

Is OFDM Here to Stay?

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Thanks to my Postdoc. Dr. Anil Y.

History of OFDM

Harmonic telegraph by Bell (1870) (Elisha Gray and Edison)



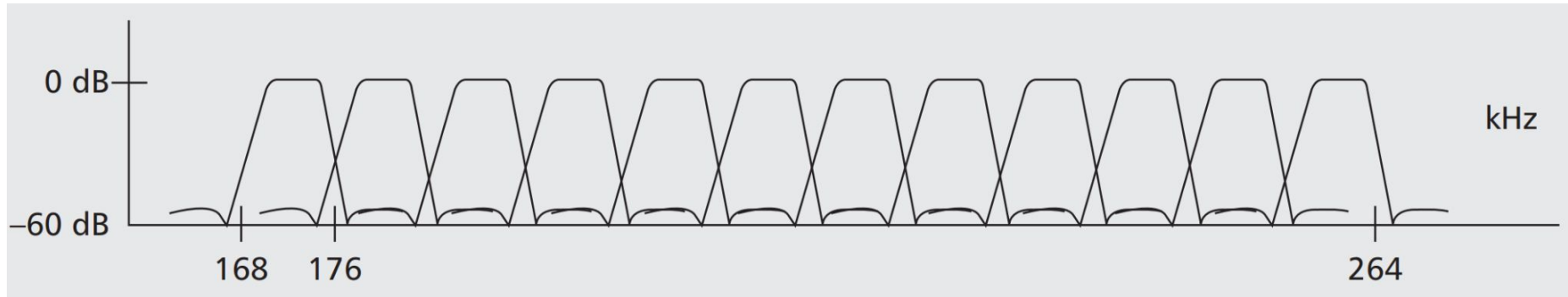
U.S. patent 174,465, "Improvement in Telegraphy," Alexander Graham Bell, Mar. 7, 1876.

U.S. Patent 166,095, "Electrical Telegraph for Transmitting Musical Tones," Elisha Gray, July 27, 1875.

U.S. Patent 182,996, "Acoustic Telegraph," Thomas Edison, Oct. 10, 1876.

FDM : George Squier, a major in the U.S. Army Signal Corps, in 1910

AT&T developed five channel FDM in 1918. Became a main **multiplexing strategy**



1960: N2 carrier system frequency spectrum for 12 telephone subchannels (8KHz sub-channel spacing)

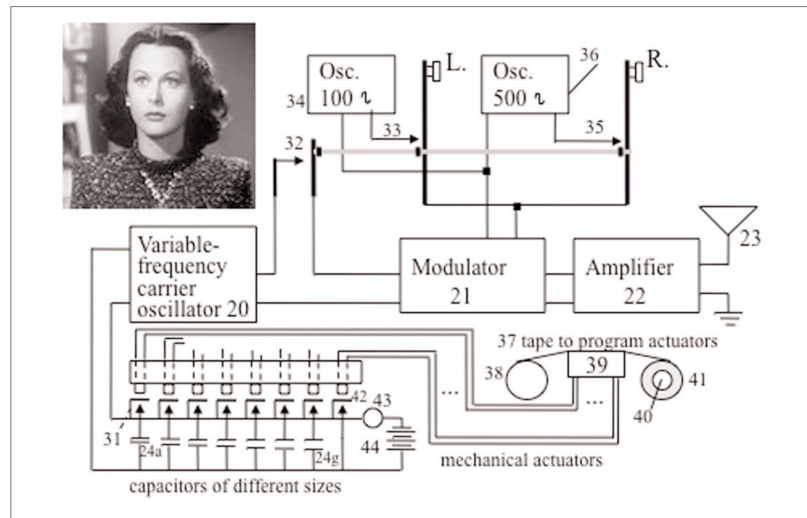
1970: Digital telephony (MOS), FDM channels replaced with TDM/FDM and pure FDM

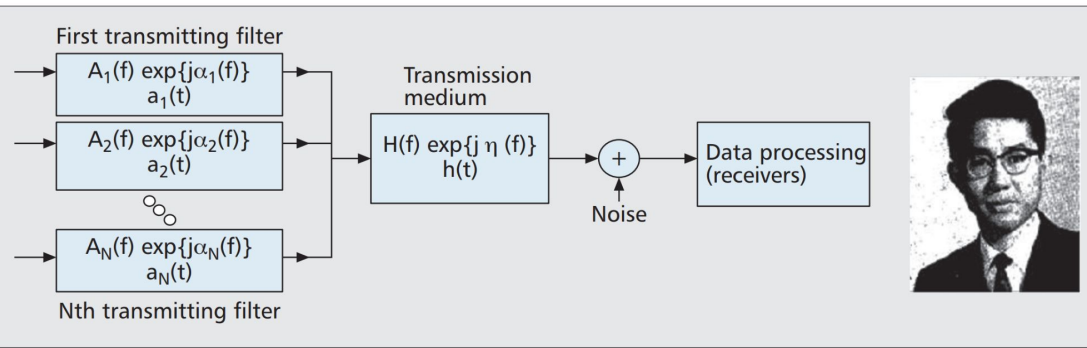


Observed: Faster data rate $\rightarrow$ Larger bandwidth $\rightarrow$ Higher selective fading $\rightarrow$ Require more sub-carriers

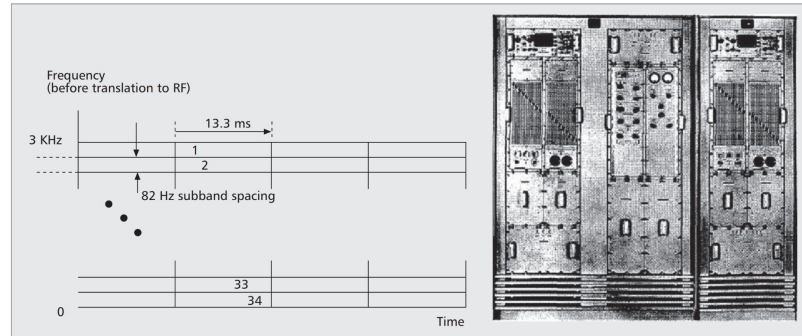
- FDM wastes resources for guard bands (freq).
- Too much complex circuits

- 1942 patent of Hedy Kiesler
 - Frequency hopping for narrowband jam resistance
 - Tunable hardware oscillator (rather than DFT)
- Flarion flash OFDM systems (now in Qcomm)
 - Minimize interference



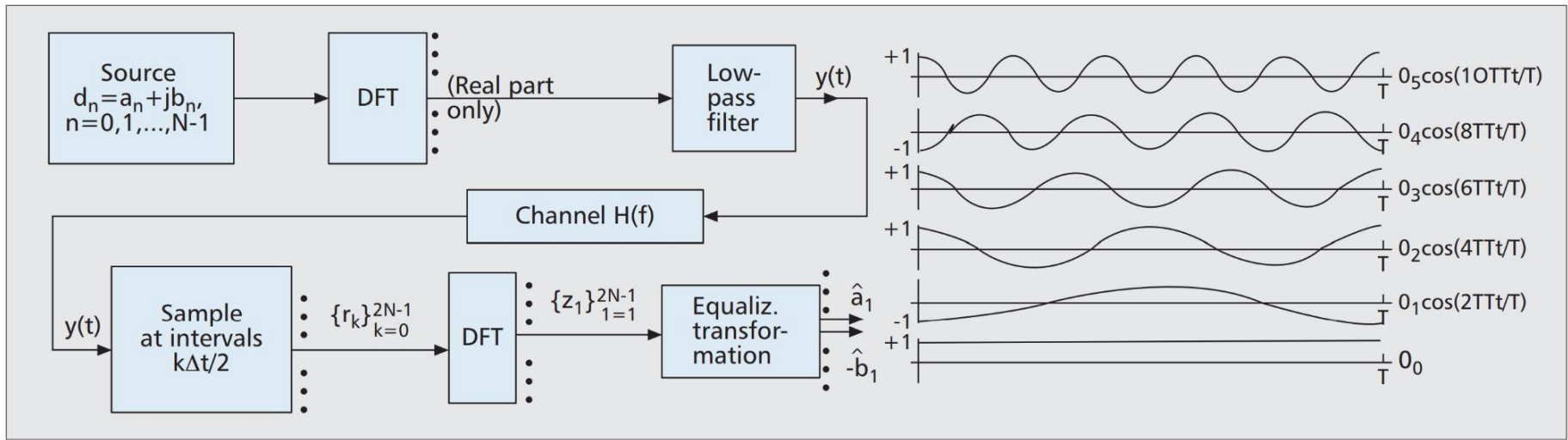


- Chang (Bell Labs, 1970) - first multicarrier modulation scheme using overlapped but non interfering (orthogonal) subcarriers
- Saltzberg - quantified performance benefits



Zimmerman and Kirsch : 1967 KATHRYN high-frequency radio OFDM system

Analog FFT with 34 channels in 3KHz Bandwidth



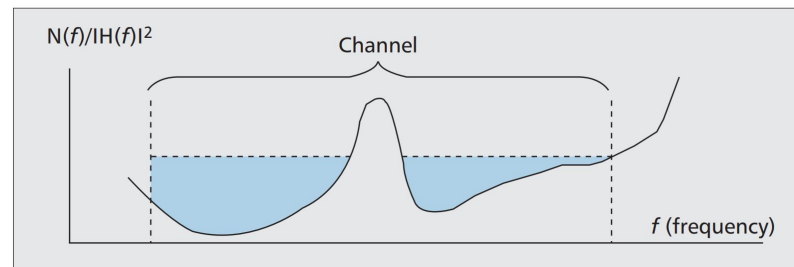
1971: Weinstein-Ebert paper, Application of FFT/DFT for OFDM

- No interest (even in Bell)
- Patent was not even filed

Not too much activity for a further 20 years!!

ADSL (1990's)

- Bell studied OFDM & CAP (Carrierless amplitude-phase modulation)
 - Choose CAP for DSL modems
- Cioffi and his company, Amati developed discrete multitone (essentially OFDM)
 - Won a competition with CAP in a Bellcore-sponsored test in January, 1993
 - Waterfilling: Capacity achieving scheme
 - Bit loading
- Early adopters
 - France, Britain, Australia
 - US (Bell) adopted in 1997
- TI purchased Amati for 450Mil\$ in 1997



2000s to present

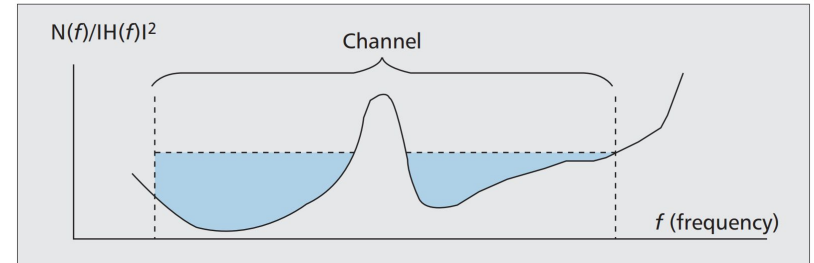
- WiFi
- ADSL (v2...)
- WiMAX
- DVB-T
- LTE
- 5G-NR
- 6G?

Why should we rethink the waveform for 6G?

- Support extremely high frequencies and bandwidths
- Improve energy efficiency
 - PAPR
- Support high mobility scenarios, robustness to doppler
 - Need to mitigate Inter-carrier interference (ICI) above ~ 500 km/h
- Reduced overhead and latency
- Diverse 6G service requirements
 - Sensing
 - NTN
- Enhanced coverage
 - Beyond what DFT-s-OFDM can achieve

Case for OFDM

- Multicarrier modulation technique that divides a wideband channel into multiple narrowband subcarriers
 - Subcarriers are orthogonal
 - Each subcarrier can be modulated by a conventional modulation scheme (QPSK, QAM etc)
- Used in WiFi, 4G LTE and 5G NR
- One candidate for 6G
- Capacity achieving
 - Different rate for each subcarrier



OFDM strengths

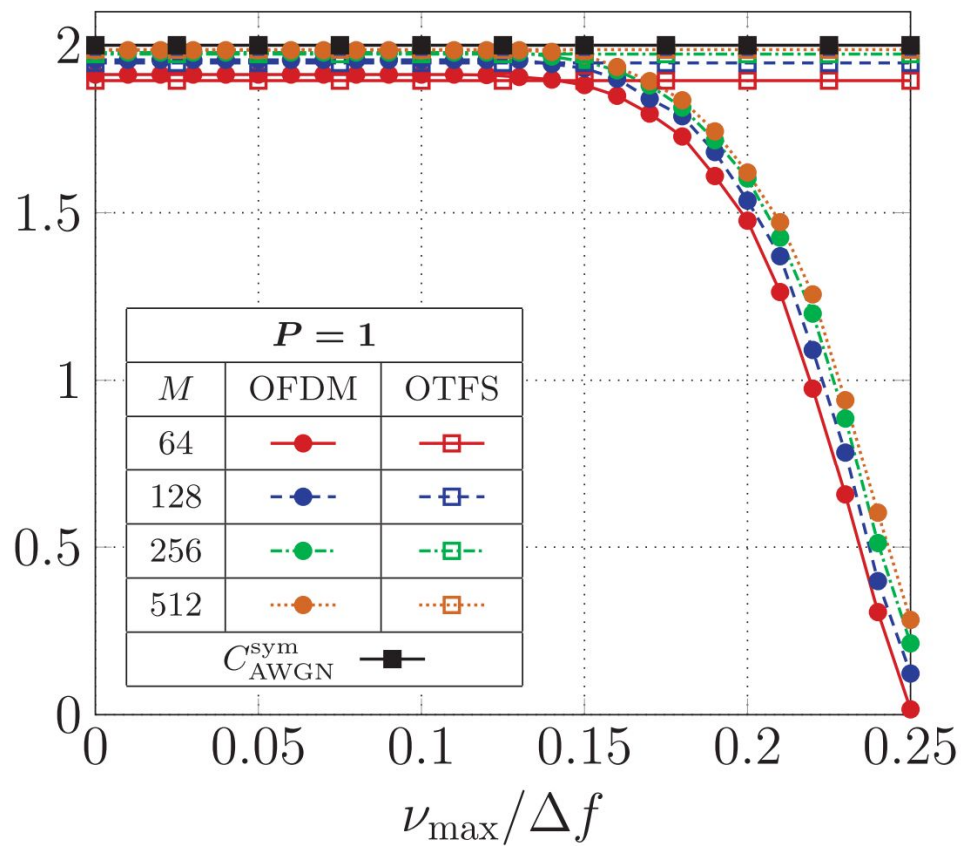
- **Frequency diversity and multipath resilience**
 - Converts frequency selective channel into flat channel in each subcarrier
- **High spectral efficiency**
 - Tightly packed orthogonal subcarriers
- **Reliability**
 - Cyclic prefix gives robustness against multipath fading
- **Scalable bandwidth**
 - Flexible numerology
- **Low complexity equalization**
 - Requires a single division operation per subcarrier
- **Efficient Hardware implementation**
 - FFT based processing
- **Works well**
 - Tested over billions of devices
 - Law of inertia

2 Main Variants of OFDM in 5G

- CP-OFDM
 - 5G NR Downlink and Uplink
 - Direct mapping of QAM symbols to subcarriers
 - High PAPR
 - Low PA efficiency
 - Lower complexity (no extra DFT/IDFT)
 - Good for base station deployment
- DFT-s-OFDM (and variants)
 - 5G NR Uplink
 - QAM symbols to subcarriers after DFT operation
 - Low PAPR (resembles single carrier structure)
 - High PA efficiency
 - Can enhance coverage
 - Higher complexity (extra DFT/IDFT)
 - Good for low power UE implementation

Drawbacks of OFDM

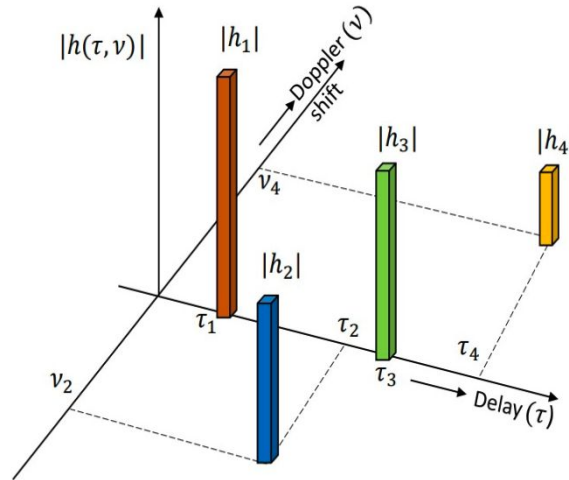
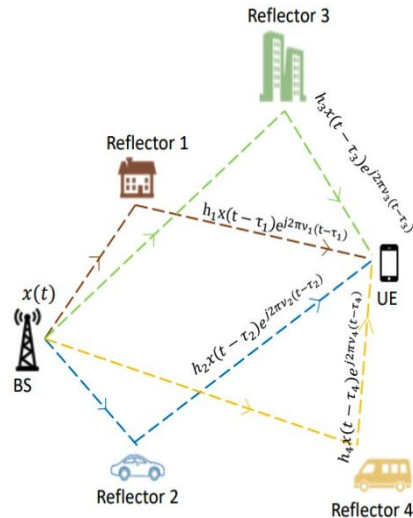
- High PAPR
- Sensitivity to synchronization errors - Carrier frequency offset (CFO) and timing errors
- Out-of-band emissions - Requires filtering or windowing to meet spectral mask requirements.
- Both OFDM/DFT-s-OFDM are not suitable for very high mobility scenarios
 - Up to 4 out of 14 symbols allocated for DMRS
 - Estimates derived from DMRS symbols are used to equalize data symbols - performance degrades
 - Increasing DMRS/time-interpolation improves doppler mitigation but at increased overhead and complexity



OTFS vs. OFDM in the Presence of Sparsity: A Fair Comparison

OTFS - Orthogonal Time Frequency Space

- Models wireless channel in Delay-Doppler (DD) domain
 - DD domain is closely related to the physical geometry of the channel
 - Suitable for high mobility and multipath environments (high?)

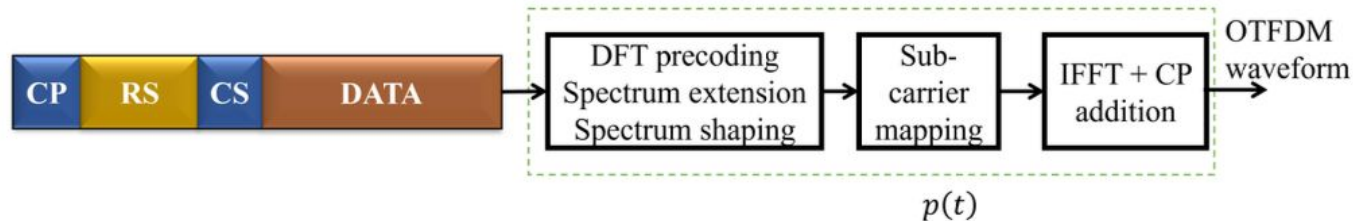


OTFS - Orthogonal Time Frequency Space

- Compact and Sparse representation of wireless channel
- Suitable for Sensing apart from communication
 - ISAC and V2X
- New waveform/Modulation technique
 - Embeds information symbols in DD domain
- What are its challenges
 - Fractional delays
 - Fractional dopplers

OTFDM - Orthogonal Time Frequency Division Multiplexing

- Uplink waveform
- Multicarrier modulation technique
- Low latency and low PAPR
 - Low latency: Multiplexes data and reference signals in one time domain symbol
 - Low PAPR: DFT spreading, spectrum extension, spectrum shaping



Parameters to evaluate a waveform

- Scalability
 - Multiple channels (control, channel, Initial access...)
 - Multiple applications (Communication, Sensing...)
 - Coordination with other technologies such as NTN
- Integration with MIMO
- Robustness to Channel Conditions
 - Channel computation in high mobility scenarios
 - Multipath scenarios
 - Equalization issues
- Solution for current and future generation standards
 - URLLC, XR applications, massive devices (IoT), sensing
 - Backward compatibility
- Ease of Implementation

Some thoughts

- 6G main frequency is 6.5 to 11 GHz
 - Main application is FWA
 - Mobility and long distances in this frequency is not practical because of link budgets
 - No mobility in FWA
 - Since it is FWA, better PA's (with some linearisation) can handle PAPR
- High speed mobility
 - OFDM has issues (after 500 Km)
 - Might be addressed with pilot changes
 - Aeroplane connectivity
 - Might require newer look (Depends on the relative mobility)
- Non terrestrial networks
 - A small part of 6G
 - Capacity provided by NTN is really unknown
 - PAPR is an issue
 - Might require new waveform
- IoT
 - Low power waveform required
 - Integrate into the time-frequency grid
 - on/off keying, chirp signals
- ISAC
 - Waveform won't be the bottleneck
 - Realistically getting 5–10 m accuracy in deployments will be nice
 - Other issues will dominate

OFDM still has time left!