Information & Communication Technologies
for the Internet-of-Things

Wireless Propagation.
Modulation.

Pedro Santos

Fully original content.

Thanks to:

Peter Steenkiste (CMU)

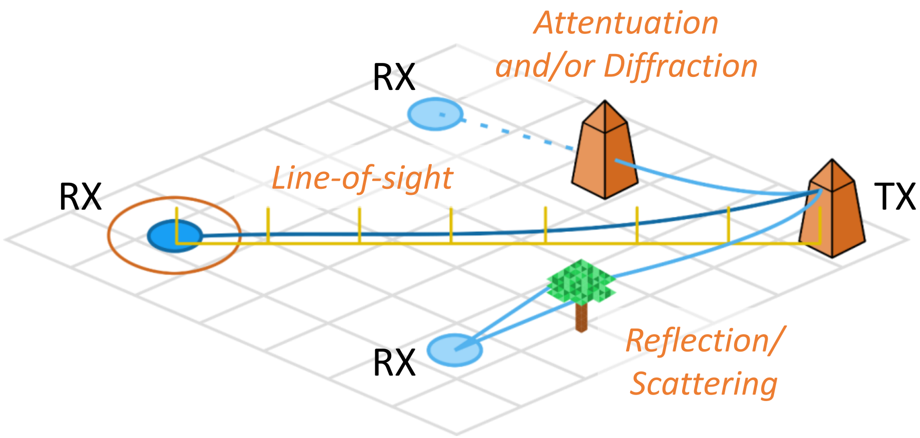
T. Rappaport

Outline

- Wireless Propagation
- Modulations
- Orthogonal Frequency Division Multiplexing
- Multiple-Input Multiple Output

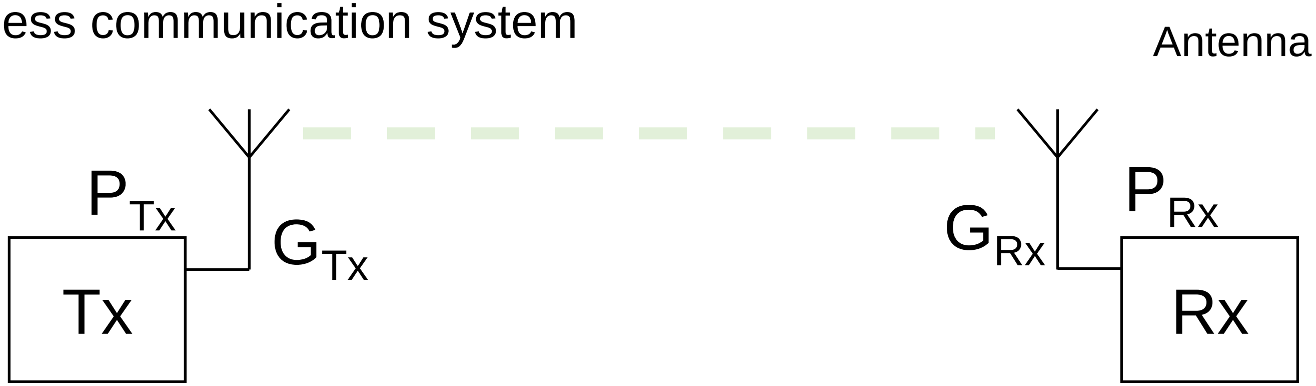
What is channel modelling?

- Electromagnetic (EM) / Radio-frequency (RF) waves suffer power attenuation between transmitter and receiver – this is called the **path loss**
- It is useful to be able to estimate the received power, given a known transmit power
- The RF power degradation can be due path loss
  - This is a physical-world rule
- The way a particular setting affects



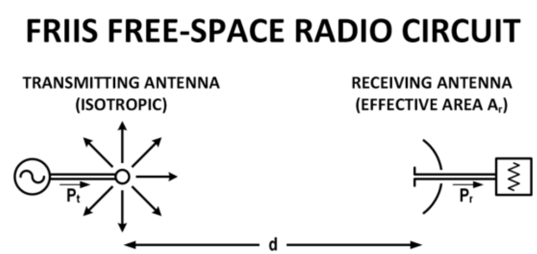
Communication Systems

- Wireless communication system



- Friis transmission equation
  - P_r – Received power
  - P_t – Transmitted power
  - G_r – Antenna gain of receiver
  - G_t – Antenna gain
  - λ – Wavelength
  - d – Distance

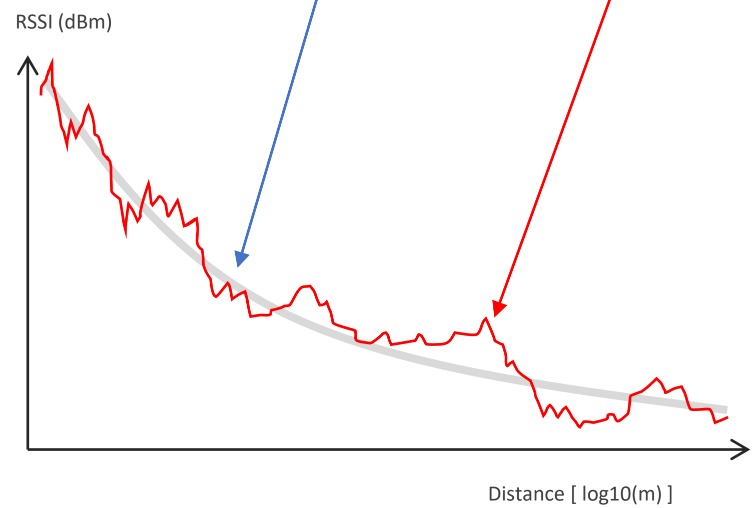
$$P_r = GtGr\,\overbrace{\left(\frac{\lambda}{4\pi d}\right)^2}^{\text{Free Space Path Loss (FSPL)}} P_t$$



Propagation Components

- A propagation model can be broadly broken down into two main components
  - **Large-scale Propagation**
    - Typically modelled as deterministic
    - Includes
      - Path loss
      - Obstacle Attenuation
      - Reflections
      - Diffraction
      - Scattering
  - **Small-scale Fading**
    - Typically modelled as stochastic

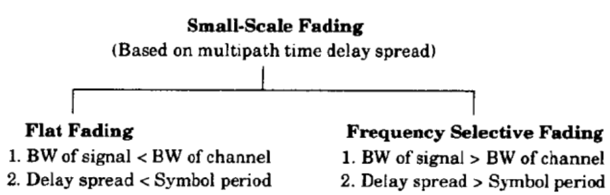
$$\rho_{[\text{dBm}]}(d) = \underbrace{\rho_0 - 10\,\alpha\,\log\left(\frac{d}{d_0}\right)}_{\textit{Deterministic component}} + \underbrace{X_\rho, \qquad X_\rho \sim N_{\sigma_\rho}}_{\textit{Stochastic component}}$$

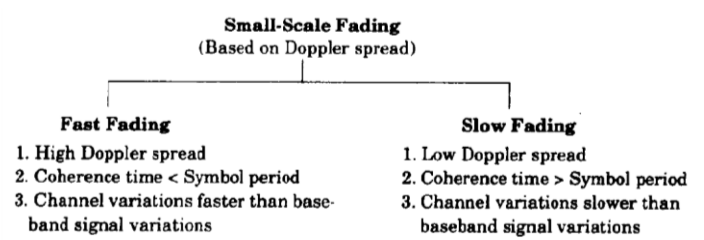


Propagation Components

- **Large-scale Propagation**
  - Path loss
  - Reflection: occurs when a propagating electromagnetic wave impinges upon an object that has very large dimensions when compared to the wavelength of the electromagnetic wave.
  - Diffraction: occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities (edges).
  - Scattering: occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large.

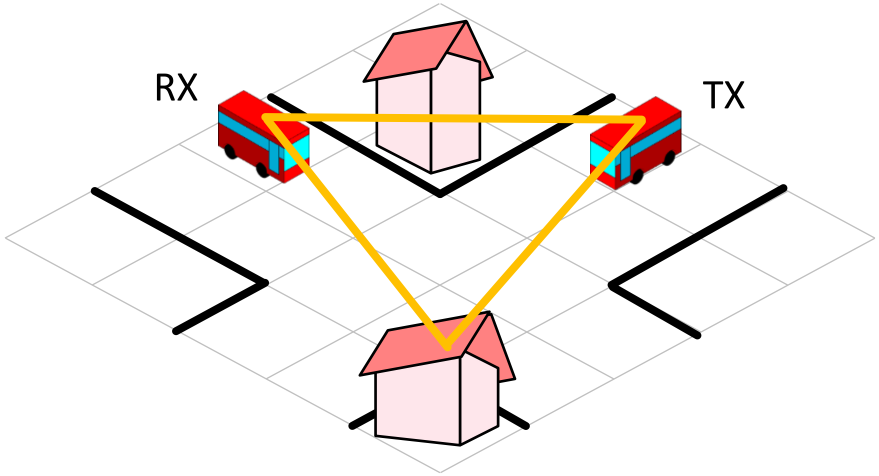
- **Small-scale Fading**





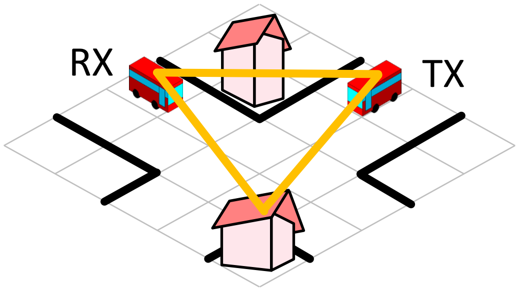
Line-of-sight (LoS)

- Line-of-sight refers to the direct, unobstructed line between transmitter and receiver
- However, communication can still occur even if an obstacle exists!
  - Wavelengths typically used in RF can pass through solids, unlike visible wavelengths, although with attenuation
    - This is related to the wavelength size in proportion to the solid’s dimension.
  - Reflections can still occur! This is very important, as reflections can:
    - Affect received signal
    - Actually be the main component (if no LoS exists)



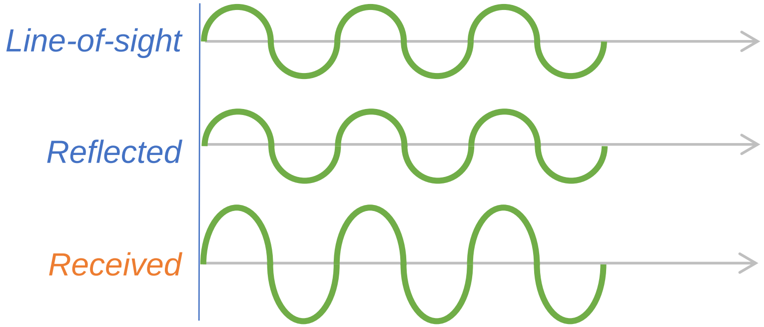
Obstacle Attenuation

Reflections

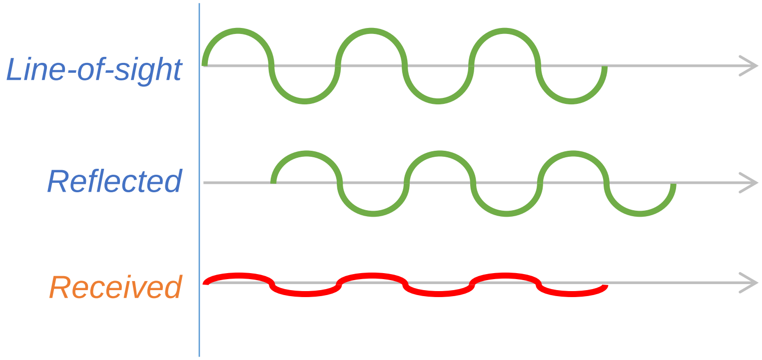


- Rays reflected by environmental objects will arrive to the receiver
- This is very dependent on the scenario in which propagation is happening
  - Can be parametrized in the model
  - Develop geometry-based models
- The power of the reflected signals is normally inferior to the LoS signal
- Depending on the phase shift between LoS ray and reflected rays, the receiver may experience constructive or destructive interference.
- But that's for just two rays…

Constructive Interference

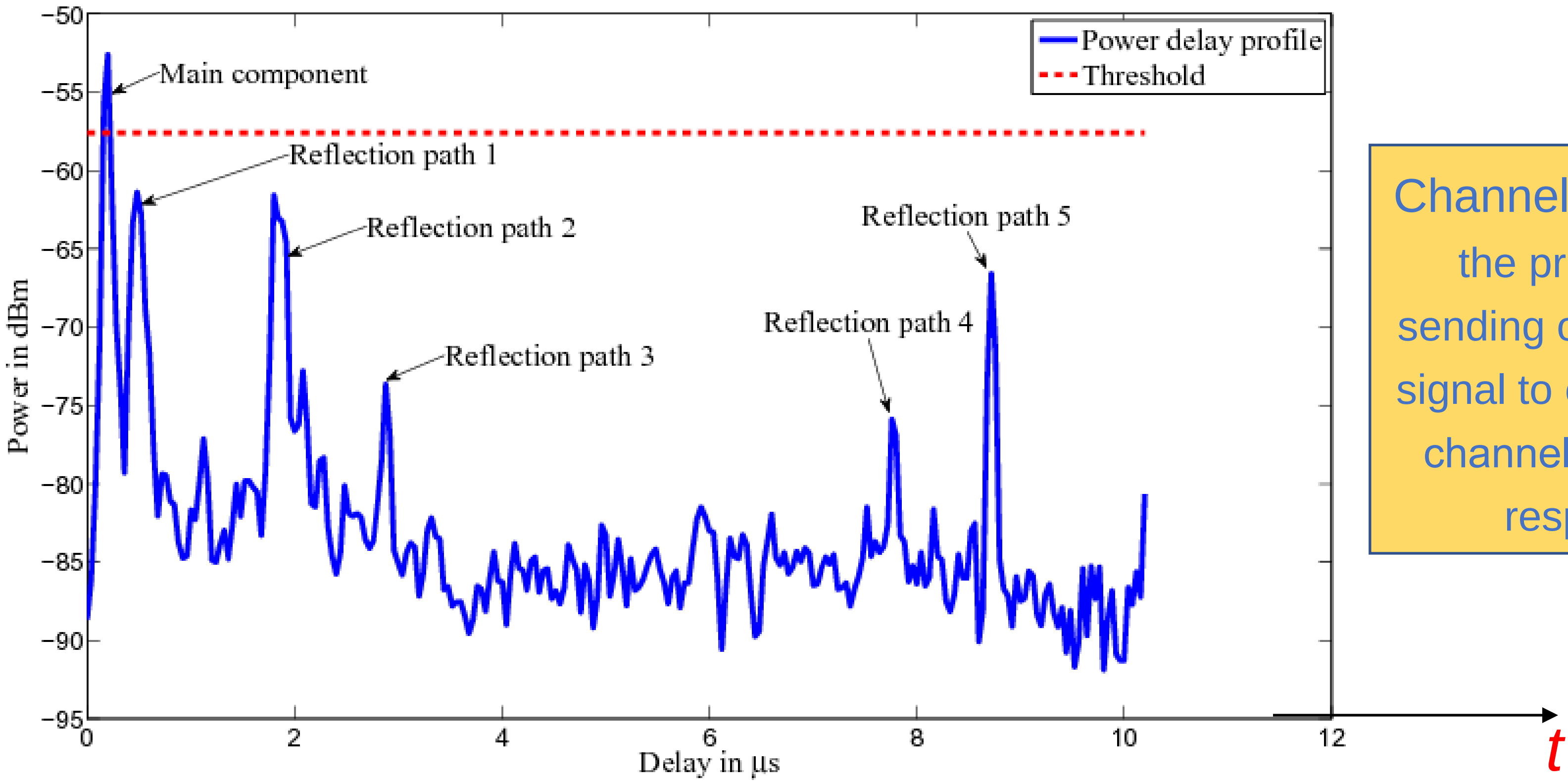


Destructive Interference



Reflections

- You can have multiple reflections arriving with different times!
- This is dealt with at the signal modulation stage.



Channel sounding: the process of sending one impulse signal to observe the channel’s impulse response

Yang, Kun & Roste, Terje & Bekkadal, Fritz & Ekman, Torbjörn. (2010). Channel characterization including path loss and Doppler effects with sea reflections for mobile radio propagation over sea at 2 GHz. 1-6. 10.1109/WCSP.2010.5633545.

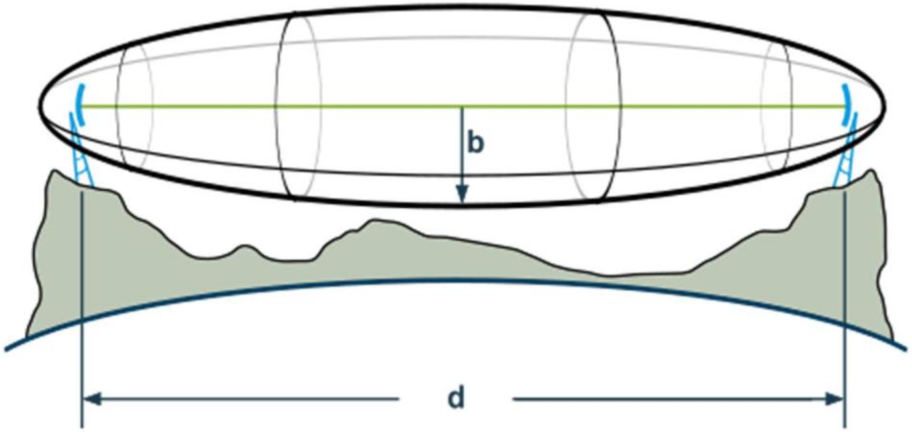
Diffraction

- Diffraction allows radio signals to propagate around the curved surface of the Earth, beyond the horizon, and to propagate beyond obstructions – Rappaport

- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities (edges).
- The secondary waves resultaing from the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of waves around the obstacle, even when a line of sight does not exist between transmitter and receiver.

Diffraction & the Fresnel Ellipsoid

- Sequence of ellipsoids centered around the LOS path between a transmitter and receiver
- The zones identify areas in which obstacles will have different impact on the signal propagation
  - Capture the constructive and destructive interference due to multipath caused by obstacles



Scattering

- Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelenght, and where the number of obstacles per unit volume is large.
- Scattered waves are produced by rough surfaces, small objects or by other irregularities in the channel.
- In practice, foliage, street signs and lamp posts induce scattering in a mobile communications systems.

Types of Scenarios

- Channel models can be parametrized for the type of scenario
- Examples
  - Indoor
    - Office building
    - Residential
    - Industrial
  - Outdoor
    - Open field
    - Vehicular
      - Urban / urban canyon
      - Semi-urban
      - Highway

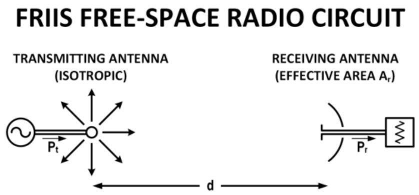
Classes of Propagation Models

- **Simple Path Loss**
  - Free-space path loss (FSPL)
  - Empirical log-distance path loss: drawn from measurements
- **Geometry-based**
  - Two-ray ground reflection model
  - N-ray (or Ray Tracing)

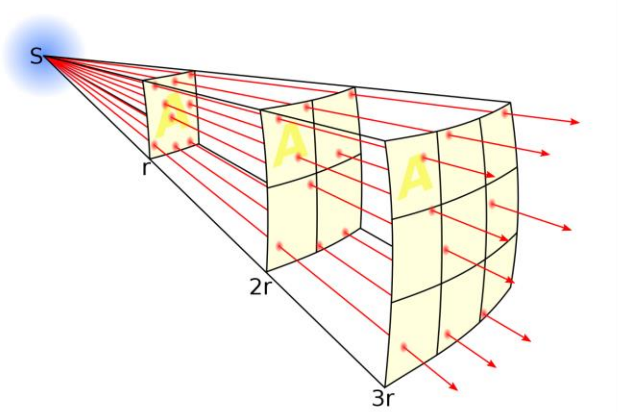
Free Space Path Loss (FSPL)

d – distance
f – frequency
c – light speed

- Model defined from physical EM propagation rules
- Associated to the Friis transmission equation



$$\mathrm{FSPL} = \left(\frac{4\pi d f}{c}\right)^2$$

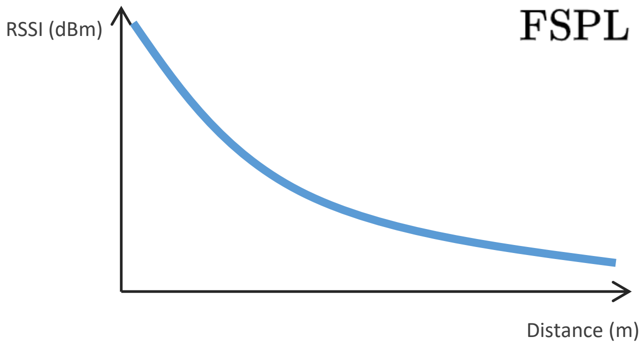


A few clarifications

- Log-normal representation

$$\text{FSPL}(\text{dB}) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

Received Signal Power



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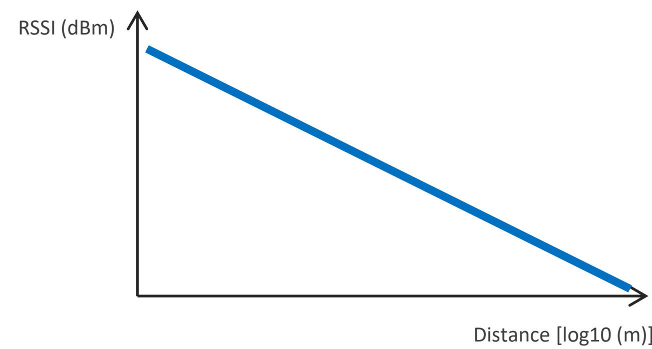
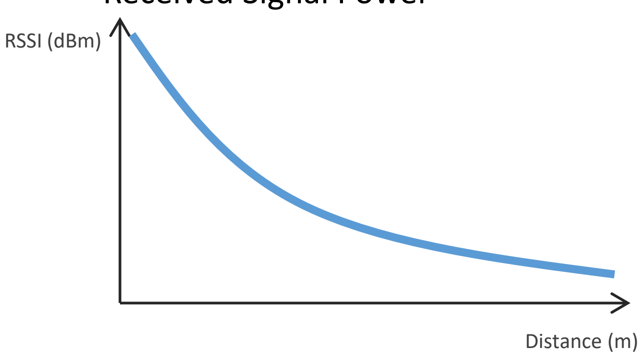
Received Signal Power



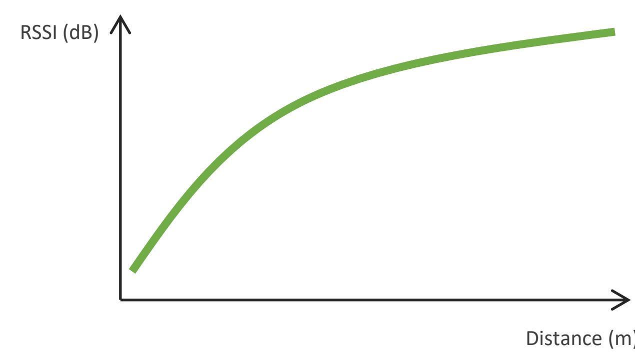
- Received Signal Power vs. Path Loss Attenuation

Received Signal Power



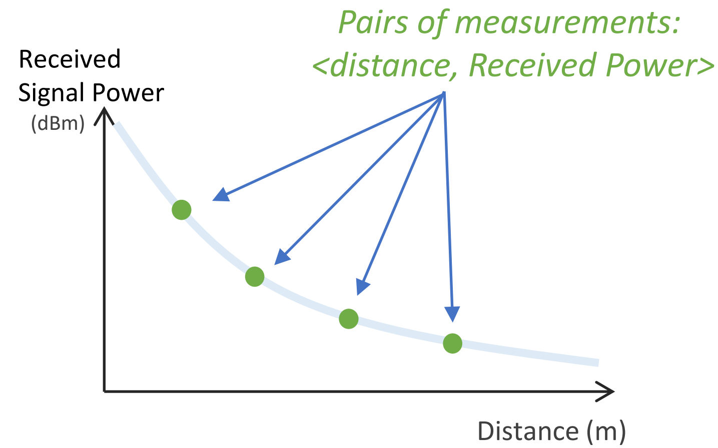
$$\boxed{P_r} = GtGr \boxed{\left(\frac{\lambda}{4\pi d}\right)^2} P_t$$

Path Loss



Empirical Path loss

- You can take measurements at a given location, specifically pairs of <distance, received signal power>
- Through regression (normally linear), you can obtain parameter values specific for that environment
  - Path loss exponent - α



Path loss Exponent (estimated via regression)

Measurement distances (measured)

$$\rho_{[\mathrm{dBm}]}(d) = \rho_0 - 10\,\alpha\,\log\left(\frac{d}{d_0}\right) + X_\rho, \qquad X_\rho \sim N_{\sigma_\rho}$$

Received Power (measured)

Power at reference distance (single measurement)

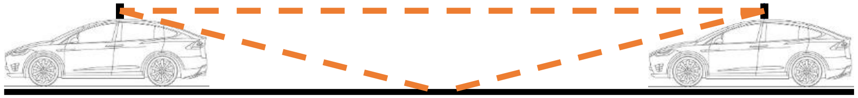
Reference distance (single measurement)

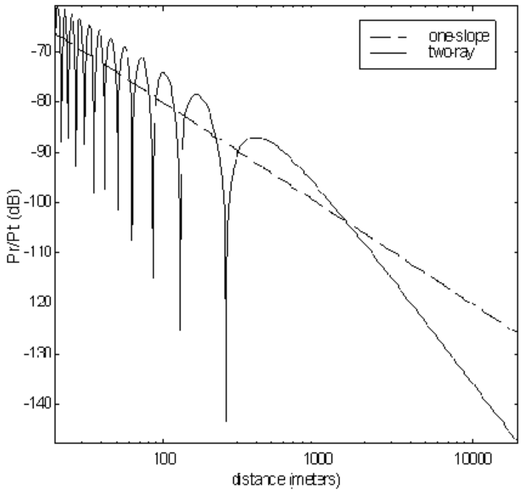
Table 3.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Two-ray Ground Reflection

- The two-ray ground reflection model accounts for the LoS ray and the ray reflected on the ground

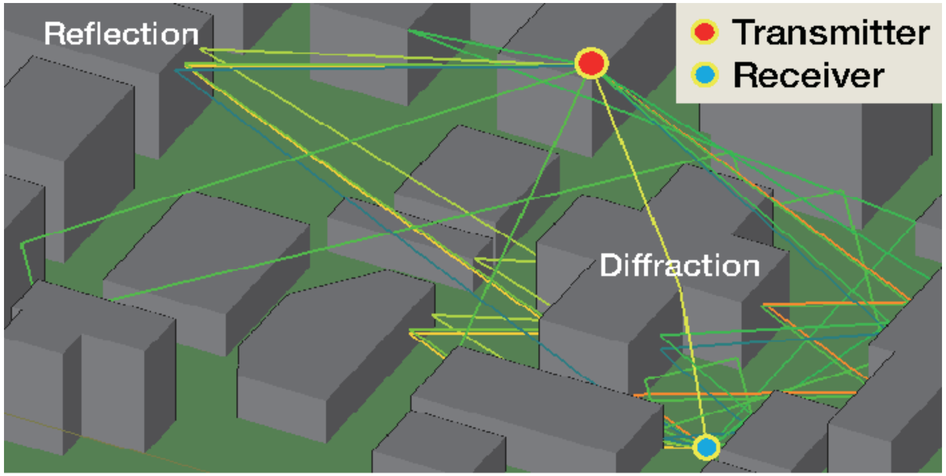




Thomas Schwengler. Wireless and Cellular Communications. http://morse.colorado.edu/~tlen5510/text/classwebch3.html

N-ray models, or Ray-Tracing

- Some works attempt to model extensively a significant number of rays in a given environment
- This tends to lead to very computationally expensive methods
- Cost-benefit trade-off can be dubious sometimes

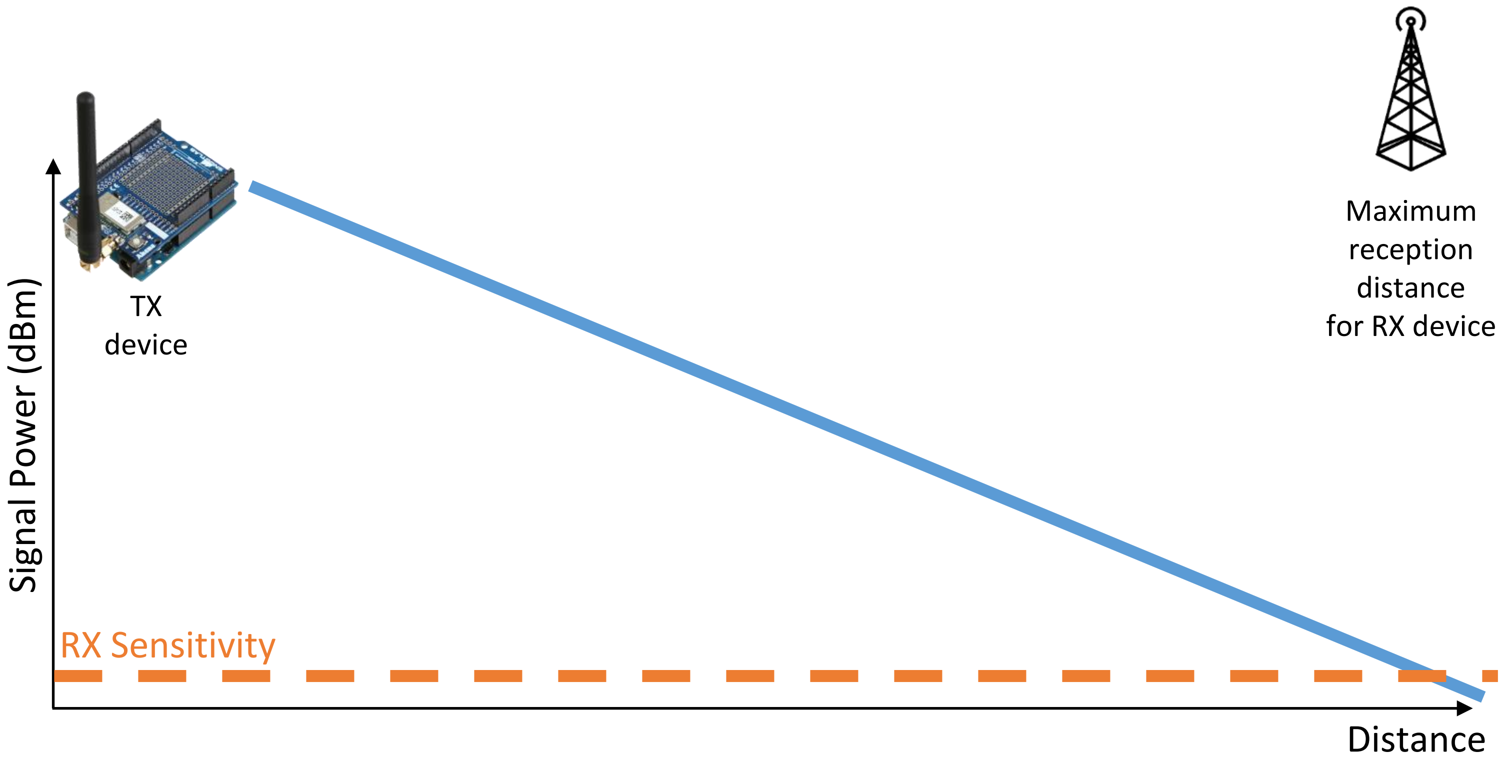


(c) Example of ray-tracing with the strongest 25 rays

Chang, Y., Baek, S., Hur, S., Mok, Y.J., & Lee, Y.: "A novel dual-slope mm-Wave channel model based on 3D ray-tracing in urban environments". In IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC), pp. 222-226, 2014.

Link Budget

- Transmit power (Transmitter)
- Sensitivity (at Receiver)



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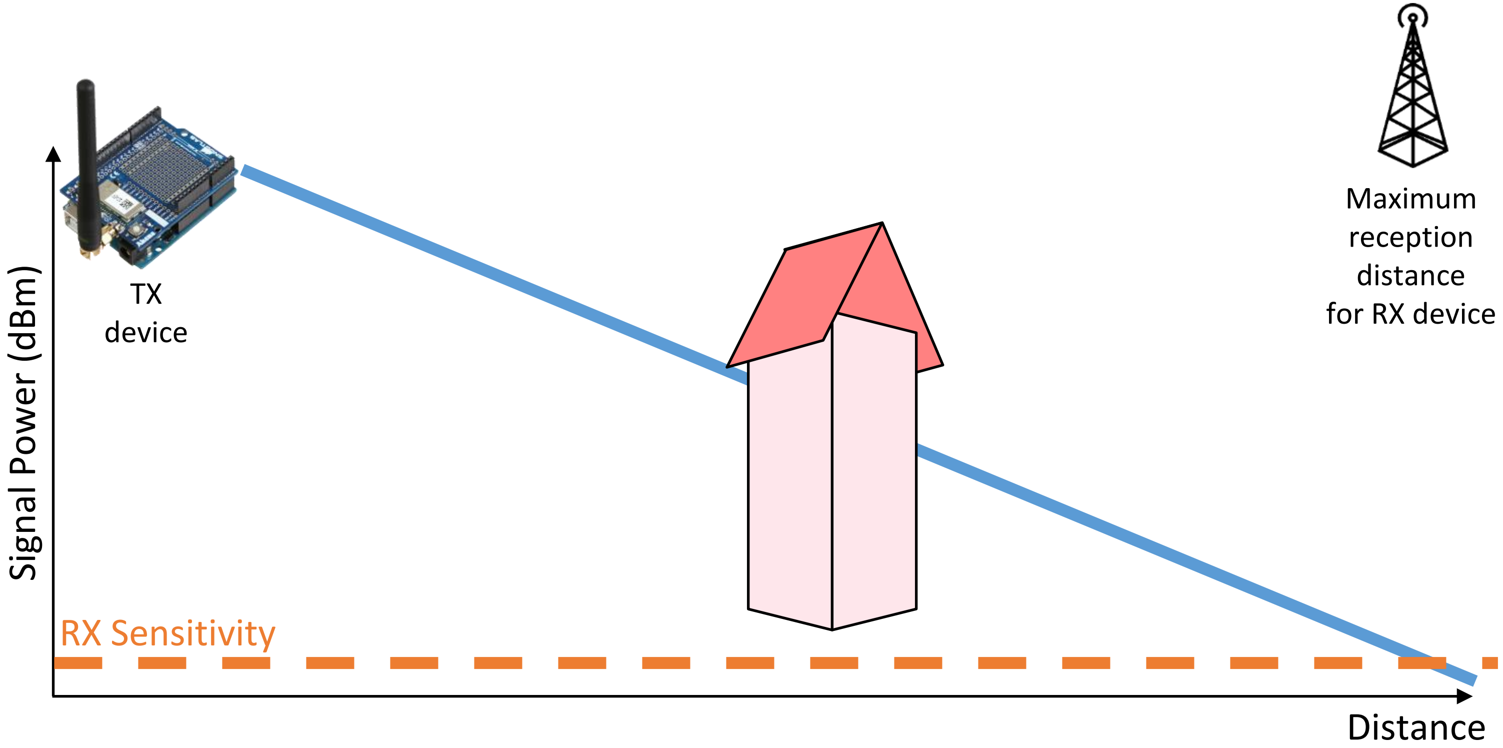

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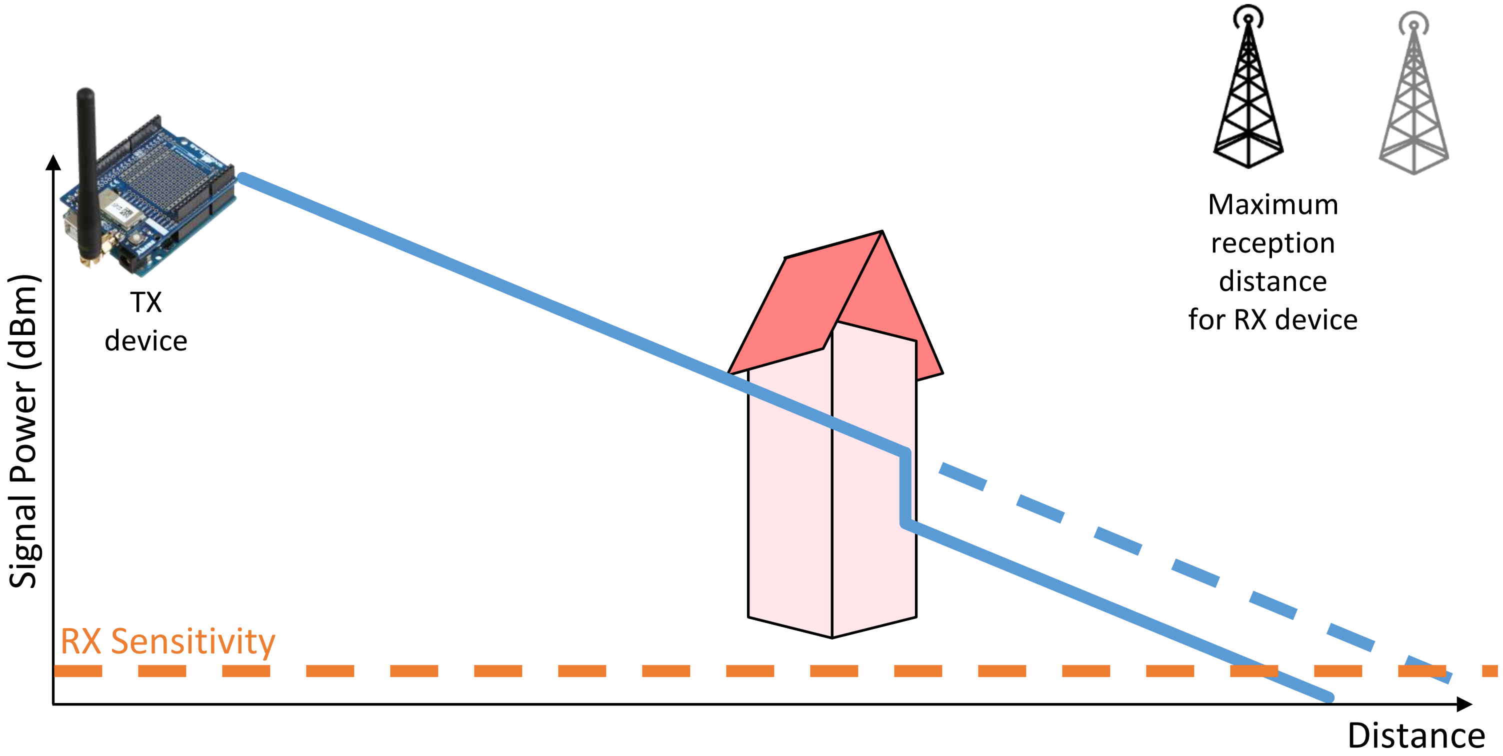

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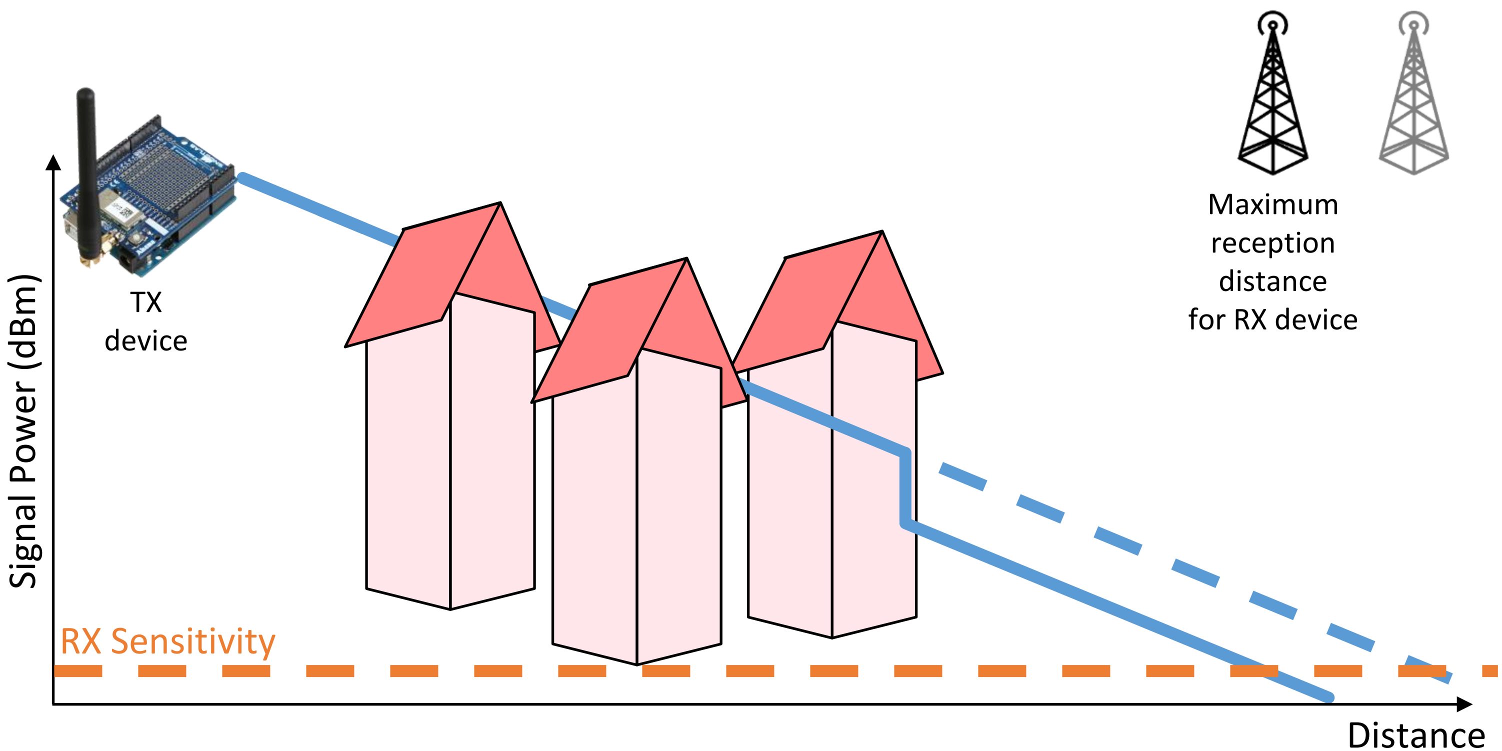

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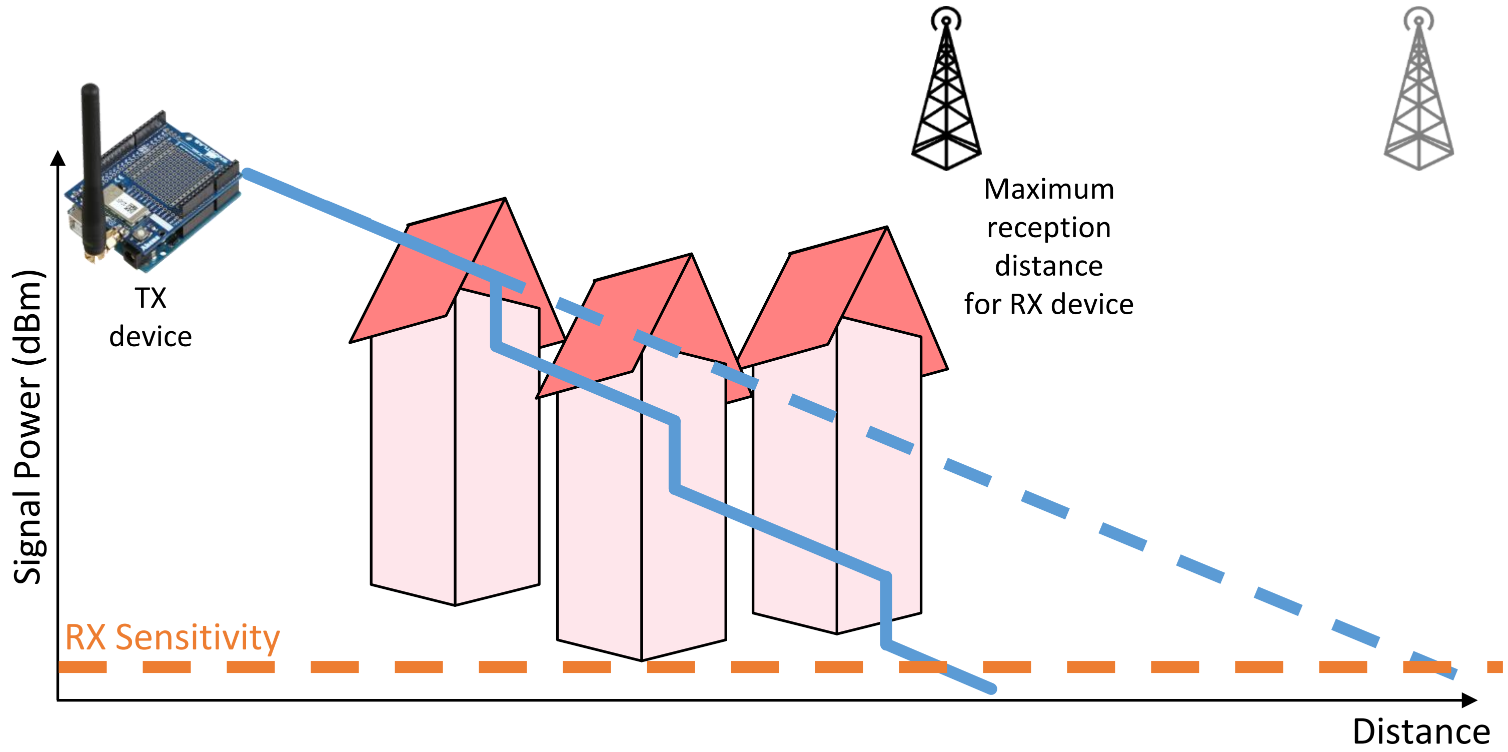
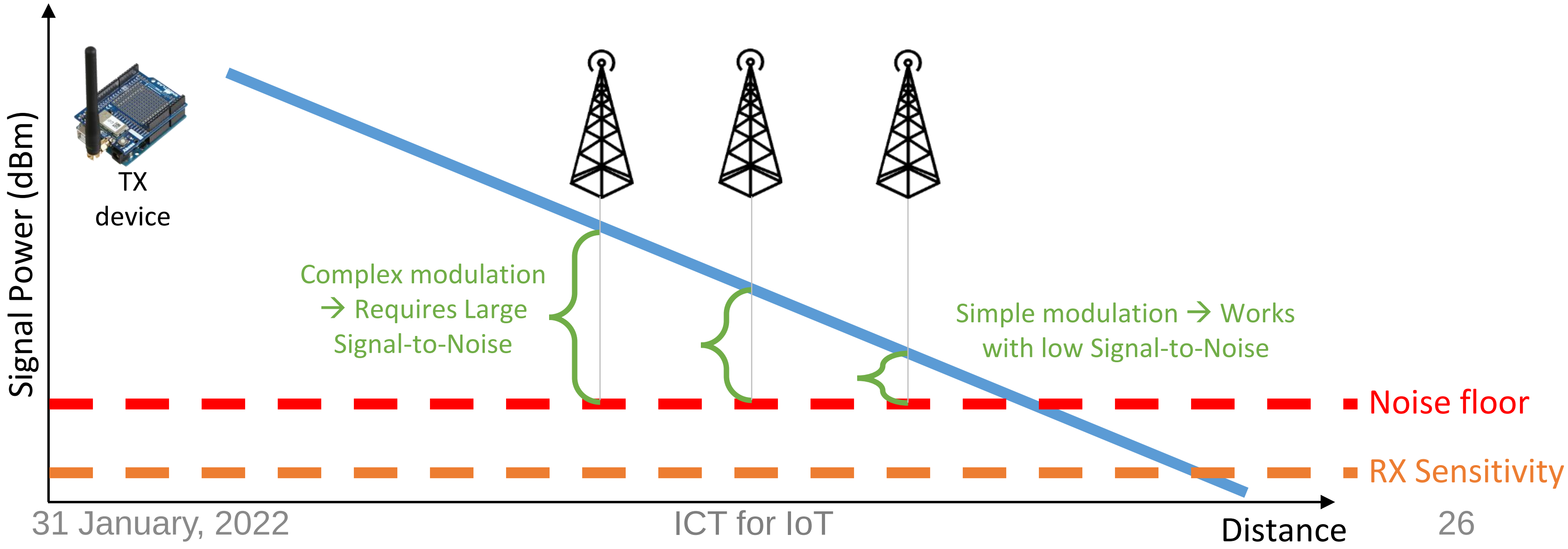


Signal-to-Noise Ratio

- Noise is all the electromagnetic radiation that creeps above the sensitivity threshold
- Noise is often modelled as Additive White Gaussian Noise (AWGN)
  - Additive: just adds over the signal of interest; no weird operations such as convolutions
  - White: affects all frequencies equally
  - Gaussian: follows a Gaussian distributions with respect to an average value
- Signal to Noise Ratio (SINR) is the ratio between received signal power and noise floor
- SINR affects the Bit Error Rate of modulations (but differently per modulation)



Signal Encoding and Modulations

Outline

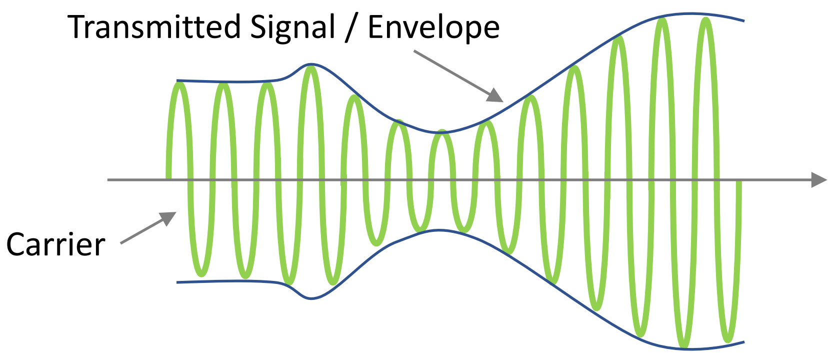
- Signal Encoding
  - Form of encoding the original signal into a physical variable
  - Techniques:
    - Analog encoding: Amplitude & Frequency (AM/FM)
    - Digital encoding: Binary Phase-Shift Keying

- Modulation
  - Treatment performed on the encoded signal to:
    - **To increase channel capacity utilization** – i.e., transmit more information at once
    - **Have better resilience against path loss and interference**
  - Tecnhiques
    - Frequency Hopping
    - Spread Spectrum
    - Orthogonal Frequency Division Multiplexing
    - Multiple-Input Multiple Output

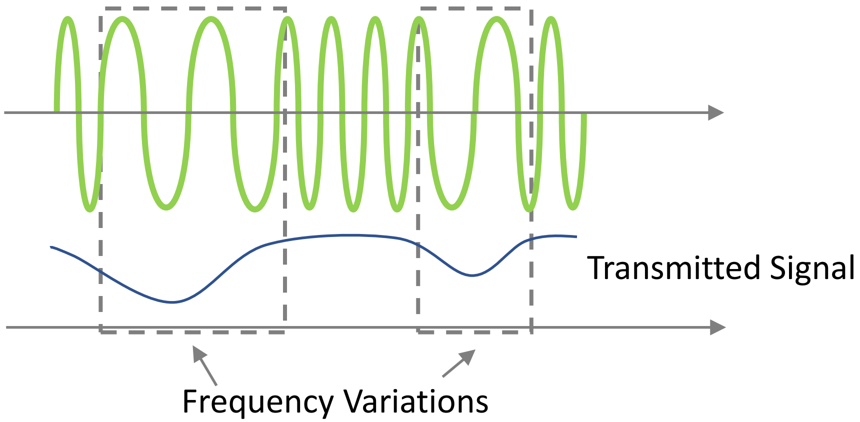
Analog Signal Encoding

- Analog signal is encoded in a feature of the carrier
- Amplitude Modulation (AM)
  - Information is encoded in transmitted power variations
- Frequency Modulation (FM)
  - Information is encoded in carrier frequency variations

Amplitude Modulation

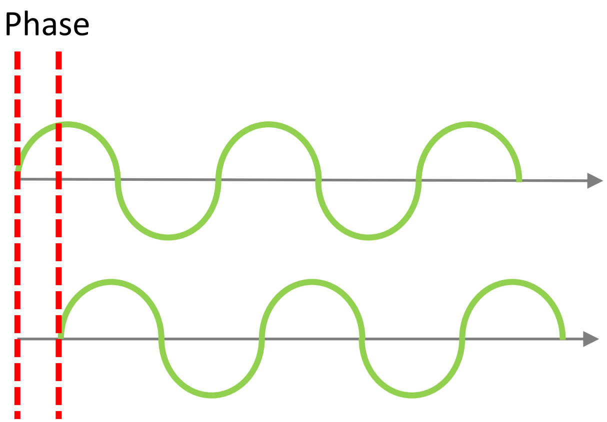


Frequency Modulation

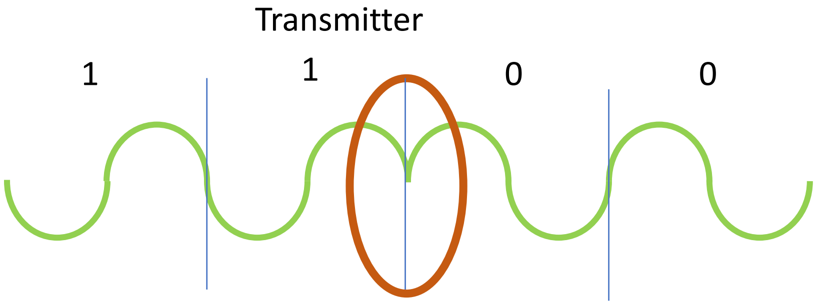


Digital Signal Encoding

- In digital signals, only 1s and 0s need are transmitted
  - No need to transmit a continuously-valued signal
- Besides amplitude and frequency, other feature can be explored: phase
- Binary Phase-Shift Keying (BPSK)
  - 180º phase shifts indicate a binary digit different than previous



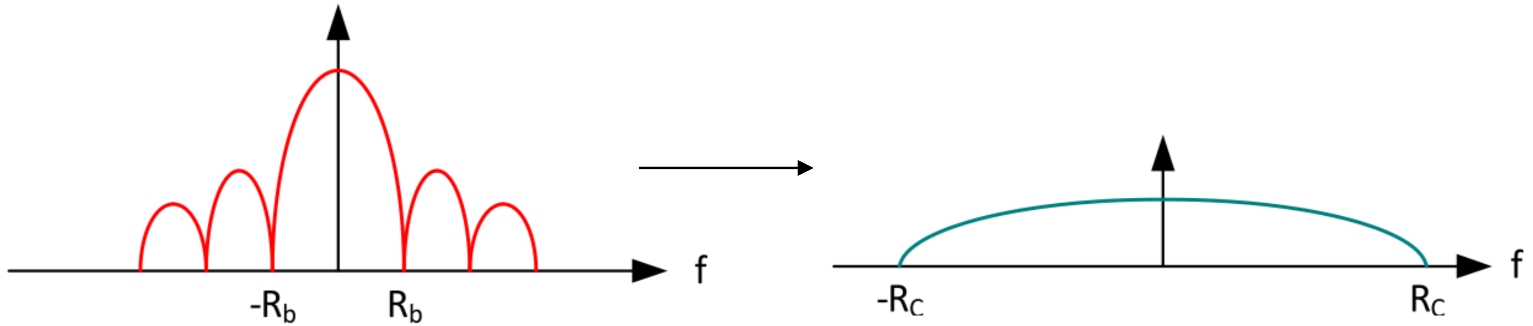
Binary Phase-Shift Keying (BPSK)



Frequency Hopping

Spread Spectrum Modulation

- Direct-sequence spread spectrum (DSSS) takes a signal for transmission and produces a related signal with a larger spectrum (wideband) prior to transmission over wireless link



- Same power, but spread over more frequencies
- What's the point?
  - Resilient against in-band and out-of-band interference
  - May be transmitted below the noise floor (security)
  - Allows to trade-off range and rate

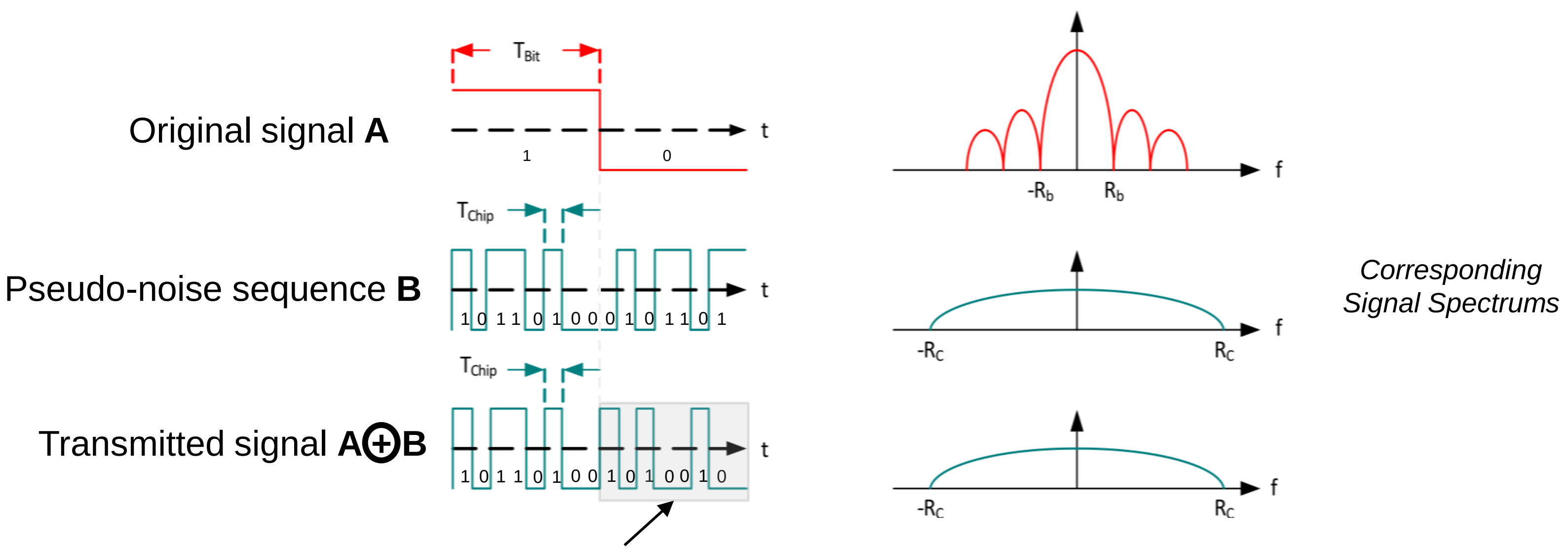
Spread Spectrum

1. Modulation/spreading (at TX):

1. Consider two signals: the signal to be transmitted **A**, and a higher-frequency pseudo-noise (PN) sequence **B** *(note: bits in sequence B are called chips)*.

2. Signals A and B are XORed. Resulting signal has an expanded spectrum – it is **wideband**.

3. Wideband signal is transmitted over the wireless link.

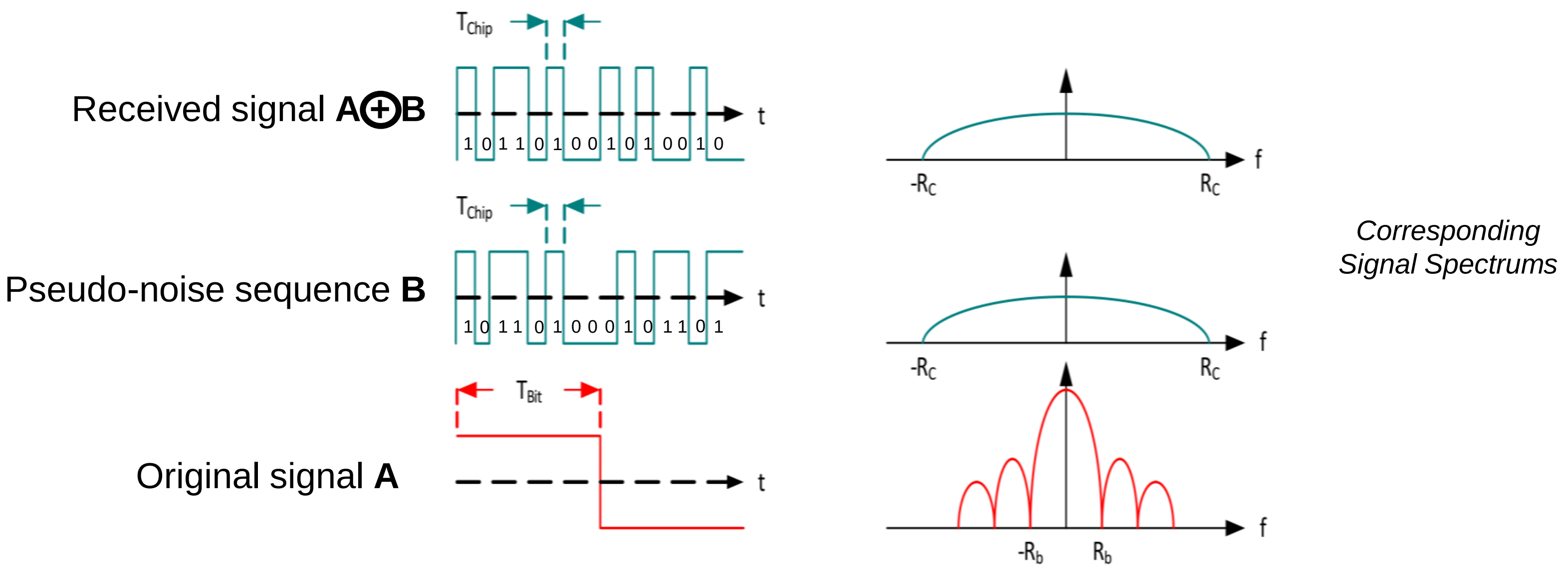


Note the inverted chips w.r.t. sequence B.

Spread Spectrum

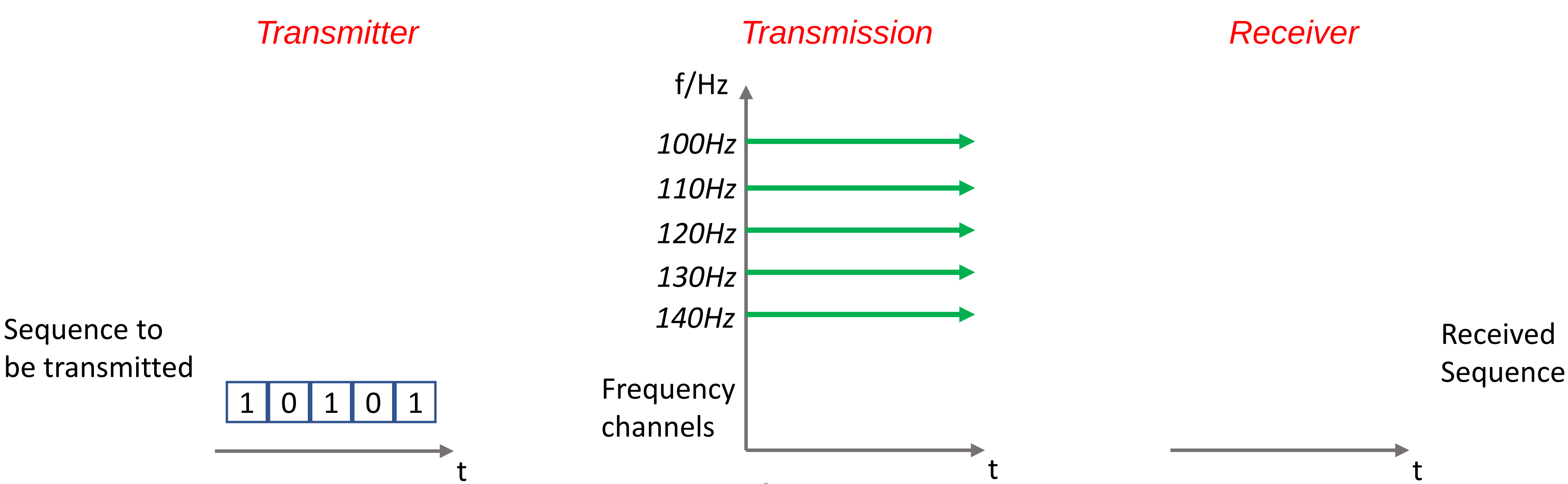
2. Demodulation/de-spreading (at RX):

1. Received signal A⊕B is again XORed again with PN sequence (receiver knows it)
2. This retrieves signal **A.**



Orthogonal Frequency Division Multiplexing

- OFDM assigns bits – more generically, symbols – represented in a temporal sequence to separate frequency channels
- All symbols of the sequence are transmitted simultaneously – i.e., within the same symbol time – in different sub-channels
- At the receiver, symbols are reverted back to the time domain
- Challenges:
  - Uneven power attenuation or interference among channels



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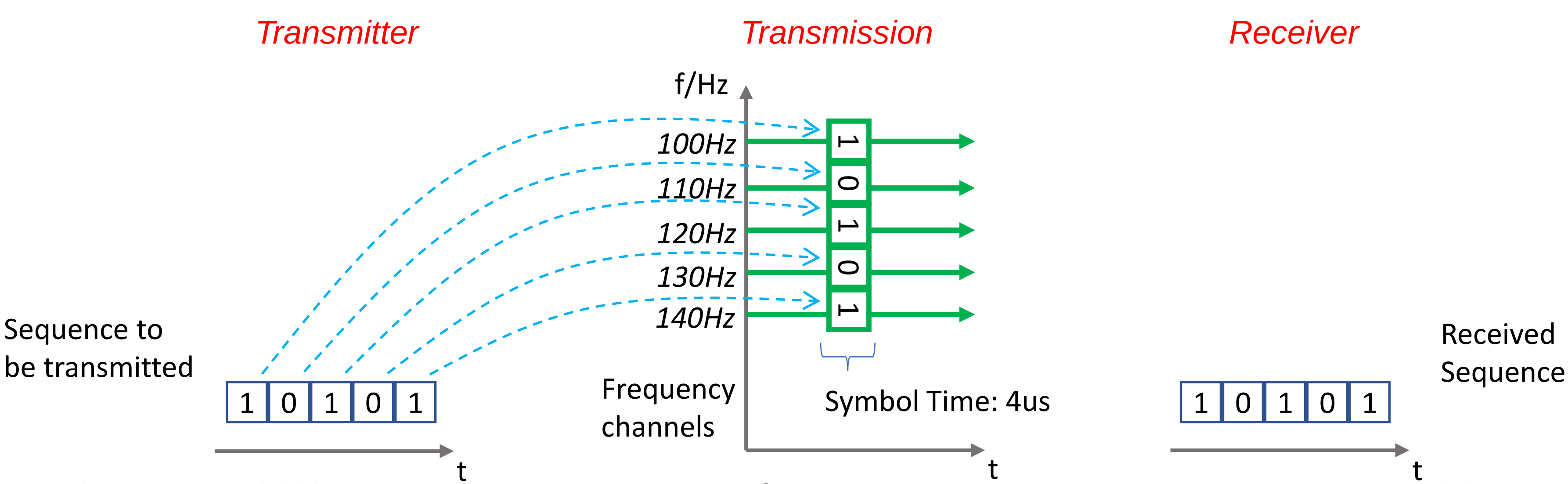

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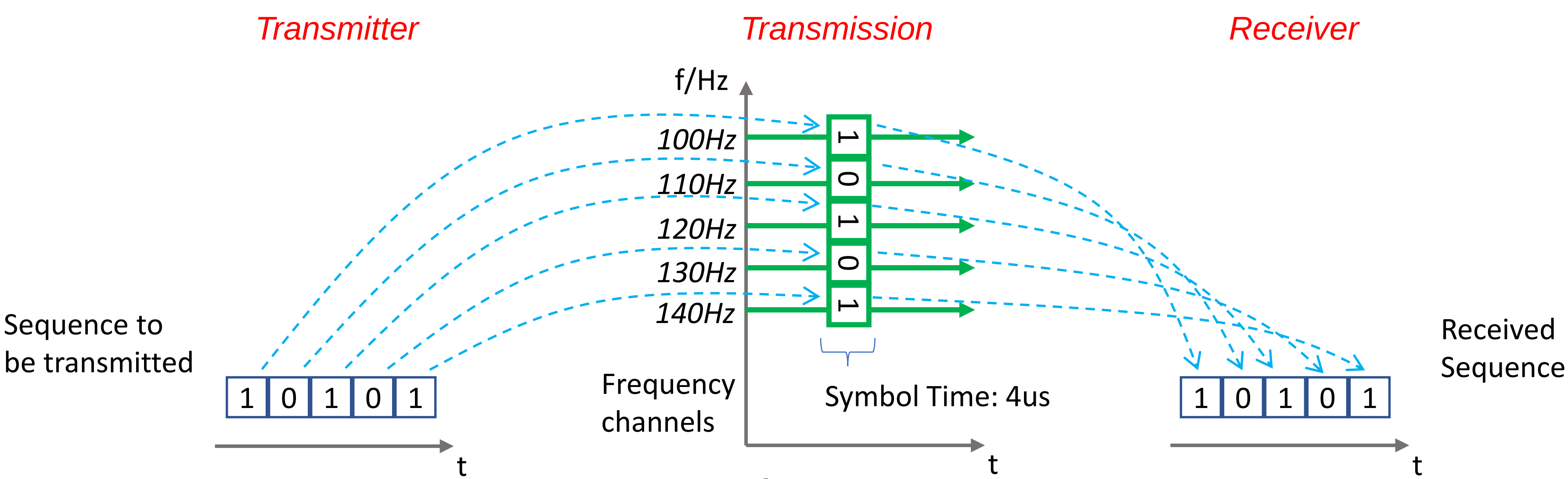
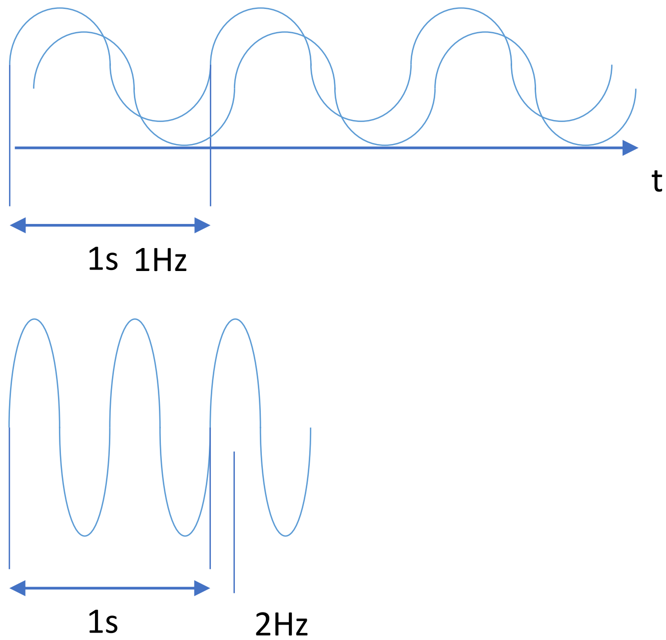
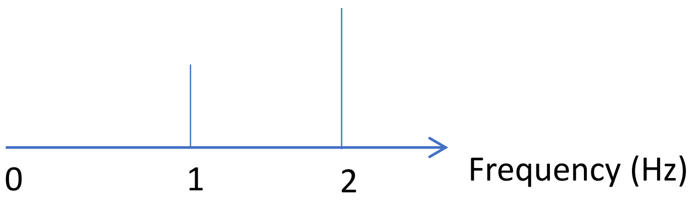


Temporal Domain



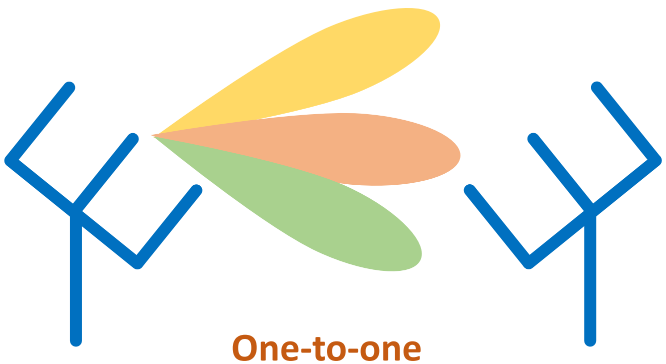
Frequency Domain



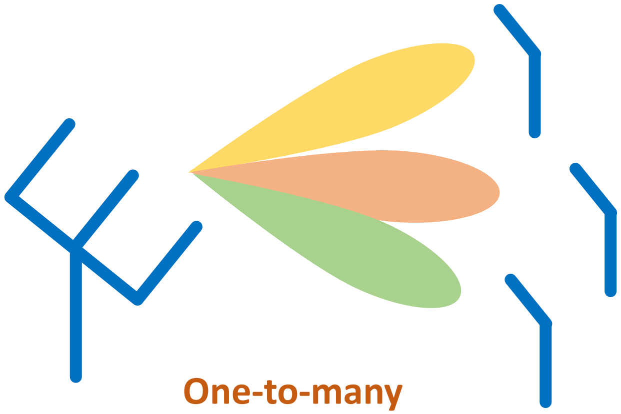
MIMO & Massive MIMO

A few examples of MIMO application:

- **Multiple-Input Multiple-Output** is a well-established communication technology, used by both by open LAN standards and cellular specification
- Based on signal processing
- Parameters in the system
  - Number of antennas per device – **N**
  - Number of users either RX or TX) – **M**
- There can be various combinations:
  - 1 TX with N antennas, 1 RX with N antennas (device-to-device)
  - 1 TX with N antennas, M RX with 1 antenna each (one-to-many)
  - M TX with 1 antennas; 1 RX with N antennas (many-to-one)
  - M TX with N antennas; M RX with N antennas (many-to-many)



One-to-one



One-to-many

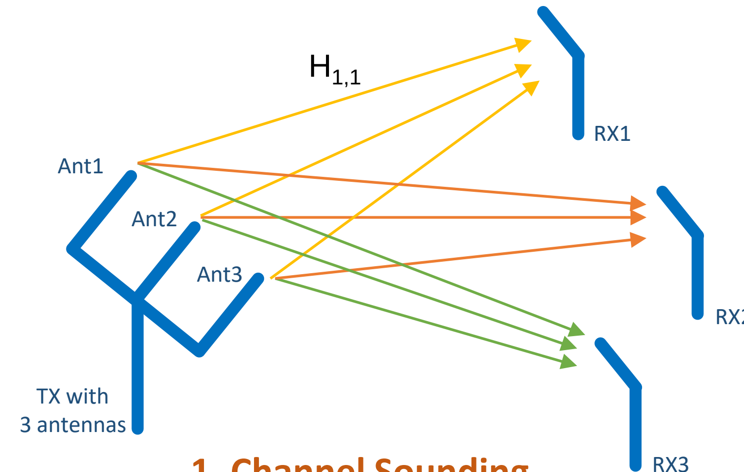
Multiple-Input Multiple Output

- Let's take the situation of 1 TX with 3 antennas, M RX with 1 antenna each (one-to-many)
- Channels between each TX antenna and each one of RX antennas are independent, i.e., it affects the transmitted signal in a different way.
- This leads to a matrix system that can be solved: $\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x}$

$$\underset{\textit{Signal Received}}{\begin{bmatrix} Y_{1,3} \\ Y_{2,3} \\ Y_{3,3} \end{bmatrix}} = \underset{\textit{Channel matrix}}{\begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} \\ H_{2,1} & H_{2,2} & H_{2,3} \\ H_{3,1} & H_{3,2} & H_{3,3} \end{bmatrix}} \underset{\textit{Signal Transmitted}}{\begin{bmatrix} X_{1,3} \\ X_{2,3} \\ X_{3,3} \end{bmatrix}}$$

- It is in fact IMPERATIVE that the channels are very different! Otherwise, the channel matrix may not be invertible, and then the system is not solvable!
- The TX can learn the channels to each RX through a mechanism named Channel Sounding. Knowing the channel matrix, the TX can transmit to all receivers simultaneously.

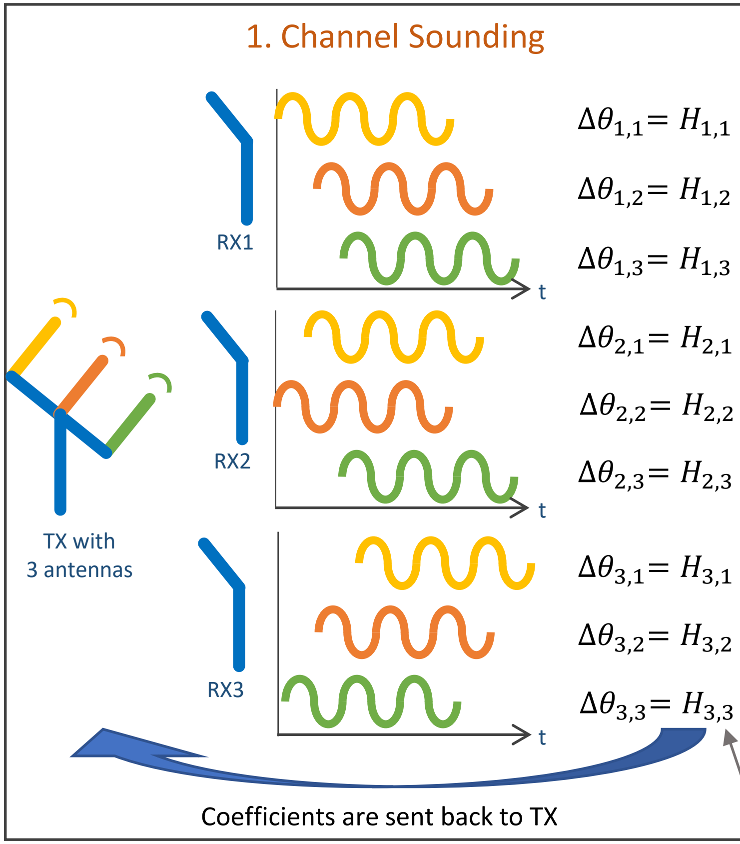
$$\boldsymbol{m} = \boldsymbol{H}^{(-1)}\boldsymbol{H}\ \boldsymbol{m}$$

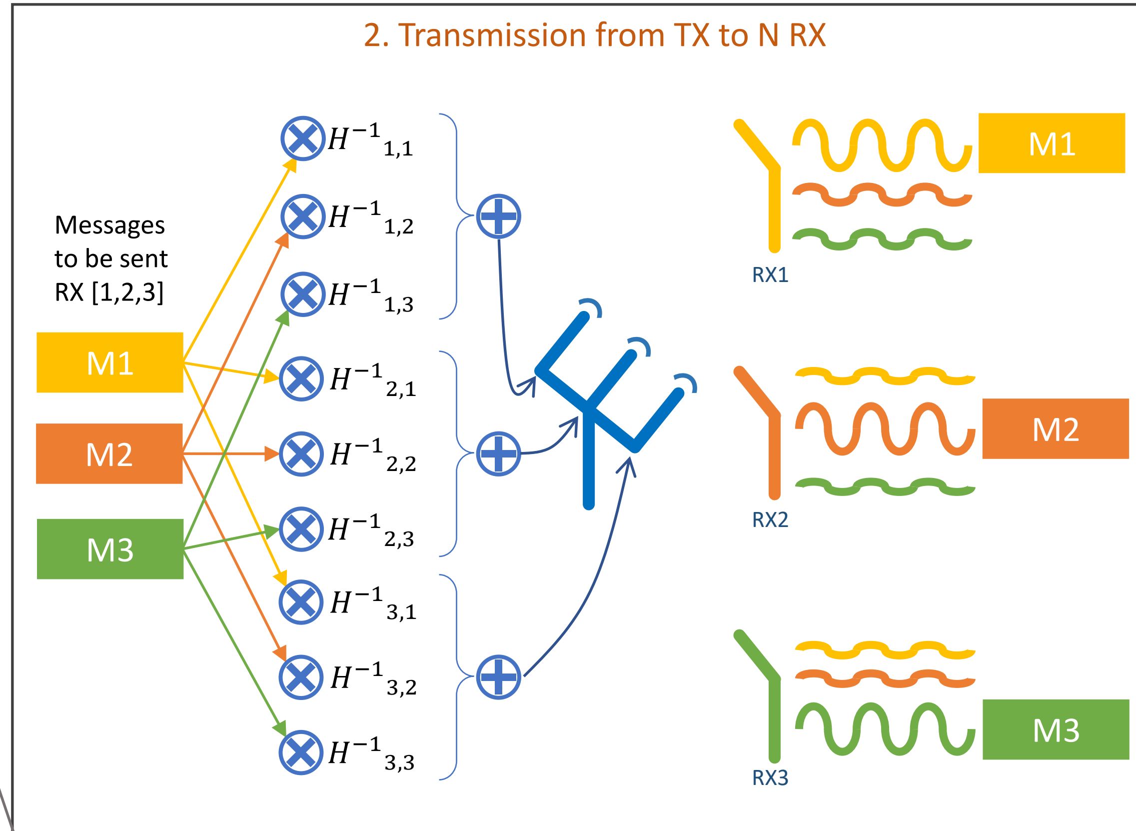


1. Channel Sounding

2. Transmission from TX to N RX

MIMO Transmission Example: 1-to-many



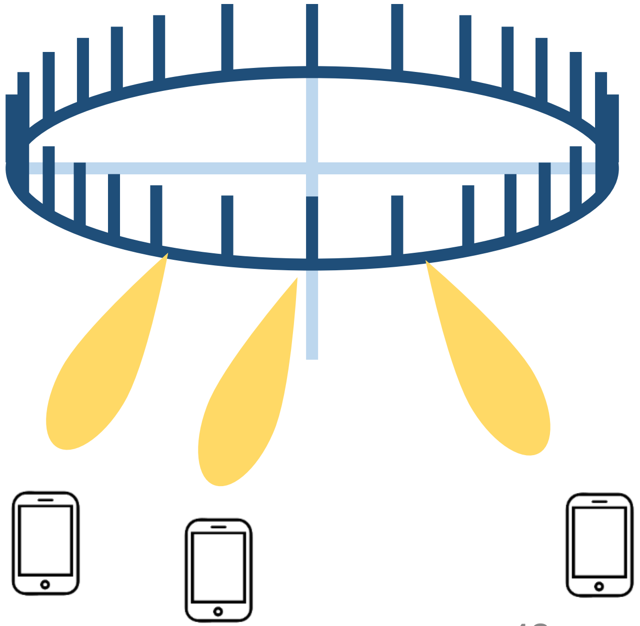


In this example, channel information is simplified to refer only
to measuring time differences between the various signal arrivals.

MIMO & Massive MIMO

- All this signal processing seems complicated! Why not just send messages in different channels?
  - Hard to make radios to transmit multiple carriers at the same time
  - Receivers need to know which channel should they be listening to
  - MIMO allows **frequency reuse**, increasing overall capacity!

- Massive MIMO
  - The previous example used only 3 receivers
  - Massive MIMO refers to the application of the technology at a larger scale (e.g., M users > 50), thus requiring a base-station with N > M antennas
  - Same principle, but additional technical challenges in making it work in practice



Thank you