Projects 15, 16, 17, 18

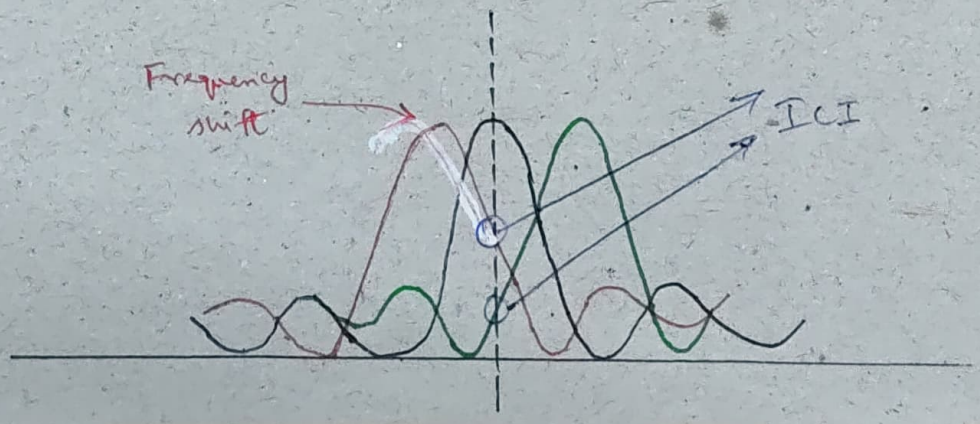
Orthogonal Time Frequency Space (OTFS) modulation

OTFS - Motivation

- 6G wireless networks are envisioned to support extremely high data rates, in high mobility scenarios.
- The mobile velocities can be upto 400-500 Km/hr. for high-speed trains (HSTs)
- In a high-mobility scenario, the wireless channel is doubly-selective
  - → Frequency and Time selective
  - (i) Frequency selectivity
    - Causes distortion in Time domain
    - Results in inter-symbol interference (ISI)
  - (ii) Time selectivity
    - Causes frequency shift in Frequency domain
    - Arises from Doppler shifts due to mobility
    - Results in inter-carrier interference (ICI)

OFDM Disadvantage

OFDM based systems are resilient to ISI. However, they experience severe performance degradation due to ICI, in high mobility (Doppler) scenarios.



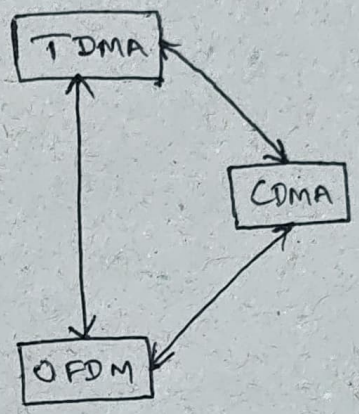
How to overcome this challenge ?
- This is achieved via OTFS !!!

OTFS

OTFS is designed to operate in the delay-doppler (DD) domain, rather than in the time-frequency (TF) domain such as OFDM, FBMC.

2G and 3G Waveform

- TDMA (2G)
  - Pulses localized in time
  - Low PAPR (peak to average power)
- CDMA (3G)
  - Spread both in time and frequency
  - Resilient to narrowband interference



4G Waveform

- OFDM (4G)
  - Pulses localized in frequency
  - Orthogonality of basis functions

Disadvantages of 2G, 3G, 4G

- Disadvantages of TDMA
  - Complex equalization
- Disadvantages of OFDM
  - Out of band (OOB) radiation
  - High PAPR
- Disadvantages of CDMA
  - Limited number of orthogonal codes

OTFS Advantages

OTFS waveform is simultaneously
- localized in time, like in TDMA
- localized in frequency, like in OFDM
- and Spread Spectrum, like CDMA

} OTFS combines all the benefits !!!

DD Domain properties

OTFS has two key aspects.

- Modeling the wireless channel in the DD domain
- Placement of information symbols in the DD domain. (OTFS modulation)

Conventional Representation

Time Frequency

Time Delay

⊙ TF-domain $h(t,f)$ and TD-domain $h(t,\tau)$ representations of the channels vary with time.

⊙ This makes channel estimation and processing difficult.

How to overcome this problem ?

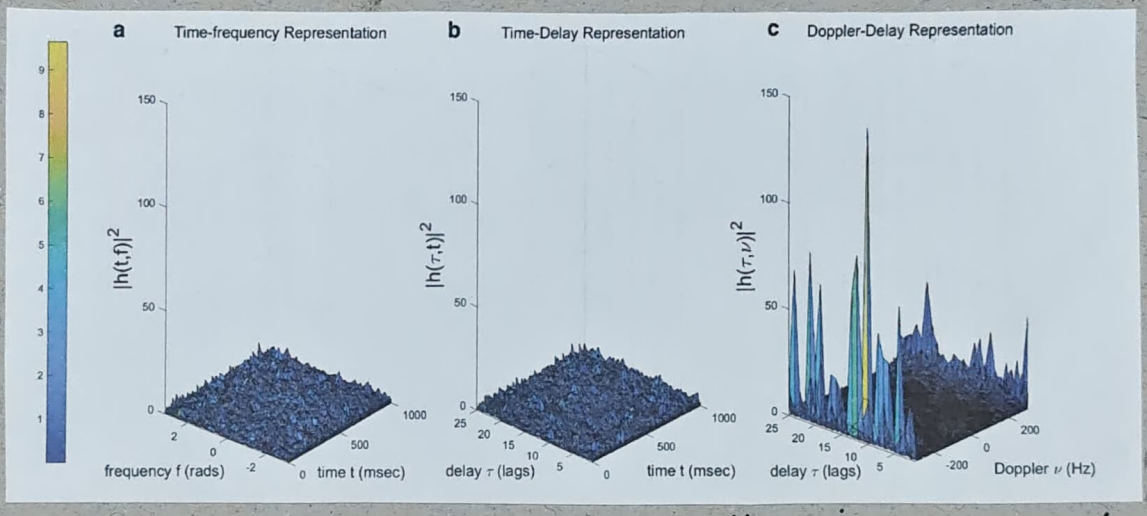
- Via DD-domain representation $h(\tau,\nu)$!

DD-domain Representation

Delay Doppler

DD domain channel is time-invariant for a much longer duration, since velocity, distance and reflectivity gain of the reflectors remain approximately constant.

Channel Estimation
Signal processing
} becomes easier



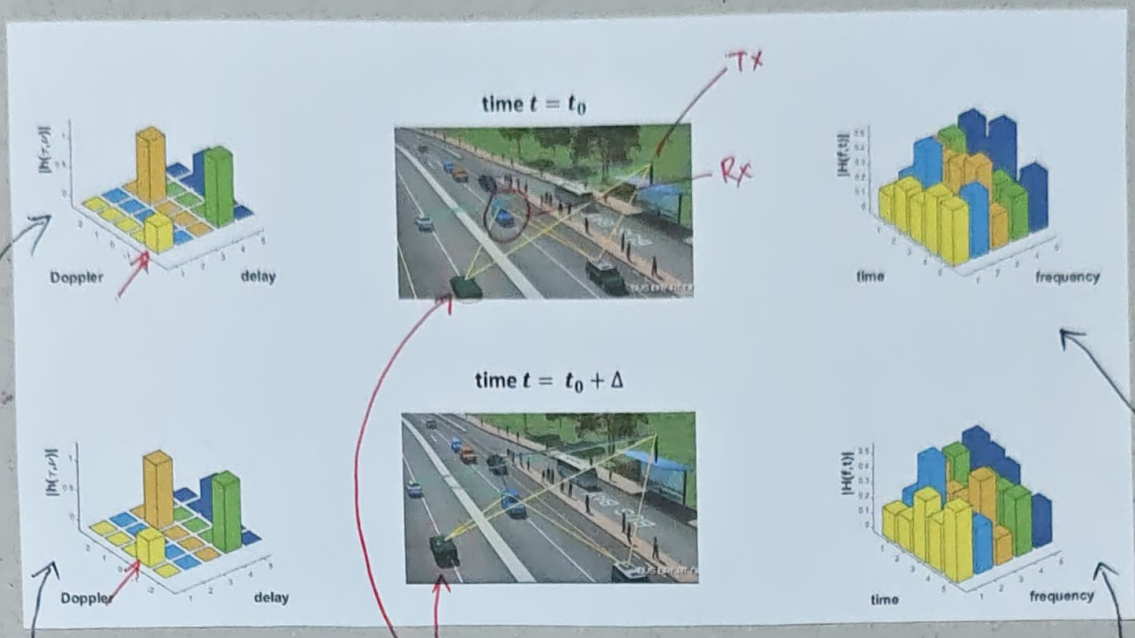
* Not compact
* Difficult to track

* Very compact representation
* channel is constant

Fig. Response of a 300Hz Doppler channel

DD-domain Advantages

- Reduces channel dimensionality significantly
- Slow varying ⇒ Channel Estimation needed less frequently.
- Enables better prediction of the channel
- Enables estimation with minimal overhead.

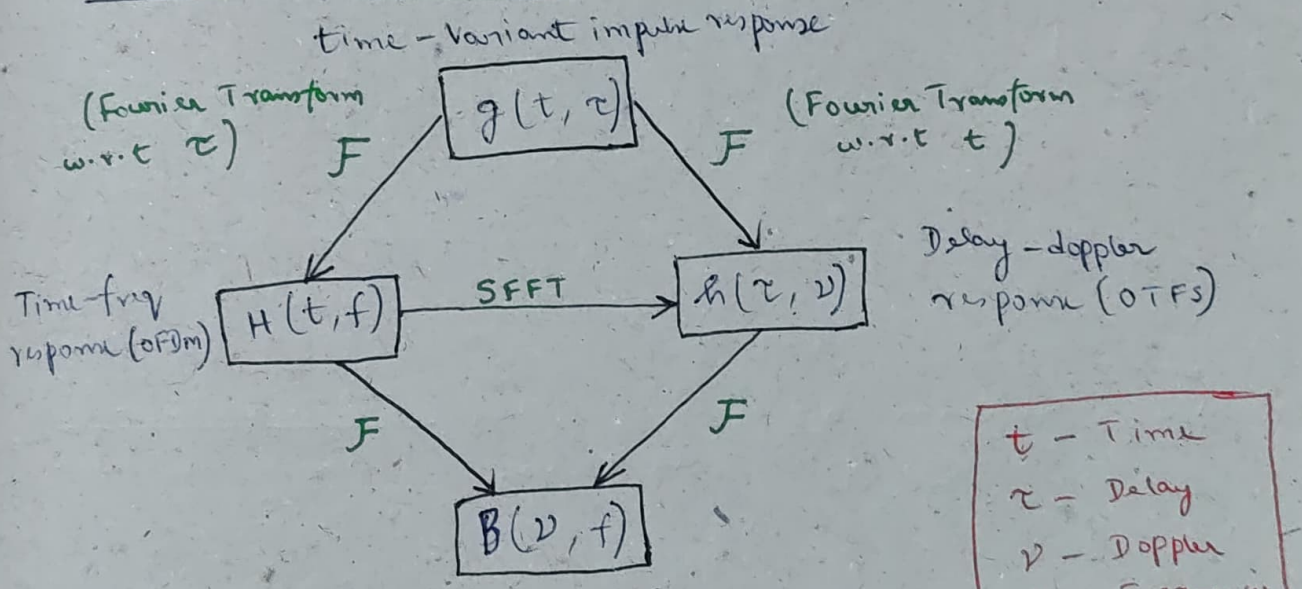


Few Towers (compact)

This car has moved significantly. So, there is shift in the DD domain representation.

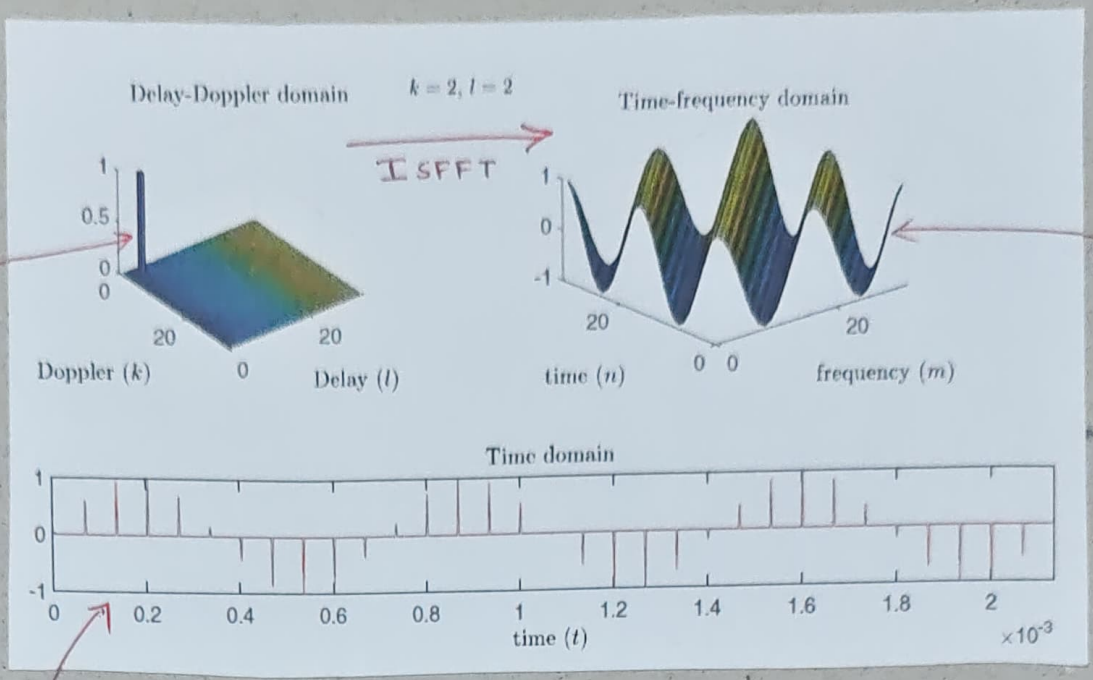
Dense Towers (chaos)

Channel representations



t – Time
τ – Delay
ν – Doppler
f – Frequency

OTFS Basis function in DD, TF and TD



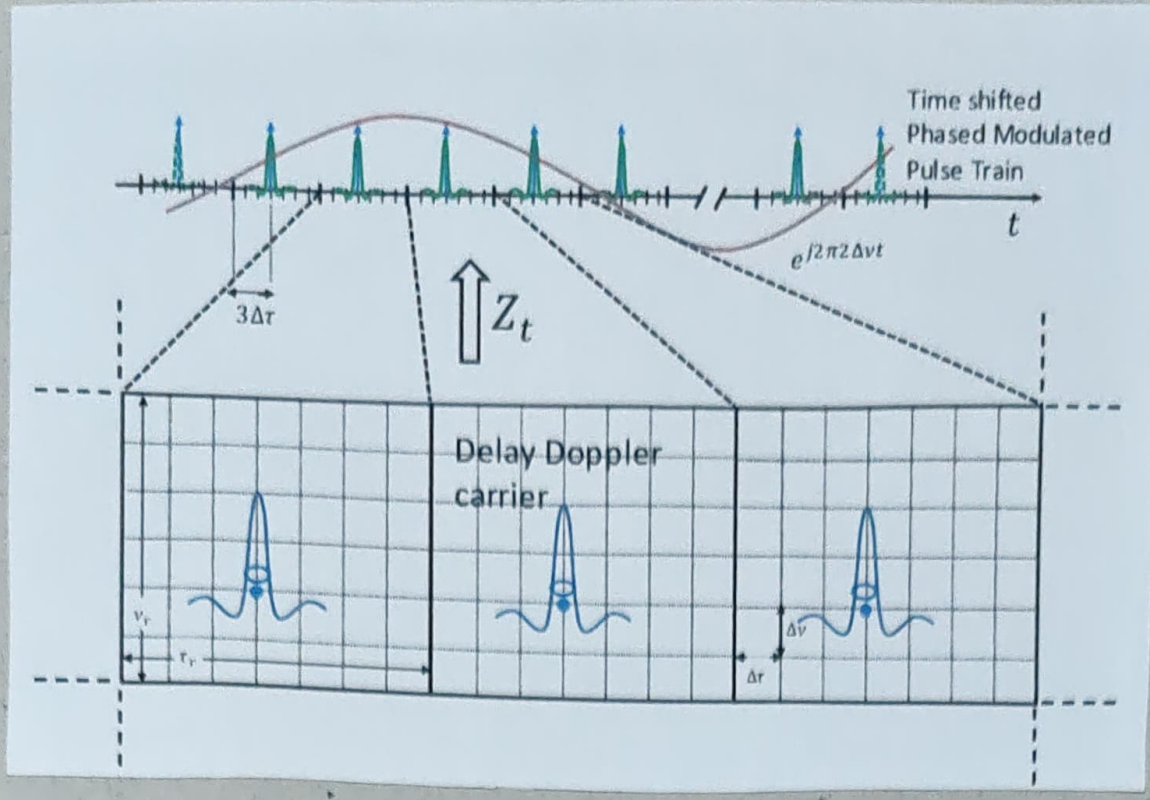
Impulse is varying w.r.t. Sinusoid

OTFS Waveform

- OTFS Waveform is a Sequence of pulses, evenly spaced in time. Each pulse is multiplied by a complex phase, and the phases are rotating in IQ plane.
- Locally, it looks like a pulse, Globally it behaves like a tone. In addition, it is Spread Spectrum.

OTFS Waveform Properties

- Delay coordinate of the DD-domain pulse specifies the time displacement of the pulse train
- Delay resolution $\Delta\tau$ of the pulse is inversely proportional to the bandwidth
- Doppler coordinate of the pulse specifies the frequency of the tone.
- Doppler resolution $\Delta\nu$ of this pulse is inversely proportional to the duration of the pulse train.

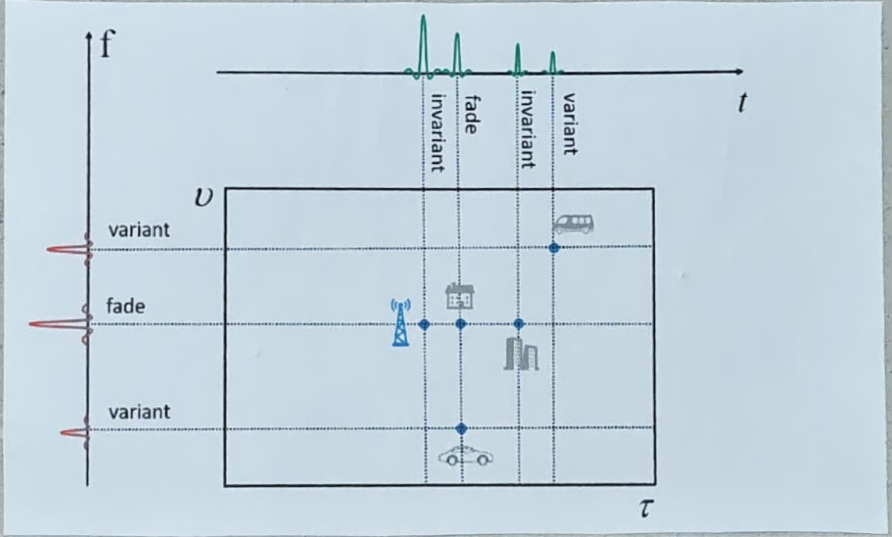


OTFS Key Advantage

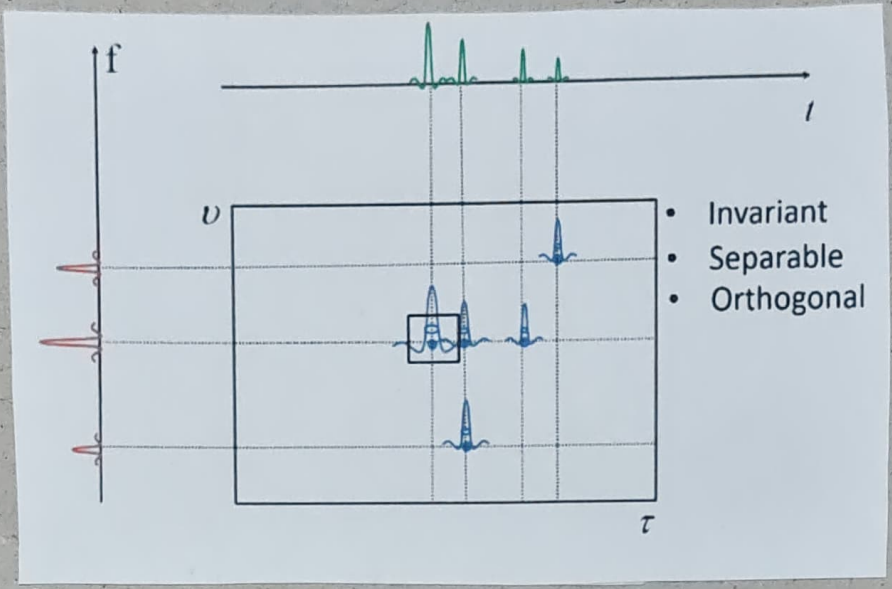
OTFS removes fading!

(i) No superposition between multipath components in DD-domain!

- Consider transmission of time-domain impulse.
- Each of the reflected echoes arrives at the receiver at a delayed time (multipath effect) and possibly also shifted in frequency (Doppler effect)
- Amplitude of the middle echo changes due to the superposition of signals, sharing the same delay but differing in doppler
- Time-domain pulse is unable to separate reflectors along Doppler.



- Consider a frequency-domain impulse, echoes at ~~frequency~~ specific frequency, which correspond to the Doppler shifts induced by the various reflectors
- Amplitude of the middle echo changes due to superposition of signals, sharing the same doppler but differing in delay.
- Frequency-domain pulse is unable to separate reflectors along delay.



- Transmitting a localized OTFS pulse in the delay-doppler representation
- Echoes appear at specific delay-doppler displacements, which corresponds to the delay and doppler shifts introduced by the various reflectors.
- OTFS Channel-Symbol Coupling is a two dimensional convolution between the delay-doppler impulse response and the transmitted symbols.
- Thus, if chosen properly, there is NO FADING in OTFS.