WWRF 47

Plenary Session 2: Spectrally-Efficient Transmissions

- Delay-Doppler plane Multicarrier Modulations

  Prof Jinhong Yuan, University of New South Wales, Australia

- New Physical Layer Paradigm for Future Systems: Moving away from orthogonality to save energy and bandwidth

  Prof Izzat Darwazeh, UCL, UK

- Non-orthogonal SEFDM Waveform: Intelligence, Applications and Prototyping

  Dr Tongyang Xu, UCL, UK

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A Delay-Doppler Plane Multicarrier Modulation

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Outline

1. Introduction
2. Wireless Channels with Delay-Doppler (DD) Domain Representation
3. OTFS Modulation
4. Multi-Carrier (MC) Modulation on DD plane
5. DD Plane Orthogonal Pulse and ODDM Waveform
6. Results and Discussions

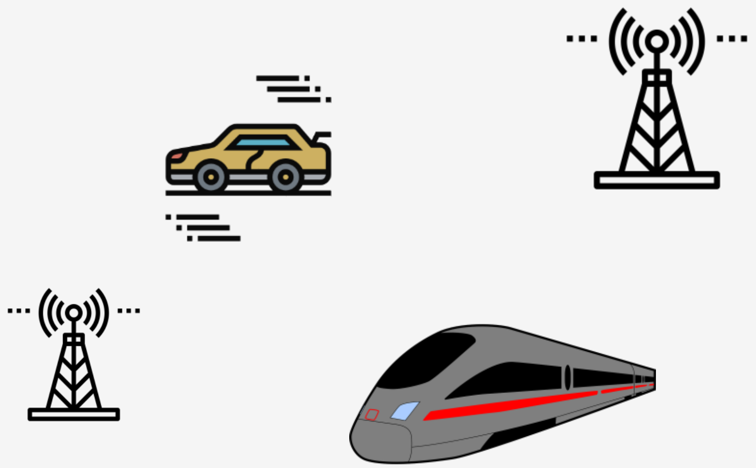
Introduction

Cellular Evolution	1G (1980's)	2G (1990's)	3G (2000's)	4G (2010's)	5G (2020's)
Waveform	Analog FDMA	TDMA, CDMA	CDMA	OFDM	OFDM
Data Rate	2.4 kbps	64 kbps	100 kbps - 56 Mbps	Up to 1 Gbps	> 1 Gbps
Carrier Frequency	800-900 MHz	850-1900MHz	1.6-2.5GHz	2-8 GHz	Sub- 6GHz, mmWave

- Design TX waveforms to support high rate, deal with fading and interference
    - TDMA
    - CDMA
    - OFDMA, MIMO-OFDMA
- Combating channel fading (1G, 2G, 3G) to exploiting channel fading (4G, 5G)

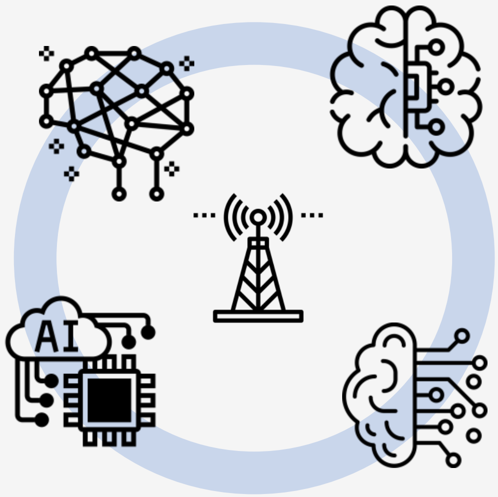
Introduction-6G Scenarios

- High Mobility



High Reliability Communication (HRC)

- Connected AI



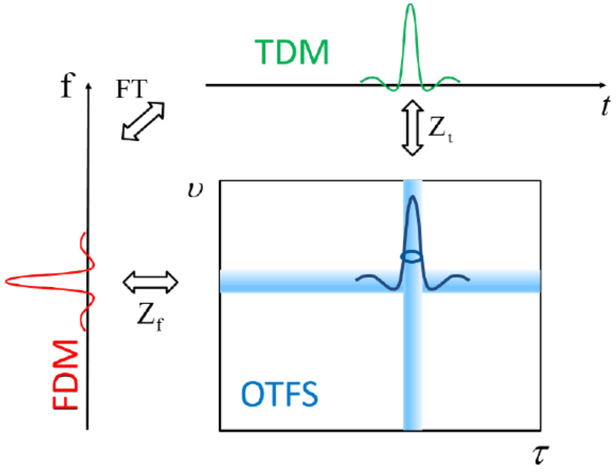
Integrated Sensing and Communication (ISAC)

Is there any signal waveform better interacting with wireless channels?

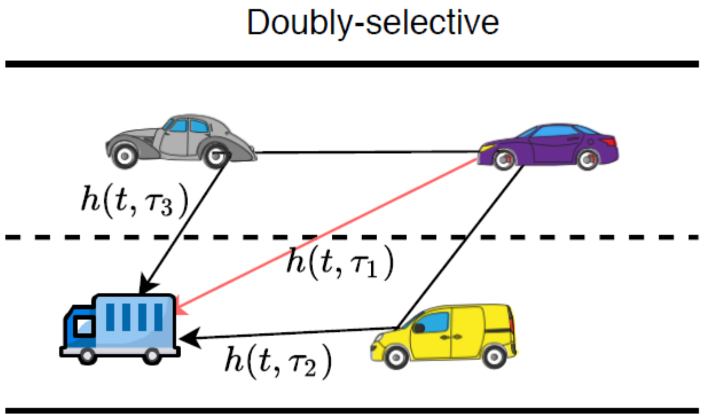
- **Robust and reliable against** to distortion/impairments of doubly-selective channels?
- **Viable choice** for ISAC over doubly-selective channels?

Introduction-OTFS Modulation

- A new two-dimension modulation technique, compatible with 4G/5G OFDM
- Works well in high Doppler fast fading wireless channels
- Key idea: exploit underlying property: compact and sparse channel property in DD domain [Bello1963].
- Carries information in DD domain, couple with DD channel
- Aims to have minimal cross-interference as well as full diversity in DD domain



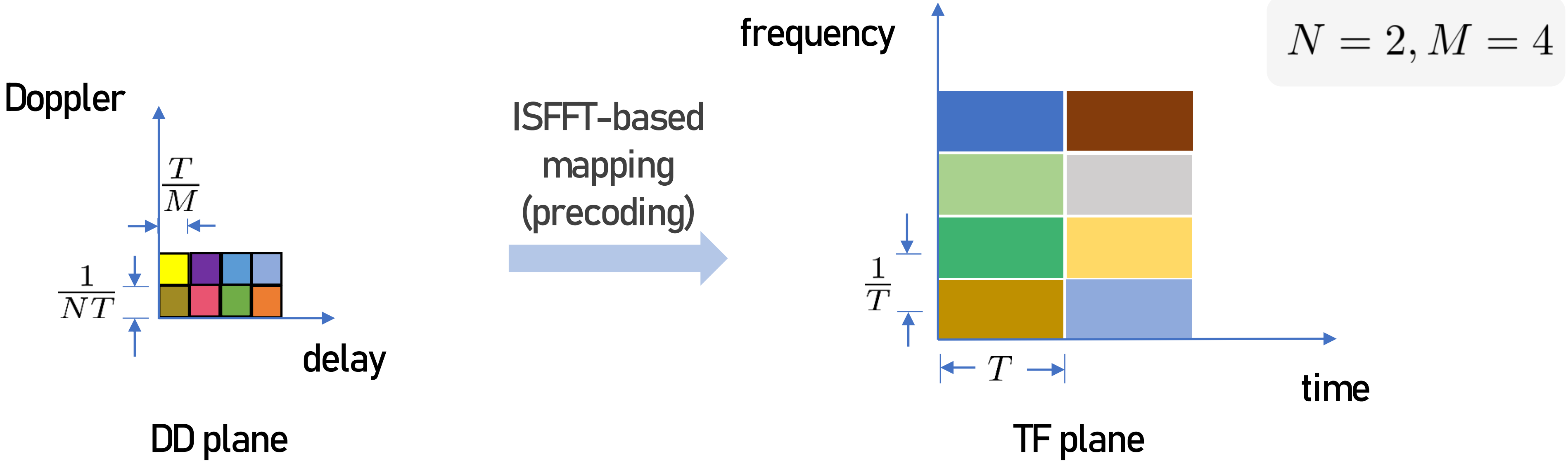
DD domain modulation [Hadani 2017]



High-mobility environment

R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch, and R. Calderbank, "Orthogonal time frequency space modulation," in Proc. IEEE WCNC, 2017, pp. 1–6

Introduction-OTFS Modulation



- Maps signals from DD plane to TF plane, then use OFDM
- OTFS waveform is orthogonal with respect to TF plane's resolution ($\mathcal{R} = \mathcal{TF} = 1$)
- OTFS's ideal pulse is assumed to satisfy **biorthogonal robust property**, which however cannot be realized.
- Suffers high OOBE, complicated ISI and ICI and the subsequent approximate IO relation

Introduction-OTFS Modulation

- Modulation

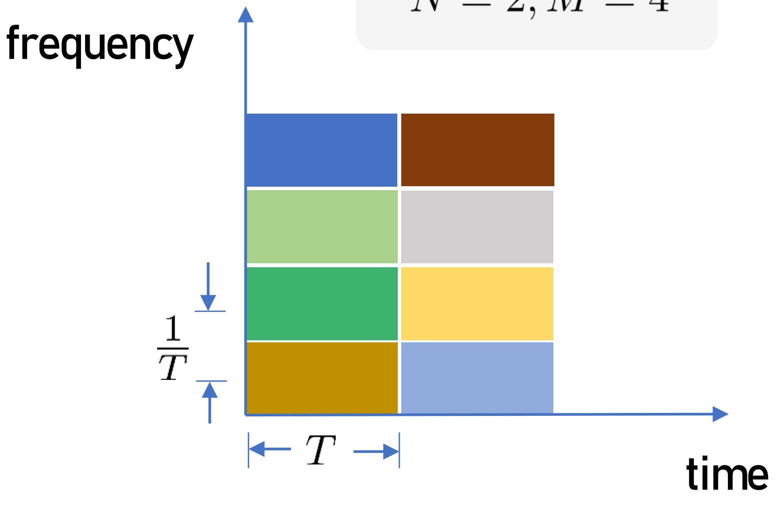
Transmit Pulses

$$x(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} X_{m,n} g(t - m\mathcal{T}) e^{j2\pi n \mathcal{F}(t - m\mathcal{T})}$$

Symbol Mapping

TF Lattice

$N = 2, M = 4$

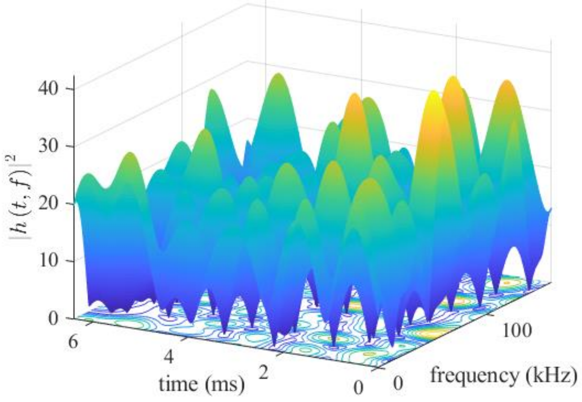


TF plane

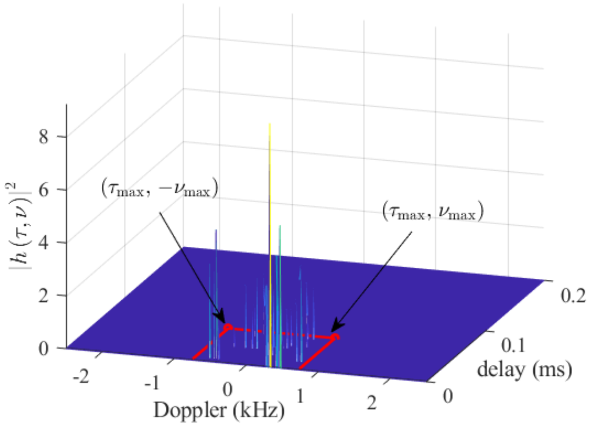
- Pulse is a fundamental element of any modulation
  - defines the shape of signal in both time and frequency domains
  - determines how energy spread over the time and frequency
  - affects signal characteristics significantly (efficiency, localization, orthogonality, etc.)
- This talk
  - Introduce DD plane MC modulation
  - Design orthogonal pulses w.r.t DD resolutions

Wireless Channel with DD Domain Representation

Time-variant channel in high-mobility environments



Time-frequency (TF) domain



Delay-Doppler (DD) domain

- TF domain channel is **dense and changes quickly**, difficult to perform estimation
- DD domain channel is **compact and stable**, allows **accurate and low overhead channel estimation**
- **Deterministic model**: delay-Doppler spread function, namely spreading function
- **Path based model** : $\tilde{h}(\tau,\nu) = \sum_{p=1}^{\tilde{P}} \tilde{h}_p \delta(\tau - \tilde{\tau}_p)\delta(\nu - \tilde{\nu}_p)$

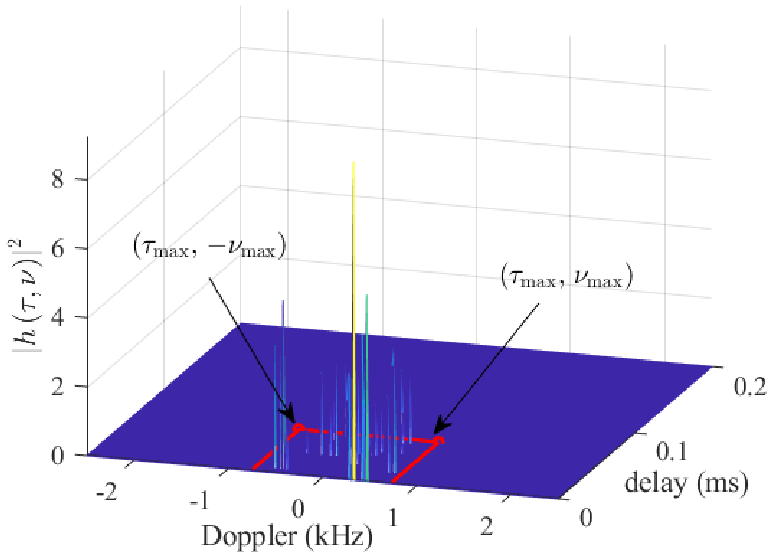
Wireless Channel with DD Domain Representation

- "All real-life channels and signals have an essentially finite number of DoF, due to restrictions on time duration and bandwidth." [Bello1963].

- The sampled channel model with combined time and frequency constraints (discrete equivalent on-the-grid channel model)

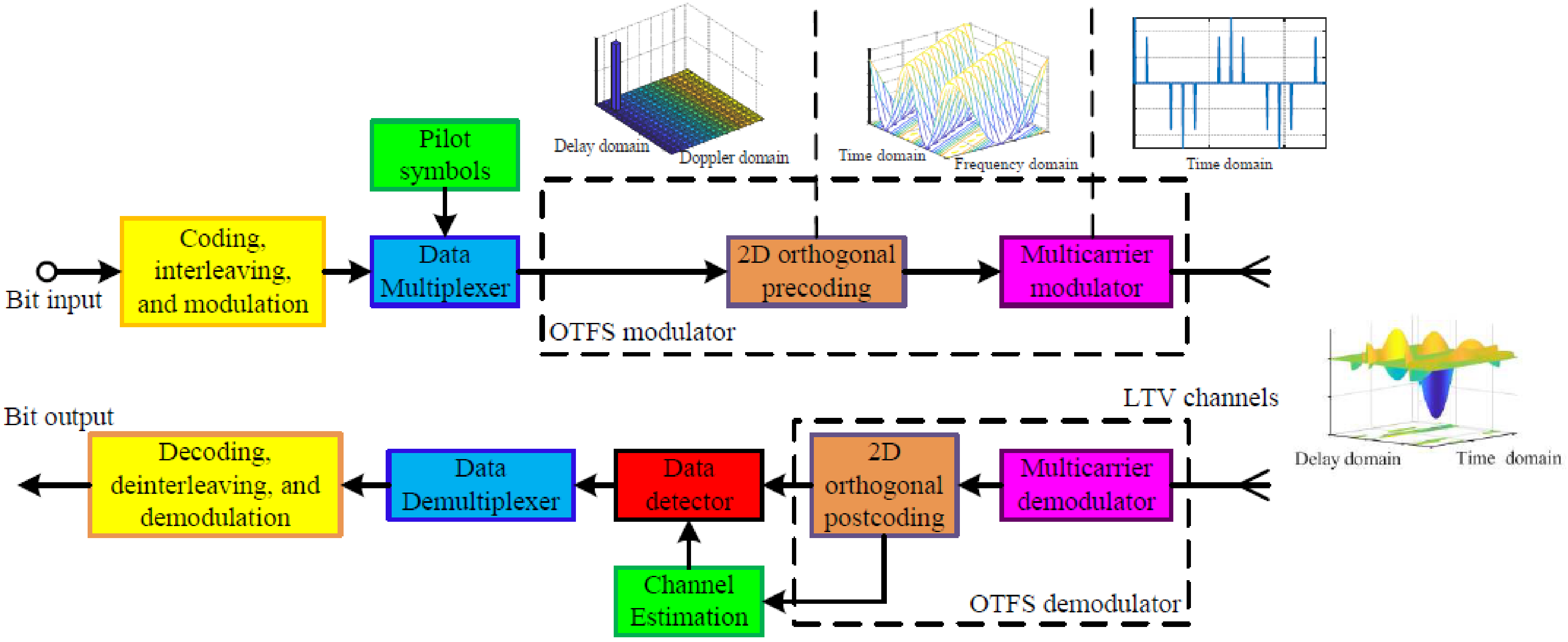
$$h(\tau,\nu) = \sum_{p=1}^{P} h_p \delta(\tau - \tau_p)\delta(\nu - \nu_p)$$

$$\tau_p = \frac{l_p}{M\Delta f}, \nu_p = \frac{k_p}{NT}$$



- $M\Delta F$ is the sampling rate ➔ delay resolution being $1/(M\Delta F)$
- NT is the frame duration ➔ Doppler resolution being $1/NT$
- l_p: delay index; k_p : Doppler index
- Neither fractional delay nor fractional Doppler

OTFS Modulation



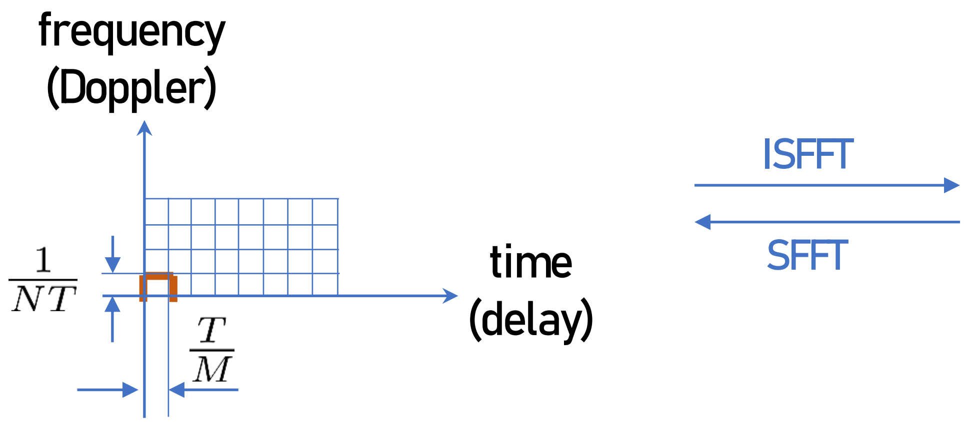
- ✓ 2D orthogonal precoding **from DD domain to TF domain**, such as ISFFT (inverse Symplectic Finite Fourier Transform) and Walsh-Hadamard transform
- ✓ Multi-carrier modulator **from TF domain to time domain**, such as OFDM and FBMC

OTFS Modulation

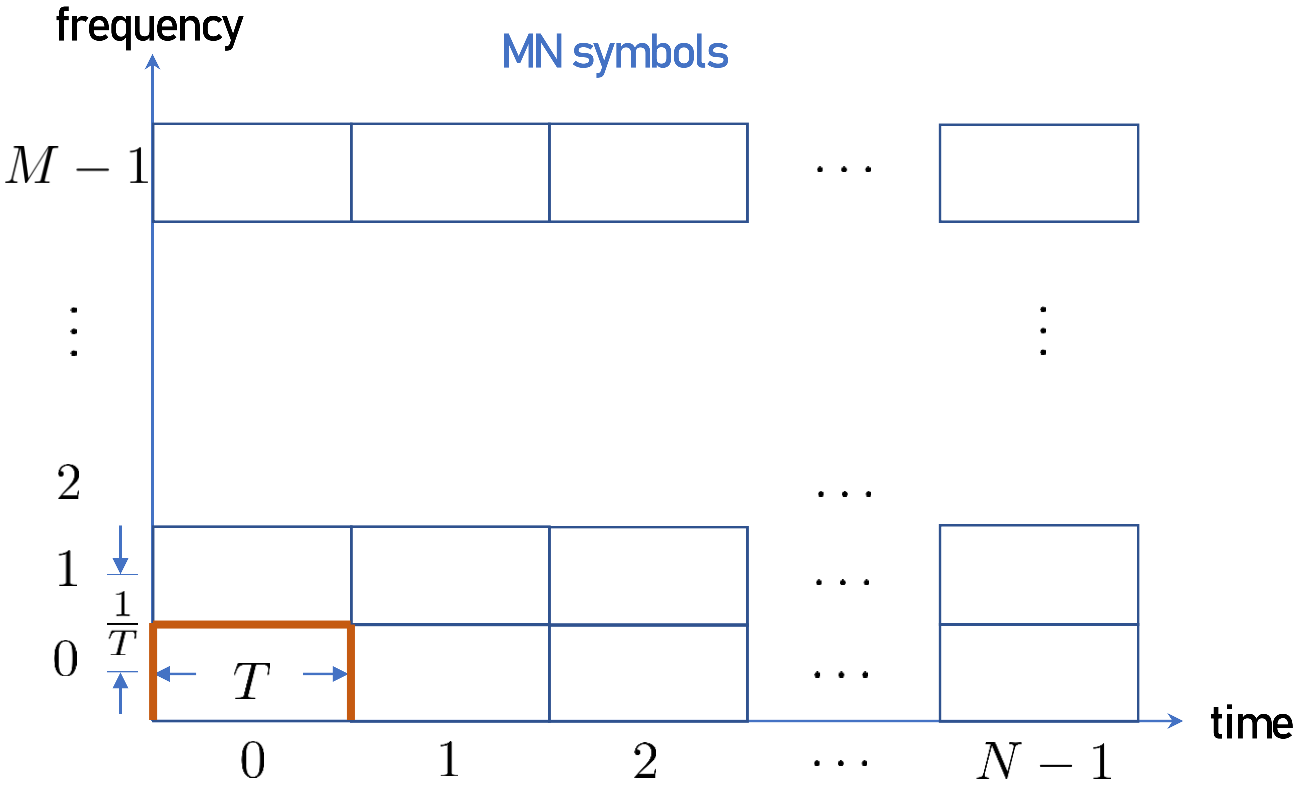
- A frame: N time slots, each with T sec
- Frame length NT

- Multi-carrier: M subcarrier, each with ΔF Hz
- Bandwidth $M\Delta F = \frac{M}{T}$

- Delay resolution: $\frac{T}{M}$
- Doppler resolution: $\frac{1}{NT}$



DD plane

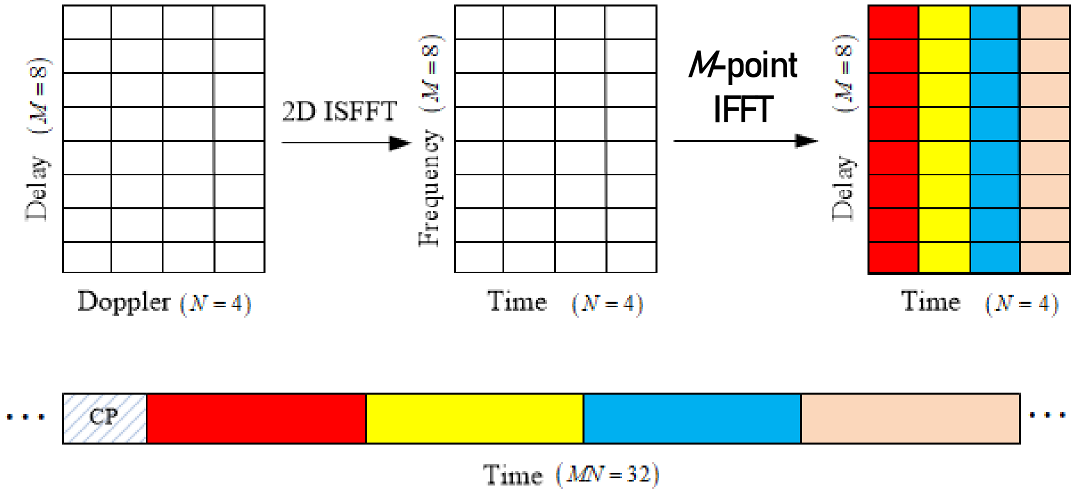


TF plane

Different TF resolution

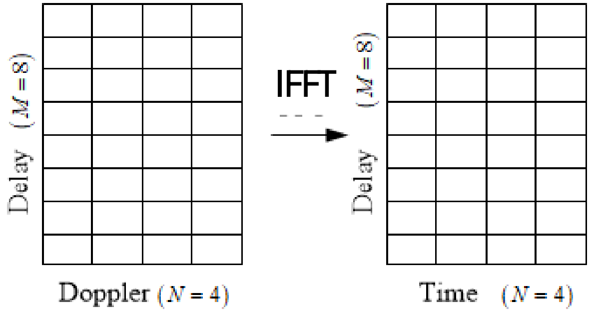
OTFS Modulation

- Direct implementation of OTFS Tx



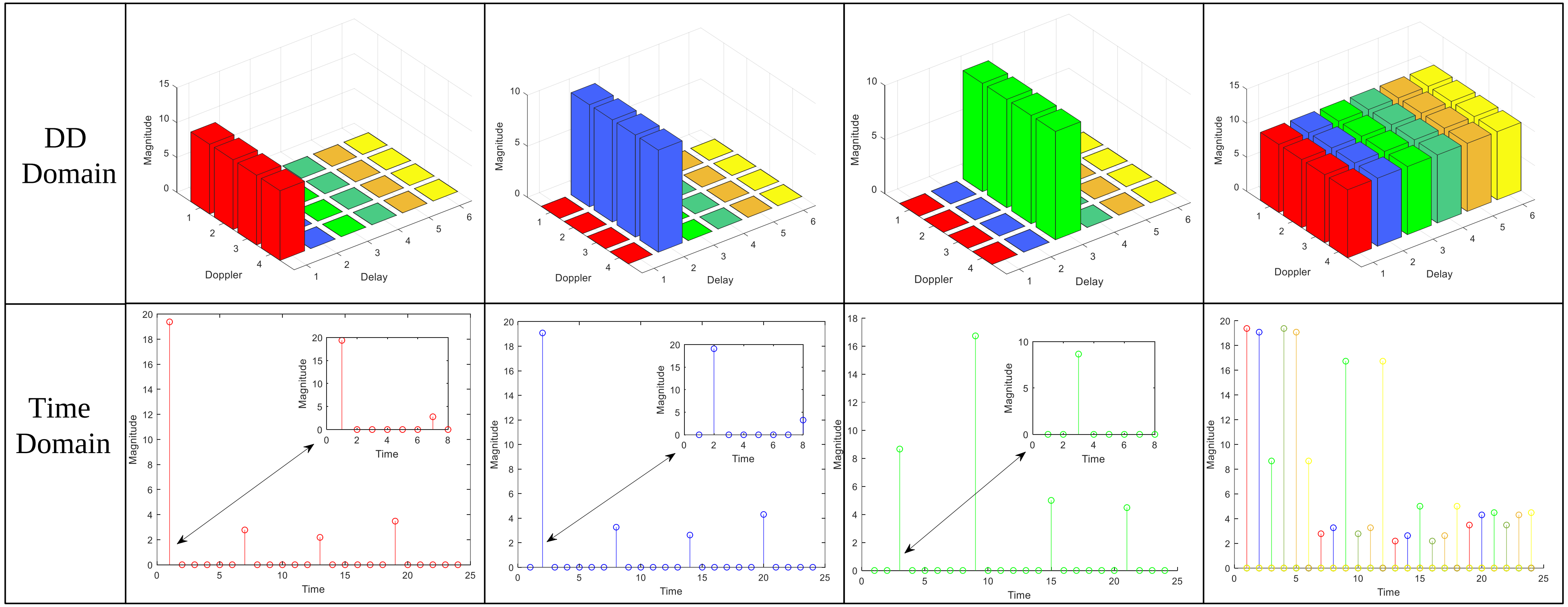
- Simple implementation of OTFS Tx

Complexity: $MN\log N$
PAPR: $\propto N$



[Ref: Yi,Viterbo, Tutorial ICC 2019]

OTFS Modulation

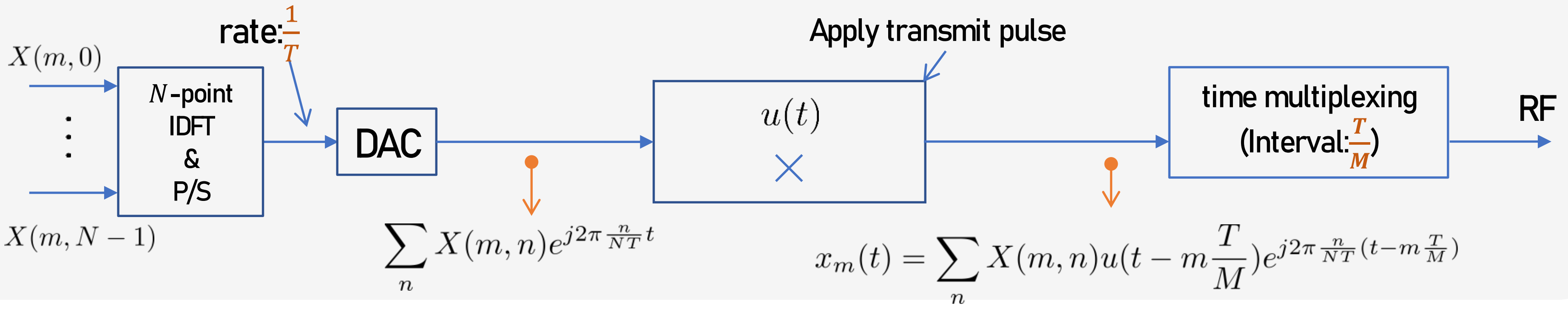


Connections between OTFS and OFDM

Is it possible to design a DD plane orthogonal pulse ?

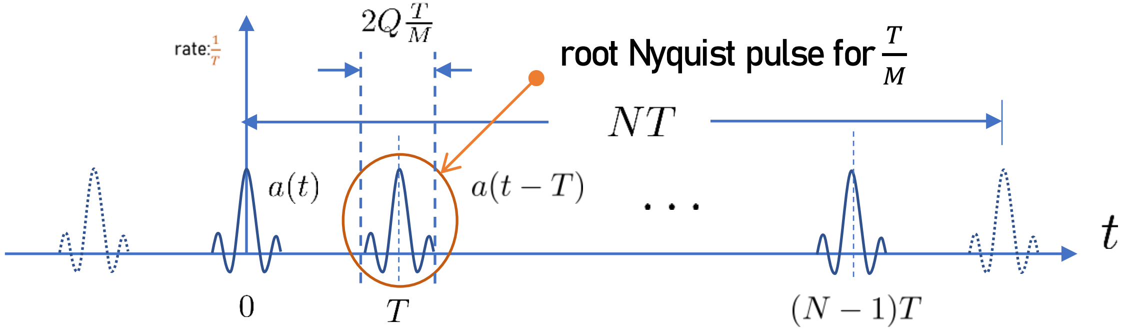
Transmit Pulse for DD Plane MC Modulation

- Symbol interval $\frac{T}{M} \ll$ Symbol period NT



$$u(t) = \sum_{\dot{n}=0}^{N-1} a(t-\dot{n}T)$$

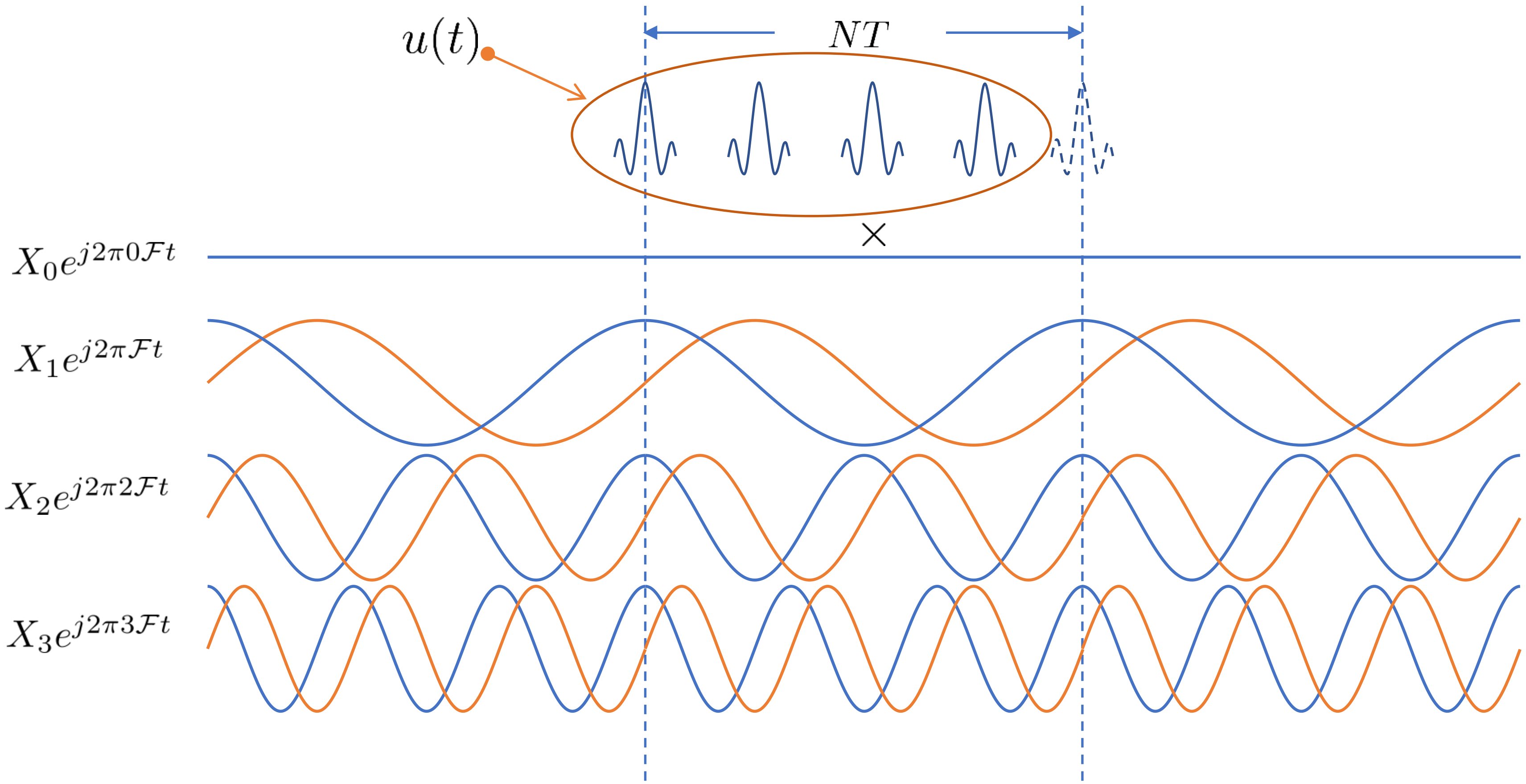
DD Plane Orthogonal Pulse



- Ambiguity function of $u(t)$

$$A_{u,u}\left(m\frac{T}{M}, n\frac{1}{NT}\right) = \delta(m)\delta(n), \forall|m| \leq M-1, |n| \leq N-1$$

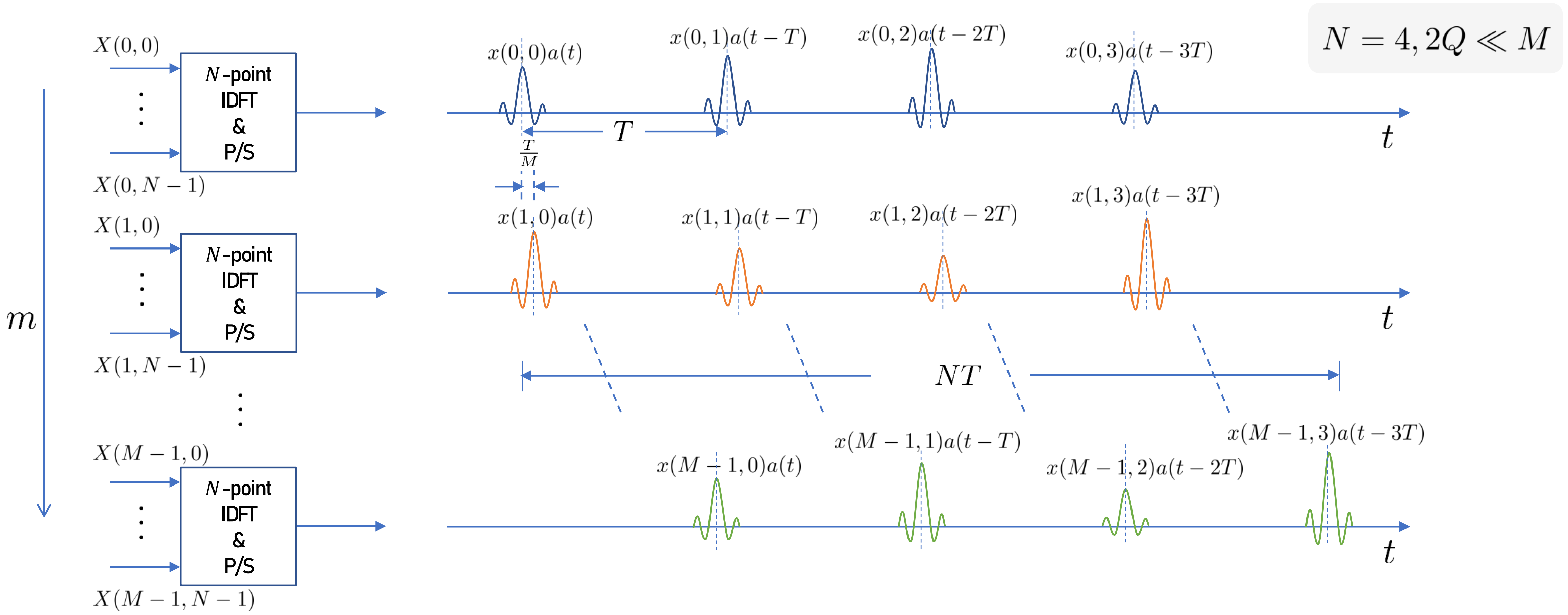
Orthogonal Delay-Doppler Division Multiplexing (ODDM)



$N = 4$

$\mathcal{F} = \frac{1}{NT}$

IDFT-based Implementation of ODDM (Approximation)



➢ Add a frame-wise CP to keep the periodicity

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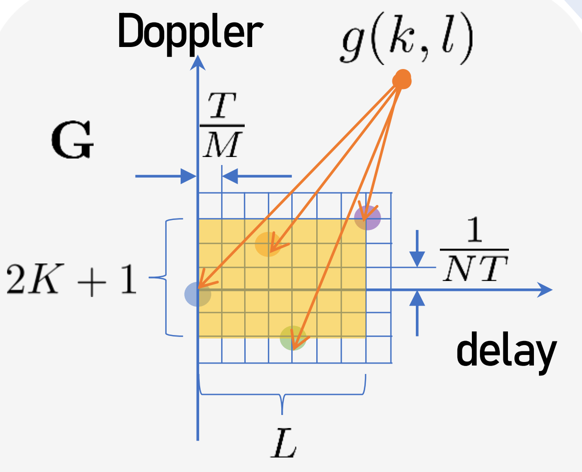
DD Domain Input-Output Relation

- Receive pulse（matched filter）： $u(t-m\frac{T}{M})e^{-j2\pi\frac{n}{NT}(t-m\frac{T}{M})}$
- Path's delay is integer multiples of $\frac{T}{M}$
- Path's Doppler is integer multiples of $\frac{1}{NT}$
- OFDM with integer timing/frequency offset
- See from the nth subcarrier of the mth symbol

$g(k,l)$ ：gain g corresponds to on-the-grid ISI (ICI) from the $[n-\hat{k}]_N$th subcarrier of the $[m-l]_M$th symbol



$\hat{k}=k-K-1$

$$
\begin{bmatrix} \mathbf{y}_0 \\ \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_{M-1} \end{bmatrix}
=
\begin{bmatrix}
\mathbf{H}_0^0 & & & & \mathbf{H}_{L-1}^0\mathbf{D} & \cdots & \cdots & \mathbf{H}_1^0\mathbf{D} \\
\vdots & \ddots & & & & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & & & & \ddots & \vdots \\
\mathbf{H}_{L-2}^{L-2} & \ddots & \ddots & \mathbf{H}_0^{L-2} & & 0 & & \mathbf{H}_{L-1}^{L-2}\mathbf{D} \\
\mathbf{H}_{L-1}^{L-1} & \ddots & \ddots & \ddots & \mathbf{H}_0^{L-1} & & & \\
 & \ddots & \ddots & \ddots & \ddots & \ddots & & \\
 & & \ddots & \ddots & \ddots & \ddots & \ddots & \\
0 & & & \mathbf{H}_{L-1}^{M-1} & \ddots & \ddots & \ddots & \mathbf{H}_0^{M-1}
\end{bmatrix}
\begin{bmatrix} \mathbf{x}_0 \\ \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_{M-1} \end{bmatrix}
+
\begin{bmatrix} \mathbf{z}_0 \\ \mathbf{z}_1 \\ \vdots \\ \mathbf{z}_{M-1} \end{bmatrix}
$$

$$\mathbf{H}_l^m = \sum_{k=1}^{2K+1} g(k,l)e^{j2\pi\frac{\hat{k}(m-l)}{MN}}\mathbf{C}^{\hat{k}}$$

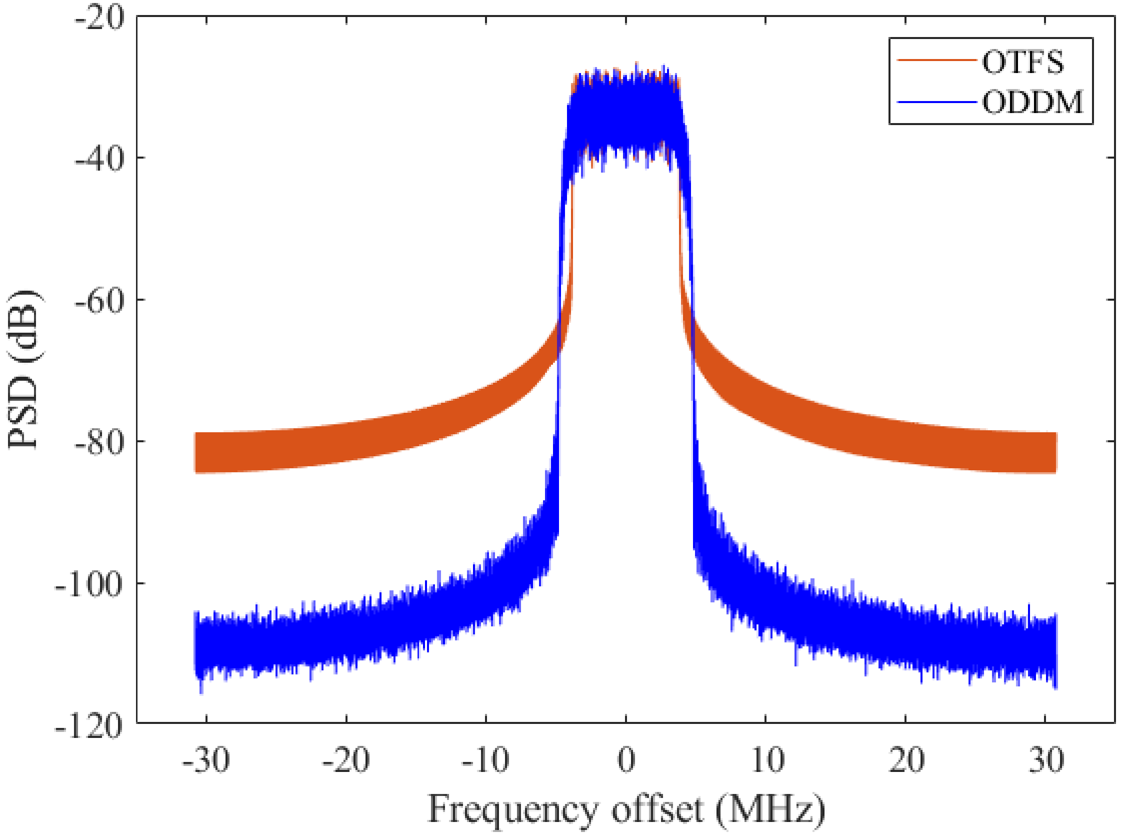
$$\mathbf{D} = \mathrm{diag}\left\{1, e^{-j\frac{2\pi}{N}}, \ldots, e^{-j\frac{2\pi(N-1)}{N}}\right\}$$

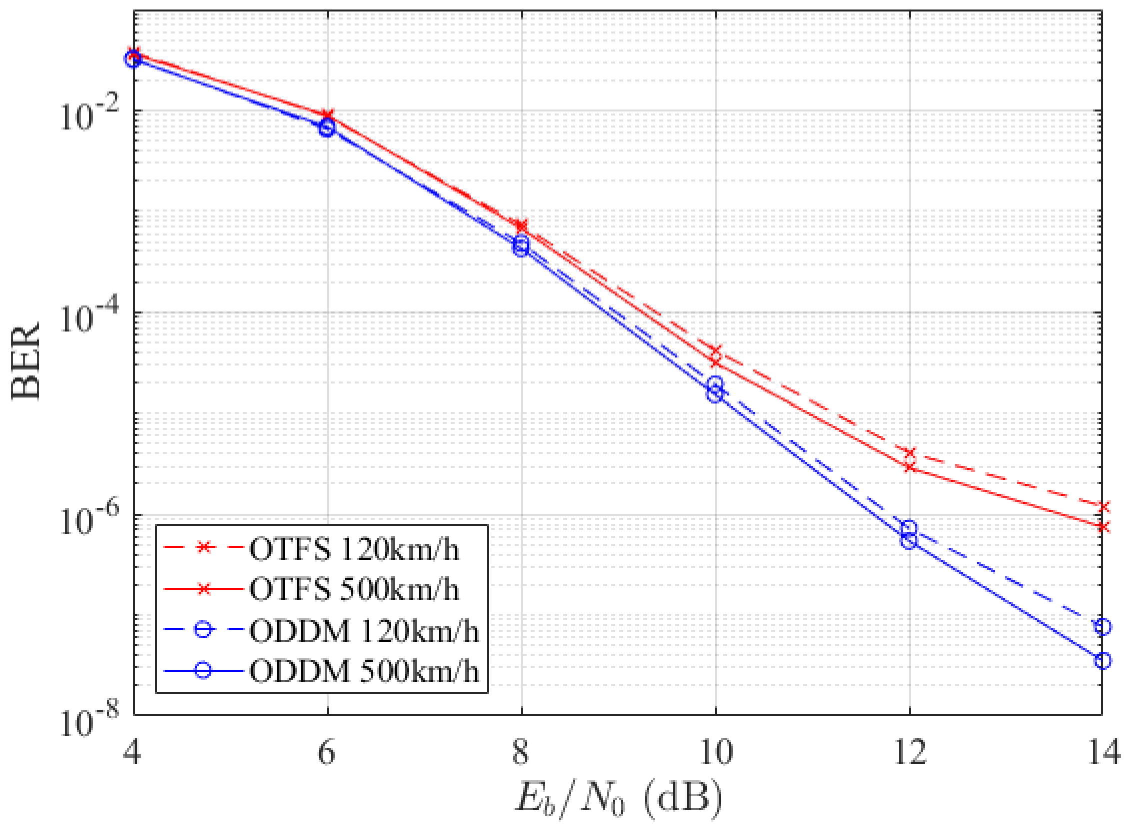
$\boldsymbol{C}$: $N \times N$ cyclic permutation matrix

block-circulant-like structure brought by time and frequency domain CP

- Equalization：MP, MMSE, DFE,...

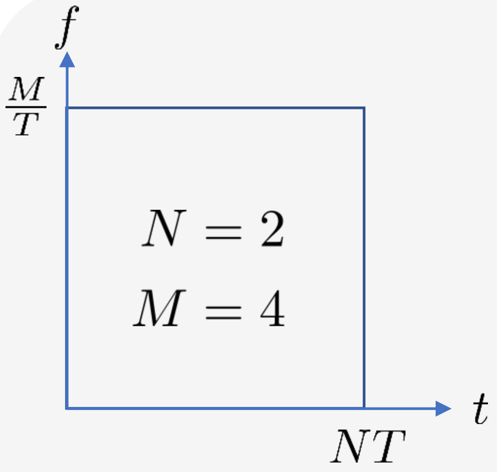
Simulation Results





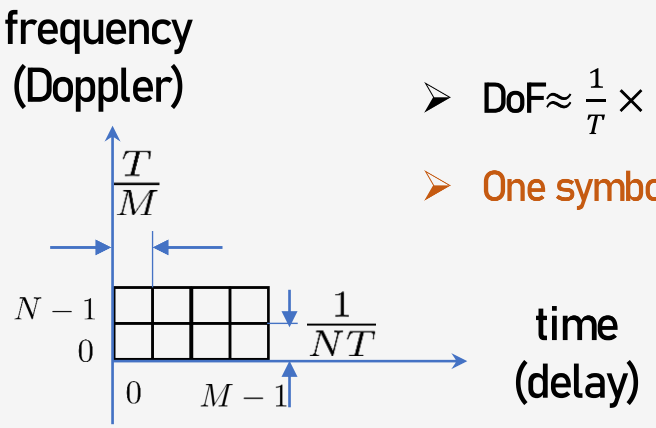
- $M = 512,\ N = 64,\ \frac{1}{T} = 15\text{kHz}, f_c = 5\text{GHz}$, EVA Channel
- $Q = 16$, roll-off factor = 0.25, Uncoded 4-QAM, MP Equalization

From the Viewpoint of DoF



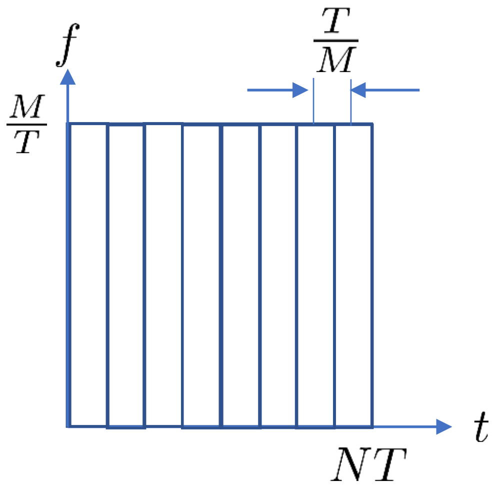
TF plane

- Landau-Pollak Theorem
- DoF$\approx \frac{M}{T} \times NT = MN$
- MN symbols

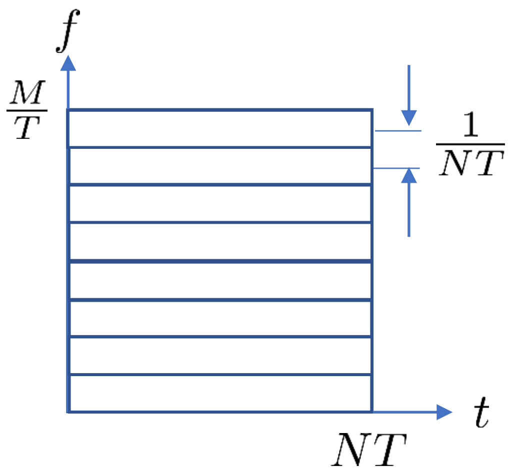


DD plane

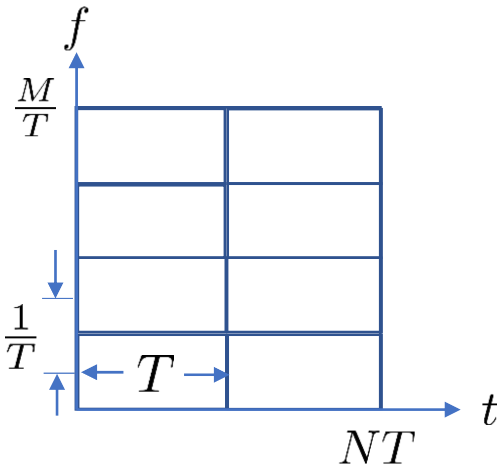
- DoF$\approx \frac{1}{T} \times T = 1$
- One symbol !



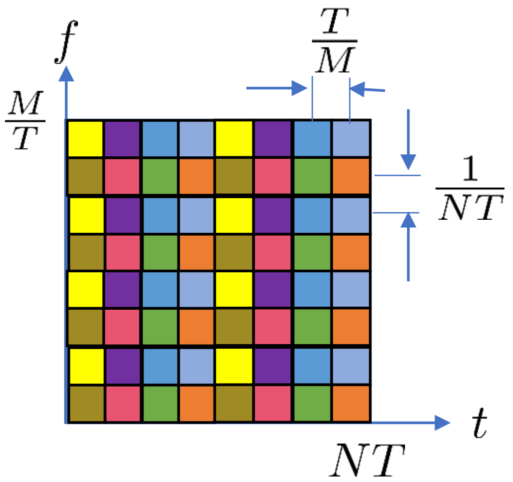
TDM(SC)
DoF: MN



FDM(OFDM)
DoF: MN

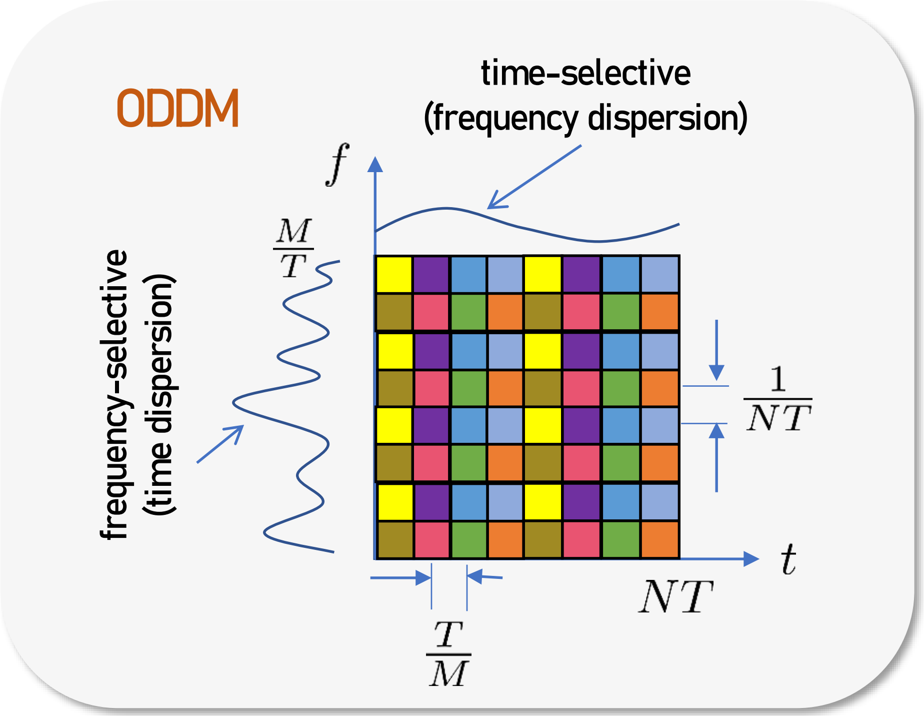


OFDM
DoF: MN



ODDM
DoF: MN

Conclusion



- **A Novel Multicarrier Modulation Waveform**
- **DD Plane Orthogonal Pulse**
- Orthogonal MC with respect to DD resolution
- Low OOBE, flexible bandwidth
- Potential for future
    - High reliability communication
    - ISAC

- H. Lin and J. Yuan, "Multicarrier Modulation on Delay-Doppler Plane: Achieving Orthogonality with Fine Resolutions," in Proc. IEEE ICC, 2022, pp. 1–6.

Joint work

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Thank you for your attention!