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Multi-G

Enabling Waveform Innovation in 6G

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Problem Statement

- Massive investment in 5G infrastructure with ROI lower than expected
  - Perception of resistance from Operators to make further hardware investments in the RAN without proven performance benefits
- The bar is high
  - But this should not *preclude* future waveform or other innovations from enhancing the operator network
- The evolution of wireless should allow for continuous innovation

Has the industry really given up on waveform innovation in 3GPP?

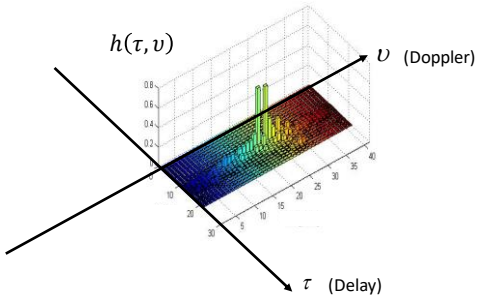
- Current perception is that 3GPP is not going to seriously consider waveform innovations
- Academic researchers clearly have not given up!
  - ~2,000 global publications on OTFS in the past few years
  - Performance and use case advantages theoretically proven and documented for Zak-OTFS
- 6G must not shut the door on continuous innovation
- 3GPP should study new waveforms and define open interfaces to enable future innovation

Background

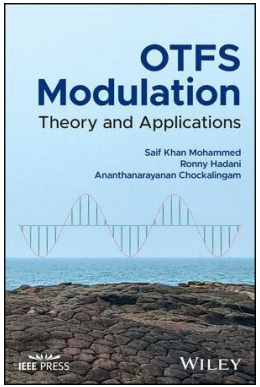
- OTFS research started in 2011
- MC-OTFS submitted into 3GPP 5G in 2016
  - OTFS approximation to enable precoding to OFDM
  - Ultimately discovered this **limited the performance advantage**
- Original Zak-OTFS (direct 2D transform from *d-D* to *t*) shows significant performance advantages in doubly-spread channels
- Academic understanding and acceptance is widespread

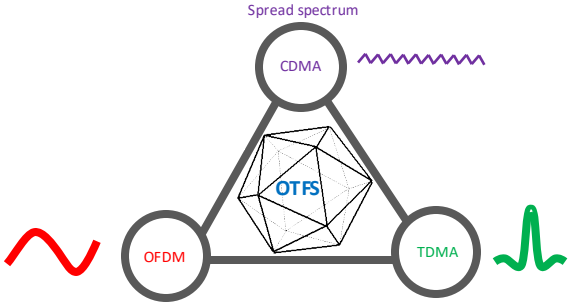
MU-OTFS Basics

INFORMATION MULTIPLEXING IN DELAY-DOPPLER

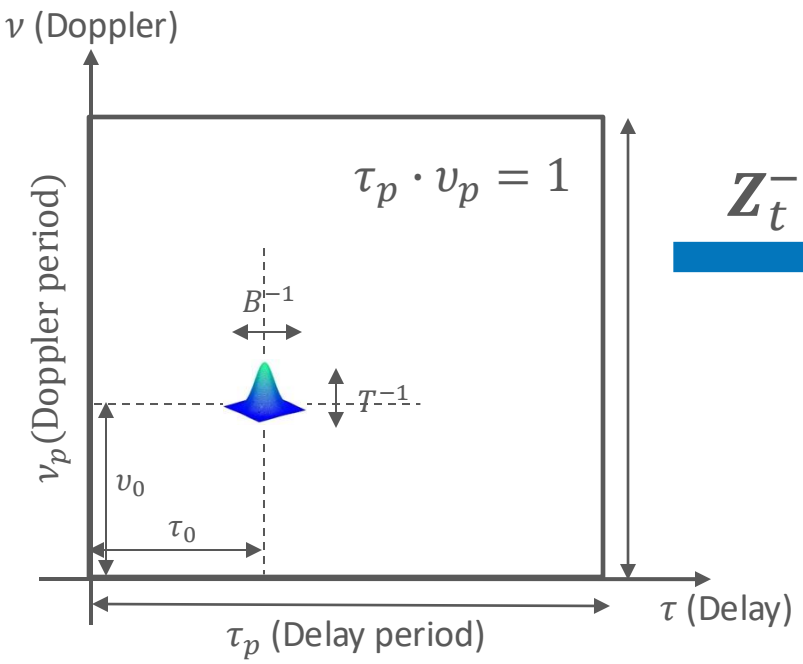


The smallest and most stable representation of the channel



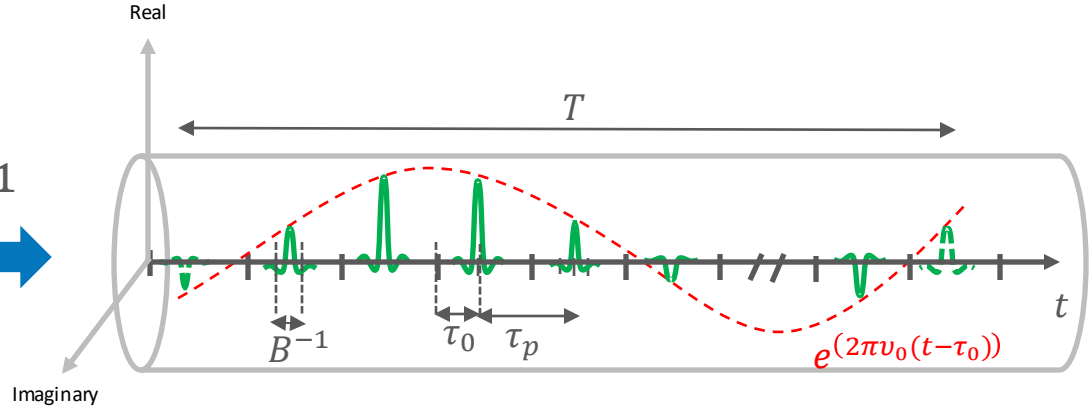


Relationship of *DD* Domain Pulse to *TD Pulsone*



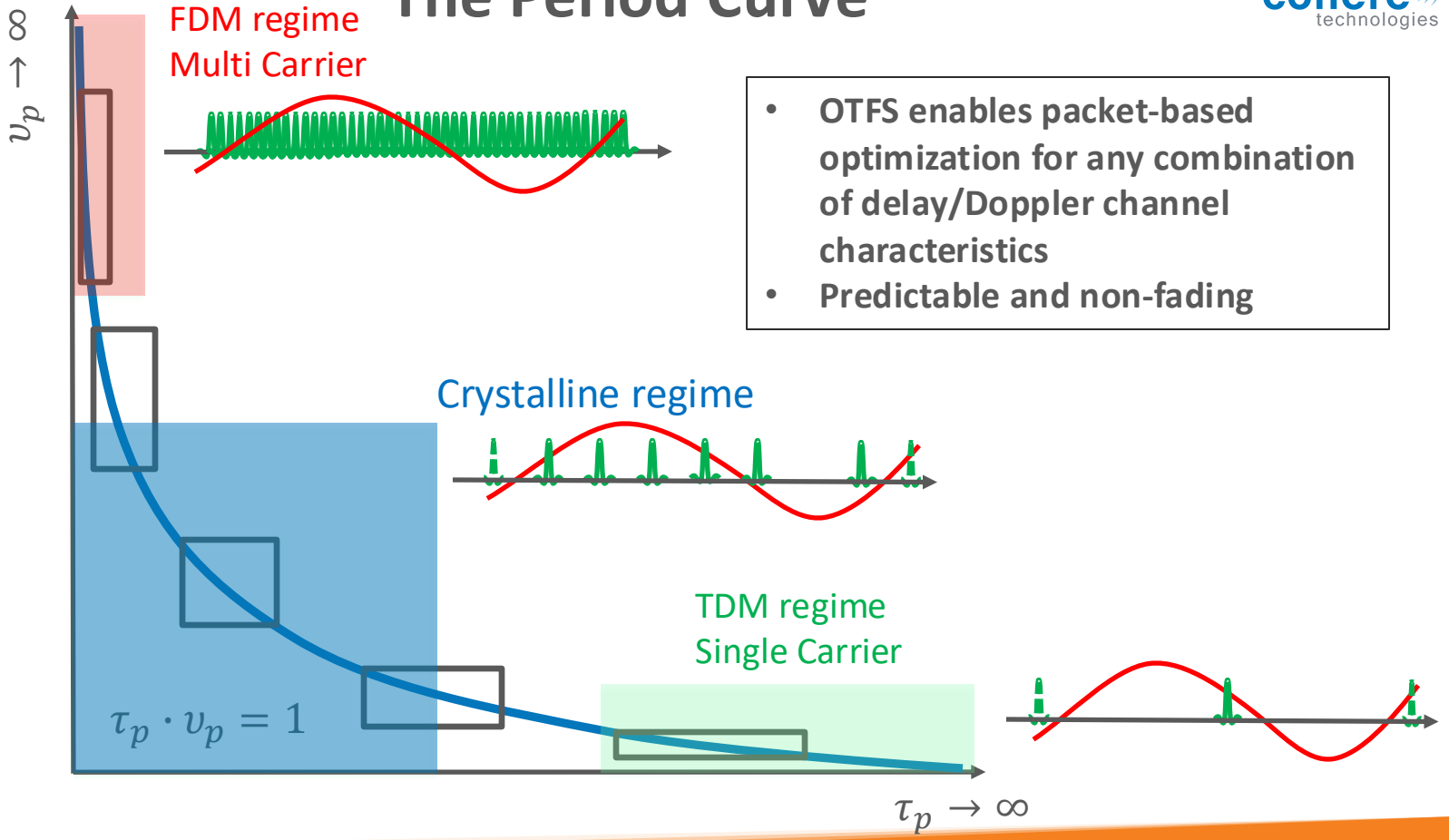
Quasi-periodic pulse in delay-Doppler

Z_t^{-1}



The Pulsone remains invariant under the operations of time delay and Doppler shift

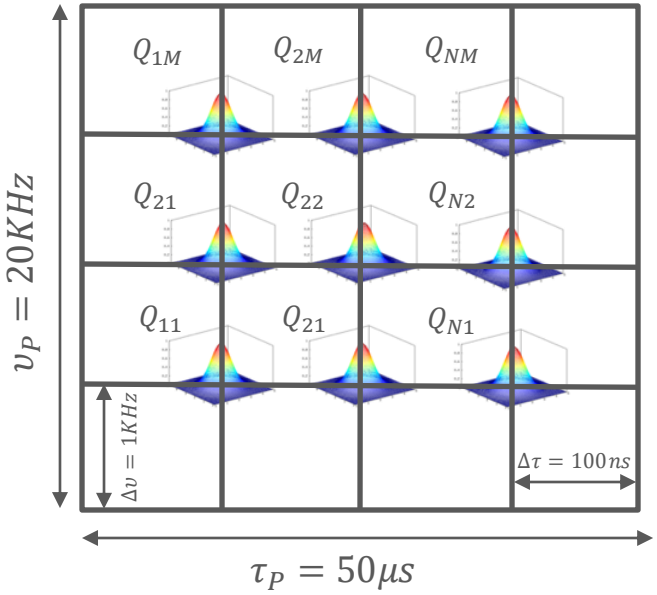
The Period Curve



- OTFS enables packet-based optimization for any combination of delay/Doppler channel characteristics
- Predictable and non-fading

Communication With Pulsones

- QAM symbols allocated in the d-D period



$$B = \frac{1}{100ns} = 10Mhz$$

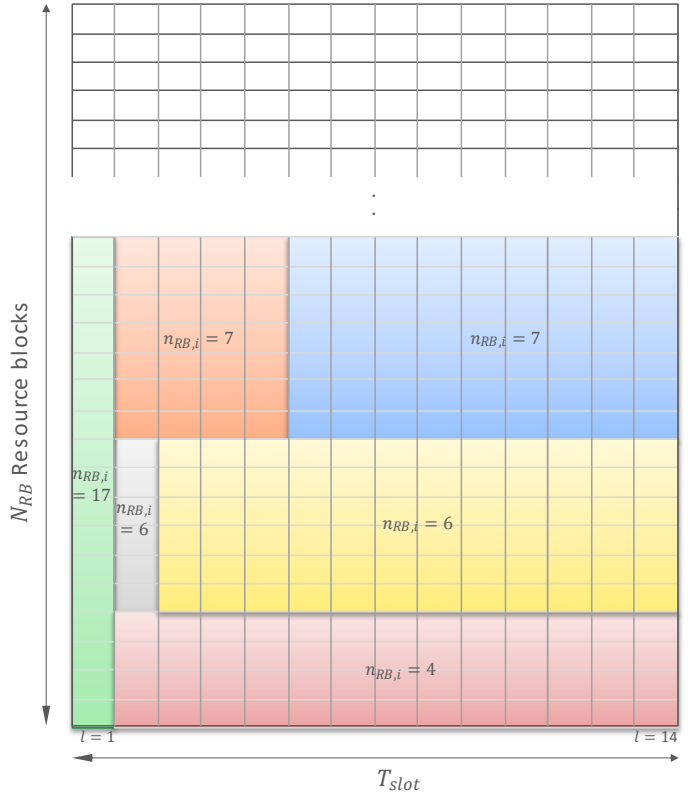
$$T = \frac{1}{1KHz} = 1ms$$

$$N = \frac{50\mu s}{100ns} = 500$$

$$M = \frac{20KHz}{1KHz} = 20$$

MU-OTFS Block in T-F

- Packet Scheduling is done in T-F as in 5G
- Delay-Doppler parameters selected on a per-packet or user basis to support channel characteristics
- Modulated symbols assigned in the *d-D* domain
- Signal Zak-transformed to the time domain and shifted into the T-F grid



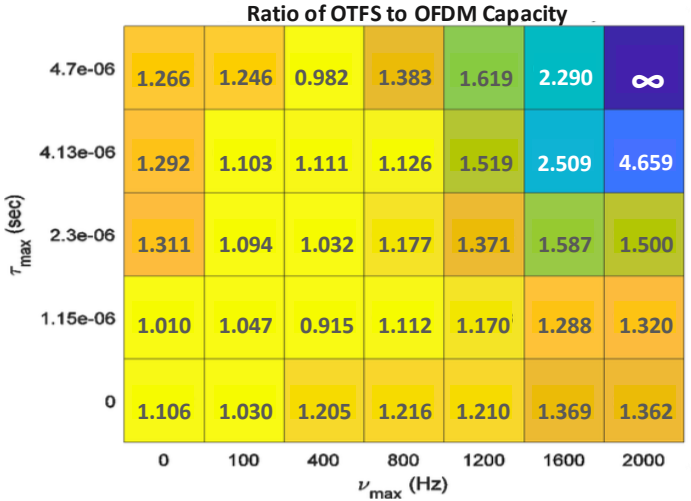
OTFS Benefits

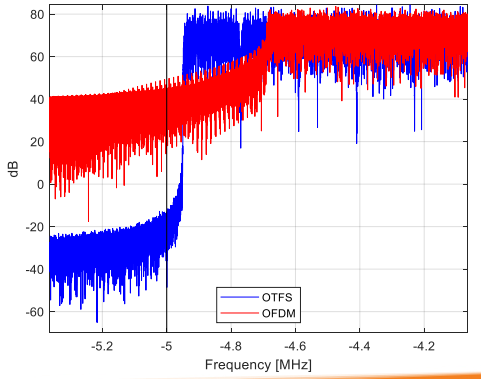
- Performance Advantages
  - Capacity advantages in doubly spread channels
  - Spectrum Utilization
- Architecture Flexibility
  - Packet-based parameterization optimized to user mobility and channel
  - TDMA-like mode (low PAPR) with less complexity than OFDM
- New Use Cases
  - NTN, THz, AI
- 3GPP Compatibility
  - Seamless alignment with resource allocation numerology

Performance Advantages

- Advantage in doubly-spread channels
  - 6G brings new frequency bands and more complex channels
  - FR3 networks overlaid with FR1 will have similar delay spread
  - Doppler is proportional to mobility, but also to the frequency and will be much higher in the new 6G bands

- Spectrum Utilization Advantage
  - Improved packing efficiency (e.g., in 10MHz)
    - OFDM (15/30kHz) = 52 / 48 PRBs;
    - OTFS = 55 PRBs (6% - 15% additional advantage)
  - Reduced out-of-band emissions





Architecture Flexibility

- Packet-based parameterization optimized to user mobility and channel
  - Delay / Doppler periods can be dynamically selected
  - No need for the equivalent of different SCS to handle higher Doppler or to avoid large FFT sizes
- Minimum Doppler period (**TDMA-like**) mode
  - Collapsing Doppler dimension to 1 results in TDMA-like waveform (Low PAPR)
  - Lower Tx/Rx complexity than OFDM
  - Still supports up to 5μs of delay spread and up to 14kHz Doppler spread
- Small payload allocation
  - Low complexity, power, PAPR

New Use Cases - NTN

- The evolution of NTN is considered a key 6G requirement and OTFS high Doppler benefit is obvious
- *Uplink* communication with multiple LEO satellites with widely varying Doppler has potential for huge performance gains
  - OFDM requires Doppler pre-compensation, thus multiple radios
  - OTFS does **not require** Doppler pre-comp => single radio
  - Ephemeris information from satellite not required for OTFS

New Use Cases - THz

- Sub-THz communication is being considered for 6G
  - Massive increase in Doppler support is required
  - Natural use case for OTFS
  - **Over-the-air OTFS testbench already demonstrated at AFRL**

New Use Cases - ISAC

- ISAC is an important new 6G use case requiring acquisition of many targets (e.g., traffic, drones, people)
- OTFS is *the* optimum waveform for ISAC
  - OTFS is, *by its nature,* a radar waveform - **Information and pilots are carried in the *delay-Doppler* / sensing domain**
  - OTFS directly senses *d-D* parameters
  - Compared with OFDM chirp, Zak-OTFS has 4x better resolution, can resolve 4x more targets and has lower complexity*
- OTFS enables jointly optimizing radar ambiguity functions and communications waveform

*D. Nisar, S. Mohammed, R. Hadani, A. Chockalingam, R. Calderbank, "Zak-OTFS for Identification of Linear Time-Varying Systems," arXiv:2503.18900

AI Is One Of *The* Critical New 6G Capabilities

- OTFS signals are invariant to delay and Doppler and provide a **robust, stable and predictable** view of the network environment
- AI/ML training is enhanced with predictable/repeatable data
  - Enables large scale predictability of channels
    - Supporting enhanced dynamic network architecture parameters
    - Improved scheduling and network stack optimization
  - Simple characterization of complex wireless channels

3GPP Numerology

- MU-OTFS is aligned with 3GPP resource allocation numerology
  - Same packet time-frequency scheduling and allocation
- Compatible with 5G upper layers
- OTFS is compatible with MRSS

Conclusion

- OTFS brings real advantages in performance and use cases
- 3GPP *MUST* support open interfaces in 6G to enable future waveform and upper layer innovations
- 3GPP *MUST* include new waveforms in the 6G study item
  - Anything less would be giving up on physical layer innovations
  - OTFS should be studied alongside other waveforms for the above-mentioned applications