Wireless Connectivity:
An Intuitive and Fundamental Guide

Chapter 10: Space in wireless communications

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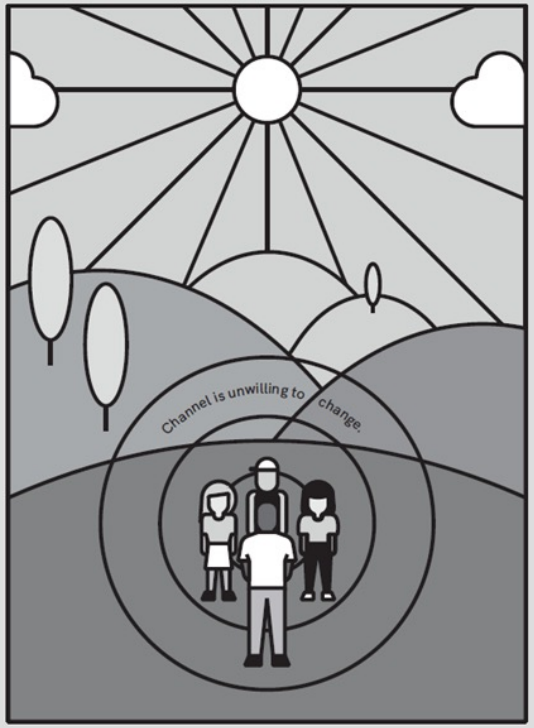
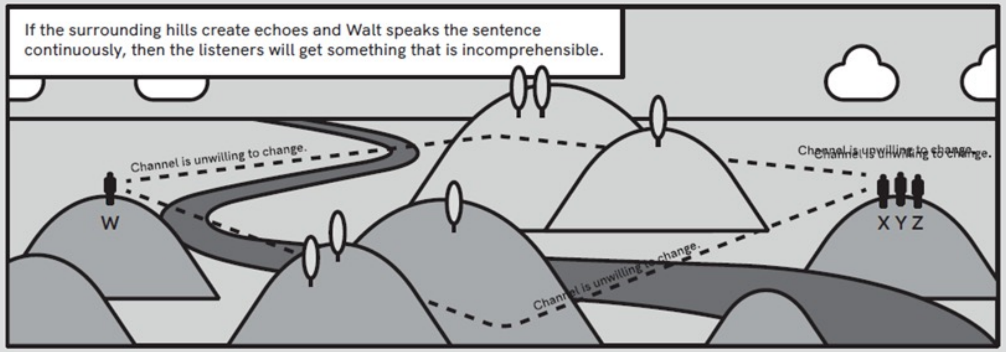
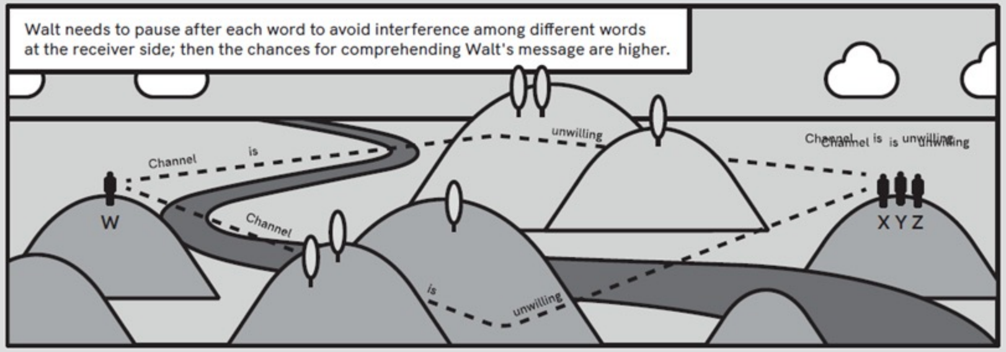
Modules

1. An easy introduction to the shared wireless medium
2. Random Access: How to Talk in Crowded Dark Room
3. Access Beyond the Collision Model
4. The Networking Cake: Layering and Slicing
5. Packets Under the Looking Glass: Symbols and Noise
6. A Mathematical View on a Communication Channel
7. Coding for Reliable Communication
8. Information-Theoretic View on Wireless Channel Capacity
9. Time and Frequency in Wireless Communications
10. **Space in Wireless Communications**
11. Using Two, More, or a Massive Number of Antennas
12. Wireless Beyond a Link: Connections and Networks

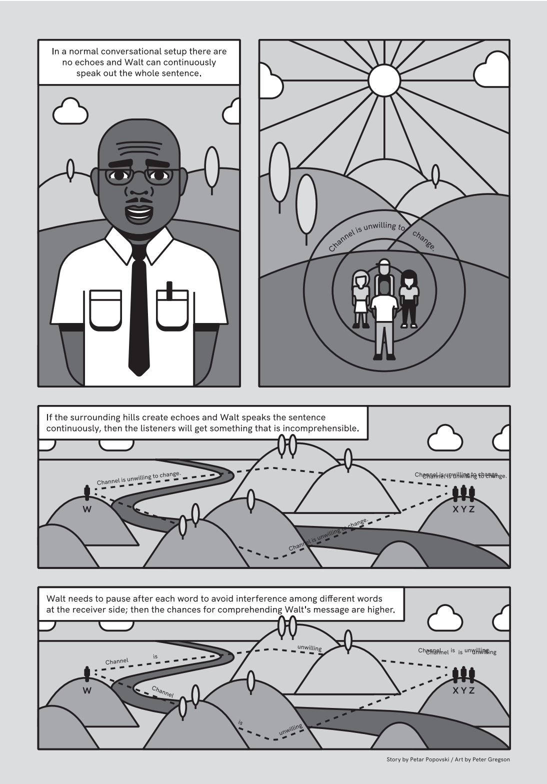

In a normal conversational setup there are no echoes and Walt can continuously speak out the whole sentence.


Channel is unwilling to change.


If the surrounding hills create echoes and Walt speaks the sentence continuously, then the listeners will get something that is incomprehensible.
Channel is unwilling to change.
W
X Y Z


Walt needs to pause after each word to avoid interference among different words at the receiver side; then the chances for comprehending Walt's message are higher.
Channel
is
unwilling
W
X Y Z

Information carriers in space



- Information is modulated on a physical carrier and propagates in space
- We have a limited control over the paths through which information propagates
- Need for methods that will make use of multiple propagation paths for reliable data recovery

What will be learned in this chapter

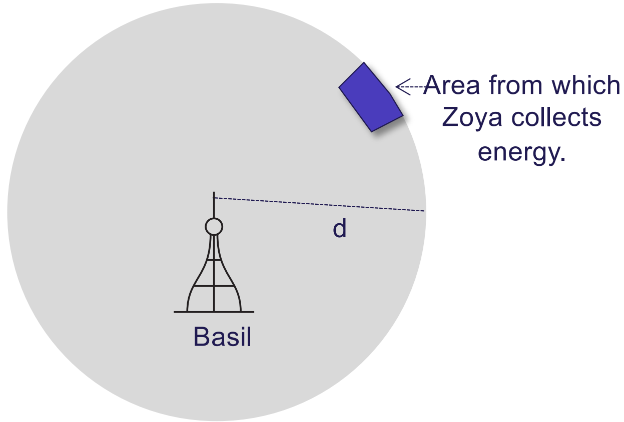
- Basic facts about antennas, propagation and dependence on frequency
- Radiation patterns and antenna directivity
- Multipath propagation, fading and shadowing
- Time-frequency dynamics of the radio channel
- Dealing with multipath: Wideband (CDMA) and narrowband (OFDM)
- Statistical models of wireless channels
- Reciprocity and its importance

Communication range and coverage area

Model:

$$y = hz + n$$

h depends on the **spatial placement** of the devices

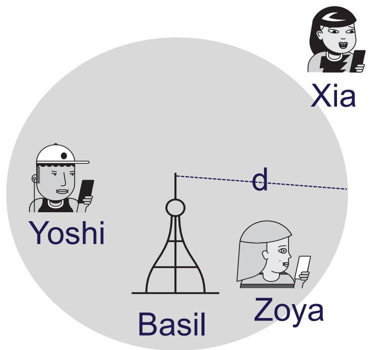


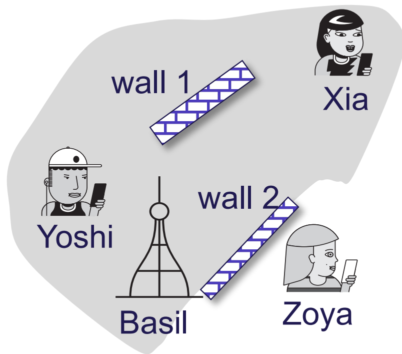
Free-space propagation:

$$P_Z = P_B \frac{A}{4\pi d^2}$$

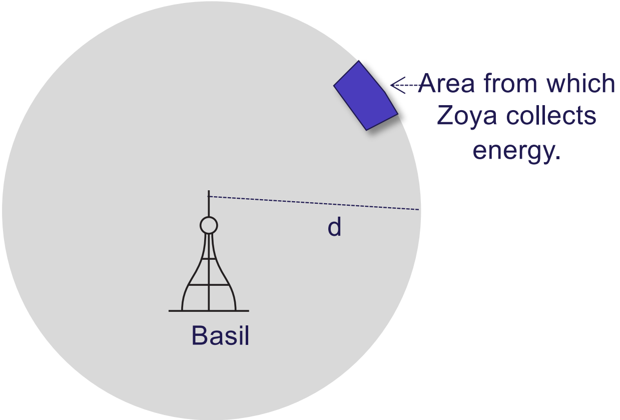
Communication range: **largest distance** where the SNR is larger than a threshold

Coverage area: positions where this occurs





The myth about the frequencies that propagate badly



In free space far field: **Friis** equation:

$$P_r = P_t \frac{G_r G_t}{(4\pi d)^2} \lambda^2 = P_t \frac{G_r G_t}{(4\pi d)^2} \frac{c^2}{f^2}$$

Path loss: $L = 10 \log_{10} \left(\frac{(4\pi d f)^2}{c^2} \right)$ [dB]

The antenna gain is $G = \frac{4\pi A}{\lambda^2}$

Then $P_r = P_t \frac{A_r A_t}{d^2} \frac{1}{\lambda^2} = P_t \frac{A_r A_t}{d^2} \frac{f^2}{c^2}$ what if A is independent of frequency?

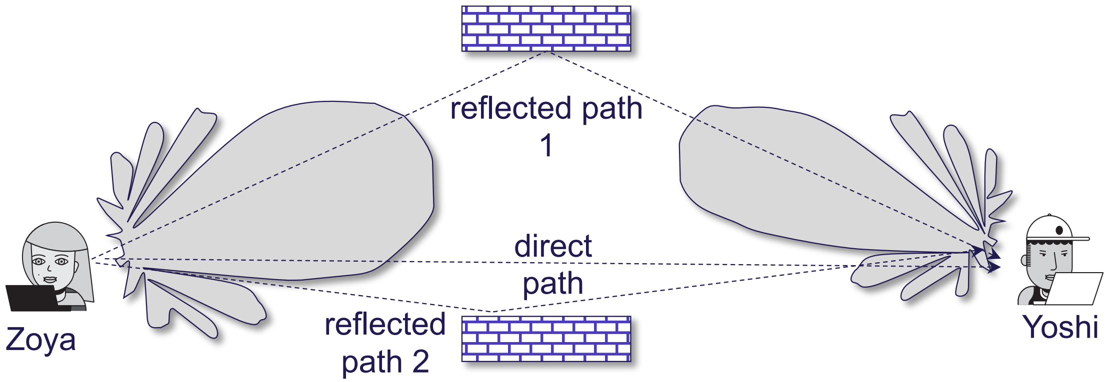
One should interpret these with **caution**

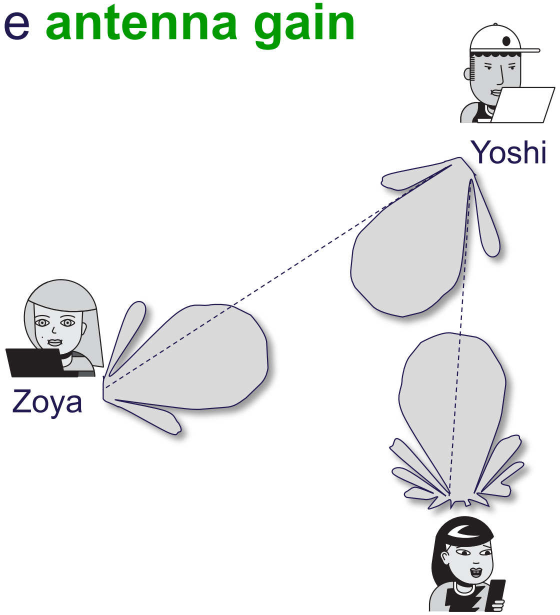
The worldview of an antenna

Practical antennas are almost **never isotropic**

Rather, they exhibit **directivity** in the **radiation pattern**

The value of the **radiation pattern** in a direction is the **antenna gain**

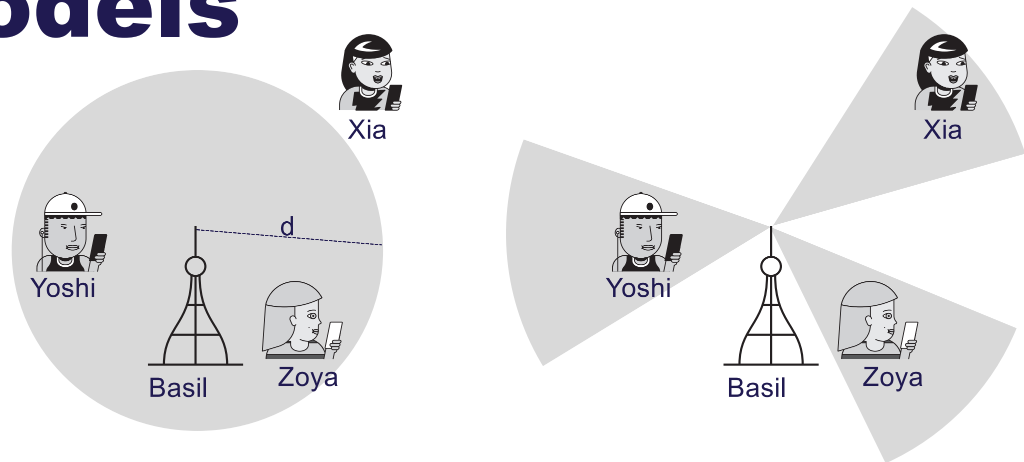




Directivity changes communication models

When are omnidirectional useful?

- Broadcast
- Rendezvous protocols
- Random access



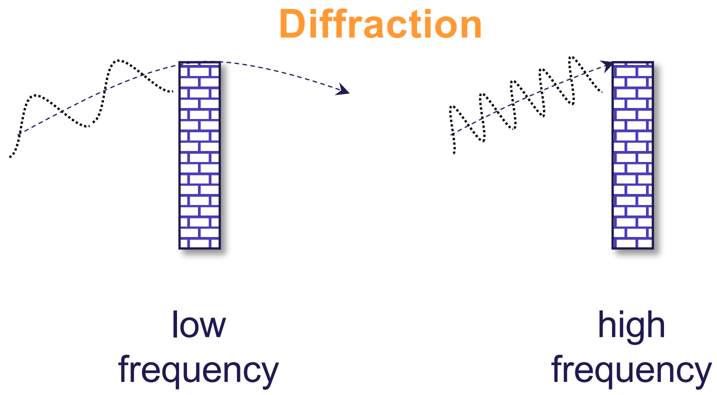
However, if the **position of users** and the environment are **known**, omnidirectional antennas **waste** a large fraction of energy

Using directional antennas is **challenging** when devices are **moving**

Common cellular comm. often assume sectorized cells (with directive antennas) and users with omnidirectional antennas

The idea of **hybrid operation**: omni+directive

Multipath and shadowing: space is rarely free



Free space: **LoS** path loss

Shadowing: ***large-scale* fading**

Reflection + Diffraction + Scattering

Reflection: with partial absorption of energy

Diffraction: bending of waves around obstacle edges (depends on ratio between wavelength and obstacle size)

Scattering: wave hits an object comparable to wavelength, energy spread over multiple waves

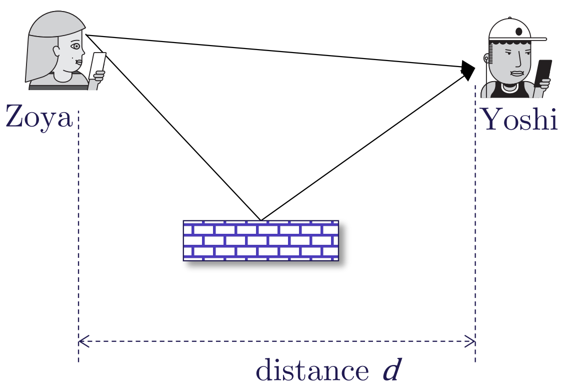
Effects highly dependent on frequency!

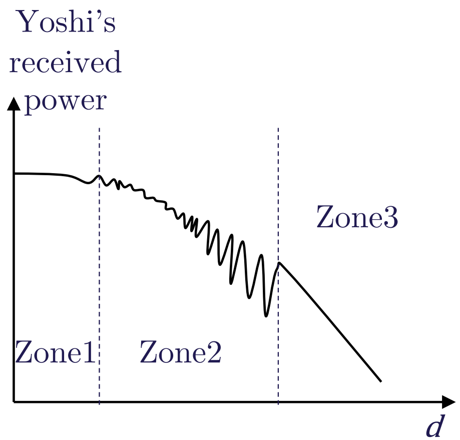
Example: mmWave vs. sub-6 GHz

Two-ray propagation and fading

Zone2: oscillations within small distances comparable to the wavelength

Fading, more specifically, **small-scale fading**





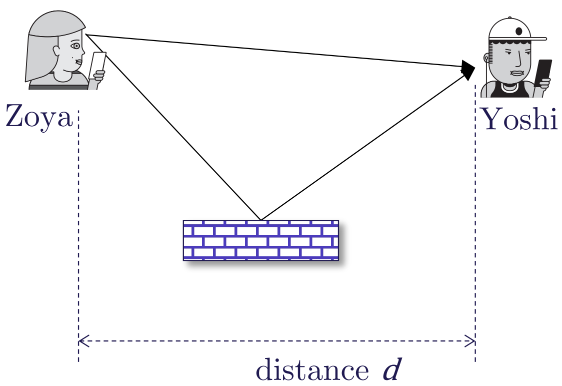
Two-ray propagation and fading

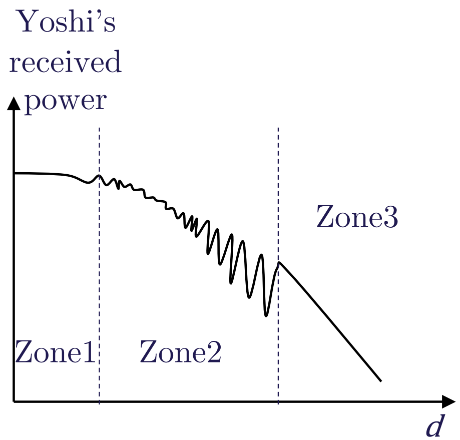
Zone2: oscillations within small distances comparable to the wavelength

Fading, more specifically, **small-scale fading**

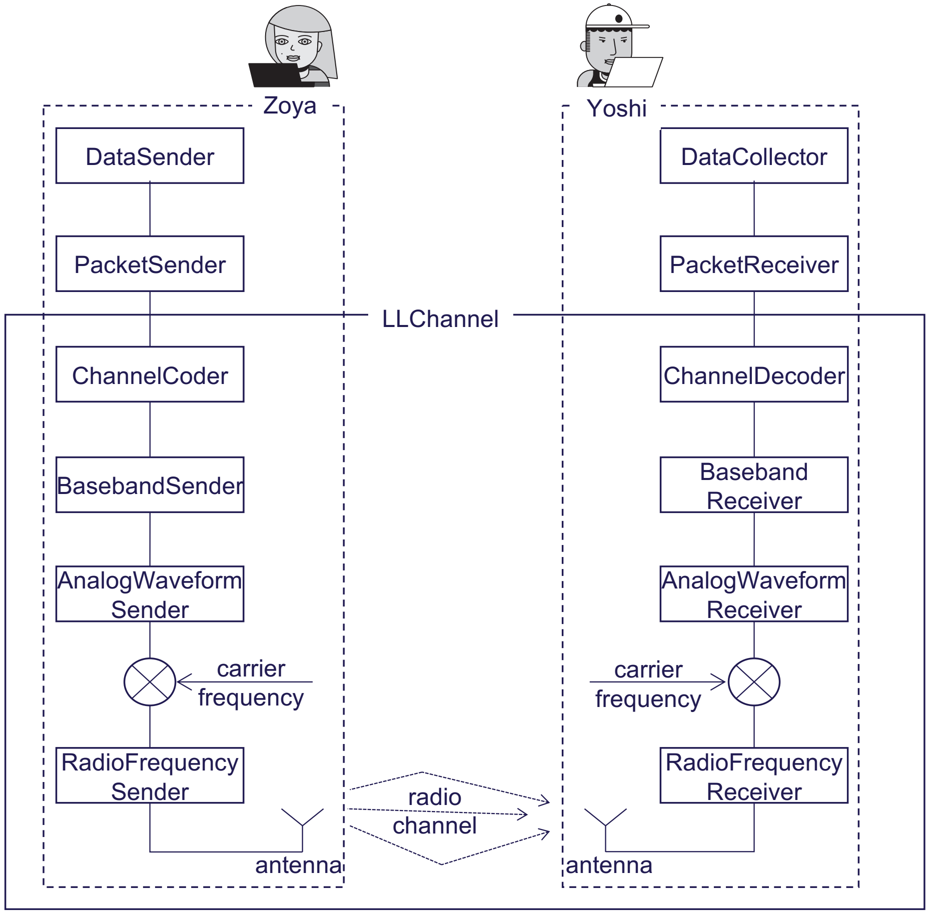
Moreover, multipath incurs a **delay spread** $\tau = \frac{\Delta x}{c}$

Delay spread can give rise to **inter-symbol interference**





The final missing link in the layering model

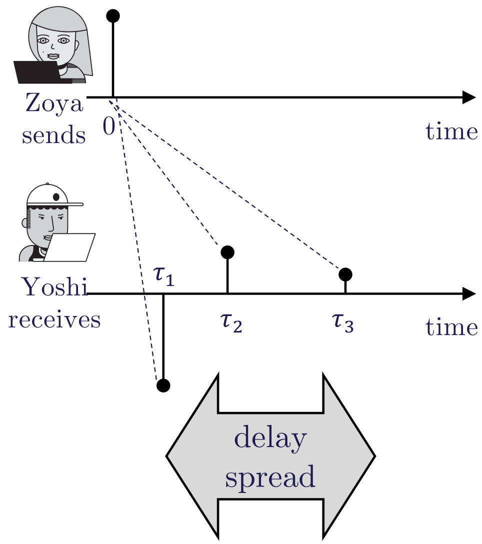


Time-frequency dynamics of the radio channel

The part of the system which we are **least able to change**

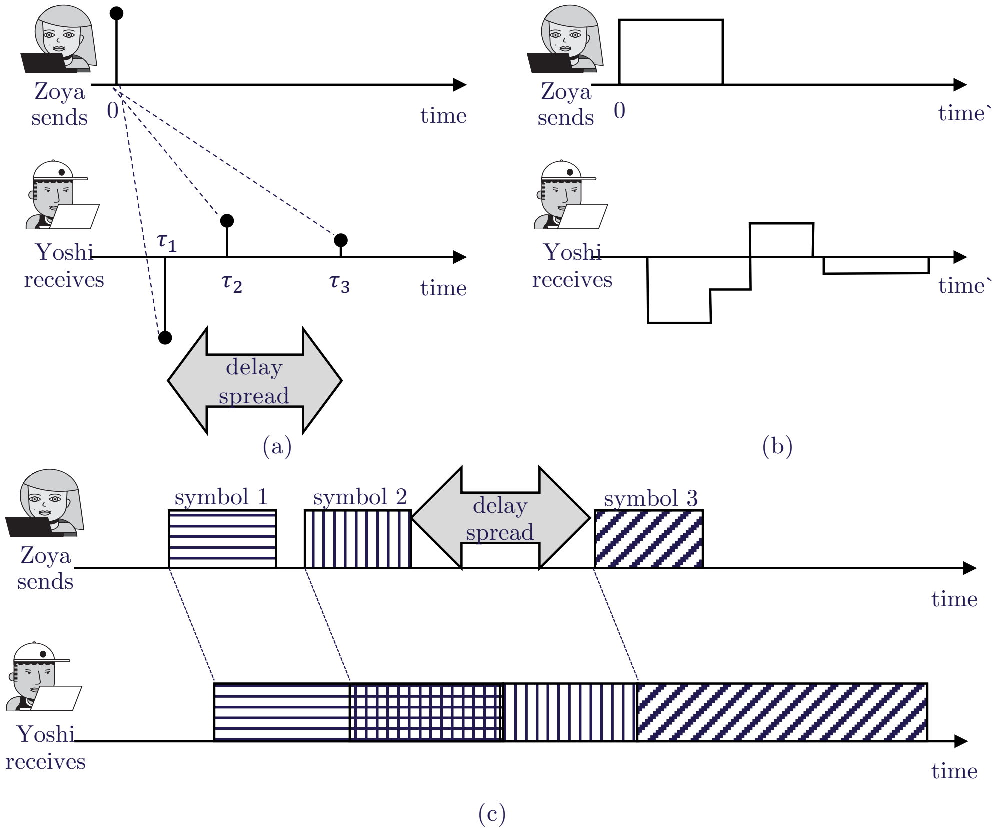
Time-invariant channel

Assume: 3 path propagation described by



$$y(t) = g_1\delta(t-\tau_1) + g_2\delta(t-\tau_2) + g_3\delta(t-\tau_3) + n(t)$$

Time-frequency dynamics of the radio channel



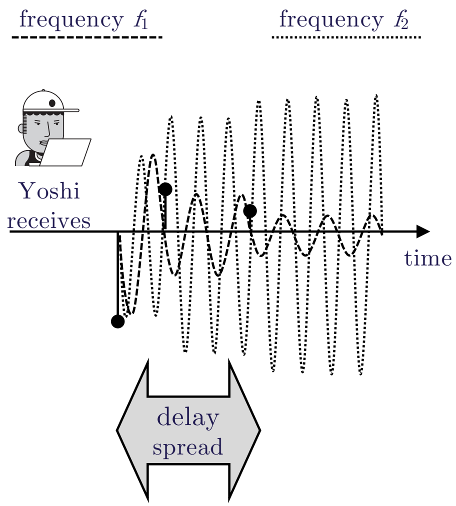
Frequency selectivity, multiplexing, and diversity

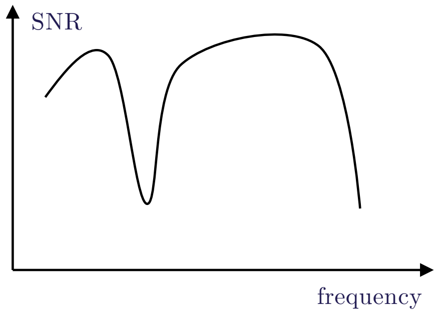
Note: the superposition due to multipath is *always sinusoidal*

Coherence bandwidth: maximum separation of frequencies s.t. the correlation of their SNRs is above a threshold

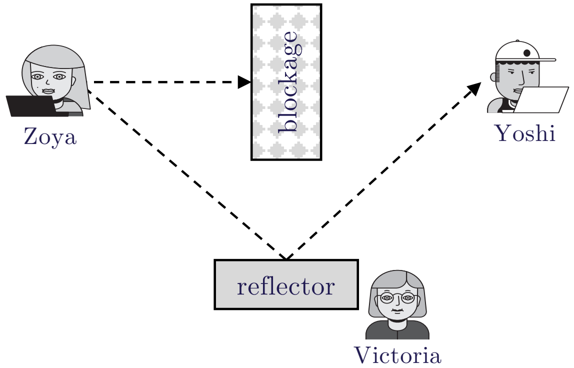
Coherence bandwidth is **inversely proportional** to the *root mean square* of the **delay spread**

Depending on CSIT availability and coherence bandwidth size, TX can either **multiplex** data, or use all coherence frequencies for **diversity**





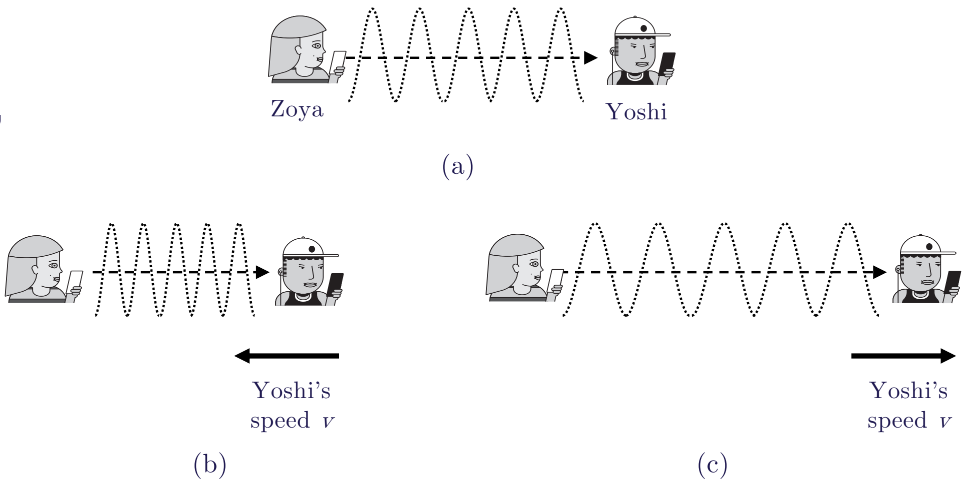
Time-variant channel



Assume Victoria can control the reflector with the phase and amplitude of $g(t)$

$$y(t) = g(t)z(t) + n(t)$$

$g(t)$ acts as a channel for $z(t)$



Now, assume Yoshi moves with speed v, then we have **Doppler effect**

$$f_Y = f_Z \pm f_Z \frac{v}{c}$$

Time dynamics is captured with the **coherence time**

Combined time-frequency dynamics

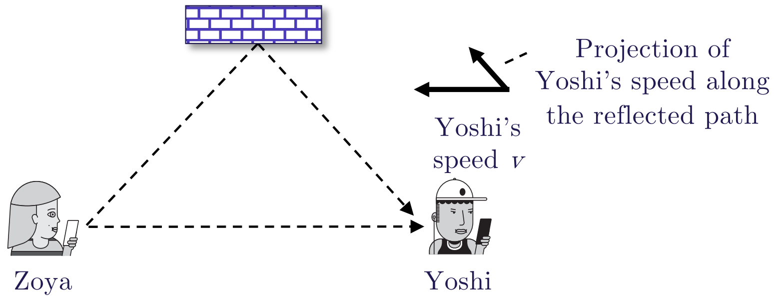
Assume two path channel and movement of Yoshi

Movement induces **different Doppler shifts**
for each of the paths

Multipath propagation is not all bad, and can be exploited

Assume Zoya chooses a symbol of duration $T_S < \Delta\tau$

Because the symbol is **small**,
this is called a ***wideband* system**



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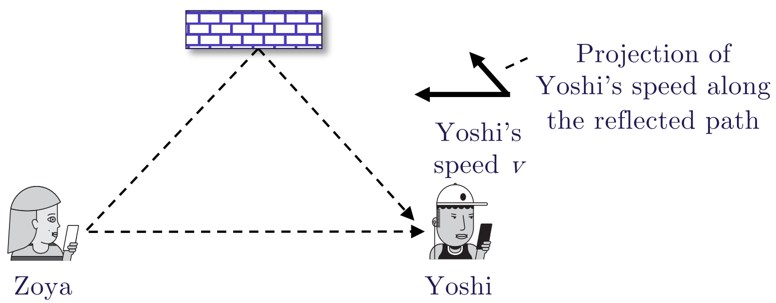
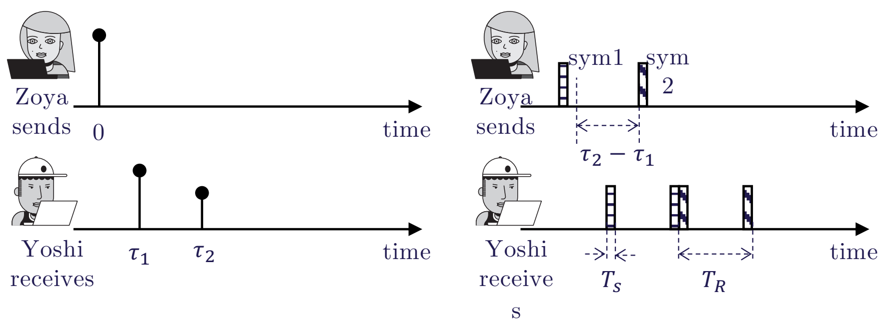
However, this means that $T_R > T_S$ which limits the rate

$$R \leq \frac{\log_2 M}{T_R}$$

MRC is used $\gamma = \gamma_1 + \gamma_2$

$$\gamma_i = \frac{|h_i|^2 P}{\sigma^2}$$





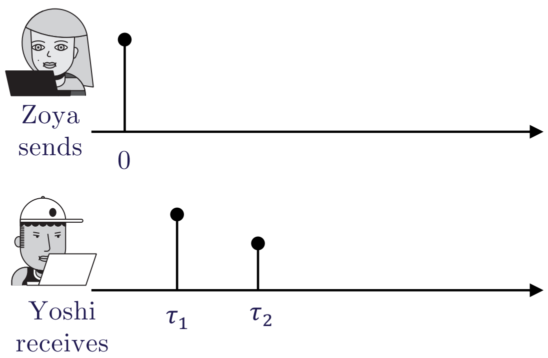
Wideband: spread spectrum and RAKE receiver

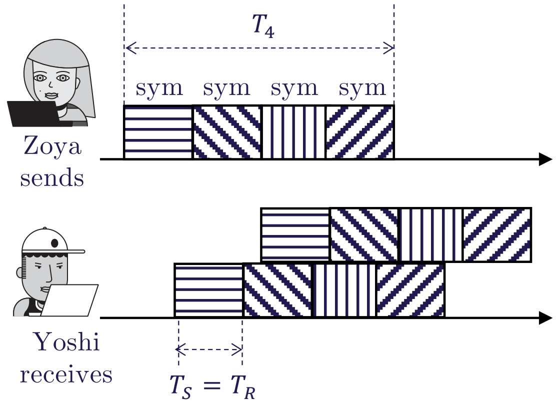
Assume spread spectrum $T_S = GT_c$

Yoshi uses a **pilot** to determine the **two paths**

Then, he uses the good **autocorrelation** properties of the spreading sequence and then **MRC**

SINR slightly deteriorated, but **rate is increased**





Narrowband: OFDM and guard interval

Introducing a guard interval $T_G \geq \tau$

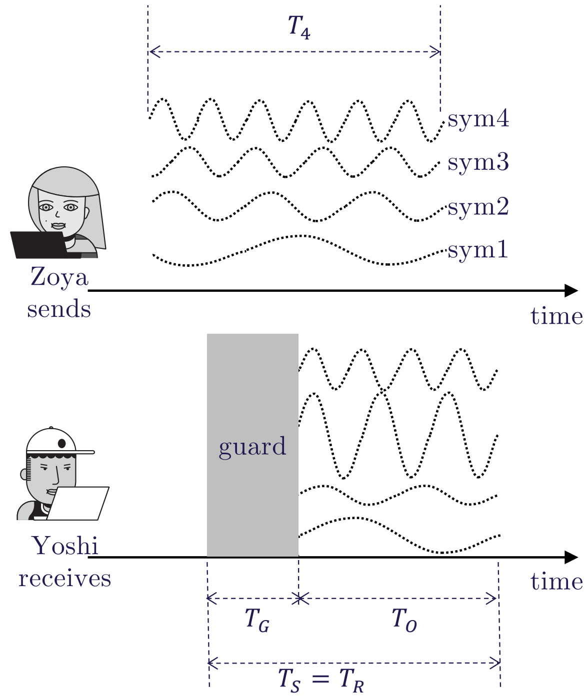
$T_S = T_G + T_O$ and $\eta_T = \frac{T_O}{T_S} = \frac{T_O}{T_R} = \frac{T_O}{T_G + T_O}$

The idea is to use **multiple narrowband signals**, modulated on **different subcarriers**, carrying **different symbols**

Subcarrier frequencies should be **integer multiples of** $\frac{1}{T_O}$

Choice of T_G

- Commonly: chosen to be likely equal to the maximum delay spread of an environment
- Practical implementation: **guard interval** is replaced with a **cyclic prefix**

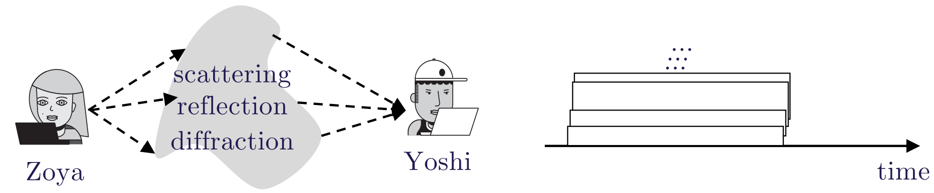


Statistical modeling of wireless channels

Wideband channel characterization based on **the tapped delay model**

Narrowband channel characterization is also useful since $y = hz + n$ is a **narrowband model**, where the **physical effects** are summed up in the **complex coefficient h**

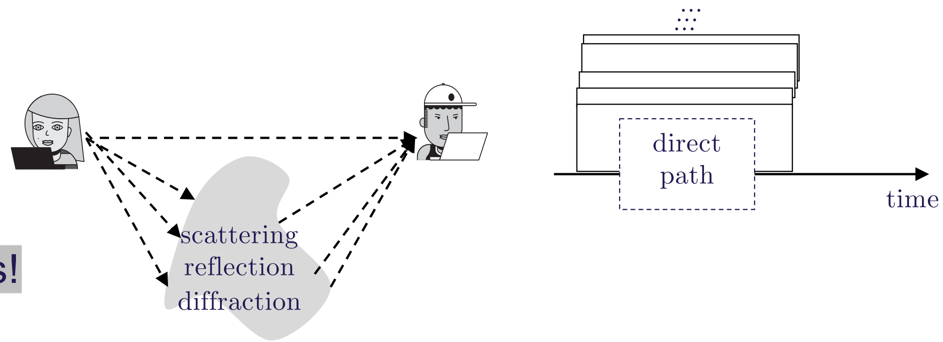
- Rayleigh: $h = \sum_{k=1}^{\infty} a_k e^{j\phi_k}$
- **Amplitude distribution** is **Rayleigh**
- **Power distribution** is **exponential**



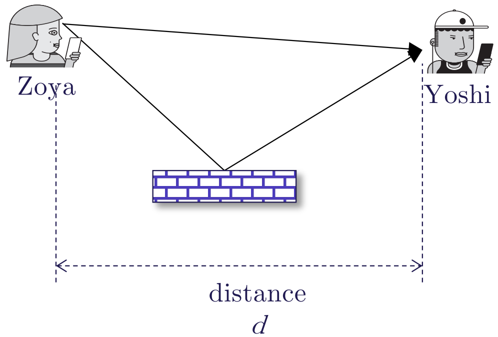
Dominant path: **Rician** channel

- Particular case: two path model $h = a_1 + a_2 e^{j\phi_2}$

Note: correlation may need to be considered in some cases!



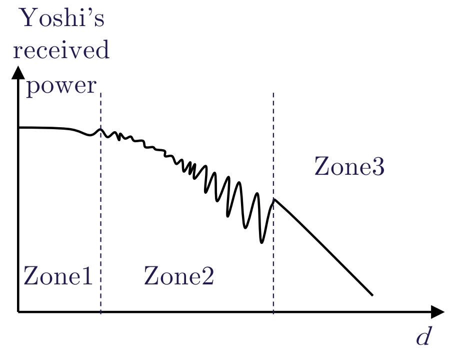
Randomness in path loss



Recall:

Shadowing: **large-scale fading**

Reflection + **Diffraction** + **Scattering** = **multipath (*small-scale* fading)**



Shadowing commonly modeled statistically with a **lognormal distribution**

$L_{\text{total}} = L \prod_{i=1}^{I_D} L_i$, due to each **diffraction** attenuating the signal

$$\log L_{\text{total}} = \log L + \sum_{i=1}^{I_D} \log L_i$$

Can be approximated as Gaussian

Randomness in path loss

Recall:

Shadowing: **large-scale fading**

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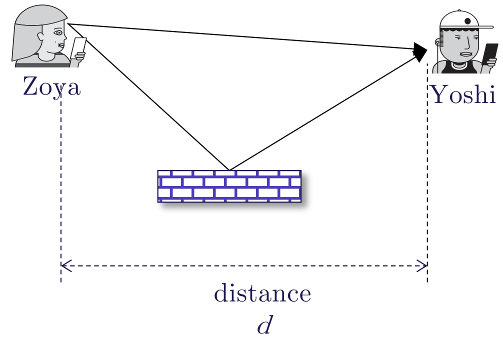

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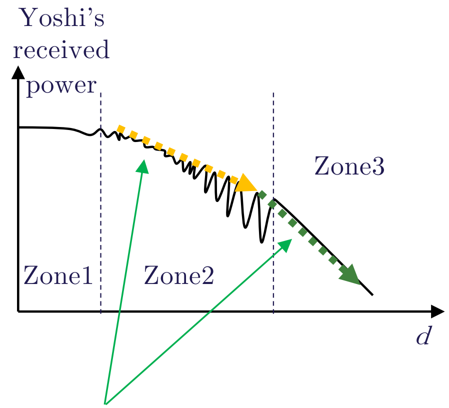

Models with dual slope

Reciprocity and how to use it

Assume: TDD to transmit and receive in the same frequency band

Then **identical devices** transmitting at **identical powers**
using the **same frequency band** with TDD experience the **same SNR**

Reciprocity is preserved even in the case of **reflection, diffraction, scattering**

Extremely useful for **adaptive modulation and coding**
and reducing the steps needed in a communication protocol

Outlook and takeaways

- Antenna properties
- Free space vs. real propagation
- Why are lower frequencies more precious
- Time-frequency dynamics
- Multipath propagation and ways to deal with it
- Channel reciprocity