6G Wireless - Illuminating New Directions in Waveform Design

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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. Commercial interest in OTFS as a 6G Waveform. Commercial and Government interest in feasibility of moving MU-MIMO scheduling to the cloud.
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.
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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 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
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
Good Questions are Less Ambiguous

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

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

\[ e^{j2\pi v_0 \cdot t} \]

\[ \tau_0 \]

\[ v_0 \]

\[ \tau_0 \]

\[ \nu \]
Connecting Delay and Doppler with Time and Frequency

- Time Representation
- Frequency Representation
- Fourier Transform
- Localized signal in the delay-Doppler plane
Capturing the Physics of Scattering

\[ f \]

\[ \nu \]

\[ \tau \]
Capturing the Propagation Environment

$h(\tau, \nu)$: 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

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

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
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: 5 µs  
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.