6G Wireless - Illuminating New Directions in Waveform Design

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New Directions in Waveform Design

ICC 2021 First Workshop on Orthogonal Time Frequency Space Modulation (OTFS) for 6G and Future High-Mobility Communications

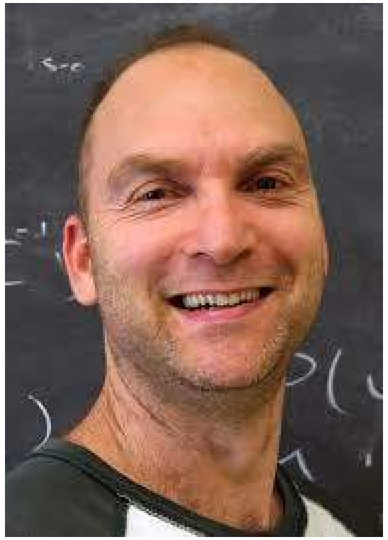
Commercial interest in OTFS as a 6G Waveform

Commercial and Government interest in feasibility of moving MU-MIMO scheduling to the cloud

OTFS modulation effectively transforms a time-variant channel into an effective 2D time-invariant channel in the Delay-Doppler domain, where attractive properties, such as separability, compactness, stability, and possibly sparsity are manifest and can be exploited

WCNC 2017 First Paper on OTFS Modulation – now with 165 citations on Google Scholar

Technical Vision



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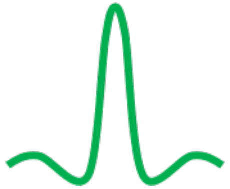
George Orwell: *Every generation imagines itself to be more intelligent than the one that went before it, and wiser than the one that comes after it.*

2G
TDMA

Voice



Localization in
Time

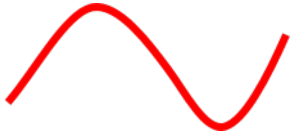
3G
CDMA

Voice +Data

Localization
in Code

4G
OFDM

High Speed
Data



Localization
in Frequency

5G & Beyond
OTFS

Massive IoT
Extreme Mobility
Extreme Broadband

Localization in
Delay / Doppler

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CDMA

CDMA spreads a narrowband information signal across a wideband channel

Interference can be treated as noise since codes are weakly correlated

Equalization is very difficult since the spreading code is not connected to channel evolution

OFDM

OFDM divides a wideband channel into narrowband tones each subject to time-varying flat fading.

A transmitter with knowledge of the instantaneous gain can adapt to maximize transmission rate

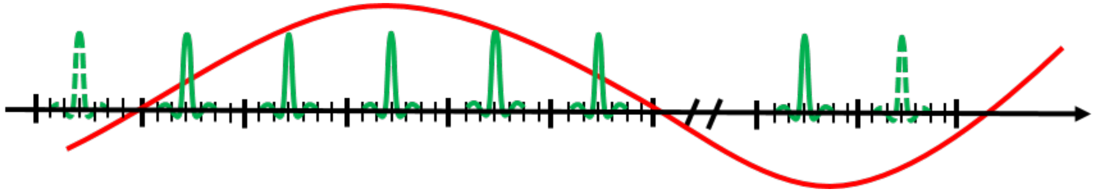
Resilience to high Doppler is a challenge, as is signal processing complexity for MU-MIMO

Localization in Delay and Doppler

P.M. Woodward: *Probability and Information Theory, with Applications to Radar,* Pergamon Press, 1953

He viewed the problem of localizing a scatterer in delay and Doppler as using a waveform to ask questions of the operator defined by the radar scene

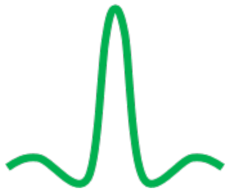
How to Design a Question:



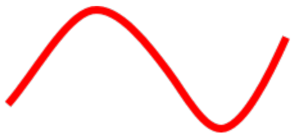
Good Questions are Less Ambiguous

Radar Scene or Channel: Scatterers $D(\tau_i, \nu_j)$ at range τ_i and Doppler ν_j

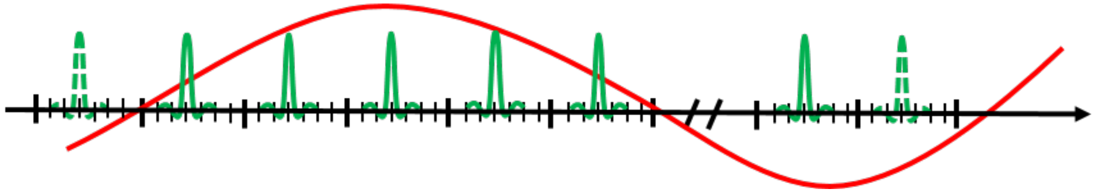
Waveforms are questions, returns are answers, ambiguity is that not revealed by correlation



Eigenfunctions of Phase Shifts $D(0, \nu)$: No information about Doppler

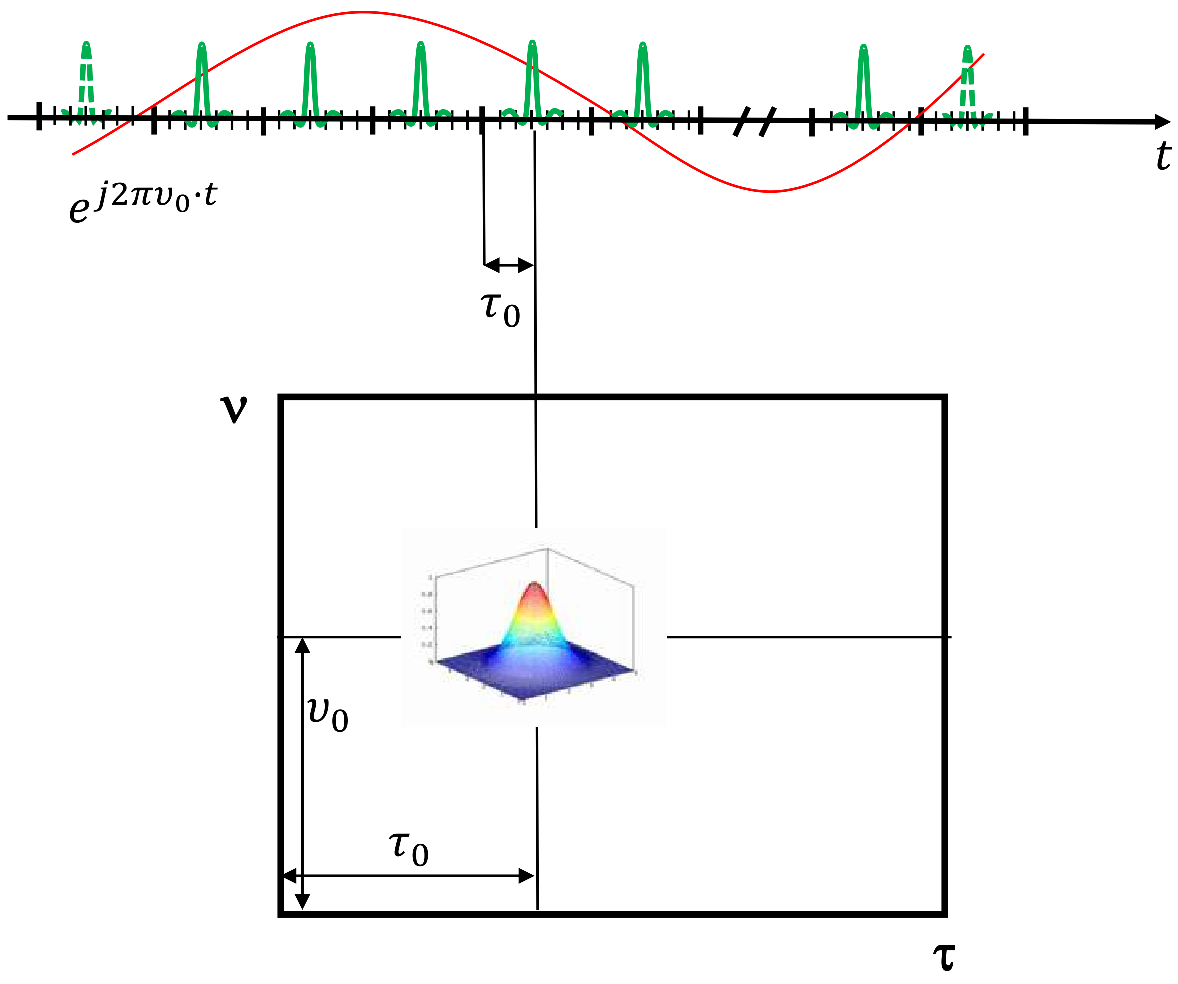


Eigenfunctions of Time Shifts $D(\tau, 0)$: No information about Delay

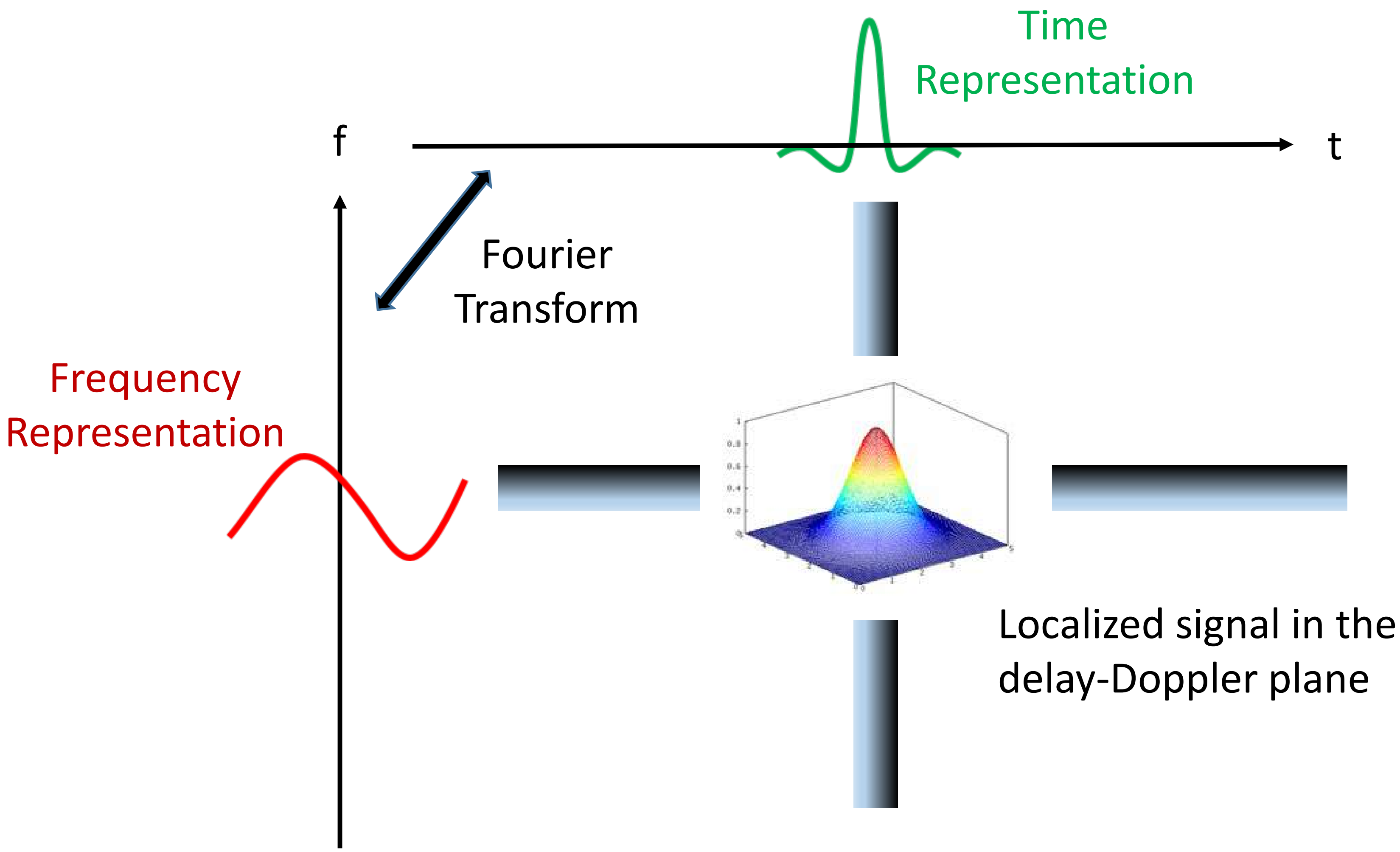


Information about Doppler and Delay

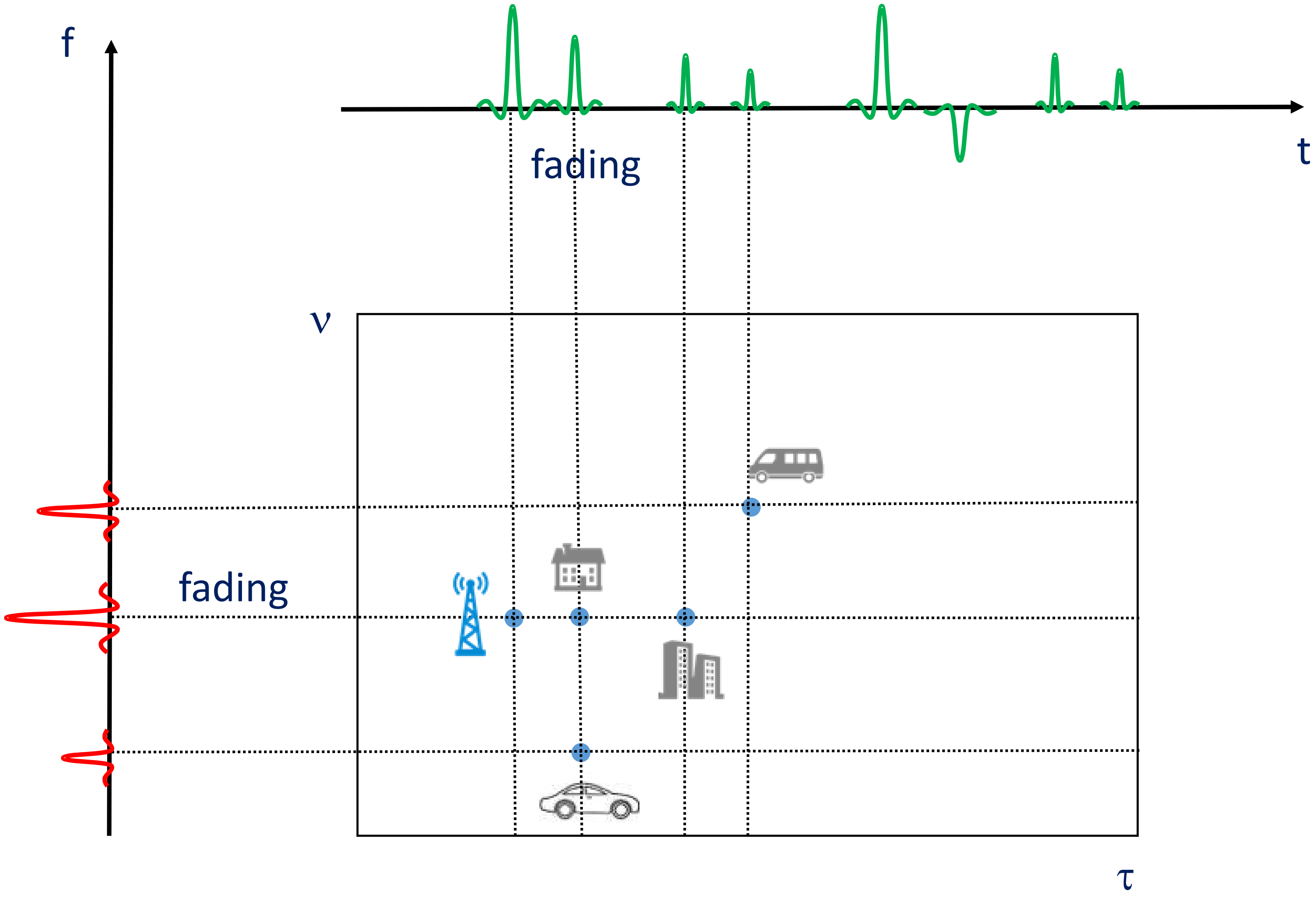
Grid Position Parameterizes the OTFS Waveform



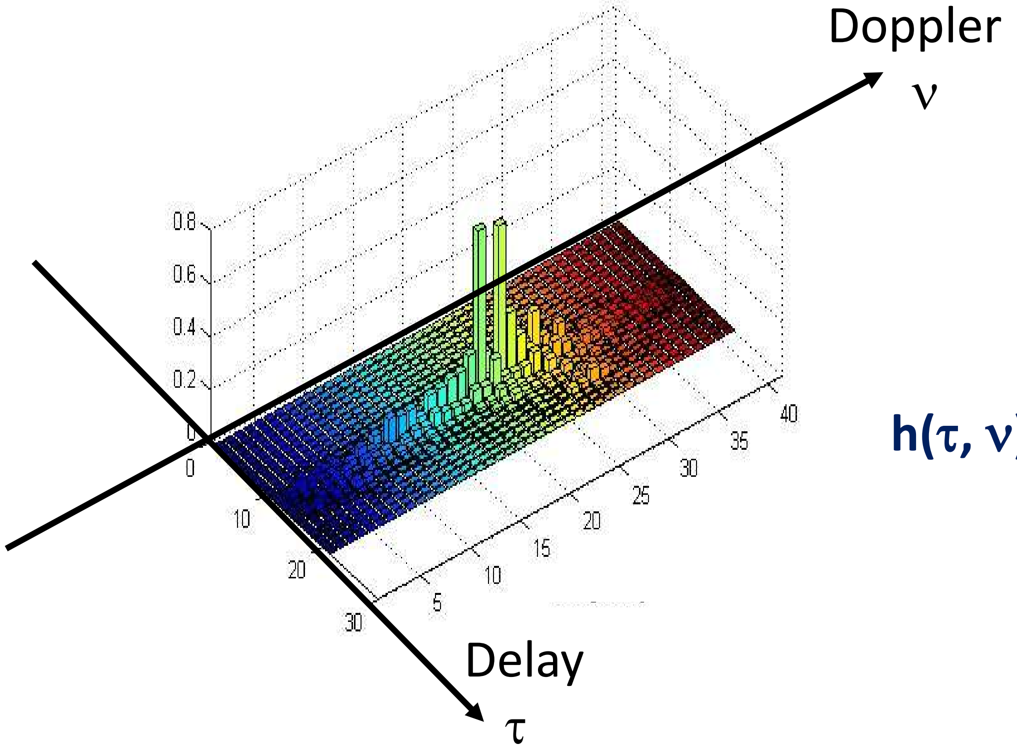
Connecting Delay and Doppler with Time and Frequency



Capturing the Physics of Scattering

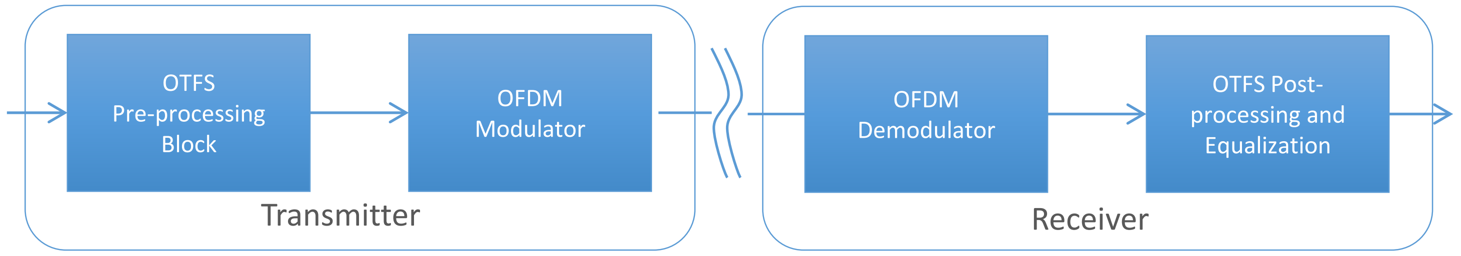


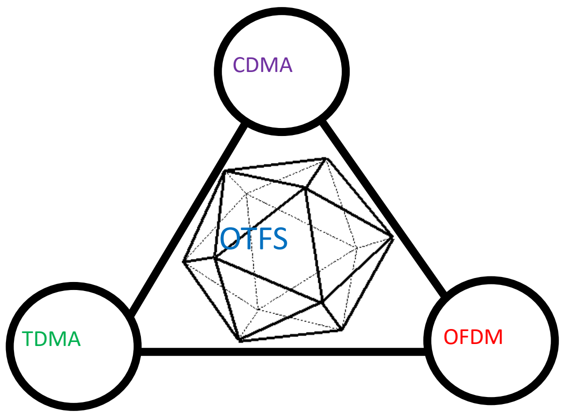
Capturing the Propagation Environment



h(τ, ν): Delay-Doppler Representation of the Wireless Channel

OTFS System Summary





OTFS is a theoretical generalization of OFDM and TDMA

OTFS is a 2D extension of CDMA

OTFS provides the benefits of OFDM, TDMA and CDMA

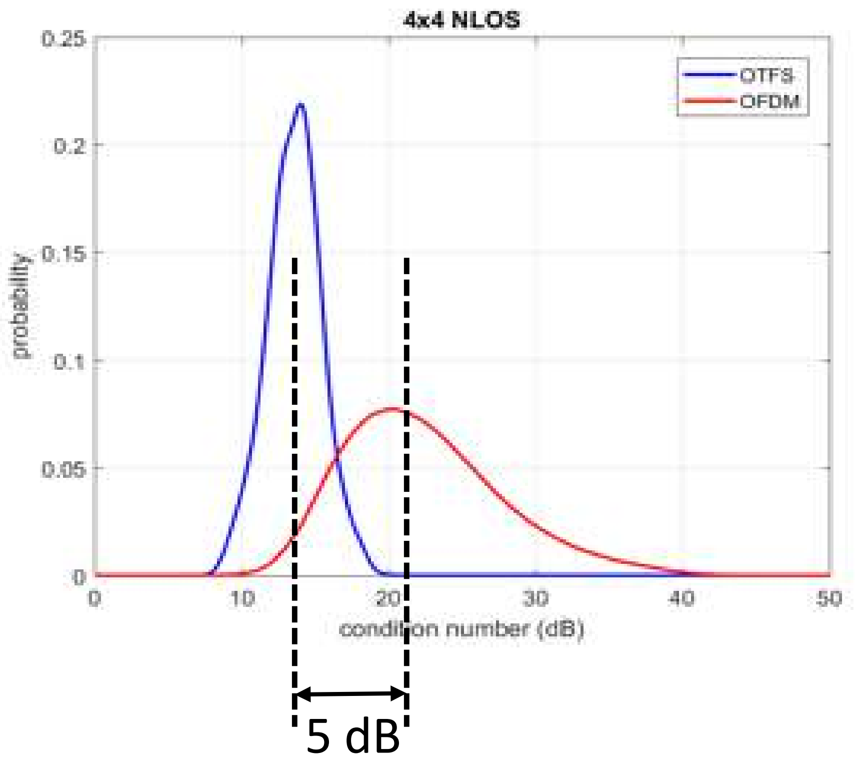
- Scheduling, Low PAPR, Interference resilience

OTFS is fully compatible with NR/Release 15

OFTS Value to 5G Use Cases

USE-CASE	ADVANTAGE	GAIN	REASON
eMBB	Better scale with MIMO order (higher capacity)	>8dB SNR gain per user in MU-MIMO using delay-Doppler THP	Lower condition number of the channel MIMO matrix
Mobility	Performance consistency under dynamic channel conditions	>7dB SNR gain for 1% reliability	time-frequency diversity gain independent of packet size
URLLC	Resilience to narrow band interference	∞ gain under 2% non-indicated URLLC interference	Processing gain due to spreading
IoT	Wider coverage under power and reliability constraints	>7dB extended link budget for 1% reliability compared to SC-FDMA	Low PAPR combined with time-frequency diversity gain
mm-Wave	Longer range under power and reliability constraints	>8 dB extended link budget for 1% reliability compared with SC-FDMA	Low PAPR combined with time-frequency diversity gain

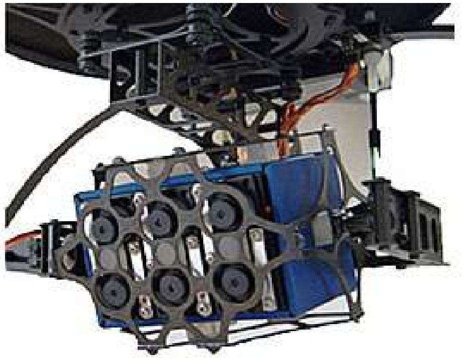
Signal Processing Complexity depends on the Coupling Matrix



High Condition Number (OFDM): Sphere decoder converges slowly (at best)

Highly Variable Coupling Matrix (OFDM): Requires significant parallel computation

Drones

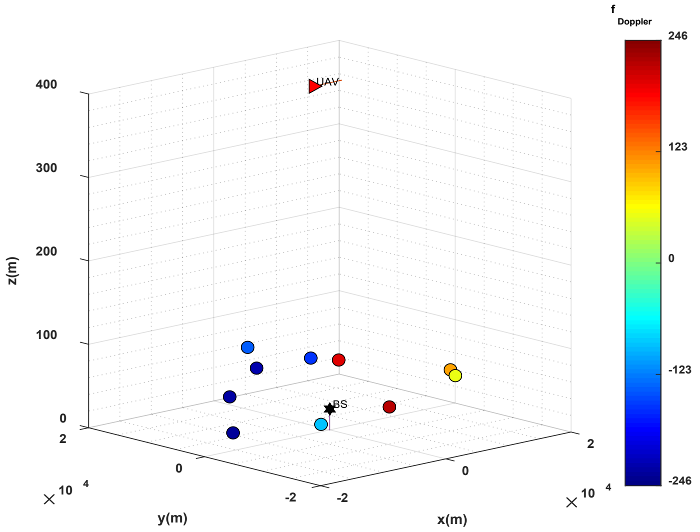


Drones gather sensor data that is high dimensional, multi-spectral and high resolution

Asymmetry: Uplink >> Downlink

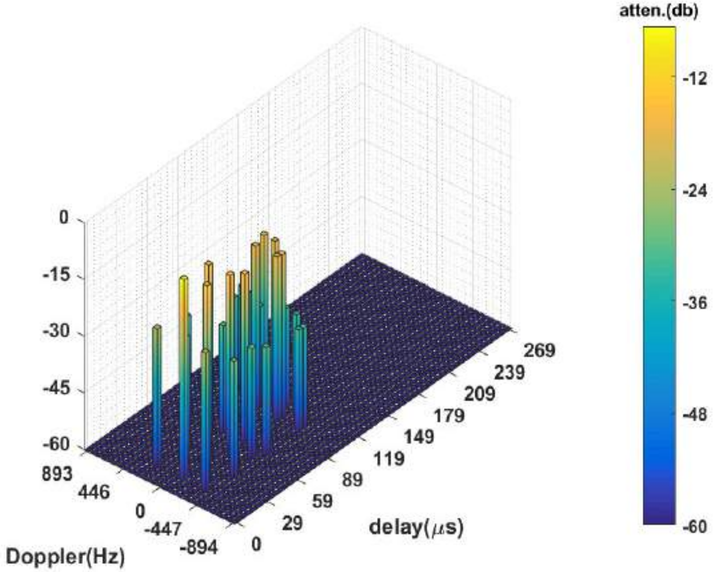
Not Covered Here: Use of the Delay-Doppler representation for physical layer security

Aerial Channel Impairments



Geometric Channel

Delay-Doppler Channel



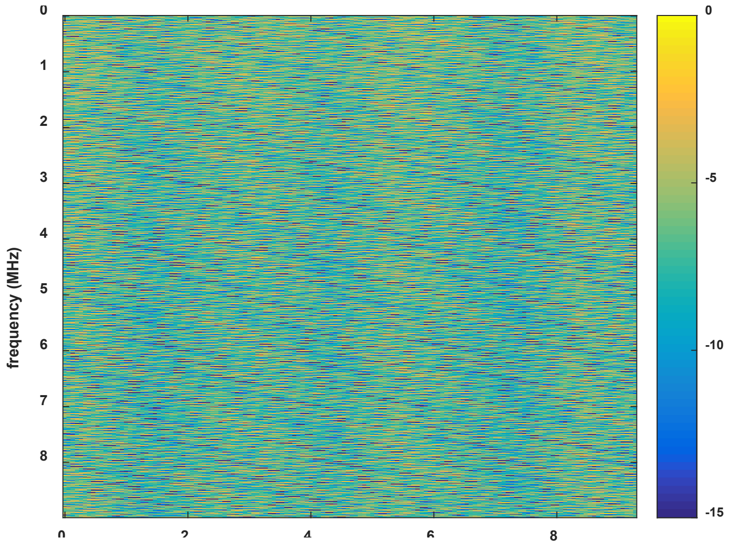
High Delay Spread due to increased altitude

High Doppler spread due to travel velocity

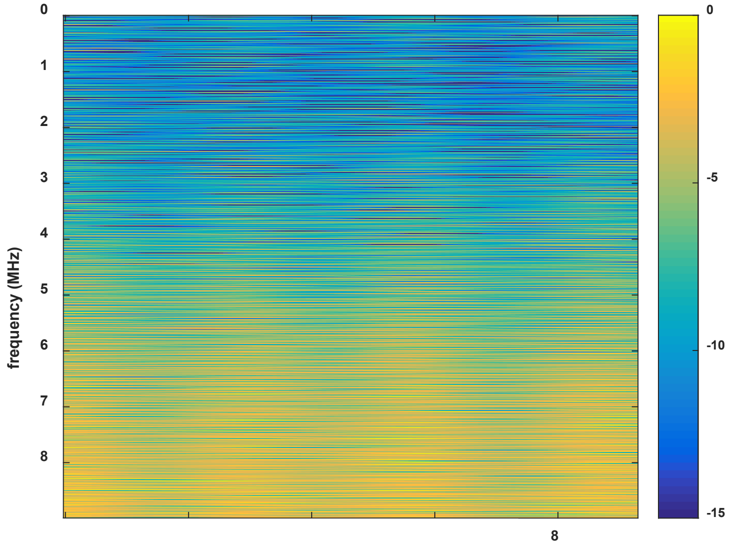
Motion of propeller blades induces time-varying Doppler modulation

Time-Frequency Representation of the Aerial Channel

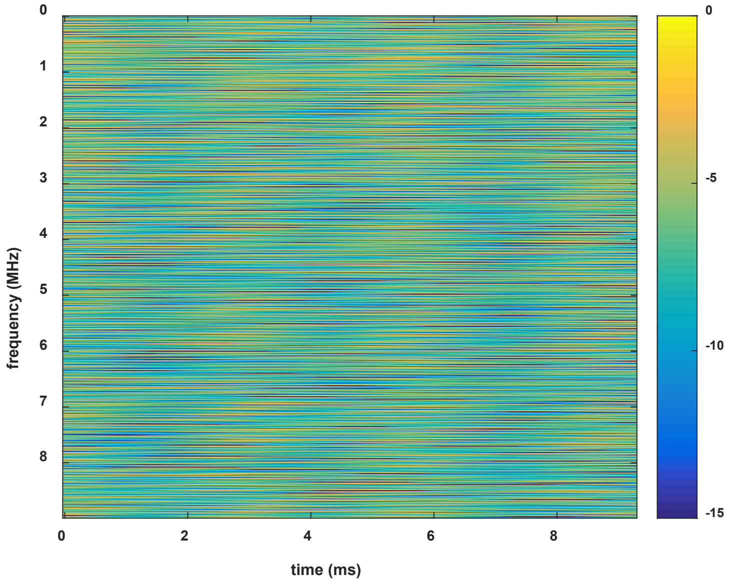
High Velocity



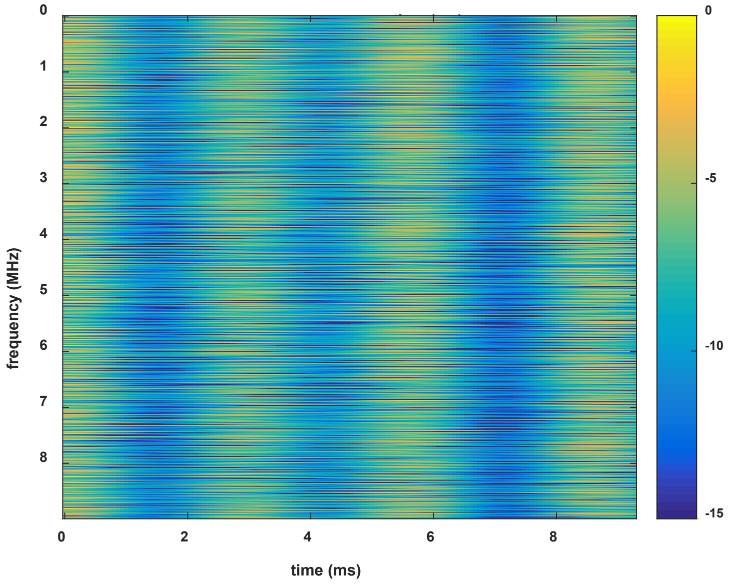
High Altitude



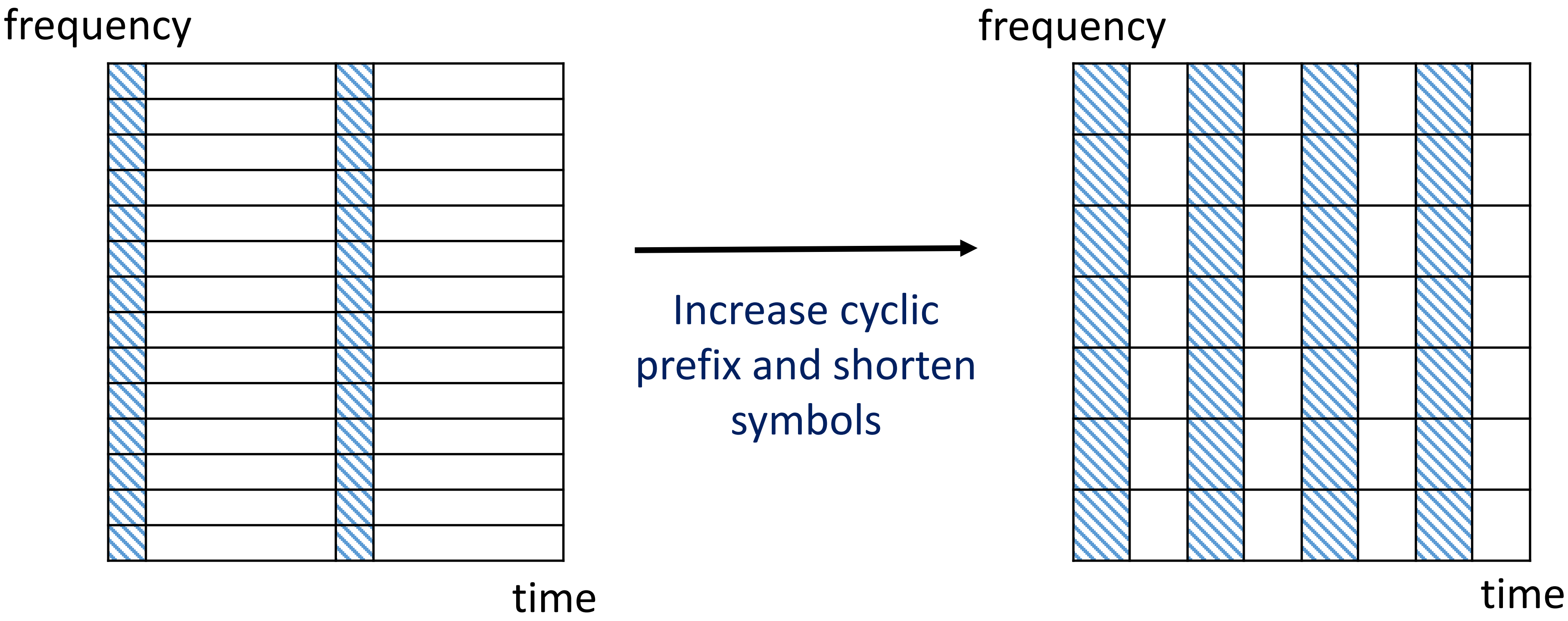
Foliage



Propeller Blades



Systems Tradeoffs

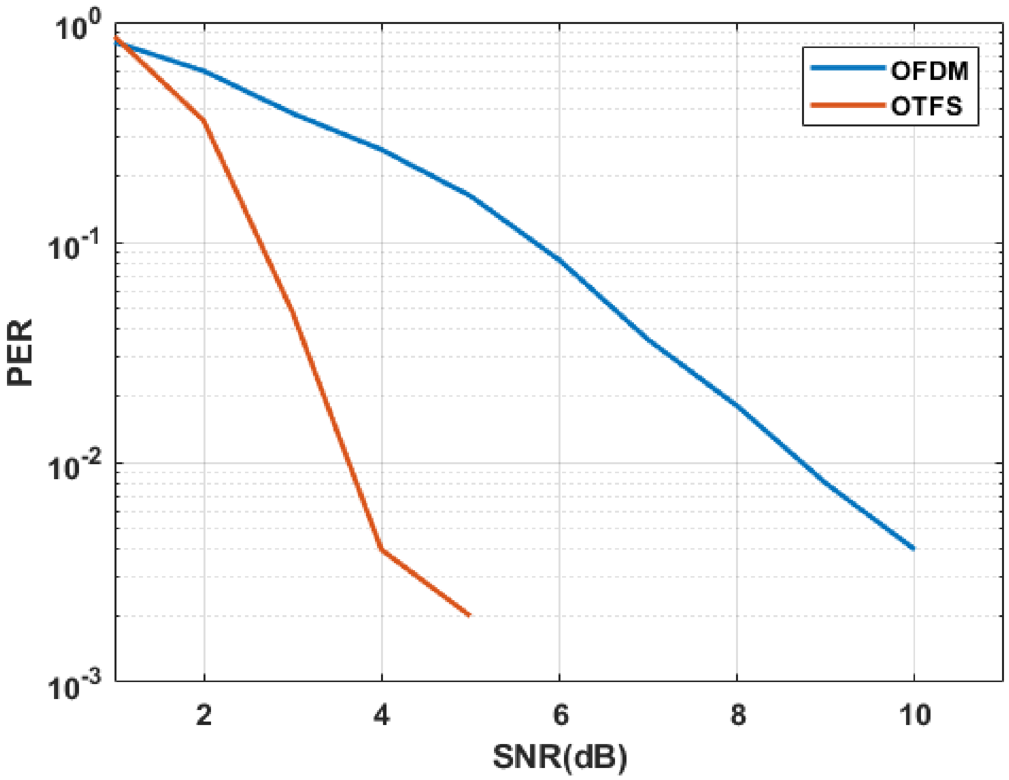


Increase cyclic prefix (CP) to combat Delay Spread
Shorten symbol length to combat Doppler Spread

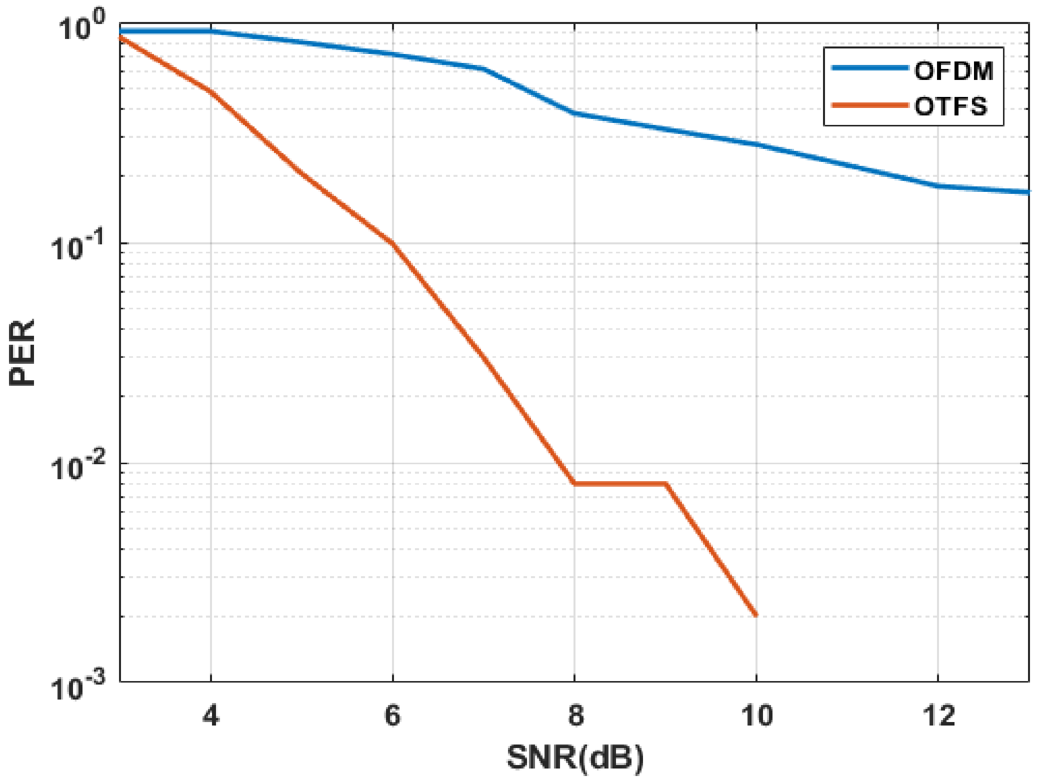
Both steps reduce spectral efficiency – to what extent is this necessary?

Performance Results

OTFS benefits from full time-frequency diversity and does not break under high Doppler



Moderate Delay Spread: 5μs
Moderate Doppler Spread: 490 Hz



High Delay Spread: 25 μs
High Doppler Spread: 700 Hz

Conclusion

OTFS is a development in waveform design, with deep mathematical roots in the theory and practice of radar, that offers a path to future-proofing 6G, and a new playground for wireless communication theorists.