Communication in the Delay Doppler Domain

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What is OTFS

- Paradigm of communication in the delay-Doppler Domain:
  - Model and process the wireless channel in the delay-Doppler domain
    - Delay-Doppler channel representation
  - Multiplex information in the delay-Doppler domain
    - OTFS modulation/waveform

- Mathematical unification of communication and radar theory
  - Framework for joint communication and sensing

(*) More than 300 scientific publications on OTFS
The delay-Doppler Channel Representation

ADVANTAGES

- Reduces channel dimensionality
  - Efficient channel acquisition
  - Efficient channel prediction
  - Efficient channel equalization
The delay-Doppler Channel Representation

Main observation: the wireless channel is governed by stationary parameters:

- Reflector delay: $\tau = \frac{\text{range}}{c}$
- Reflector Doppler: $\nu = f \cdot \frac{\text{velocity}}{c}$
- Reflector propagation loss:
  $$h = e^{j2\pi \theta} \times r$$

$\{\tau, \nu, r\}$ change slowly in time and independent of carrier frequency
INFORMATION MULTIPLEXING IN DELAY-DOPPLER
THE OTFS MODULATION
The Mother Waveform

- CDMA
- TDMA
- OFDM
- OTFS

Spread spectrum
The OTFS Waveform Carrier: Pulsone

The pulsone remains **invariant** under the operations of time delay and Doppler shift.
Invariance to Channel Conditions

performance consistency and robustness under all channel conditions
The Mathematics of the pulsone

Localized up to Quasi-periodicity

\[ \tau_p \cdot \nu_p = 1 \]

\( \tau_p \) (Delay period)

\( \nu_p \) (Doppler period)
Quasi-Periodic Extension

(Doppler) $\nu$

$\tau$ (delay)

$e^{j2\pi\nu \tau_p}$

$e^{-j2\pi\nu \tau_p}$

Quasi-periodicity
The delay-Doppler (quasi-periodic) Signal Representation

$$\tau_p \cdot \nu_p = 1$$

Quasi periodicity

$$e^{-j2\pi \tau_p \nu}$$

$$e^{j2\pi \nu \tau_p}$$

$$\nu_p$$ (Doppler period)

$$\tau_p$$ (Delay period)
A pulsone is the time realization of a quasi-periodic pulse in delay-Doppler.
OTFS Packet Structure and Numerology

- $B = \frac{1}{100\text{ns}} = 10\text{MHz}$
- $T = \frac{1}{1\text{KHz}} = 1\text{ms}$
- $N = \frac{50\text{μs}}{100\text{ns}} = 500$
- $M = \frac{20\text{KHz}}{1\text{KHz}} = 20$

Diagram:

- $\nu_p = 20\text{KHz}$
- $\Delta\nu = 1\text{KHz}$
- $\Delta\tau = 100\text{ns}$
- $\tau_p = 50\text{μs}$
The complexity of the Zak transform is half the complexity of the FFT.
Time-Frequency Localization through Channel Coupling

Fading is **NOT** an intrinsic property of the channel

Fading is an attribute of the interaction of the channel with a specific waveform
The OTFS Channel Coupling
Communication Theory Revisited

TDMA

OFDM

(Doppler) $\nu$

OTFS

$\tau$ (delay)
OTFS Universality

\[ \tau_p \cdot \nu_p = 1 \]

Frequency representation

Time representation

\[ \tau_p \rightarrow \infty \]
SNR Distribution Comparison

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Min SNR</th>
<th>Max SNR</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFDM</td>
<td>5.00</td>
<td>32.76</td>
<td>4.25</td>
</tr>
<tr>
<td>OTFS 1 ms</td>
<td>18.70</td>
<td>24.99</td>
<td>1.10</td>
</tr>
<tr>
<td>OTFS 10 ms</td>
<td>22.00</td>
<td>23.36</td>
<td>0.22</td>
</tr>
</tbody>
</table>
OTFS is Resilient to Inter Carrier Interference (ICI)

- OTFS 15 kHz outperforms OFDM 60 kHz
OTFS Achieves SC PAPR while extracting full time and frequency channel diversity
OTFS Advantages

- Resilience to delay and Doppler spread
  - No cyclic prefix overhead
  - No inter carrier interference
  - Full channel diversity
  - Efficient pilot structure (independent of # coherence time intervals)

- Spread spectrum
  - Processing gain
  - Security communication

- Joint communication transceiver and radar sensing
THANK YOU