Multicarrier Modulation on Delay-Doppler Plane: Achieving Orthogonality with Fine Resolutions

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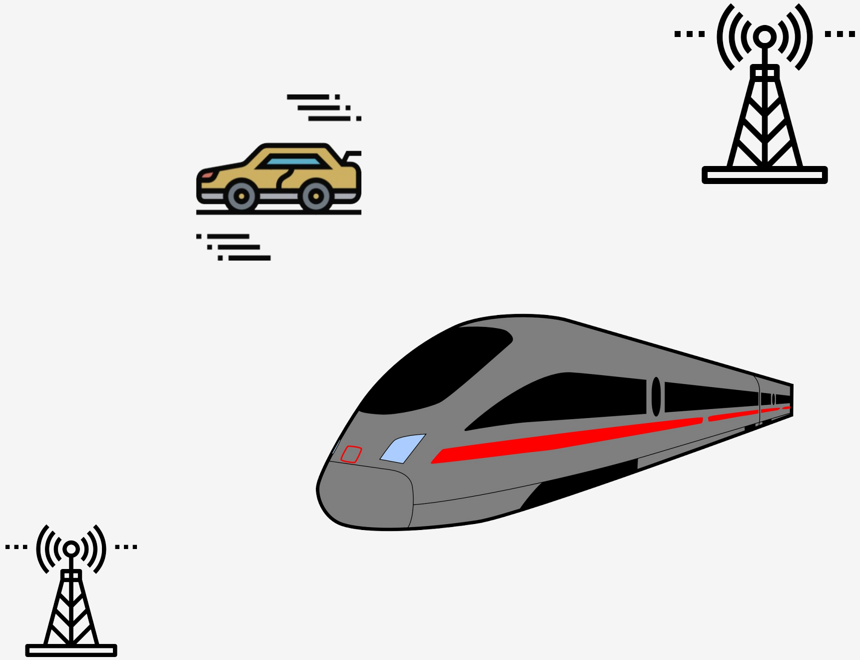
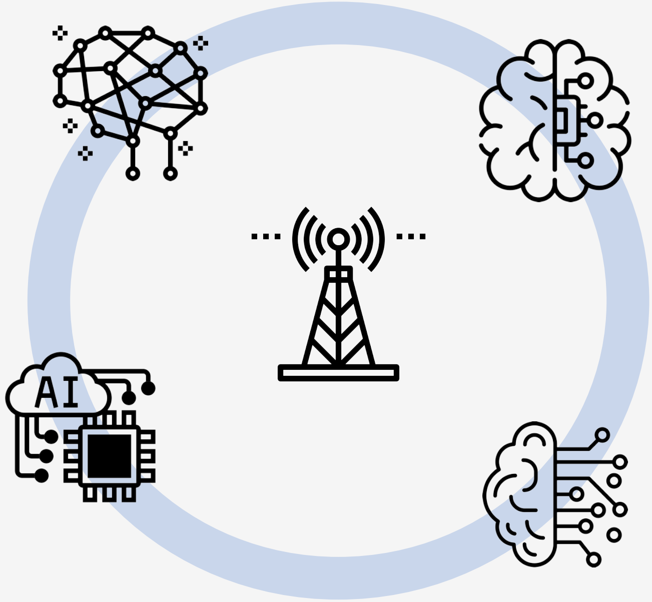
6G Scenarios

- High Reliability Communication



High mobility environment

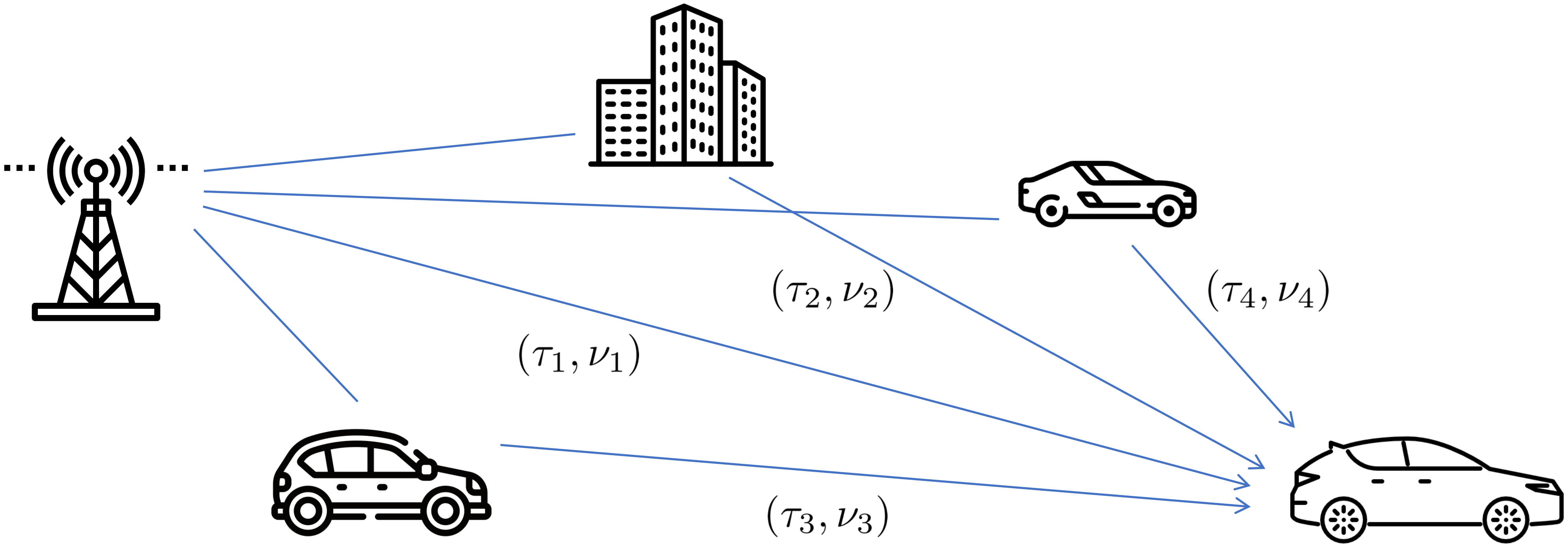
- Connected Intelligence



Integrated sensing and communication (ISAC)

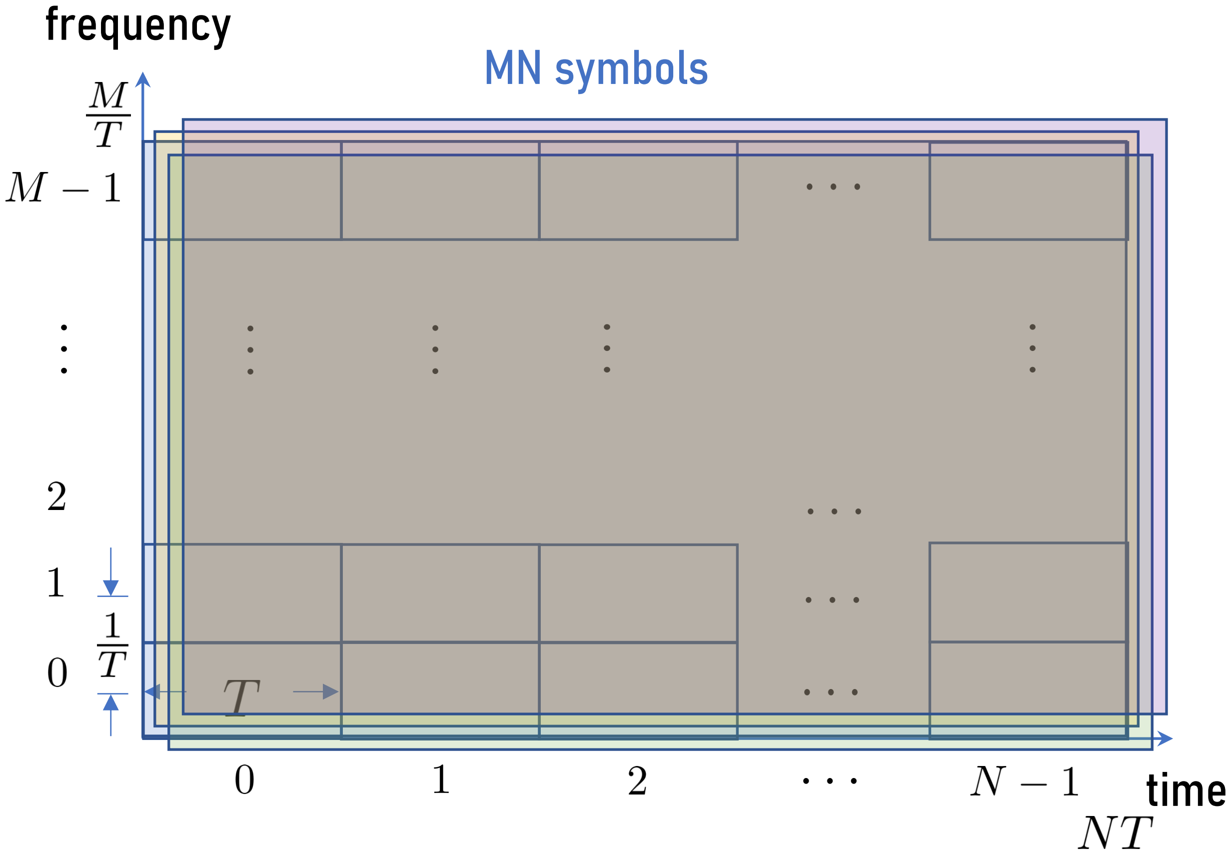
➢ 6G: The Next Horizon: From Connected People and Things to Connected Intelligence, W. Tong and P. Zhu, Cambridge University Press, 2021

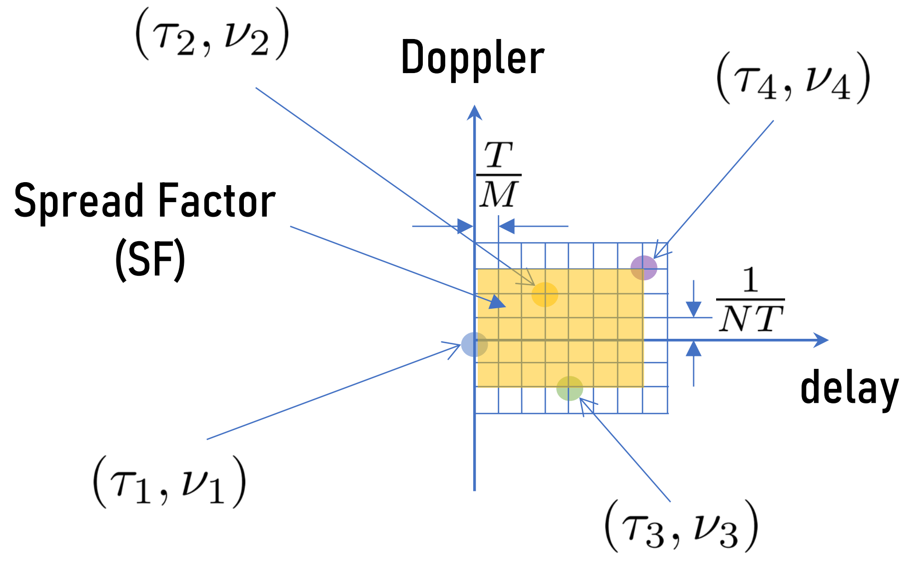
Mobile Channel Models



- Doubly-selective channel with both time and frequency dispersion
- Statistical models: WSSUS, Rayleigh, Rician, Nakagami-m
- **Deterministic model**: delay-Doppler spread function, namely spreading function $\mathcal{S}(\tau, \nu)$
  - **Path based model** : $h(\tau, \nu) = \sum_{p=1}^{P} h_p \delta(\tau - \tau_p)\delta(\nu - \nu_p)$

Time-Frequency (TF) and Delay-Doppler (DD) Planes





$$\tau_p = l_p \frac{T}{M}, \ \nu_p = k_p \frac{1}{NT}, \ l_p, k_p \in \mathbb{Z}$$

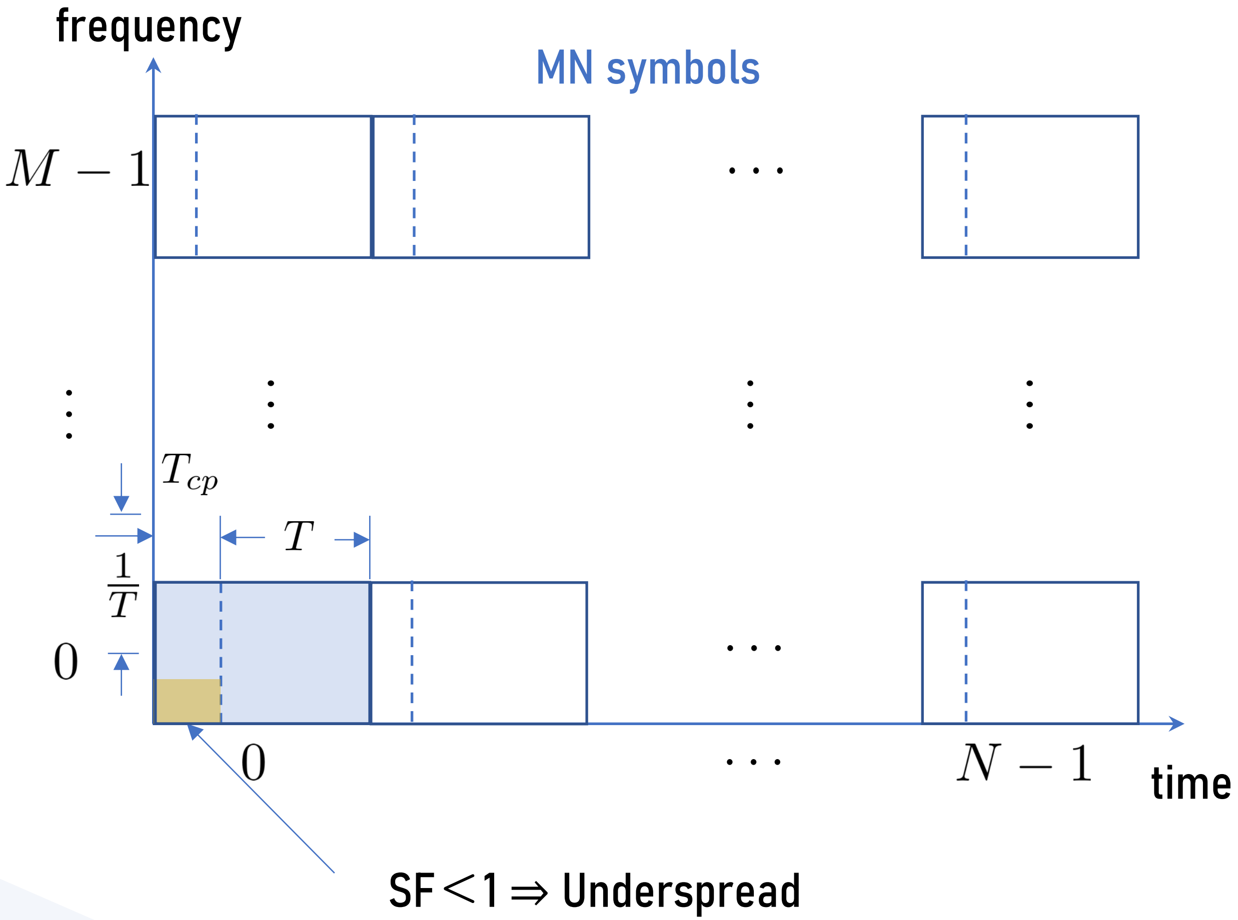
Sampling rate : $\frac{M}{T}$ Duration : NT

TF plane for modulation ⟷ DD plane for channel

TF resolution mismatch

Complicated ISI and ICI (off-the-grid)

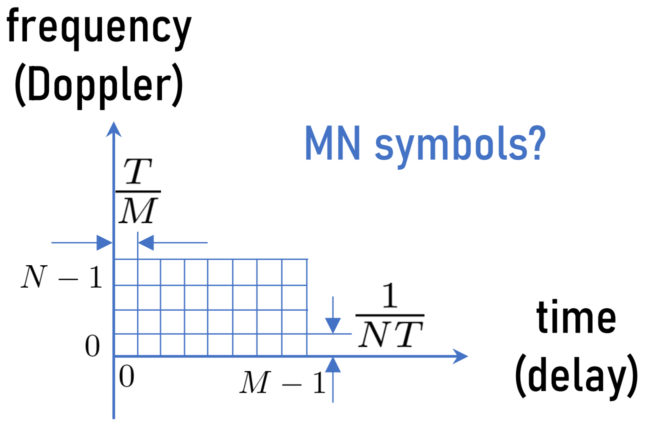
Delay and Doppler in 4G/5G OFDM



- 4G/5G OFDM : **TF plane** MC modulation
- Strategy : Avoid the DD-induced ISI and ICI
- Approach : Introduce redundancy based on SF
- CP per symbol and/or large subcarrier spacing ⇒ low spectral efficiency
- Low signal resolution ⇒ Sensing and communication are handled separately

A Candidate Waveform for 6G

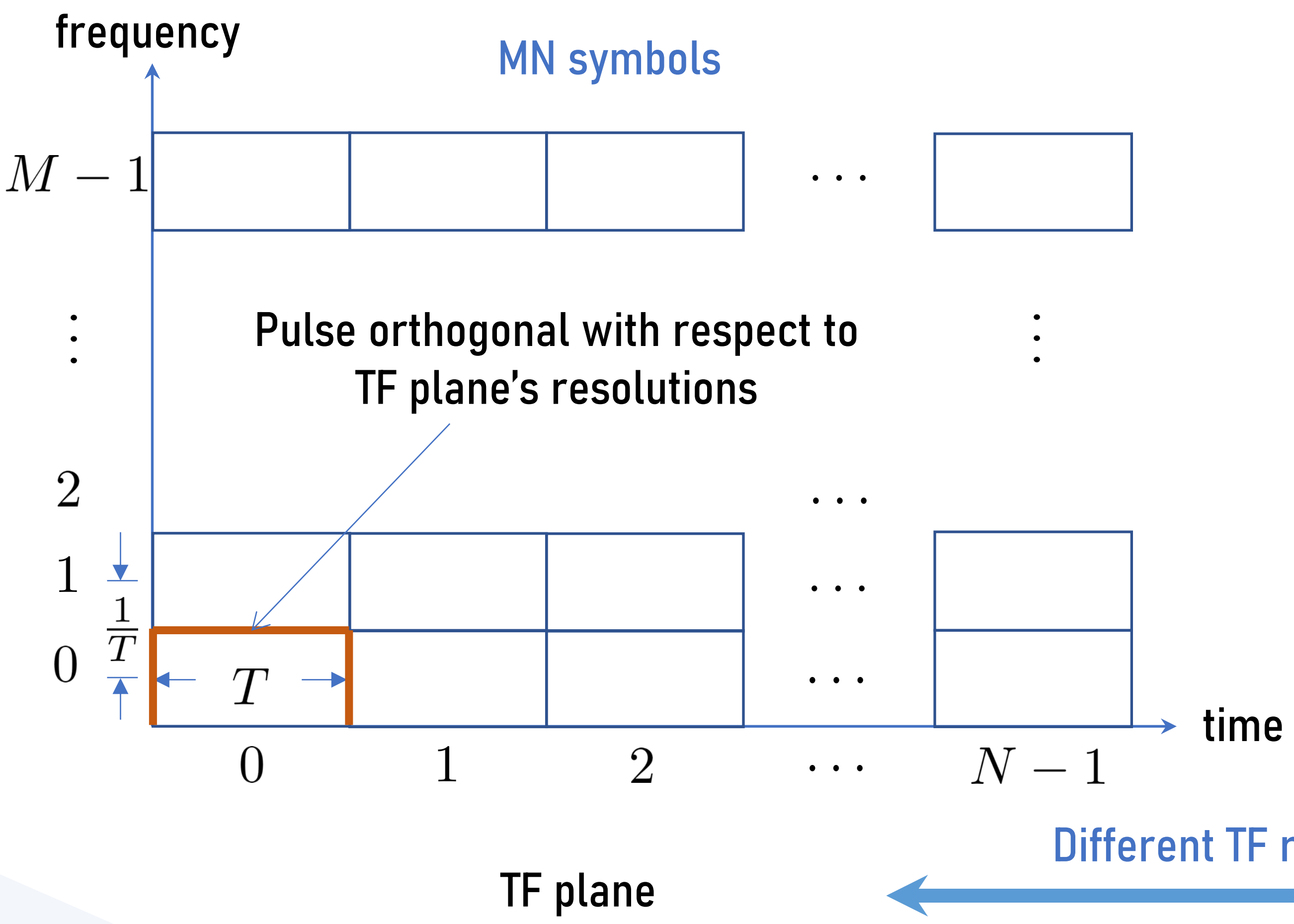
- 6G : **DD plane** MC modulation?
- Strategy : Harvest path-induced TF diversity
- Approach : Match signal and channel's resolution
- On-the-gird ISI and ICI (low-complexity equalization)
- TF diversity ⇒ High reliability communication
- Minimum redundancy ⇒ High spectral efficiency
- High signal resolution ⇒ ISAC



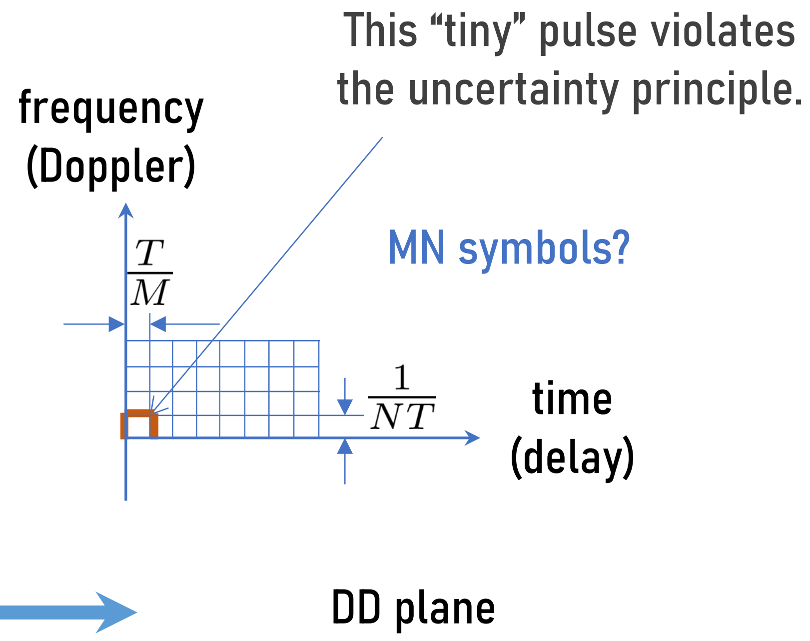
DD plane

Fundamental Issue of DD Plane MC Modulation

- Principle of modulation： One pulse for one symbol

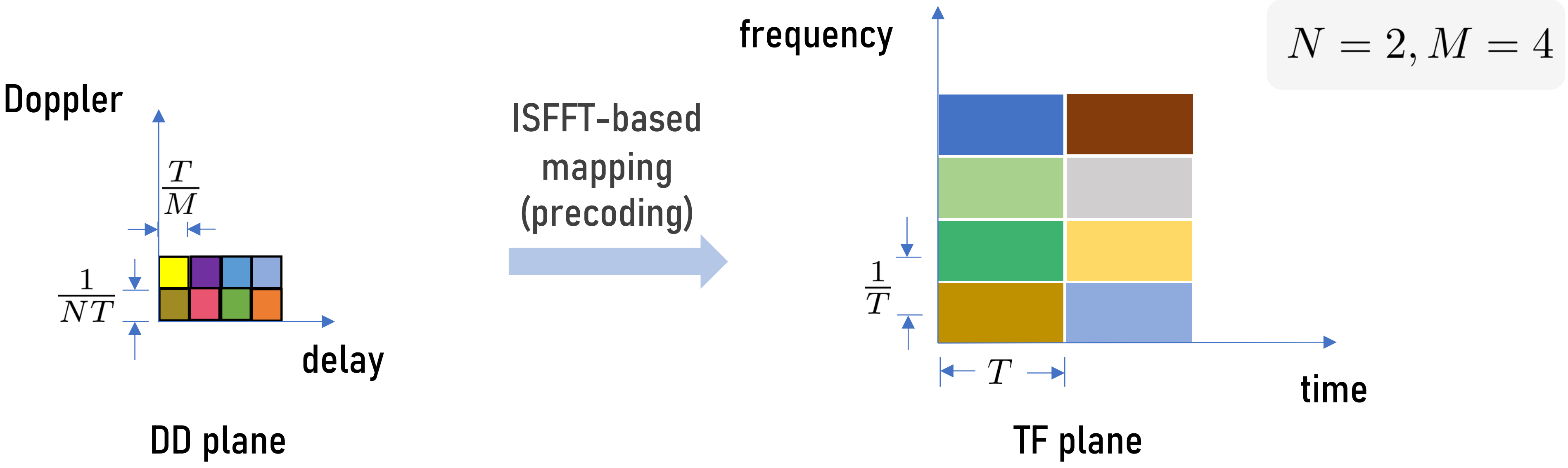


No DD plane orthogonal pulse?



Different TF resolution

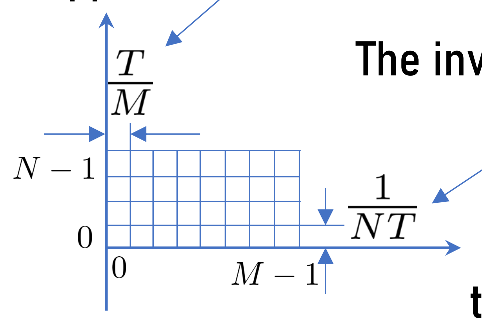
Orthogonal Time Frequency Space (OTFS) Modulation



- Maps signals from DD plane to TF plane, then use OFDM
- OTFS waveform is still orthogonal with respect to TF plane's resolutions
- OTFS's ideal pulse is said to satisfy **biorthogonal robust property**, however cannot be realized in practice.
- Suffers high OOBE and complicated ISI and ICI

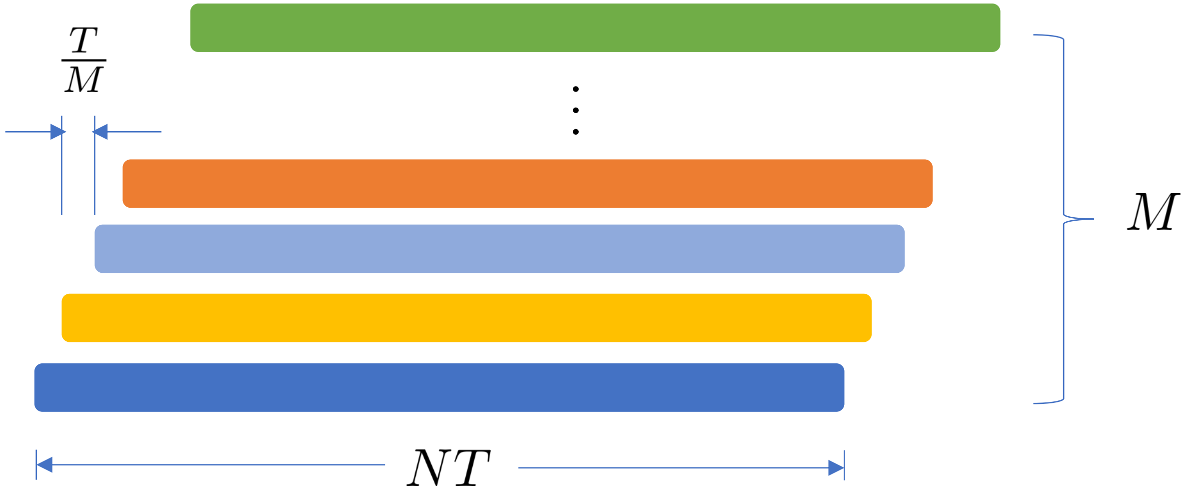
DD Plane MC Modulation

Time resolution is symbol interval, rather than symbol duration.



The inverse of frequency resolution is symbol period.

DD plane

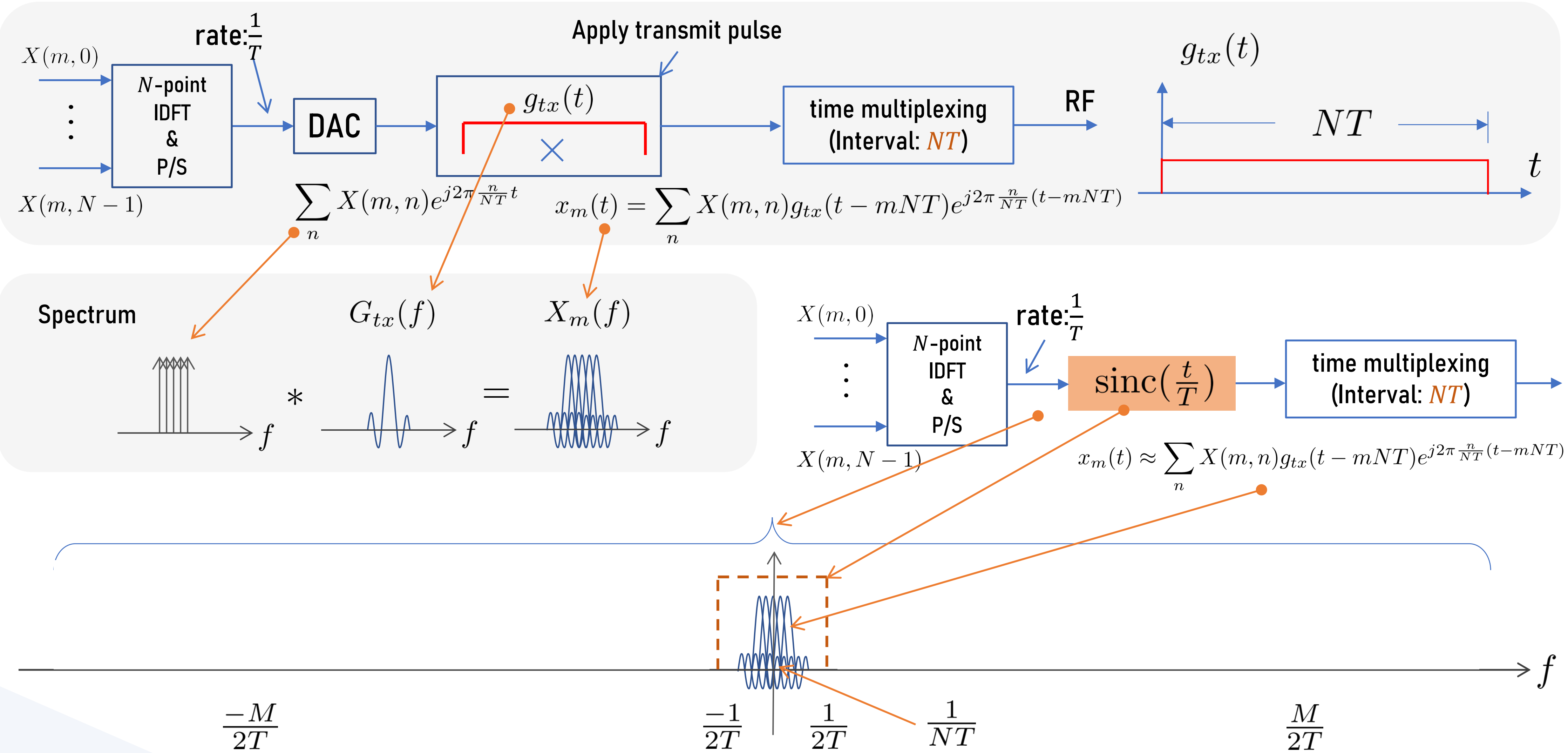


M MC symbols (NT-length, N subcarriers) stagger/overlap.

- DD plane MC modulation ⇒ A type of staggered multitone（SMT） modulation
- Long symbol period ⇒ Narrowband, Short symbol interval ⇒ Wideband. How is this possible?

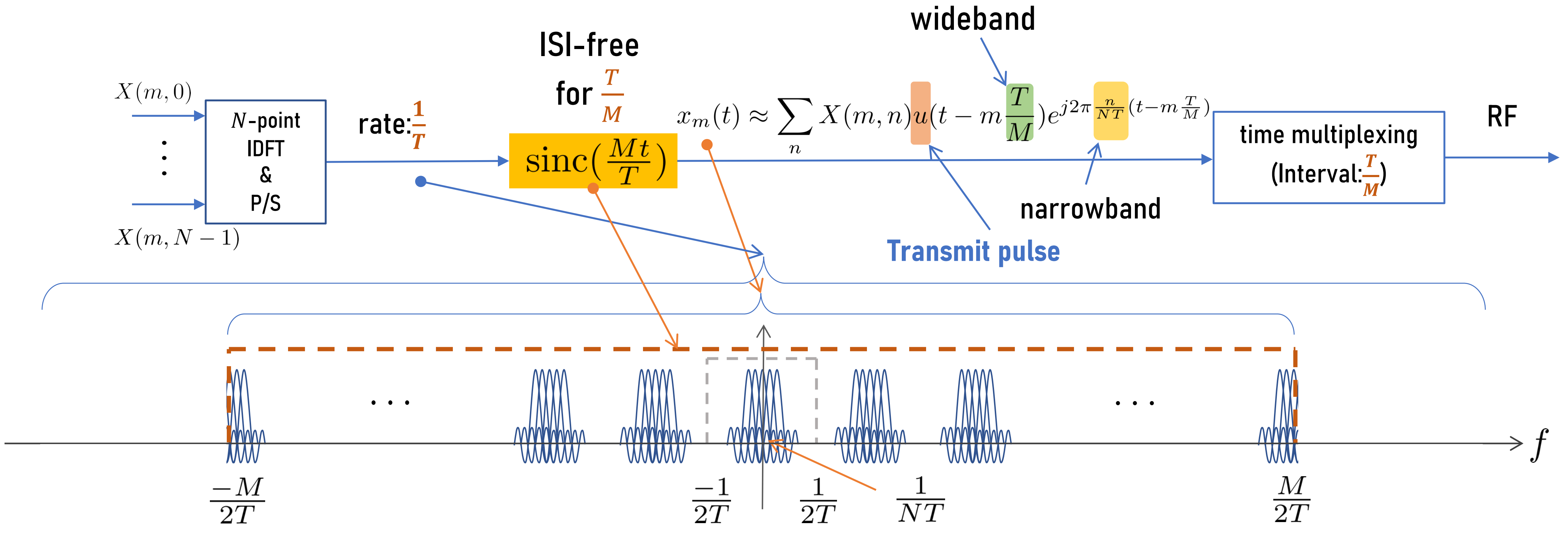
Revisit OFDM Pulse Shaping

- CP-free OFDM: Symbol interval = Symbol period NT



Pulse Shaping for DD Plane MC modulation

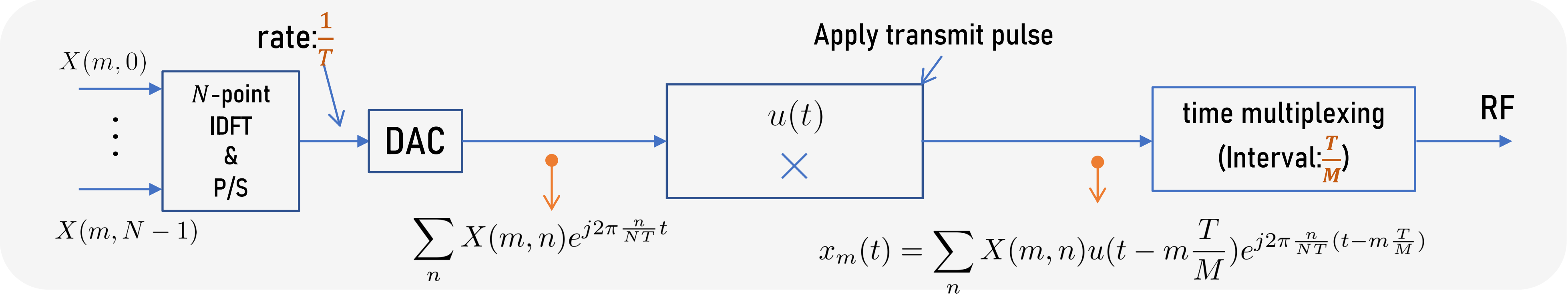
- Symbol interval $\frac{T}{M} \ll$ Symbol period NT



- Like SC modulation, use root Nyquist pulse for symbol interval $\frac{T}{M}$ (wideband)
- Keep the aliasing parts of signal to form CP and cyclic suffix in frequency domain

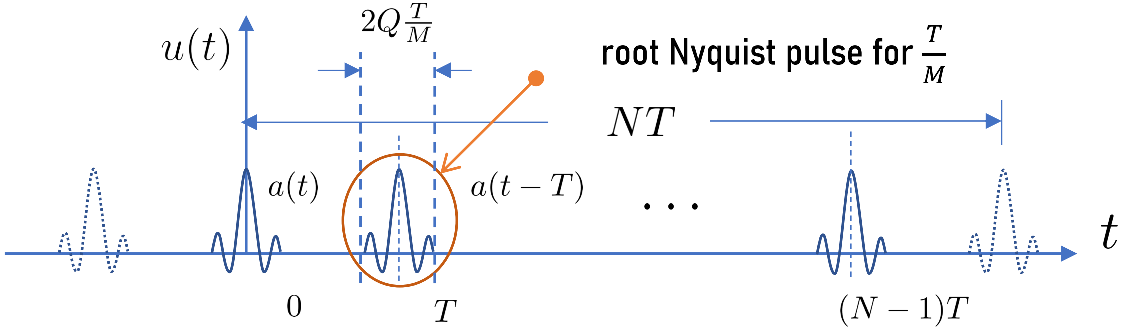
Transmit Pulse for DD Plane MC Modulation

- 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



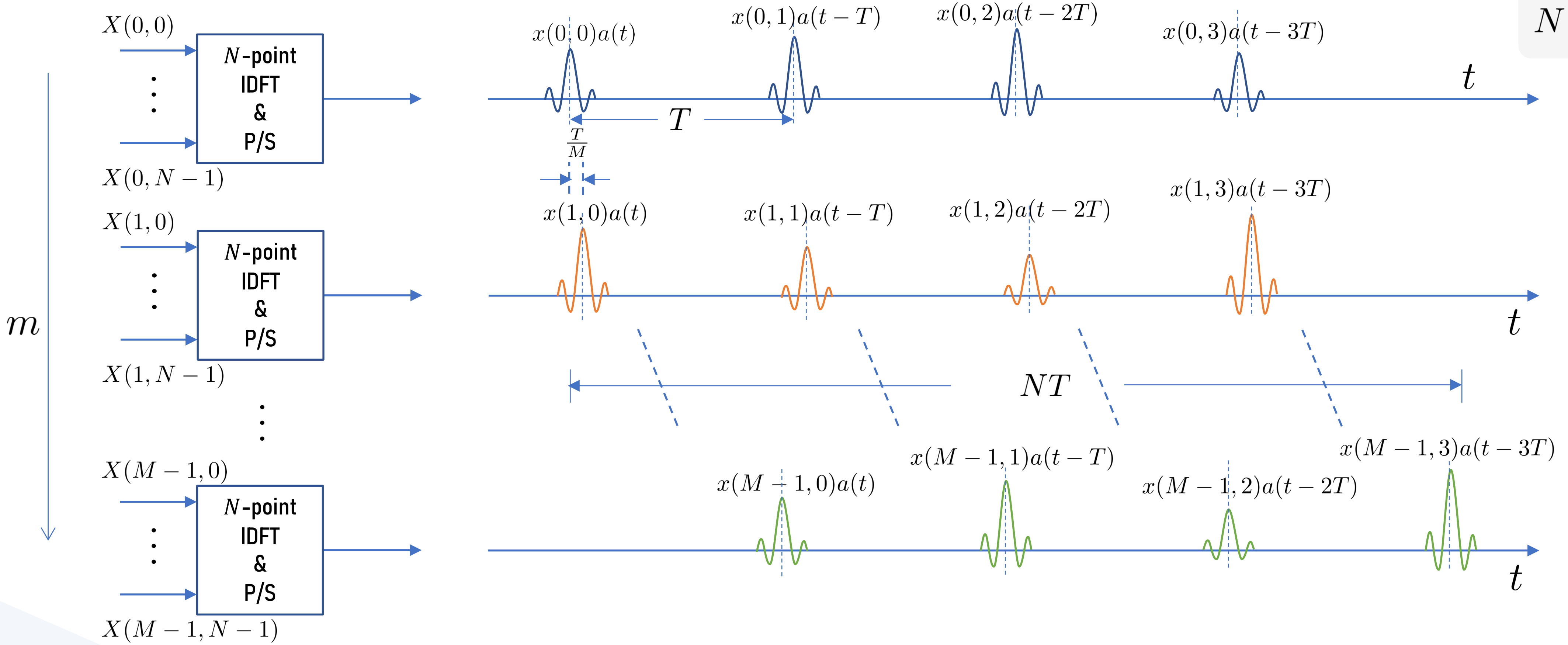
- Ambiguity function of $u(t)$

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

Orthogonal Delay-Doppler Division Multiplexing (ODDM) Modulation

- ODDM is pulse-shaped by $u(t)$ and therefore orthogonal with respect to the DD plane's resolutions $\frac{T}{M}$ and $\frac{1}{NT}$.
- When $2Q \ll M$, the combination of N-point IDFT and a(t)-based filtering **approximates** ODDM waveform.

$N = 4, 2Q \ll M$

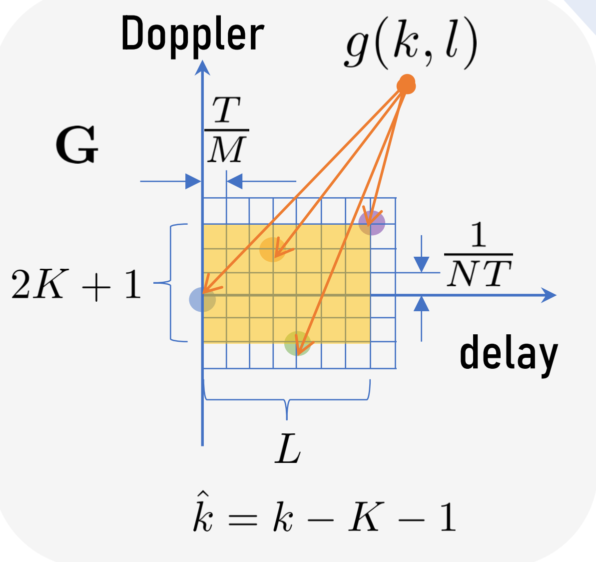


- Add a frame-wise CP to keep the periodicity

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



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

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

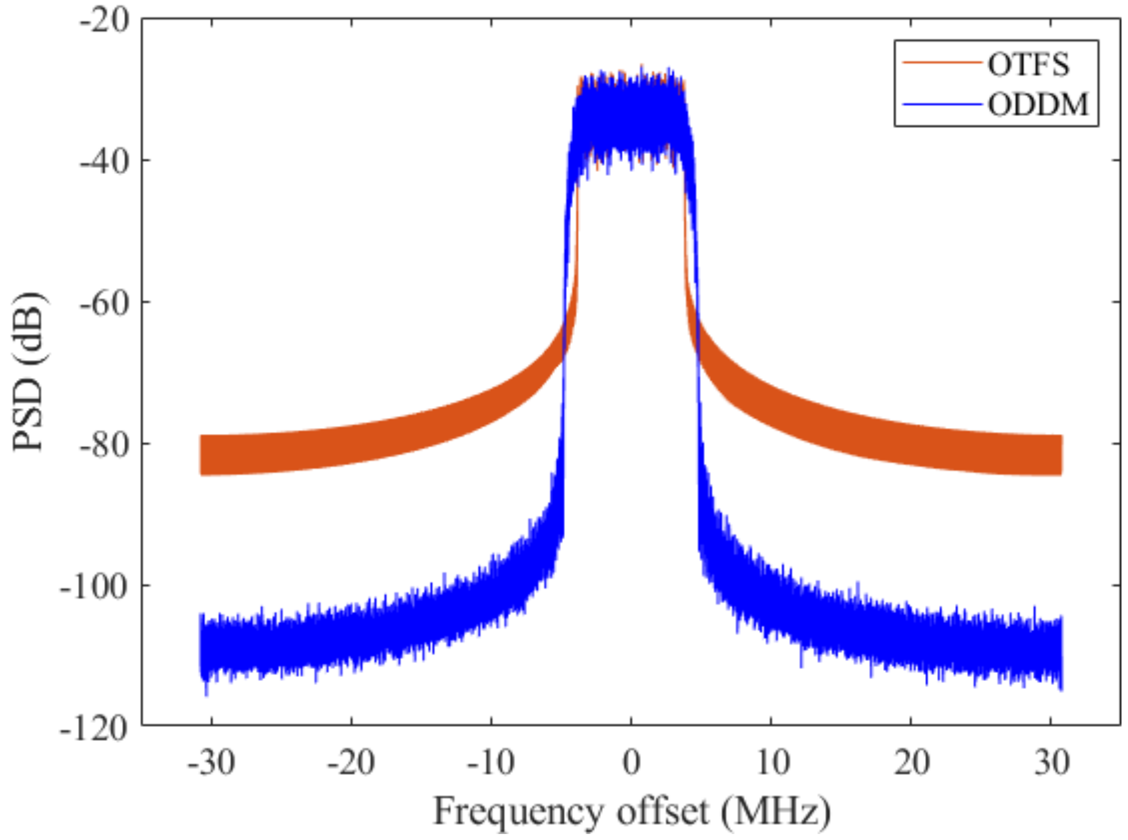
$$\mathbf{D}=\mathrm{diag}\left\{1,e^{-j\frac{2\pi}{N}},\ldots,e^{-j\frac{2\pi(N-1)}{N}}\right\}$$

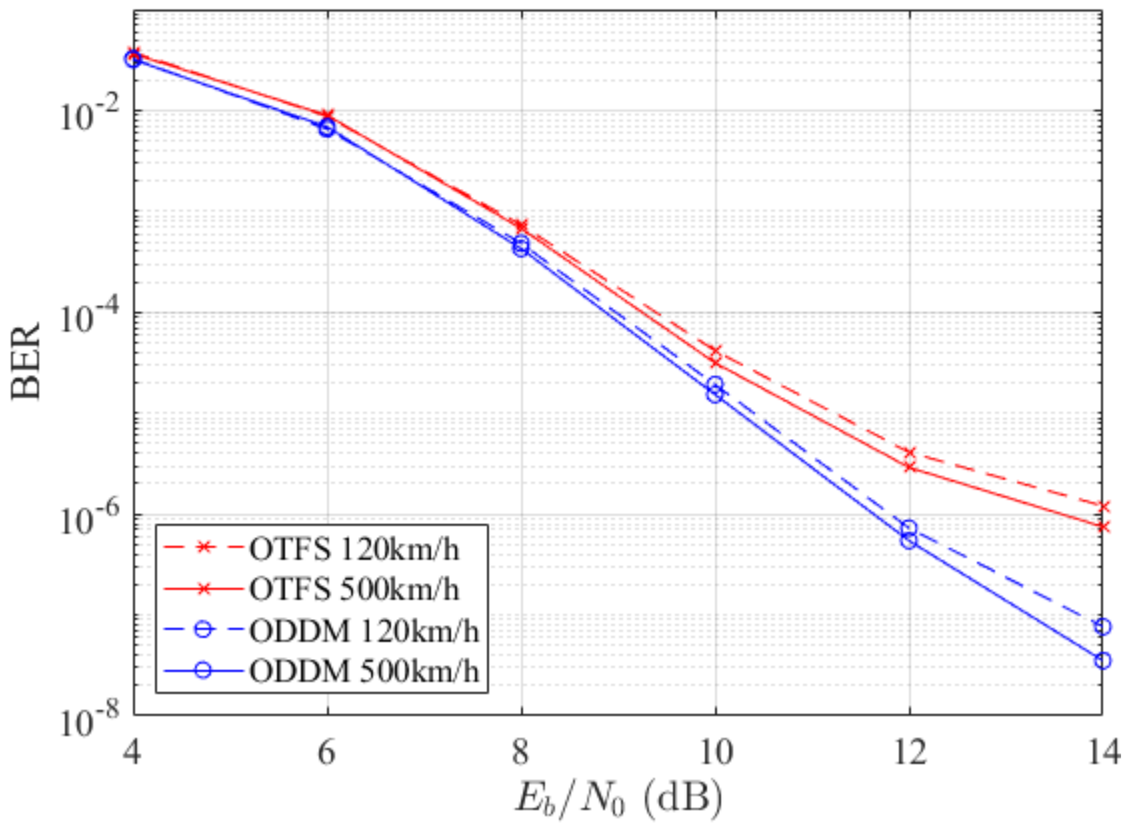
$\boldsymbol{C}$: $N\times N$ cyclic permutation matrix

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

- Equalization：MP, MMSE, DFE, …

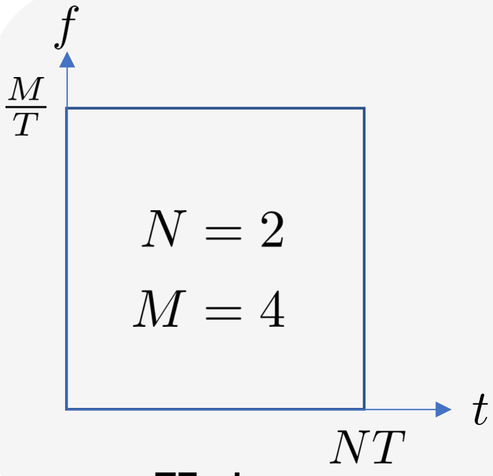
Simulation Results





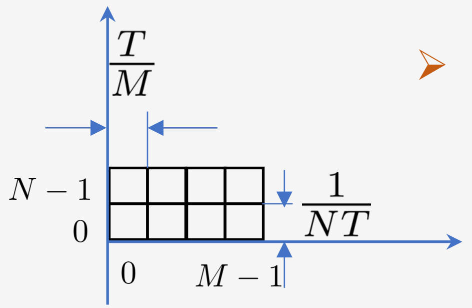
- $M = 512,\ N = 64,\ \frac{1}{T} = 15\text{kHz}, f_c = 5\text{GHz}$, EVA Channel
- $Q = 16$, roll-off factor = 0.25, Uncoded 4-QAM, MP Equalization

From the Viewpoint of DoF



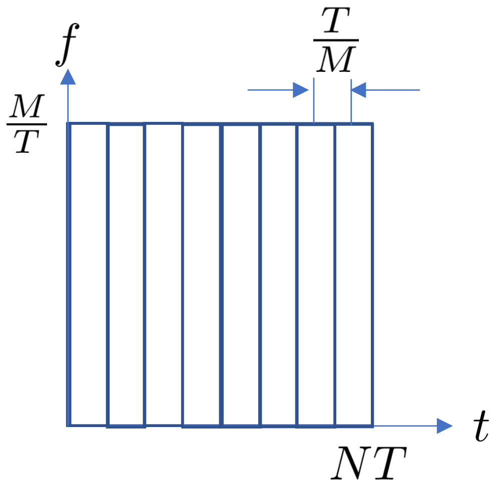
TF plane

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

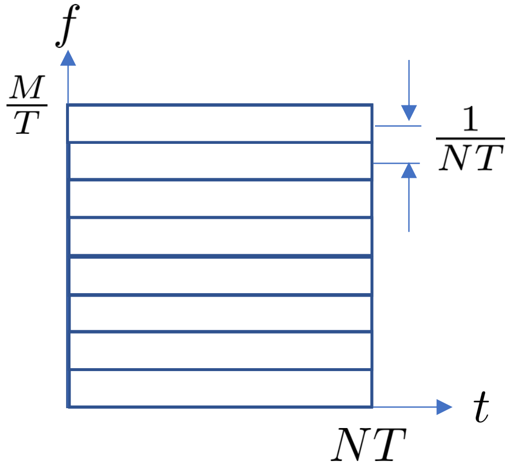


DD plane

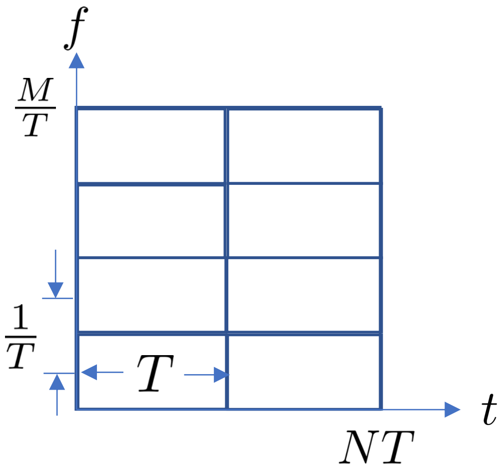
- DoF$\approx \frac{1}{T} \times T = 1$
- One symbol!



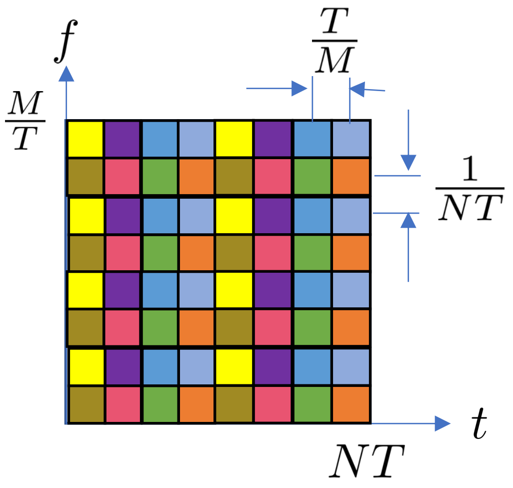
TDM(SC)
DoF: MN



FDM(OFDM)
DoF: MN

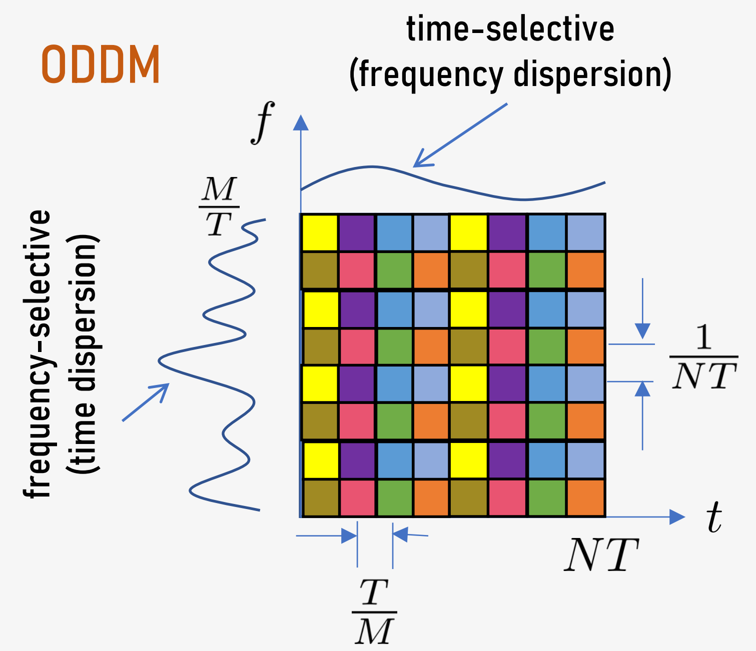


OFDM/OTFS
DoF: MN



ODDM
DoF: MN

Conclusion



- A Novel Multicarrier Modulation Waveform
- Based on a newly discovered orthogonal pulse
- Orthogonal MC with respect to DD resolution
- A hybrid of TDM and FDM
- Coupling between signal and channel
- Low OOBE, Low PAPR
- Flexible bandwidth, high spectral efficiency
- For high reliability communication
- For ISAC in future mobile communications

Thank you for your attention!