Orthogonal Frequency Division Multiplexing (OFDM) is a digital multi-carrier modulation technique extending the concept of single subcarrier modulation by using multiple sub-carriers over the channel.

Rather than transmit a high-rate stream of data with a single carrier, OFDM makes use of a large number of closely spaced orthogonal sub-carriers that are transmitted in parallel.

Each sub-carrier is modulated with a conventional digital modulation scheme (such as QPSK, 16-QAM, etc.) at a lower symbol rate. However, the combination of many sub-carriers enables data rates similar to conventional single-carrier modulation schemes using similar bandwidths.
OFDM Benefits

Q: What are the benefits of using OFDM?

A: First and foremost, spectral efficiency, also called bandwidth efficiency. That means one can transmit more data faster within a given bandwidth in the presence of noise. Spectral efficiency is measured in bits per second per Hertz, or bps/Hz.

Within a spectrum space, different modulation methods give widely varying maximum data rates for a given bit error rate (BER) and noise level. Simple digital modulation methods like amplitude shift keying (ASK) and frequency shift keying (FSK) are simple, but don’t give the best BER performance. BPSK and QPSK do much better. QAM is very good but more susceptible to noise and low signal levels issues. Code division multiple access (CDMA) methods are even better performance.

But none is better than OFDM with respect to maximum data capacity in a given channel bandwidth. OFDM approaches the Shannon limit defining maximum channel capacity in bits per second (bps).
First . . . Consider Discrete Multitone (*DMT*)

The fundamental idea behind *DMT* is to split the available bandwidth into a large number of sub-channels. This provides for parallel data streams, with each data stream having a lower data rate.

*DMT* allocates data so the throughput of every single sub-channel is maximized. If some sub-channels can’t carry data, they can be turned off.

*DMT* constantly shifts signals between channels to ensure the best channels are being used for transmission and reception. This is called **dynamic allocation**.
Discrete Multitone Example

The basic idea of Discrete Multitone (DMT) is to split the available bandwidth into a large number of sub-channels. Digital Subscriber Line ADSL2 is an example of DMT. Commonly telephone twisted pair line to the home.

DMT uses available frequencies on the telephone line and splits them into 256/512 equal sized frequency bins of 4.3125 kHz each.

http://educypedia.karadimov.info/computer/modemadsl.htm
Discrete Multitone Realized by using Multiple Oscillators

What is the problem with this architecture?

Answer: It is impossible to keep large numbers of oscillators in synchronization (coherent) with each other. And it’s expensive to have hundreds of oscillators in a practical system.
Can we omit the guard-bands in DMT to reduce bandwidth?

Recall from Fourier Transform theory:

Spectrum of one OFDM Sub-channel

OFDM Spectrum

Note the close packing.
OFDM divides each channel into many narrower subcarriers. The spacing is chosen so these subcarriers are orthogonal. This avoids interference between subcarriers even without guard-bands between them. The subcarrier spacing is equal to the reciprocal of symbol time. All subcarriers have integer sinusoidal cycles that sum to zero upon demodulation. Orthogonality guarantees symbol recoverability.
Example: Spectrum of a OFDM Signal Transmission

Spectrum of an OFDM transmission signal; single carriers and sum signal

8 sub-carriers
Example: Spectrum of 802.11g Wi-Fi

802.11g Wi-Fi uses **OFDM**

https://www.researchgate.net/figure/IEEE-80211g-transmitted-RF-signal-analysed-in-Spectrum-analyser_fig5_281329380
In *OFDM* the Sub-Carriers must be Orthogonal

Two conditions must be met for subcarrier orthogonality:

1. Each subcarrier has exactly an integer number of cycles in the Discrete Fourier Transform interval.

2. The number of cycles between adjacent subcarriers differs by exactly one cycle.
Illustration of Orthogonality

Orthogonality:

Time domain

Frequency domain

Four subcarriers within a single OFDM symbol

Spectra of the four subcarriers
What Makes *OFDM* Possible?

**Q:** How is *OFDM* implemented in the real world?

**A:** *OFDM* is accomplished using digital signal processing (DSP).

In particular, we use the **Discrete Fourier Transform** (also called the **Fast Fourier Transform** or **FFT**).

You can program the FFT and its inverse (IFFT) math functions on any fast PC, but it is usually done using a special DSP IC, or an appropriately programmed FPGA, or sometimes in hardwired digital logic. With today’s super-fast chips, even complex math routines like the FFT are relatively easy to implement. In brief, you can put it all on a single integrated circuit.
Subcarrier Orthogonality

\[ T_u = \frac{1}{\Delta f} \]

\( T_u \) = useful symbol period
= modulation symbol period

All sum together to make OFDM symbol
OFDM Sub-Carriers with Guard-Bands & Pilot Signals
802.11a Wi-Fi Uses **OFDM** Sub-Carriers with Pilot Signals

http://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/wlan-ofdm/content/ofdm_80211-overview.htm
802.11a Wi-Fi OFDM Burst

http://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/wlan-ofdm/content/ofdm_80211-overview.htm
802.11a/b/g Wi-Fi Range and Data Rates

**RANGE AND DATA RATE**

- **Data Rate (Mbps)**
  - 54
  - 48
  - 36
  - 24
  - 12
  - 11
  - 5.5
  - 1

- **Range (feet)**
  - 0
  - 100
  - 200
  - 300

- **Modes**
  - 64-QAM
  - 16-QAM
  - QPSK
  - BPSK

✓ As distance from the access point increases, 802.11 products provide reduced data rates to maintain connectivity.
Example: **OFDM Subcarriers in 802.11a/g Wi-Fi**

Each 20 MHz channel, whether it's 802.11a/g/n/ac, is composed of 64 subcarriers spaced **312.5 KHz** apart. This spacing is chosen because we use 64-point FFT sampling. 802.11a/g use 48 subcarriers for data, 4 for pilot, and 12 as null subcarriers. 802.11n/ac use 52 subcarriers for data, 4 for pilot, and 8 as null.

A standard Wi-Fi symbol is 4μs, composed of a 3.2μs IFFT useful symbol duration plus 0.8μs guard interval. (When using a shorter guard interval of 0.4μs then the total symbol time is reduced to 3.6μs).
14 channels are defined in the IEEE 802.11b/g channel set (but only 11 channels in US). Each channel is 22 MHz wide, but the channel separation is only 5 MHz. The channels overlap such that signals from neighboring channels can interfere with each other. There are only three non-overlapping (and thus, non-interfering) channels: 1, 6, and 11—each with 25 MHz of separation.

IEEE 802.11b provides rates of 1, 2, 5.5, and 11 Mbps. IEEE 802.11g provides data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps in the 2.4-GHz band, in the same spectrum as IEEE 802.11b.

802.11 Wi-Fi – Channels in 2.4 GHz Band

2.4 GHz ISM Band: Channels [1,11] in North America; Channels [1,13] in Europe; Channels [1,14] in Japan.
802.11b/g (Wi-Fi), Bluetooth & Zigbee in the 2.4 GHz Band

https://www.researchgate.net/figure/80211-Bluetooth-and-ZigBee-Channels-in-the-24-GHz-ISM-Band_fig1_220973226
**OFDM Highlights**

Parallel data streams (all at lower data rates)
\[ \Rightarrow \text{large number of subcarriers without guard bands} \]

Data coding based upon amplitude modulation

Multiple subcarriers are multiplexed into one symbol

Subcarriers are computed using IFFT (i.e., Inverse Fast Fourier Transform)
\[ \text{They are spaced at precise frequencies and phases} \]
\[ \text{This spacing selection provides orthogonality} \]

Orthogonality Principle results in close packing of subcarriers

Provides for **multi-user diversity**

Synchronization using pilot signals
OFDM Transmitter Implementation
Radio Wave Propagation in the Presence of Obstacles

- Reflection
- Shadowing
- Scattering
- Diffraction

In addition, absorption, polarization, dispersion, etc.
The Multipath Problem in Wireless

[Diagram showing multipath propagation with direct path and reflected paths, along with a graph of Rayleigh fading channel]
**Fast Fading and Slow Fading**

**Fast fading** from effects of constructive and destructive interference patterns due to multipath. **Slow fading** from shadowing and obstructions, such as tree or buildings, etc.
Path Losses and Fading

In wireless telecommunications, multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths.

Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings. Path losses generally vary inversely with distance, namely, \( \sim 1/d^n \), where \( n \) is approximately 2, but can be as high as \( n = 4 \).

Multipath causes multipath interference including constructive and destructive interference, and phase shifting of the signal. Destructive interference leads to fading.
**OFDM Performs To Reduce the Problem of Fading**

Multipath destroys orthogonality. The figure below shows two copies of the signal (direct path and reflected path with time difference).
Adding a Cyclic Prefix

- Direct Path
- Reflected Path
- Building

Individual Signals

- Previous Symbol
- Current Symbol
- Copy & Paste!

Combined Signals

- Full Cycles Available Within This Period: Retrievable Modulation Symbol!
Cyclic Prefix

GUARD INTERVAL AND CYCLIC EXTENSION

- To eliminate ICI, the OFDM symbol is cyclically extended in the guard interval.
- This ensures that delayed replicas of the OFDM symbol always have an integer number of cycles within the FFT interval, as long as the delay is smaller than the guard interval.
Direct and Delayed OFDM Symbol Compared

The period $T_g$ is the guard interval period.

- By adding the Guard Interval Period, ISI can be avoided.
OFDM is Resistant to Multipath Signal Fading

Q: How does fading affect OFDM?

A: OFDM is resistant to the multipath problem in high-frequency wireless. Very short-wavelength signals normally travel in a straight line (line of sight) from the transmit antenna to the receive antenna. Yet trees, buildings, cars, planes, hills, water towers, and even people will reflect some of the radiated signal.

These reflections are copies of the original signal that also reach the receiver antenna. If the time delays of the reflections are of the order of the symbol periods of the data signal, then the reflected signals will add to the most direct signal and create interference.

Multipath fading is also called Raleigh fading.
Digital Processing in OFDM Transmission System

Note: S/P is serial-to-parallel; P/S is parallel-to-serial

https://www.researchgate.net/figure/272623859_fig1_Figure-1-Block-Diagram-of-OFDM-Transmission-System
Next Topic: Antenna Diversity – MIMO

https://insight.nokia.com/making-most-mimo
Antenna Diversity

Antenna diversity, *aka* space diversity or spatial diversity, is any one of several wireless diversity schemes that uses two or more antennas to improve the quality and reliability of a wireless link.

Antenna diversity is especially effective at mitigating multipath situations. This is because multiple antennas allow a receiver several observations of the same signal. Each antenna will experience a different interference environment. Thus, if one antenna is experiencing a deep fade, it is likely that another has a sufficient signal.
Antenna Diversity

3- Spatial diversity via Multiple Antennas

- For uniform surrounding scatterers: uncorrelated power gains if antenna spacing $= \lambda/2$
- In practice: spacing $\gg \lambda$

Example: GSM900
- 2 Rx antenna @ BTS
- $\lambda = 30$ cm
- Separation = 2-3 m

$\text{Sum} = \text{Max}(1 \text{ or } 2)$

https://www.slideshare.net/AymanAlsawah/alsawah-mob2lecture03v10-multipleantenna-shared
Antenna Diversity in Cellular Telephony

Multiple-Antenna (MIMO) in the “Big Picture”

- **LTE-Advanced**: 4G, Uo to 5 x 20 MHz, 8x4 MIMO
- **LTE**: 4G, OFDM, 4x4 MIMO, All-IP
- **HSPA**: 3.5G, Carrier Aggregation (to 40 MHz), 16/64 QAM, HARQ, MIMO
- **UMTS**: 3G, WCDMA (5 MHz), QPSK/BPSK, Freq. full-reuse, fast power control
- **EDGE**: 8PSK, Adaptive Modulation & Coding
- **GPRS**: Multiple time-slots/user, packet-switching
- **GSM**: 2G, Narrow-Band FDMA-TDMA (200 KHz), GMSK

https://www.slideshare.net/AymanAlsawah/alsawah-mob2lecture03v10-multipleantenna-shared
Antenna Diversity Examples

Multiple Input Multiple Output (MIMO)

http://www.yourdictionary.com/mimo
Single-Input Single-Output (SISO)

Conventional communication systems use one transmit antenna and one receive antenna. This is **Single Input Single Output (SISO)**.

Shannon-Hartley:

\[ C = B \log_2 \left( 1 + \frac{S}{N} \right) \]
We have a nine-element transmission matrix $[H]$

Note: Antenna spacing is important in using MIMO.
Data to be transmitted is divided into individual data streams. Three transmit antennas mean three data streams. If \( m \) transmitters is not equal to \( n \) receiver antennas, then the number of data streams is the smaller of integers \( m \) and \( n \).

The capacity can increase directly with the number of data streams.

\[
C = N_D \cdot B \log_2 \left( 1 + \frac{S}{N} \right)
\]

\( N_D = \text{number of data streams} \)
This configuration doubles the data rate under ideal conditions. Why?
Multi-User MIMO (MU-MIMO)

When individual data streams are assigned to individual users we have multi-user MIMO. This mode is very useful for cellular uplinks because of the power limitations of the UE (cell phone) – it must be kept to a minimum in complexity. The base station has multiple antennas to enhance reception of the UE’s signal.
The purpose of **spatial diversity** is to make the transmission more robust. In the case shown there is no increase in the data rate.

When does it make transmission more robust?
**Receiver diversity** uses more antennas on the receiver than the transmitter. A 1 x 2 MIMO configuration is the simplest version of receiver diversity. Redundant data is transmitted to the receiver.

Receiver 1 x 2 diversity is simple to implement and requires no special coding.
Example of Receiver Diversity

\[ C = \max(A, B) \]

\[ C = (A + B) \]
The simplest transmitter diversity configuration is shown here. The same data is redundantly transmitted to the receiver.

Space-time codes are used in transmitter diversity.
Some Applications Using MIMO – Wi-Fi 802.11n

✓ IEEE 802.11n standard has adopted MIMO
  o Antenna Diversity up to 4 x 4
  o Tx Beamforming
  o Space Division Multiplexing (SDM)
✓ 2.4/5 GHz ISM band
  o 20/40 MHz Bandwidth
✓ PHY Data rates up to 600 Mbps
  o Throughput > 200 Mbps
✓ Extended Range
  o Indoor 70 m
  o Outdoor 250 m
MIMO in 4G LTE-Advanced

- 3GPP Rel 10 (LTE-A) has full featured MIMO
  - Antenna Diversity
  - Beamforming
  - Space Division Multiplexing (SDM)
- 22 Freq. bands covering 698-3600 MHz
  - Scalable Bandwidth (20-100 MHz)
- Enhanced Throughput
  - 1 Gbps Downlink
  - 500 Mbps Uplink
- Single or Multi User MIMO
  - SU-MIMO
  - MU-MIMO

Note: 3GPP stands for Third Generation Partnership Project
http://www.datamanager.it/2018/02/gli-smartphone-5g-scalpitano-arrivo-nel-2019/
Advancing to 5G Wireless

Wireless Network of the Present
- Insufficient Spectrum
- Capacity Constrained
- Competitive Alternative to Wireline for Some

Wireless Network of the Future
- Balanced Portfolio of Licensed and Unlicensed Spectrum
- Significantly Greater Capacity
- Competitive Alternative to Wireline for Many

Network Design:
- Larger cells on average
- Some small cells
- Some advanced radio methods
- Wi-Fi and cellular mostly operate independently
- Limited sharing of spectrum with government
- Frequencies: current cellular (600 MHz to 2.5 GHz)
- Total spectrum used: approximately 1 GHz

Network Design:
- Smaller cells on average
- Many small cells
- Many advanced radio methods (smart antennas, etc.)
- Unlicensed- and licensed-spectrum technologies work together in integrated network
- Selective sharing of spectrum with government
- Frequencies: current cellular bands and higher frequencies, including mmWave
- Total spectrum used: many GHz

[Image of 5G network concepts]

https://www.androidauthority.com/5g-mobile-tech-explained-798540/