OTFS
Orthogonal Time Frequency Space

A novel modulation scheme addressing the challenges of 5G

Anton Monk
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Cohere Technologies

Founded in 2009

Headquartered in Santa Clara, CA
Completed A, B and C Rounds of Financing
Industry Leading Investors

OTFS™ – An innovative form of modulation. OTFS simultaneously extracts time, frequency & spatial channel behavior resulting in greater coverage, higher capacity, and cost savings.
OTFS Air Interface Overview

• 2D (Delay-Doppler) Modulation scheme
• Utilizes a Delay-Doppler channel model that explicitly represents a stable and deterministic geometry of the channel
• Novel 2D Basis functions spread information symbols over both time and frequency
• Channel estimation is efficient, accurate and compact
  – High density pilots can be used with both OFDM and OTFS
• Enables linear scaling of performance with MIMO order in all mobility scenarios
  – *Performance is robust against Doppler*
3GPP ETU-300 Channel: $H(f, t)$ vs $h(\tau, \nu)$

\[ H(f, t) = \text{Symplectic Fourier Transform}\{h(\tau, \nu)\} \]

$H(f, t)$

$h(\tau, \nu)$

300 Hz Doppler
5 usec Delay Spread
OTFS Channel Model

- Transmitted signal is a superposition of QAM symbols, $x_{\tau,\nu}$ with their component basis functions

$$S(t) = \int \int x_{\tau,\nu} \phi_{\tau,\nu}(t) d\tau d\nu$$

- Received signal

$$R(t) = \int \int h(\tau, \nu) e^{j2\pi vt} S(t - \tau) d\tau d\nu$$

$$= \int \int \phi_{\tau,\nu}(t) \{h(\tau, \nu) * x_{\tau,\nu}\} d\tau d\nu$$

$y_{\tau,\nu} = \text{Matched filter output}$

Delay-Doppler Covariance Condition

$\phi_{\tau,\nu}(t - \tau_0) = \phi_{\tau+\tau_0,\nu}(t)$

$e^{j2\pi \nu_0 t} \phi_{\tau,\nu}(t) = \phi_{\tau,\nu+\nu_0}(t)$
OTFS – The 2D Approach For 5G
Orthogonal Time Frequency Space

\[ y_{\tau,\nu} = h(\tau,\nu) \ast x_{\tau,\nu} \]

Transmit
(Delay-Doppler Domain)
(QAM)
\( x_{\tau,\nu} \)
2D OTFS Transform
2D OTFS Transform\(^{-1}\)
(2D OTFS Transform)

\[ Y_{f,t} = H(f,t) \cdot X_{f,t} \]

Receive
(Time-Frequency Domain)
Multicarrier Filter Bank
\( Y_{f,t} \)
Multicarrier Filter Bank
\( t \)
OTFS Channel Model

\[ x_{\tau,\nu} * h(\tau, \nu) = y_{\tau,\nu} \]

- A novel, unique and \textit{time-independent} relationship
- Received OTFS symbols in the D-D domain are just the transmitted QAM symbols convolved with the Delay-Doppler impulse response!
Delay-Doppler (Information) to Time-Frequency (Signal)

\[ N_T \quad N_J \]

\[ f \quad [\Delta f] \]

\[ t \quad [\Delta \tau] \]

2D OTFS Transform

\[ N_f \]

\[ \frac{1}{N_f \Delta f} \]

\[ N_t \]

\[ \frac{1}{N_t \Delta \tau} \]

Delay-Doppler (Information)

Time-Frequency (Signal)
Reference Signals

Antenna 1

Antenna 2

Antenna 3

Antenna 4

Chan 1

Chan 2

Chan 3

Chan 4
2D OTFS Transform

- The 2D Discrete Symplectic Fourier Transform

\[
X(k, l) = \sum_{m=0}^{N_f-1} \sum_{n=0}^{N_t-1} x(m, n) b_{m,n}(k, l)
\]

\[
b_{m,n}(k, l) = e^{-j2\pi \left( \frac{lm}{N_f} - \frac{kn}{N_t} \right)}
\]

- The 2D Discrete Inverse Symplectic Fourier Transform

\[
x(m, n) = \sum_{l=0}^{N_f-1} \sum_{k=0}^{N_t-1} X(k, l) b_{m,n}^*(k, l)
\]

\[
b_{m,n}^*(k, l) = e^{j2\pi \left( \frac{lm}{N_f} - \frac{kn}{N_t} \right)}
\]
OTFS Basis Functions Span Time and Frequency

Delay-Doppler Domain

Time-Frequency Domain
OTFS Architecture & Compatibility

• OTFS is a 2D extension of proposed multicarrier modulations (OFDM, FBMC, UFMC, etc.)
• OTFS is a 2D extension of CDMA techniques
• OTFS is an evolutionary augmentation of OFDM
  – A pre-processing / post-processing block
• Architecturally compatible with LTE
OTFS PILOT ARCHITECTURE
Data & Pilot Lattices – Time-Frequency Domain

- Data Lattice (green):
- Pilot Lattice (red): Example – M=1, N=14
  – $M\Delta f$=pilot frequency spacing; $N\Delta t$=pilot time spacing
24 Antenna Ports (Ref Signals) - Delay Doppler Grid
OTFS Antenna Port Multiplexing

- Cohere claims OTFS can multiplex a large number of antenna port reference signals in the Delay-Doppler domain
  - Depends on maximum delay and Doppler spread

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LTE</th>
<th>OTFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Reference Signal</td>
<td>CRS</td>
<td>$N = 14, M = 1$</td>
</tr>
<tr>
<td># of antenna ports (AP)</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Total Overhead</td>
<td>14.3%</td>
<td>7.1%</td>
</tr>
<tr>
<td>(Overhead per AP)</td>
<td>(3.6% per AP)</td>
<td>(0.36% per AP)</td>
</tr>
<tr>
<td>Supported Channel with no CSI Degradation</td>
<td>ETU-200</td>
<td>ETU-200</td>
</tr>
</tbody>
</table>
Pilot Packing Summary

- OTFS Delay-Doppler pilot architecture significantly reduces pilot overhead
  - Supports high Doppler
- Flexible pilot tiling for different channel conditions
- Ideal for massive MIMO which requires large number of pilots
- Enables efficient channel prediction for precoding
OTFS PERFORMANCE
Spectral Efficiency – TTI = 1ms MIMO Scalability

- OTFS maintains Consistent Higher Capacity per Stream

**Parameter** | **Value**
--- | ---
SC spacing | 15 KHz
Number of subcarriers | 600
Bandwidth | 10 MHz
Multipath model | EVA, ETU
Max Doppler | 300 Hz
Transmission Time Interval length | 1 msec
Transmission scheme | 2x2, 4x4 MIMO-TM3
FEC Coding | Turbo (LTE)
Precoding | TM3 for OFDM; identity for OTFS
Channel estimation | Ideal
Equalization | Genie aided MMSE-SIC & DFE

300 Hz Max Doppler
High Mobility & Codeword Length Invariance

- OTFS performance unaffected by codeword length
- Performance gap increases with high Doppler
- Performance improves with increased observation time
- Performance gap increases with lower BLER
High Mobility & Codeword Length Invariance

- High ICI accentuates performance gap
Low vs Medium Spatial correlation – 16QAM

- Performance gap increases with medium correlated channels

![Graph showing performance gap with 1.2 dB and 2.6 dB]
Low vs Medium Spatial correlation – 64QAM

- Performance gap increases with medium correlated channels

![Graph showing BLER vs SNR with OFDM and OTFS performance curves for Low and Medium Correlation](image)
Ultra High Mobility – OTFS-Turbo vs OFDM-LMMSE

- 16-QAM, R=2/3
- Doppler = 444 Hz and 1820 Hz (ICI dominated regime)

![Graphs showing BLER vs SNR for EVA-444 and EVA-1820 with OTFS-Turbo and OFDM-LMMSE comparisons. The graphs illustrate a 1.4 dB and 5.9 dB advantage for OTFS-Turbo.]
Ultra High Mobility – OTFS-Turbo vs OFDM-LMMSE

- 16-QAM, R=3/4
- Doppler = 444 Hz and 1820 Hz

2.2 dB
Summary

• OTFS is a novel 2D modulation scheme
  – QAM symbols and reference signals carried in the Delay-Doppler domain
  – Wide frequency and observation time exploits full diversity of the channel
  – All QAM symbols experience the same channel

• Spectral efficiency advantages in high-order MIMO, low & medium correlation and high Doppler scenarios as well as small packets and high code rate

• Increased density & flexibility in reference signal multiplexing

• Opportunities for new areas of research, building on OTFS modulation concepts and receiver architectures
THANK YOU