What is Doppler shift?

With CP, you still need equalization, but it’s a single tap. Without CP, then ISI means you need a complicated equalization filter I think.

# Why OFDM?

[[Wikipedia] Orthogonal frequency-division multiplexing](https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing)

The main advantage over single-carrier is its ability to cope with severe channel conditions without needing complicated channel equalization filters (e.g. attenuation of high frequencies in a long copper wire, narrowband interference, and frequency-selective fading due to multipath).

The low symbol rate means we can use a guard interval between symbols to eliminate ISI.

Forward error correction (convolutional coding) and time/frequency interleaving are applied to overcome errors due to multipath propagation and Doppler effects.

**Summary of advantages:**

* High spectral efficiency compared to other double sideband modulation schemes, spread spectrum, etc.
* Adapts to severe channel conditions without the need for complicated equalization
* Robust against narrowband co-channel interference
* Robust against ISI and fading due to multipath propagation
* Efficient implementation using FFT
* Low sensitivity to time synchronization errors

**Summary of disadvantages:**

* Sensitive to Doppler shift
* Sensitive to frequency synchronization errors
* High PAPR, which requires linear circuits, which means poor power efficiency
* Guard interval/cyclic prefix = some loss in efficiency

## Orthogonality

Subcarriers are all orthogonal to each other:

* There is no crosstalk between sub-channels
* There is no need for inter-carrier guard bands, which means high spectral efficiency. Almost the entire available frequency band can be used. For example, in LTE, spectral efficiency is 90% (10% is for the guard band). In 5G, it’s even higher.
* Requires very accurate frequency synchronization between Rx and Tx – frequency deviation causes ICI (i.e. crosstalk). Frequency offsets are typically caused by mismatched Rx and Tx oscillators or by Doppler shift due to movement, which is worsened by multipath. This is a limiting factor of using OFDM in high-speed vehicles.

## Implementation using the FFT algorithm

The time to compute the inverse FFT or FFT must be less than the time for each symbol.

## Guard interval for elimination of ISI

Because of the long symbol duration, OFDM is much less susceptible to ISI from multipath propagation.

The long symbol duration also makes it easier to insert a guard interval between OFDM symbols. The guard interval

* Eliminates ISI
* Eliminates the need for a pulse-shaping filter (true only for signal quality, not spectral leakage)
* Reduces sensitivity to time synchronization error

**Example:**

We send 1 million symbols/second using single-carrier modulation. The duration of each symbol is 1us. This imposes severe constraints on time synchronization and requires the removal of multipath interference.

We split the 1 million symbols over 1000 sub-channels. The symbol duration increases by 1000× to 1ms. We insert a guard interval 1/8 of the symbol length between symbols. ISI is avoided if delay spread is shorter than the guard interval (125us). This corresponds to a maximum difference of 37.5km between the lengths of the paths (radio waves move at the speed of light).

**Cyclic prefix (clean this up and add equations):**

[[YouTube] What is a Cyclic Prefix in OFDM?](https://www.youtube.com/watch?v=AJg57AEBtNw)

In a multipath environment, the guard interval means that the previous symbol does not interfere with the current symbol. Why do we need the cyclic prefix?

The video explains using a single subcarrier (or carrier). With nothing in the guard interval, there is a discontinuity. When we add the cyclic prefix, there are no discontinuities (as long as delay spread is less than the cyclic prefix duration). Slicing each symbol amounts to adding shifted copies of the subcarrier, which is equivalent to a gain and phase shift that can be equalized with a single tap (no memory required). (This is phasor analysis.)

Extending to OFDM, each subcarrier experiences the same time shifts. Each subcarrier is at a different frequency, which means each one experiences a different phase shift. However, this is still single-tap equalization. This is equivalent to thinking in terms of FFT, circular shift, and frequency-dependent phase.

We discard the cyclic prefix, which contains the discontinuity between symbols.

Typically associated with OFDM but can be used in single-carrier too. <https://en.wikipedia.org/wiki/Cyclic_prefix>

The downside is loss of efficiency in data rate and in power (since you’re transmitting redundant information. When power is critical, the CP may be inserted by the receiver instead.

## Simplified equalization

# 5G physical layer

Flexible numerology – 15, 30, 60, 120, 240kHz SCS. Narrow SCS for large cell size and large delay spread; wide SCS for small cell size, small delay spread – less susceptible to frequency error and phase noise.

Scheduling interval (TTI) is 14 symbols. For 15kHz SCS, this is 1ms. For 30kHz SCS, this is 0.5ms. And so on.

BWP – UE can be configured for smaller BWP (if it doesn’t support larger BW) or larger BWP (if it wants more data)

1 RE = 1 symbol x 1 subcarrier (time-frequency grid)

RB is 12 subcarriers

**How does a phone connect to the network?**

SSB (synchronization signal block). SS/PBCH block contains PSS, SSS, PBCH, and PBCH DM-RS. This is for downlink symbol/frame timing synchronization.

PRACH is for uplink symbol/frame timing synchronization.

**Channel estimation:**

We need to accurately estimate the channel response. The phase of the incoming signal depends not only on the phase of the transmitted signal, but also on the receiver’s exact position. If the receiver moves through half a wavelength of the carrier (a distance of 5cm at a carrier frequency of 3000MHz), the received signal phase changes by 180 degrees, turning bit pairs of 00 into 11.

The transmitter inserts occasional symbols into the data stream from a demodulation reference signal (DM-RS), which have transmission time, amplitude, and phase that are defined in the specification. The receiver compares the incoming reference symbols against the specification and estimates the channel response (gain and phase shift). The receiver may then equalize the channel response (the simplest is to divide by the estimated gain and phase shift per subcarrier, a zero-forcing equalizer).

# My notes

Long symbol times – much more resistant to ISI, especially due to channel fading/multipath. Fading becomes flat instead of frequency selective. Use coding to improve diversity – I think that’s how the modulation formula is chosen.

Scales easily to higher bandwidths and bitrates

Easy channel equalization in the frequency domain

High spectral efficiency compared to single-carrier – long symbols = smaller sidebands, can pack in subcarriers because of orthogonality in FD

Less sensitive to time synchronization errors (long symbols?)

Problems:

* High PAPR – requires linear circuits – poor power efficiency
* Sensitive to Dopper shift
* ICI (e.g. sensitive to freq synchronization problems)
* Loss of efficiency b/c of CP

**How OFDM?**

Vector of symbols (constellation points) 🡪 take IFFT 🡪 this is what you transmit

With transform precoding,

Vector of symbols (constellation points) 🡪 take FFT to get new vector of symbols 🡪 take IFFT 🡪 this is what you transmit

Forward error correction (convolutional coding), time/frequency interleaving

Cyclic prefix

**5G**

15kHz SCS – 66.6us symbol

30kHz SCS – 33.3us symbol

How to modulate subcarriers