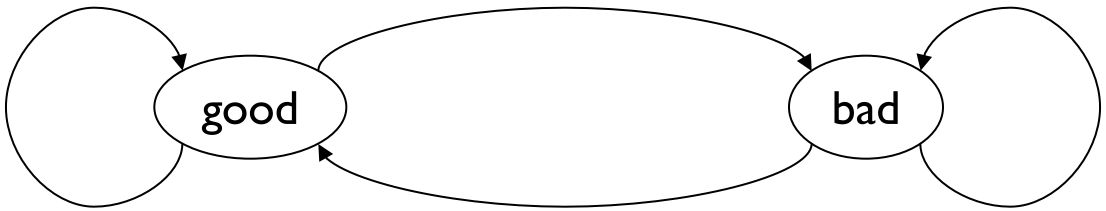
- When designing a networking application, being able to estimate the SINR (and, correspondingly, the BER) is extremely important
  - It determines for example how far apart the devices should be, how much power should they transmit, etc.
- To predict the SINR, we utilize channel models, which stochastically capture the behavior of the wireless channel
- Common channel models consider:
  - Transmission power P_{tx} is constant
  - Noise is additive, Gaussian and white (AWGN, Slide 49)
  - If free-space (no obstacles), there is one direct path for the signal → Friis equation (Slide 43)
  - If there is one dominant line-of-sight plus many indirect paths:
    - Signal has a Rice distribution (**Rice fading**)
  - If there is no line-of-sight path, but only many indirect paths:
    - Amplitude of resulting signal has a Rayleigh distribution (**Rayleigh fading**)
      - This is the model used for the majority of mobile scenarios at frequencies < 6 GHz

Channel Models



(Digital) Channel Models

- Instead of calculating signals, these are aimed at directly modeling the resulting bit error behavior
- Many models:
  - Binary symmetric channel (BSC)
    - Each bit is erroneous with constant probability, independent of the other bits
  - Markov models – states with different BERs
    - Example: Gilbert-Elliot model with "bad" and "good" channel states and high/low bit error rates



  - Fractal channel models describe number of (in-)correct bits in a row by a heavy-tailed distribution

Wireless Channel Quality – Summary

- Wireless channels are substantially worse than wired channels
  - In throughput, bit error characteristics, energy consumption, …
- Wireless channels are extremely diverse
  - There is no such thing as THE typical wireless channel
- Various schemes for quality improvement exist
  - Some of them geared towards high-performance wireless communication – not necessarily suitable for IoT
  - Some of them general-purpose
  - Energy issues need to be taken into account!

Choice of Modulation

- With all this knowledge in mind, going back to "signals", how do we pick a modulation?
  - Consider: required data rate, available symbol rate, implementation complexity, required BER, channel characteristics, …
  - Tradeoffs: the faster one sends, the longer one can sleep
    - However, power consumption can depend on modulation scheme
  - Tradeoffs: symbol rate (high?) versus data rate (low)
    - Use m-ary transmission to get a transmission over

- Adapt modulation choice to operation conditions
  - Akin to dynamic voltage scaling, introduce Dynamic Modulation Scaling

Summary of the Physical Layer

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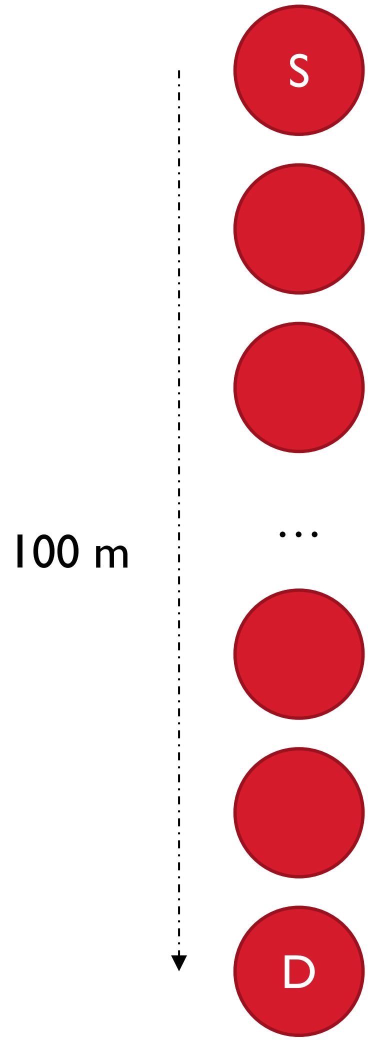
- Wireless radio communication introduces many uncertainties and vagaries into a communication system
- Handling the unavoidable errors will be a major challenge for the communication protocols
- Dealing with limited bandwidth in an energy-efficient manner is the main challenge
- Ideally, we design the hardware (transceiver and antennas) and the software (at least the physical layer) together:
  - That is why we need ECE!!!!

Class Exercise

- Consider the scenario on the right, with a source and a destination node 100 m apart. The transceiver in each node has the following specifications:
  - Transmitter:
    - Frequency of operation: 2.4 GHz
    - Transmission power, P_{tx}: 10 mW
    - Antenna gain: 0 dBi
  - Receiver:
    - Antenna gain: 0 dBi
    - Noise power model, P_N: k*B*T, where
      - k=Boltzmann constant = $1.380649\times10-23$ J/K
      - B=system bandwidth [Hz]
      - T=system temperature [Kelvin degrees]



Class Exercise

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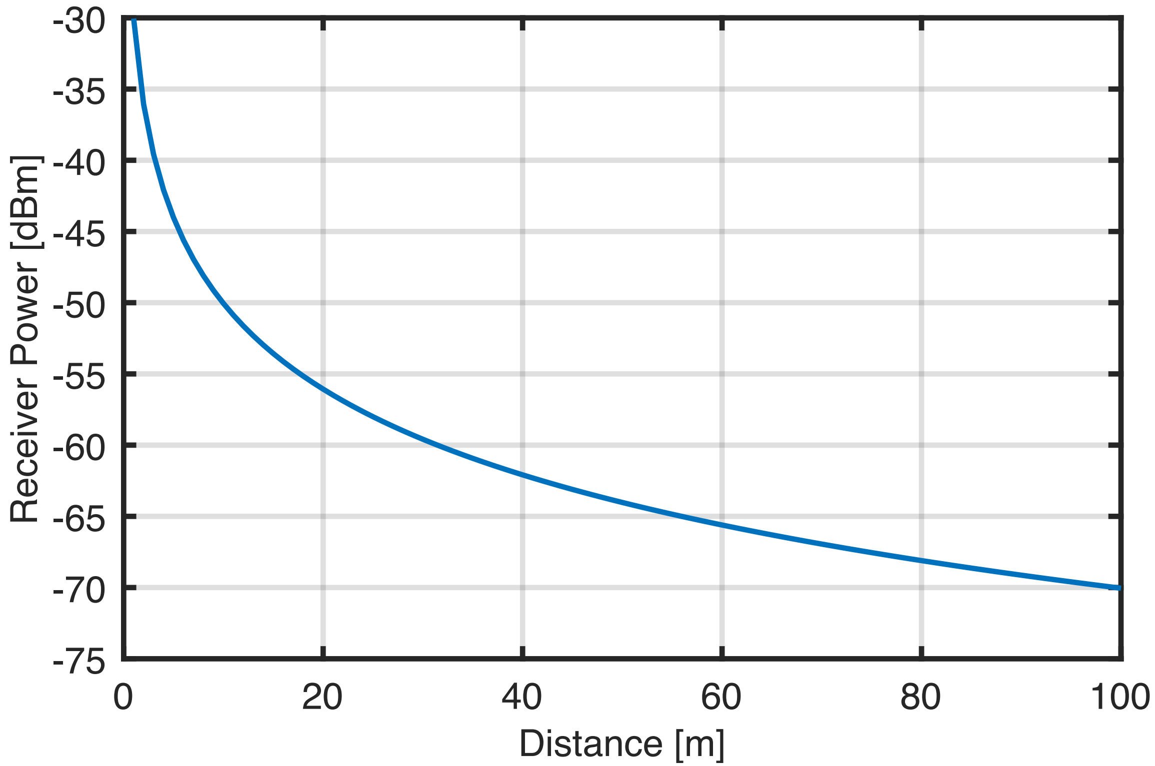
- 1) Under the assumption of free-space propagation, compute and plot the received power in dBm as a function of distance.

Class Exercise

$$P_{rx}(d) = P_{tx}G_{tx}G_{rx}\left(\frac{\lambda}{4\pi d}\right)^2$$

$$P_{rx}(d)[dBm] = P_{tx}[dBm] + G_{tx}[dBi] + G_{rx}[dBi] + 20\log_{10}\frac{\lambda}{4\pi d} \qquad \lambda = \frac{c}{f}$$

$$P_{rx}(d)[dBm] = 10\log_{10}(10\text{ mW}) + 0\text{dBi} + 0\text{dBi} + 20\log_{10}\frac{\text{c}}{4\pi\text{fd}}$$



How meaningful is this?

Class Exercise

- 2) On the same figure, plot the noise in dBm at the receiver for the following two scenarios:
  - T=1000 K, B=10 MHz
  - T=1000 K, B=100 MHz

Class Exercise

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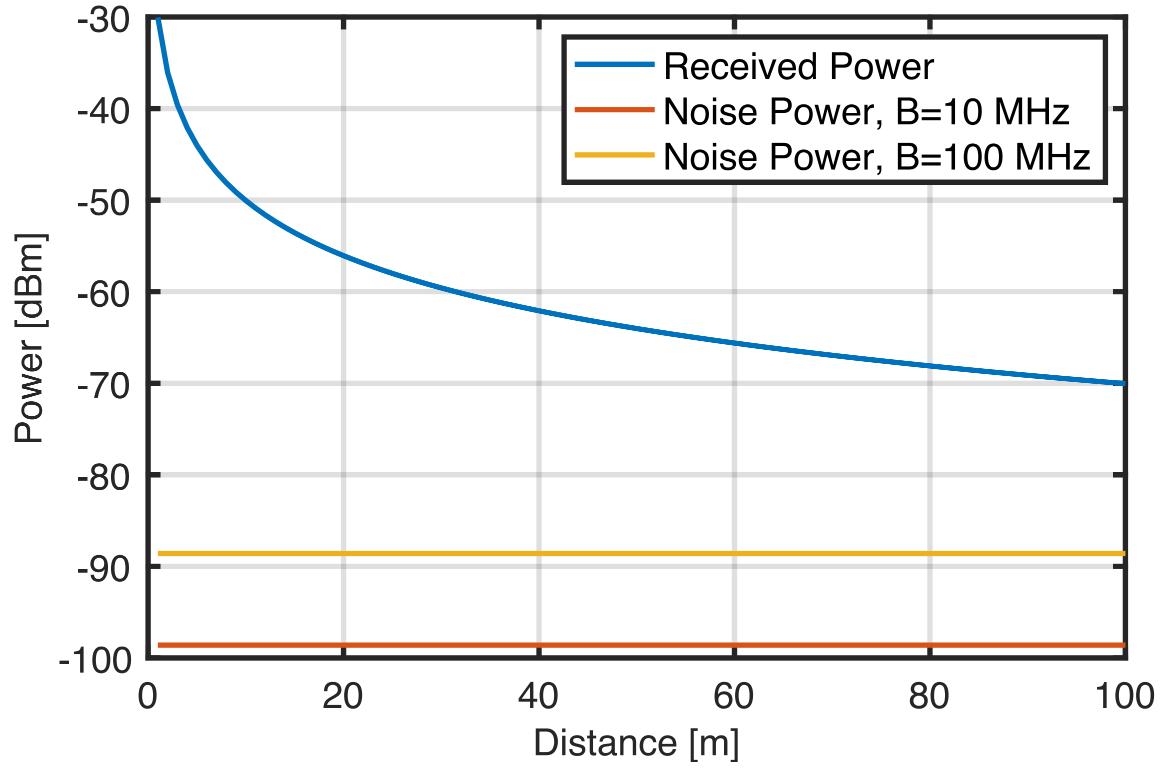
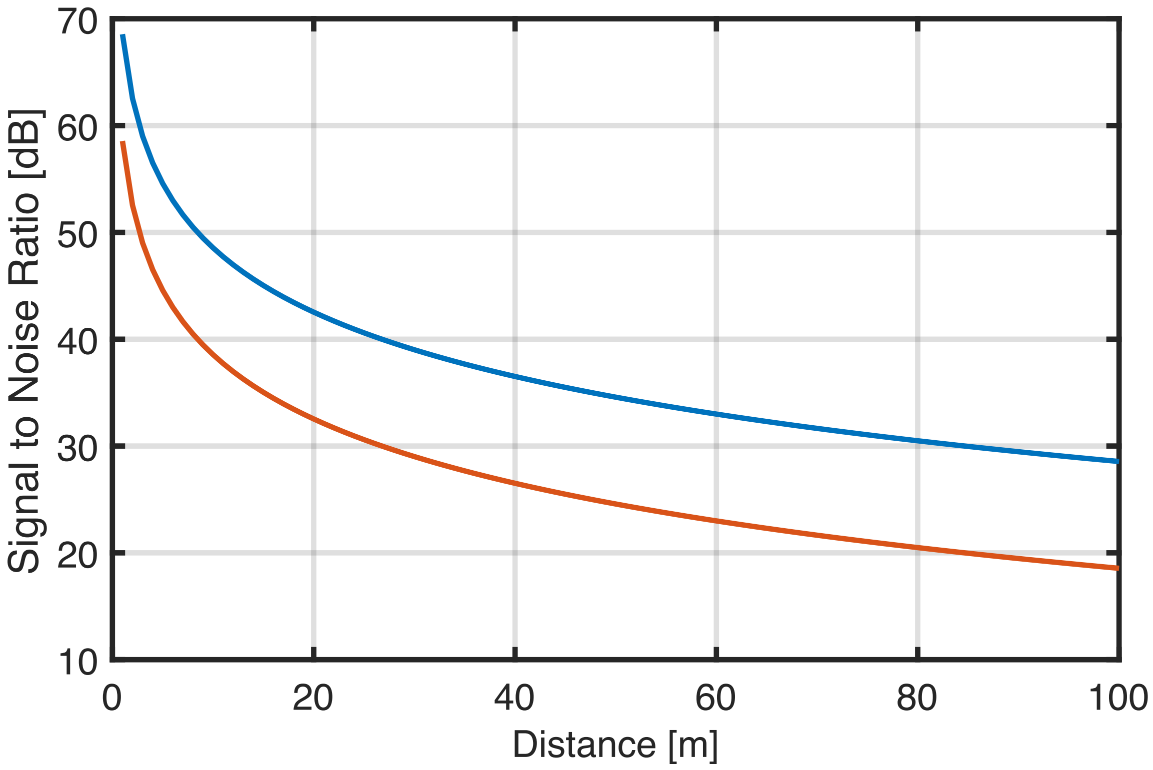
$$P_N[dBm] = 10\log_{10} kBT + 30$$ (to convert from dBW to dBm)





The power is much larger than the noise, good!

Class Exercise

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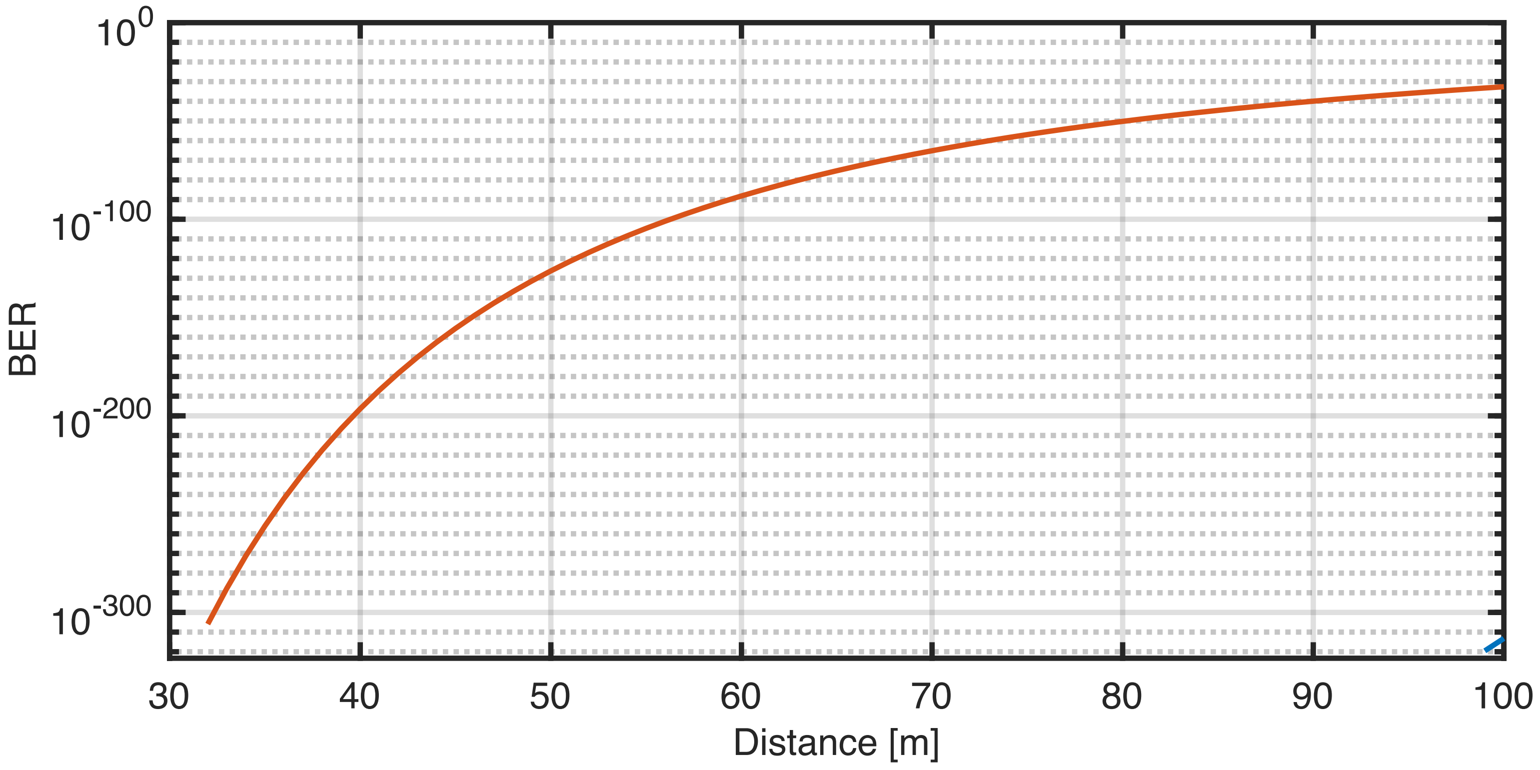
- 3) Under the assumption that a BPSK modulation is being used, what is the bit error rate (BER) as a function of distance?

Class Exercise

$$BER(SINR) = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)\ with\ \frac{E_b}{N_0} = SINR\ (only\ for\ BPSK), in\ linear\ scale$$



Class Exercise

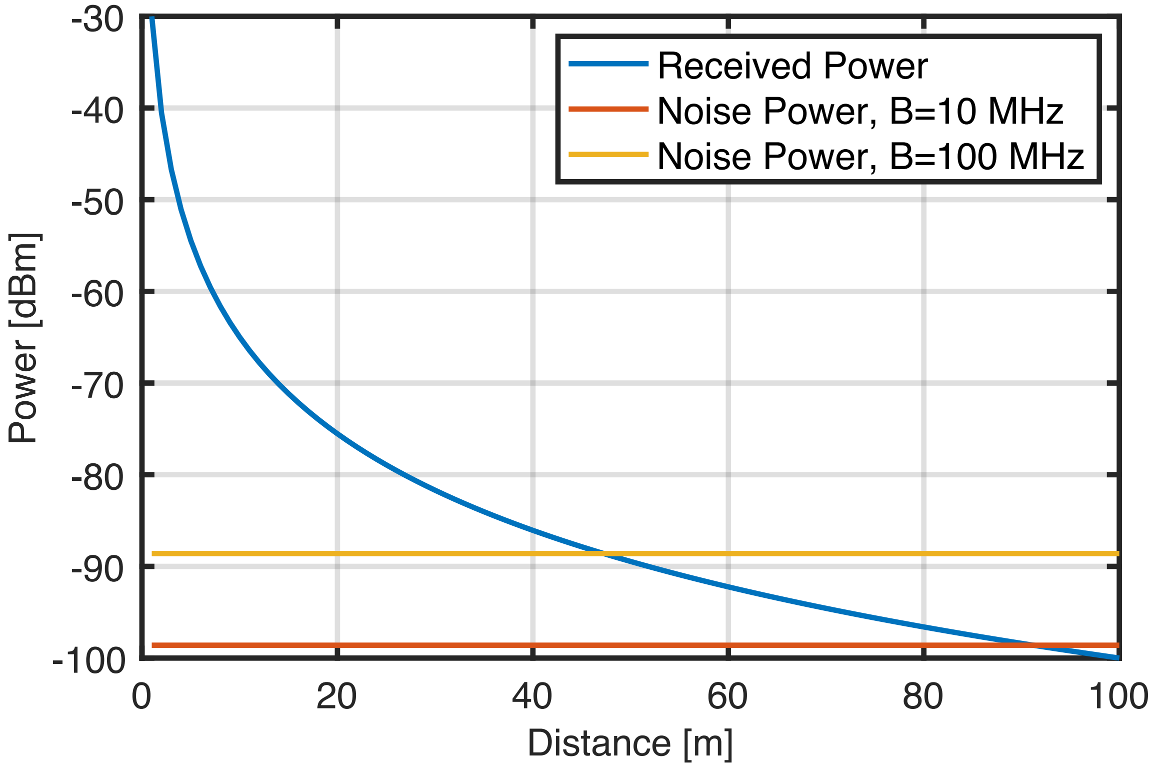
- 4) Let's consider that the system is no longer in free-space, but inside of a building, with multi-path propagation. Consider a reference distance d_0=1 m, and a propagation exponent of γ=3.5.
  - Plot the received power, the SNR and the BER as functions of distance

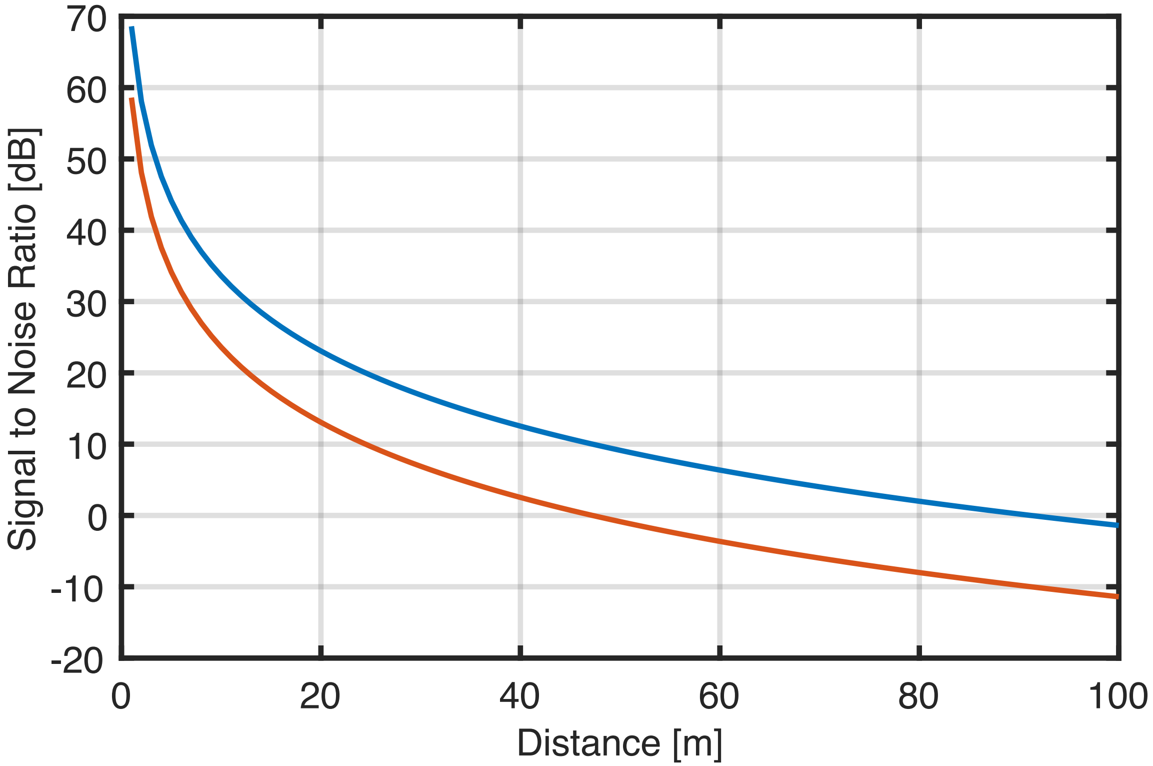
Class Exercise

$$P_{rx}(d)[dB] = P_{rx}(d_0)[dB] + 10\gamma \log_{10}\left(\frac{d_0}{d}\right)$$

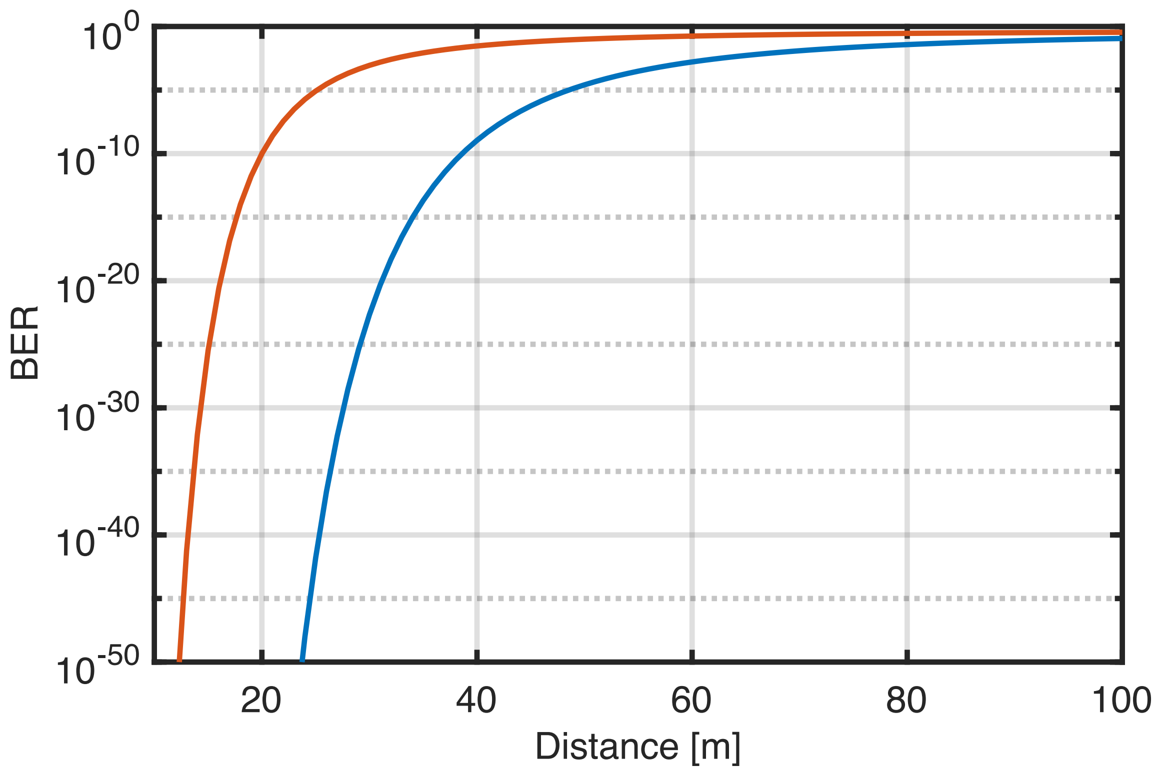
We consider free-space until 1 meter, then not free space

$$P_{rx}(d0)[dBm] = -30\ dBm$$





Class Exercise



- Now this is more of a problem.
- Things just get worse:
  - Random fading
  - Multi-user interference
- *More in your homework*