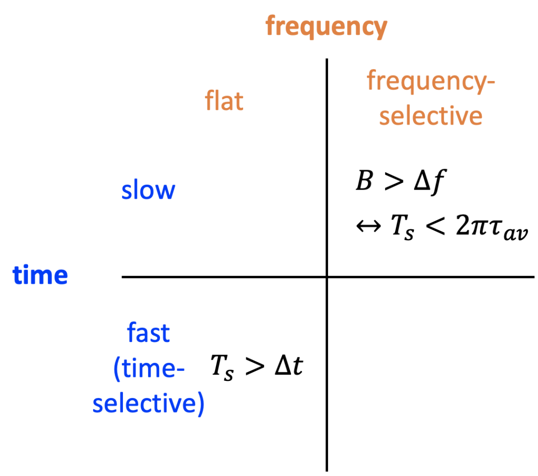
Fading Mitigation Techniques

Last time, we talked about different types of multipath channel fading. To summarize, depending on the value of the coherence bandwidth and coherence time, the channel can fall into one of the following four categories:



In this lecture, we will discuss several techniques for mitigating fading, depending on which category we fall into. Before doing that, we can work through a few examples for understanding the differences along the time and frequency axes.

Frequency-selective versus flat fading

Example 1: Consider a data rate of 10 kbps. Assuming binary modulation, we have $B = 10$ kHz, and $T_s = 1/B = 0.1$ ms. The condition for frequency-selective fading is

$$\text{delay spread} > \frac{T}{2\pi} = 0.016 \text{ ms},$$

which is unlikely even in an urban environment, where the delay spreads would be roughly 3-8 μsec. Thus, this would always result in flat fading.

Example 2: Now suppose the signal bandwidth increases to $B = 200$ kHz. This gives $T_s = 1/B = 5$ μs. Then, for frequency-selective fading, we need

$$\text{delay spread} > \frac{T}{2\pi} = 0.8 \ \mu\text{s}.$$

This will result in frequency-selective fading for urban environments, and even some suburban environments.

Example 3: Finally, consider a data rate of 54 Mbps, as in LTE. This gives $T_s = 1/B = 18.5$ ns, giving the following condition for frequency-selective fading:

$$\text{delay spread} > \frac{T}{2\pi} = 2.9 \text{ ns}.$$

This will result in frequency-selective fading for every environment. If the delay spread is much larger than this threshold, distinct signal echoes may appear, making each path individually resolvable. Still, ISI will be a problem. As we will see, OFDM helps with ISI by providing much narrower frequency transmission bands, resulting in flat fading over each band.

In general, a larger B and shorter T_s are more likely to experience frequency-selective fading.

Rate of fading

Example 1: Suppose a vehicle is traveling at $v = 100$ km/hr $= 28$ m/s. At a transmission frequency of $f_c = 1$ GHz, $\lambda = 0.3$ m, and$f_m = v/\lambda = 90$ Hz. This means that

$$\text{coherence time} = \frac{0.18}{f_m} = 2 \text{ ms}.$$

So if $T_s < 2$ ms, we have slow fading (no distortion). Otherwise, we have fast fading.

Example 2: Now, suppose a pedestrian is walking at $v = 0.1$ m/s. For the transmission frequency above, we have $f_m = 0.33$ Hz, and

$$\text{coherence time} = \frac{0.18}{f_m} = 0.55 \text{ sec},$$

meaning we need a much larger symbol duration for fast fading.

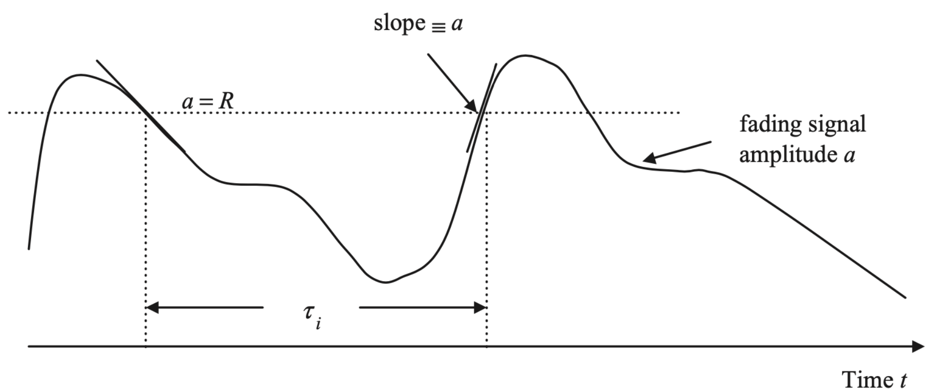
Example 3: Now, consider a much higher carrier frequency of $f_c = 30$ GHz, as in mmWave. In this case, $\lambda = 0.01$ m, and $f_m = 10$ Hz. With $v = 0.1$ m/s,

$$\text{coherence time} = \frac{0.18}{f_m} = 0.018 \text{ sec}.$$

In general, a larger velocity and higher frequency band are more likely to experience fast fading.

Fade Duration

We can be more precise about the impact of the doppler shift using Rayleigh statistics. In particular, we consider "deep fades" as times where the multipath fading component α has an amplitude a that drops below a particular level $a = R$, as depicted in the diagram below.



The **average fade duration** τ_f, i.e., the average length of a deep fade (in sec), can be obtained as

$$\tau_f = \frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}}, \tag{1}$$

where f_m is the maximum doppler shift, and $\rho = a/\sqrt{\mathbb{E}(a^2)}$ is the Rayleigh-distributed amplitude of the received signal normalized by its RMS value. This is closely related to the coherence time Δt.

For example, at a doppler shift of $f_m = 90$ Hz, if $\rho = 1$, then $\tau_f = 0.7/f_m =$ 8 ms. On the other hand, if $\rho = 0.3$, then $\tau_f = 1$ ms. As the velocity drops, the dopper shift drops, and the average fade duration increases.

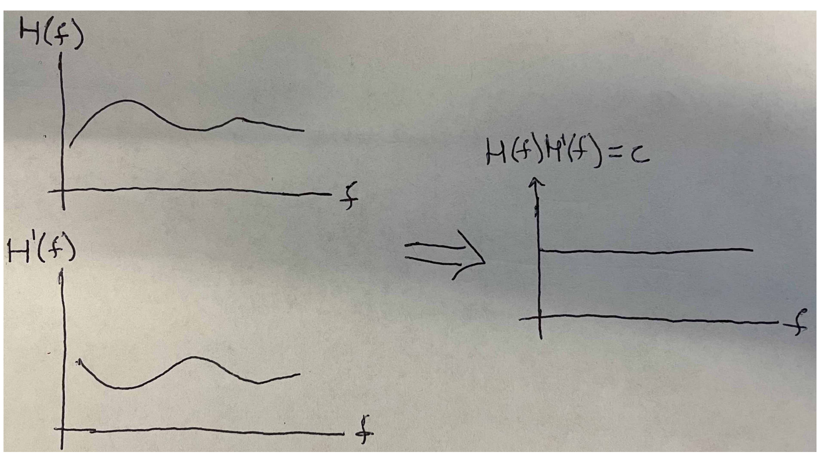
How to deal with fading?

First of all, is fading a good thing, or a bad thing? We typically think of it as something negative, but it is possible to exploit it to our advantage in certain cases. In general, we have three options when fading is present, each of which has their own merits:

1. We can simply do nothing about it at all.
2. We can work against fading.
3. We can exploit fading, through diversity techniques.

The following are some general fading mitigation techniques:

- *Power control*: Adjust transmit powers to obtain the required signal-to-interference ratios at the receiver. This is good for combating slow fading.
- *Repetition/coding*: Building redundancy into the transmission signal gives multiple opportunities for recovering the information at the receiver.
- *Interleaving*: We can spread out the transmissions in time. This is good for combating fast-fading, which causes bursts of noise appear.
- *Equalization*: We can attempt to correct a frequency-selective channel $H(f)$ by cascading it with the inverse response, $H'(f)$, as shown below:

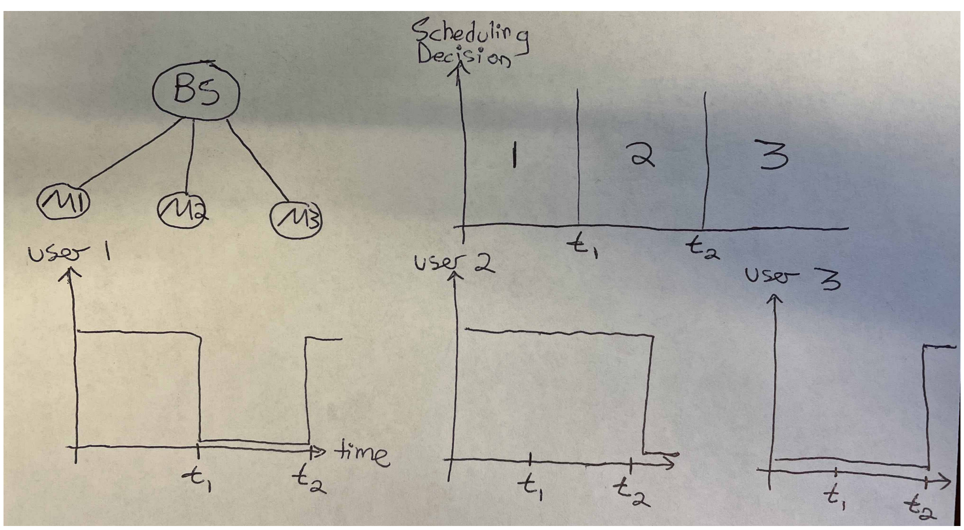


This can be used to reduce/eliminate ISI. A key challenge is that $H'(f)$ may correspond to a non-causal impulse response $h'(t)$. In such a case, $h'(t)$ is either unrealizable or requires adding a large time delay.

More specifically, there are specialized techniques to address a particular type of fading, including the following:

- *RAKE receiver*: This can improve the performance of very wideband wireless systems, such as CDMA. At a high enough symbol rate, the delay spread over a fading channel becomes greater than the symbol period, resulting in frequency-selective fading. As the symbol interval is reduced, individual components of the multipath signal may be separately distinguished. The RAKE receiver combines these separately arriving rays with time compensation and combining techniques.
- *OFDM*: OFDM is used in 4G LTE and WiMAX, as well as in WiFi standards 802.11g and 802.11a. It divides a large bandwidth signal into many smaller subcarriers, mitigating frequency-selectivity for each of the small bands.
- *Opportunistic scheduling*: This improves overall network throughput by exploiting mobile user demand diversity in time.
- *MIMO*: MIMO exploits spatial diversity through the inclusion of multiple transmit and receive antennas.

Opportunistic Scheduling



The concept of opportunistic scheduling is actually rather simple. When there are multiple receivers, the base station can schedule the receiver with the best SINR. For example, with three mobile users, we might have the scheduling result shown above.

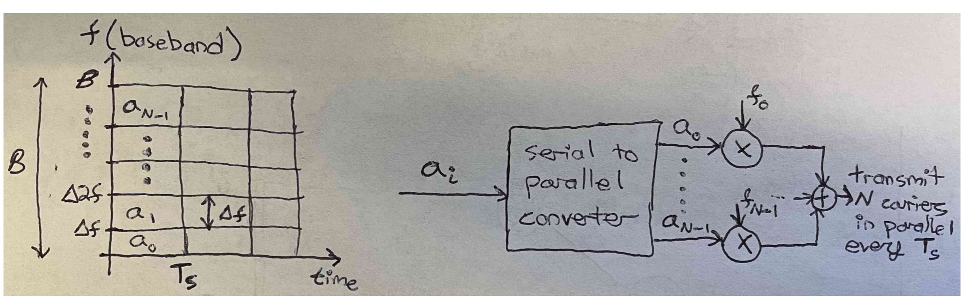
Doing so will improve the overall data throughput. However, it also increases service delay for users with poor channel conditions for prolonged periods of time. Opportunistic scheduling is effective if the coherence time is larger than the time to estimate the channel conditions, but shorter than the delay that the application can tolerate.

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM divides a large bandwidth into a number of narrowband **subcarriers**, each of which carries information. In OFDMA, we further divide time into slots, and each user can be allocated to any subset of the frequency-time slots. Although somewhat analogous to GSM's frequency-time division, there are two main differences:

- Each user can access the entire band in OFDMA.
- OFDMA does not require guard bands across the sub-carriers.

The setup for OFDM is described below. In each timeslot, we are aiming to transmit N symbols $a_0, ..., a_{N-1}$. As these symbols arrive, they are stored and serial-to-parallel conversion is carried out, with each symbol a_k being used to separately modulate a subcarrier at frequency f_k. The N subcarriers are of uniform bandwidth $\Delta f = B/N$.



The aggregate transmit signal is then

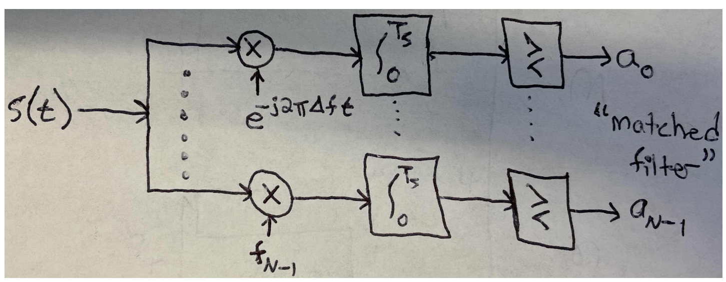
$$s(t) = \left(\sum_{k=0}^{N-1} a_k e^{j2\pi k \cdot \Delta f \cdot t} \right) \cdot e^{j\omega_c t}, \tag{2}$$

where ω_c is the carrier frequency and Δf becomes the offset from this.

We want the subcarriers to be orthogonal to each other, so that we can decode each a_k at the receiver.

- In FDMA, filters are used to extract each subcarrier, which requires guardbands and filters.
- OFDM uses a different approach based on orthogonality, which allows much tighter packing of the sub-carriers.

Specifically, at the receiver end, we would have the following type of architecture:



When stream k passes through the desired branch k, we have

$$\int_0^{T_s} e^{j2\pi k \cdot \Delta f \cdot t} \cdot e^{-j2\pi k \cdot \Delta f \cdot t} dt = T_s. \tag{3}$$

On the other hand, when stream k passes through another branch $m \neq k$, we want

$$\int_0^{T_s} e^{j2\pi k \cdot \Delta f \cdot t} \cdot e^{-j2\pi m \cdot \Delta f \cdot t} dt = \int_0^{T_s} e^{j2\pi (k-m) \cdot \Delta f \cdot t} dt = 0, \quad \forall m \neq k. \tag{4}$$

A sufficient condition for this is $\Delta f = 1/T_s$, which ensures that the set of functions $\{e^{j2\pi k \cdot \Delta f \cdot t}\}$, $k = 0, ..., N-1$ is orthogonal over $[0, T_s]$. The total bandwidth is then $\Delta f \cdot N = N/T_s$, and no guardband is needed!

LTE Case Study

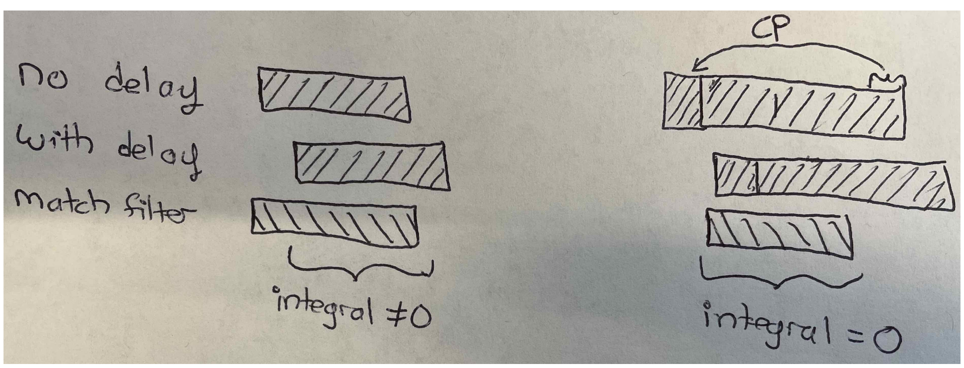
In LTE, the total bandwidth available is up to 20 MHz. Each subcarrier has a bandwidth of 15 kHz, which gives a symbol duration of $T_s = 66.67\ \mu$s and 20M/15k $\approx$ 1667 subcarriers. At 20 MHz bandwidth, the downlink can obtain up to 150 Mbps with 2x2 MIMO, and even 300 Mbps with 4x4 MIMO. The uplink can obtain up to 75 Mbps.

Without OFDM, LTE would have $T_s = 1/B = 50$ ns, which is much smaller than $2\pi\tau_{av}$ in any environment, resulting in fequency-selective fading. On the other hand, with OFDM, LTE's $T_s = 66.67\ \mu$s will be larger than $2\pi\tau_{av}$, which means each sub-carrier experiences flat fading.

As mentioned, the orthogonality property in OFDM eliminates the need for guardbands. However, the property may also be lost if another copy of the signal is delayed due to multi-path. Specifically, with $u(t)$ being the unit step function, stream k passing through branch m would experience

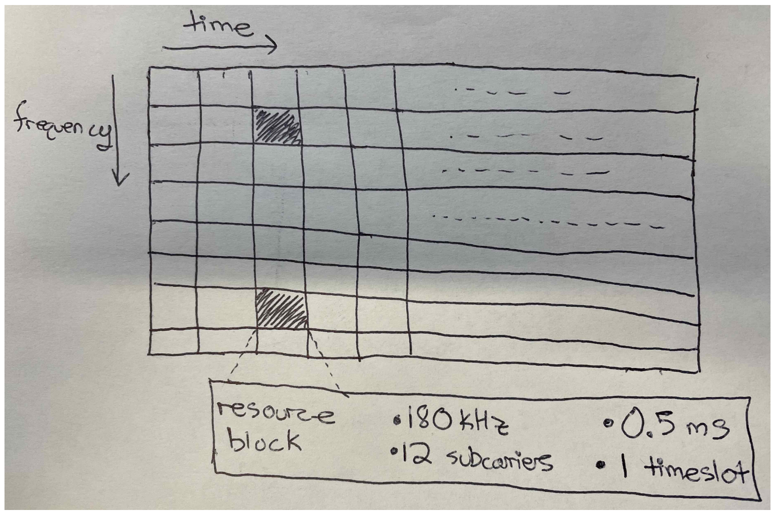
$$\int_0^{T_s} e^{j2\pi k\cdot\Delta f\cdot(t-\tau)}u(t-\tau)\cdot e^{-j2\pi m\cdot\Delta f\cdot t}dt \neq 0. \tag{5}$$

OFDM employs a **cyclic prefix**, which is a guard time made up of a replica of the time-domain OFDM waveform. The basic premise is to replicate part of the back of the OFDM signal to the front to create the guard period, as shown below.



For this to work, the cyclic prefix (CP) needs to be longer than the delay spread, so that the integral will still come out to be 0. In LTE, the normal CP is 4.7 μs, and the extended CP is 16.67 μs.

With OFDMA, the base station will schedule users to a subset of the frequency and time-slots, i.e., there is no dedicated channel. A **resource block** (RB) is the smallest unit of resources that can be allocated to a user. LTE RBs are depicted below:



In LTE, each RB is 180 kHz wide in frequency and 1 slot long in time, where the time of each slot is 0.5 ms. Each RB is typically divided into 12 sub-carriers of 15 kHz each. Subframes, half-frames, and frames consist of 2, 5, and 10 consecutive slots, respectively.

Opportunistic scheduling in OFDMA can thus take advantage of good channel conditions both in time and in frequency. This leads to the second key benefit taken advantage of in LTE: we can obtain a high peak data rate, especially when combined with the spatial diversity gains offered in MIMO. With a large number of diverse user applications, the result is higher spectral efficiency.