Joint Active User Detection and Channel Estimation for Grant-Free NOMA-OTFS in LEO Constellation Internet-of-Things

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Outline

LEO Constellation-enabled IoT

- **Opportunities** [Liu'21]

Starlink

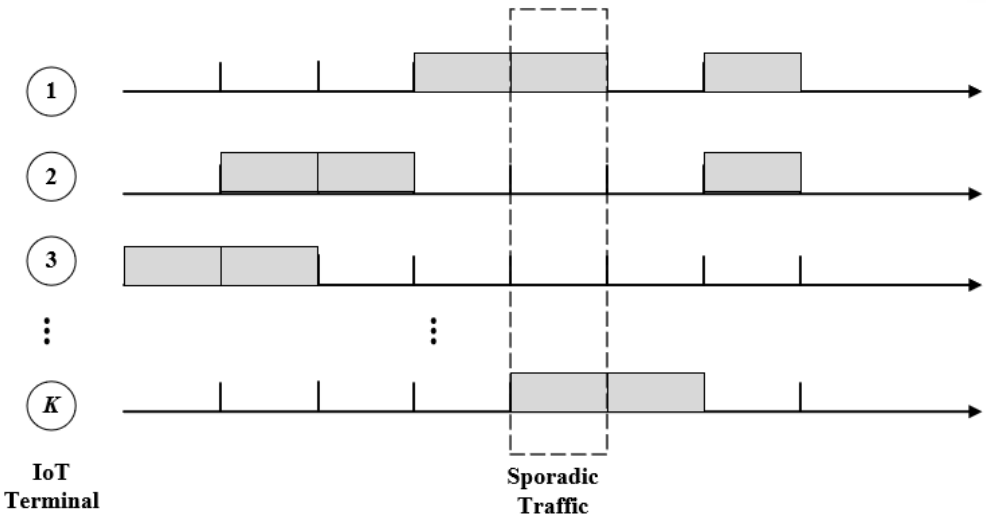
China Satcom

The emerging LEO satellite constellations provide a promising solution for supporting seamless coverage services in the Internet of Things

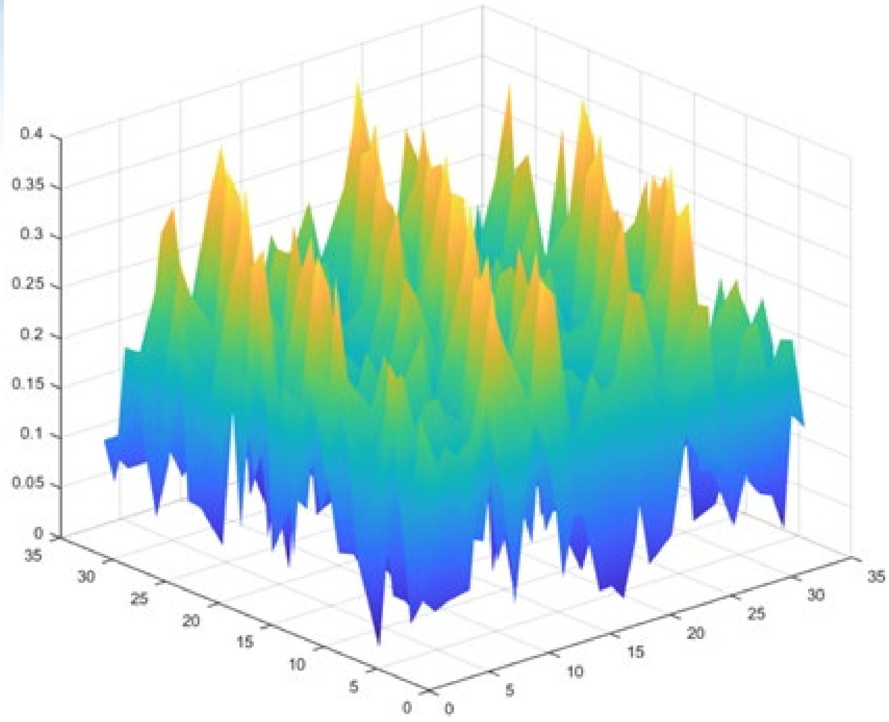
[Liu'21] S. Liu, Z. Gao, Y. Wu, D. W. K. Ng, X. Gao, K. Wong, S. Chatzinotas, and B. Ottersten, "LEO satellite constellations for 5G and beyond: How will they reshape vertical domains?", *to appear in* ***IEEE Commun. Mag.***.

LEO Constellation-enabled IoT

- **Challenges** [Zhang'20]



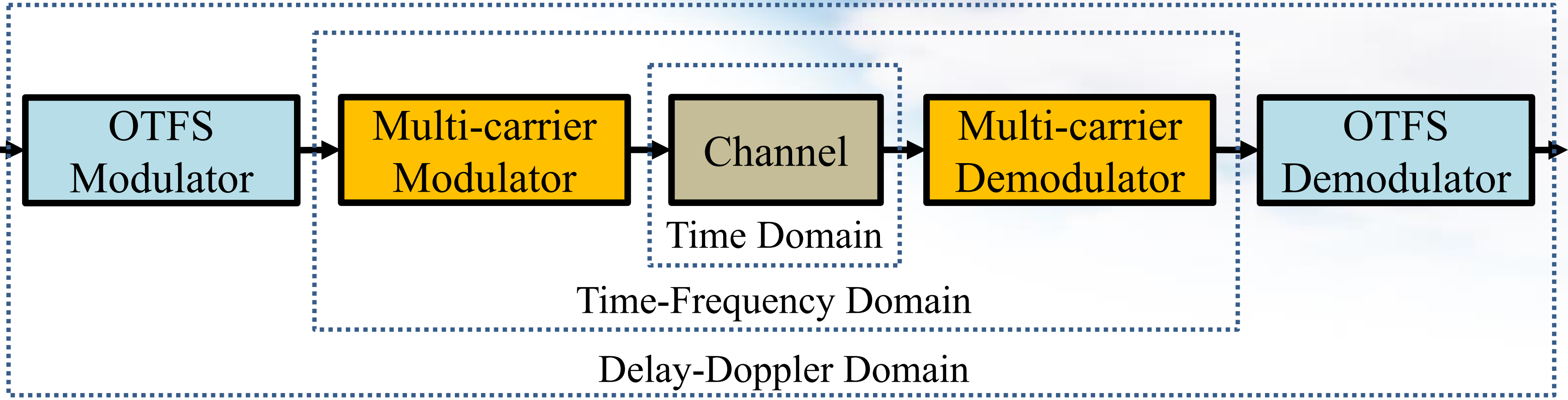
(a) Massive Machine-type Communication (mMTC)



(b) Time-Varying Terrestrial-Satellite Link (TSL)

An efficient multiple access scheme and waveform are in demand to meet the massive connectivity in LEO-IoT and combat the dynamics of the TSL

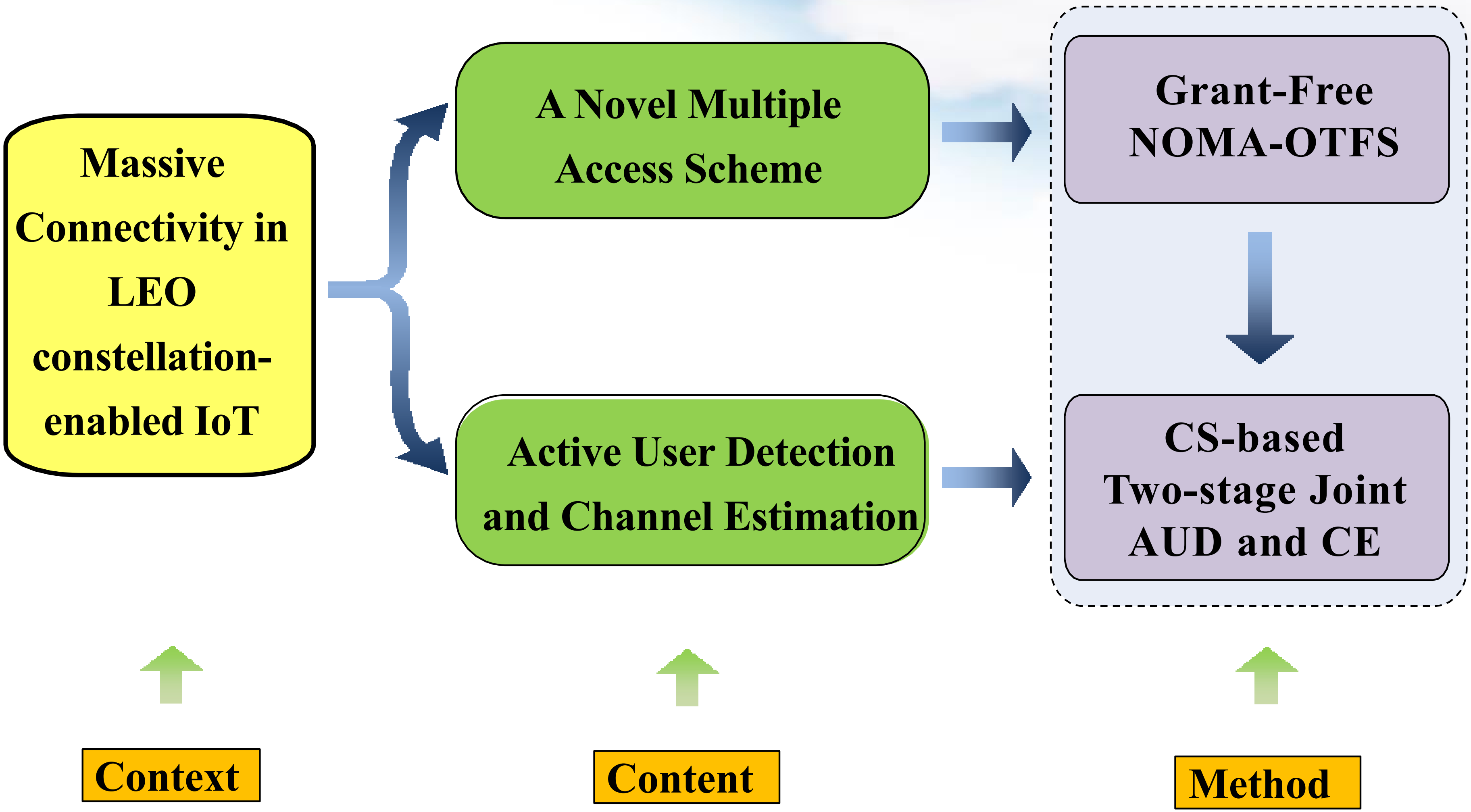
OTFS Waveform



Orthogonal Time Frequency Space (OTFS)

- **A new two-dimension modulation technique**
- **Carry information symbols in the delay-Doppler domain**
- **OTFS works well in high-Doppler wireless channels**
- **OTFS can exploit full time-frequency diversity (2D spreading)**

Contributions

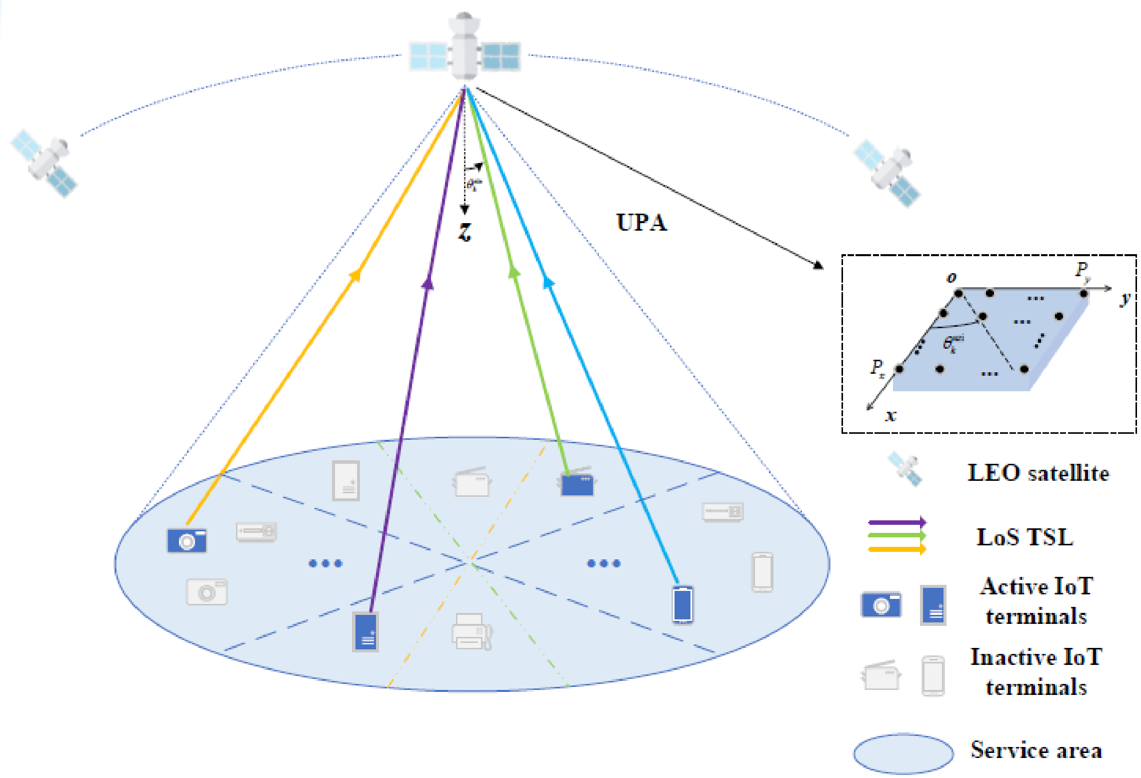


Outline

Grant-Free NOMA-OTFS

Principles

- **Grant-Free**: IoT terminals transmit frames consisting of pilot and data symbols **without grant**
- **NOMA**: IoT terminals share the **same time-frequency resource** to access the LEO satellite
- **OTFS**: The data symbols are carried in **delay-Doppler** domain and are modulated by OTFS



- **UPA of LEO:** $P = P_x \times P_y$
- **Distribution of IoT terminal:**
  - ✓ **Active vs. Total:** $K_a \ll K$
  - ✓ **Activity Indicator:** α_k

Transmission Architecture

- **Training Sequence (TS) Aided OTFS**

Data symbols of the k-th terminal

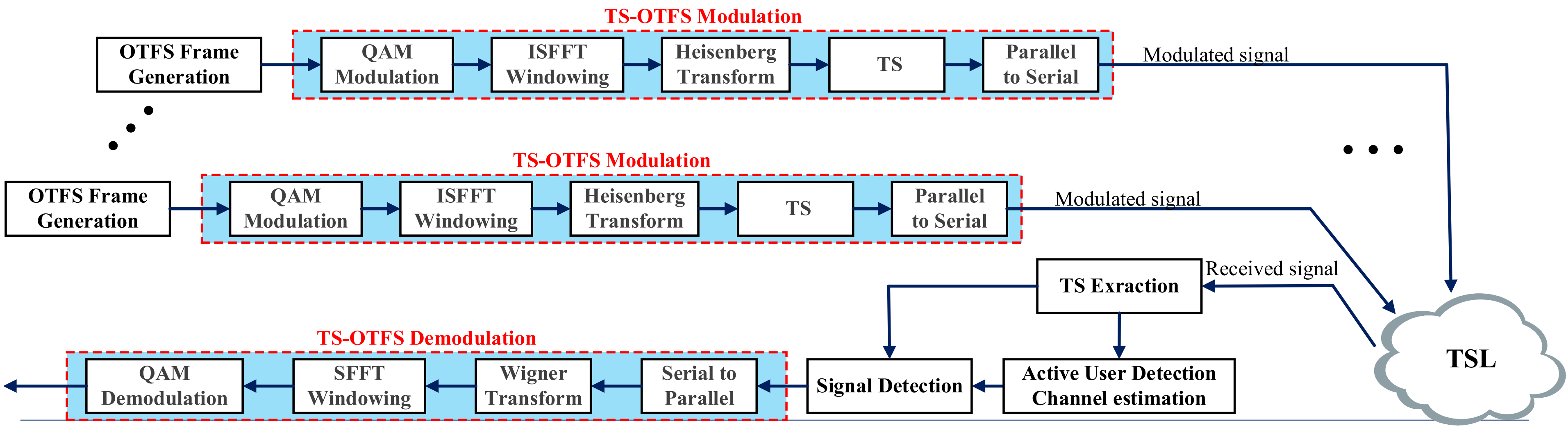
Delay-Doppler domain : $\mathbf{X}_k^{\mathrm{DD}} \in \mathbb{C}^{M\times N}$ **Time-Frequency domain** : $\mathbf{X}_k^{\mathrm{TF}} \in \mathbb{C}^{M\times N}$

Time domain : $\tilde{\mathbf{S}}_k \in \mathbb{C}^{M\times N}$ **Training Sequence:** $\mathbf{c}_k = [c_{k,0}\ c_{k,1} \ldots c_{k,M_t-1}]^{\mathrm{T}}$

Transmit Signal: $\mathbf{s}_k \in \mathbb{C}^{(M_t+M)N\times 1}$

Terrestrial-Satellite Link Channel

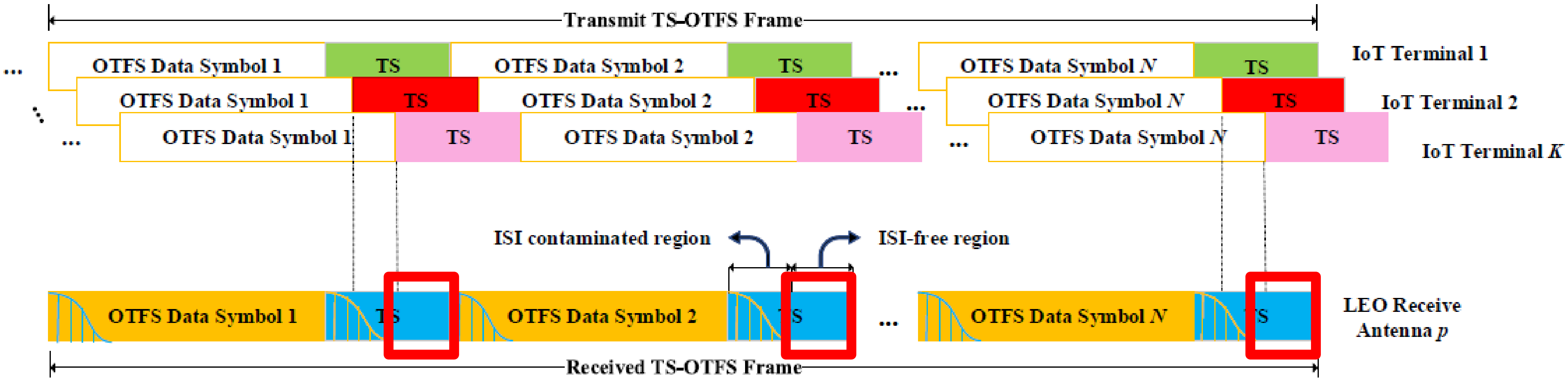
Line-of-Sight (LoS) Link: $h_{k,p}[\kappa,\ell] = g_k e^{j2\pi \frac{\upsilon_k(\kappa-\ell_k)}{N(M+M_t)}} \delta[\ell-\ell_k] \cdot [\mathbf{v}_k]_p$



Outline

Formulation of AUD and CE

● Received Signal



$$r_p(\kappa) = \sum_{k=1}^{K} \sum_{l=0}^{L} \alpha_k h_{k,p} \left[\kappa, \ell\right] s_k \left[\kappa - \ell\right] + w_p(\kappa) \tag{1}$$

The received TS's are contaminated by the previous OTFS data symbol. An effective approach is to utilize the inter-symbol-interference free (ISI-free) region, which is the rear part of the TS's and immune from the influence of the previous data symbol, to perform AUD and CE

ISI-Free Region

- **Input-Output Relationship**

$$\mathbf{r}^{i}_{\mathrm{TS},p} = \sum_{k=1}^{K} \alpha_k \mathbf{\Delta}_k \mathbf{\Psi}_k \mathbf{h}^{i}_{\mathrm{TS},k,p} + \mathbf{w}^{i}_{\mathrm{TS},p} \quad (2)$$

- **The ISI-free region of the *i*-th received TS:** $\mathbf{r}^{i}_{\mathrm{TS},p} \in \mathbb{C}^{G\times 1}$
- **The vector form of CIR:** $\mathbf{h}^{i}_{\mathrm{TS},k,p} \in \mathbb{C}^{L\times 1}$
- **Doppler shift :** $\mathbf{\Delta}_k = \mathrm{diag}\{e^{j2\pi \frac{\upsilon_k \cdot 0}{N(M+M_t)}}, e^{j2\pi \frac{\upsilon_k \cdot 1}{N(M+M_t)}}, \ldots, e^{j2\pi \frac{\upsilon_k \cdot (G-1)}{N(M+M_t)}}\}$
- **Measurement matrix:**

$$\mathbf{\Psi_k} = \begin{bmatrix} c_{k,L-1} & c_{k,L-2} & \cdots & c_{k,0} \\ c_{k,L} & c_{k,L-1} & \cdots & c_{k,1} \\ \vdots & \vdots & \vdots & \vdots \\ c_{k,M_t-1} & c_{k,M_t-2} & \cdots & c_{k,M_t-L} \end{bmatrix}$$

Approximation

- Since $\boldsymbol{\Delta}_k$ is an unknown matrix for the receiver of LEO satellite, sparse CIR vectors in (2) cannot be recovered with an unknown sensing matrix. Therefore approximate it as an identity matrix:

$$\mathbf{r}^i_{\mathrm{TS},p} \approx \sum_{k=1}^{K} \alpha_k \boldsymbol{\Psi}_k \mathbf{h}^i_{\mathrm{TS},k,p} + \mathbf{w}^i_{\mathrm{TS},p} = \boldsymbol{\Psi}\tilde{\mathbf{h}}^i_{\mathrm{TS},p} + \mathbf{w}^i_{\mathrm{TS},p} \tag{3}$$

Rationality Behind the Assumption

- The approximation error is identical for different TS's in the one frame and hence its impact on the following channel parameters can be counteracted
- The approximation error only impact the accuracy of the sparse signal recovery and each ISI-free region is always over a relatively short span of time compared to the whole data frame and hence the error is negligible

Multiple Measurement Vectors

- **Spatial Correlation**

For different receive antennas, the propagation delay and the Doppler shift of the transmit signal from the same terminal are roughly the same.

$$\mathbf{R}_{\mathrm{TS}}^{i} \approx \mathbf{\Psi}\tilde{\mathbf{H}}_{\mathrm{TS}}^{i} + \mathbf{W}_{\mathrm{TS}}^{i} \tag{4}$$

- **Temporal Correlation**

For different TS's in the one frame, the propagation delay and the Doppler shift of the transmit signal from the same terminal are roughly the same.

$$\mathbf{R}_{\mathrm{TS}} \approx \mathbf{\Psi}\tilde{\mathbf{H}}_{\mathrm{TS}} + \mathbf{W}_{\mathrm{TS}} \tag{5}$$

- $\mathbf{R}_{\mathrm{TS}} = \left[\mathbf{R}_{\mathrm{TS}}^{(1)}, \mathbf{R}_{\mathrm{TS}}^{(2)}, \ldots, \mathbf{R}_{\mathrm{TS}}^{(N)}\right] \in \mathbb{C}^{G \times NP}$
- $\tilde{\mathbf{H}}_{\mathrm{TS}} = \left[\tilde{\mathbf{H}}_{\mathrm{TS}}^{(1)}, \tilde{\mathbf{H}}_{\mathrm{TS}}^{(2)}, \ldots, \tilde{\mathbf{H}}_{\mathrm{TS}}^{(N)}\right] \in \mathbb{C}^{KL \times NP}$
- $\mathbf{W}_{\mathrm{TS}} = \left[\mathbf{W}_{\mathrm{TS}}^{(1)}, \mathbf{W}_{\mathrm{TS}}^{(2)}, \ldots, \mathbf{W}_{\mathrm{TS}}^{(N)}\right] \in \mathbb{C}^{G \times NP}$

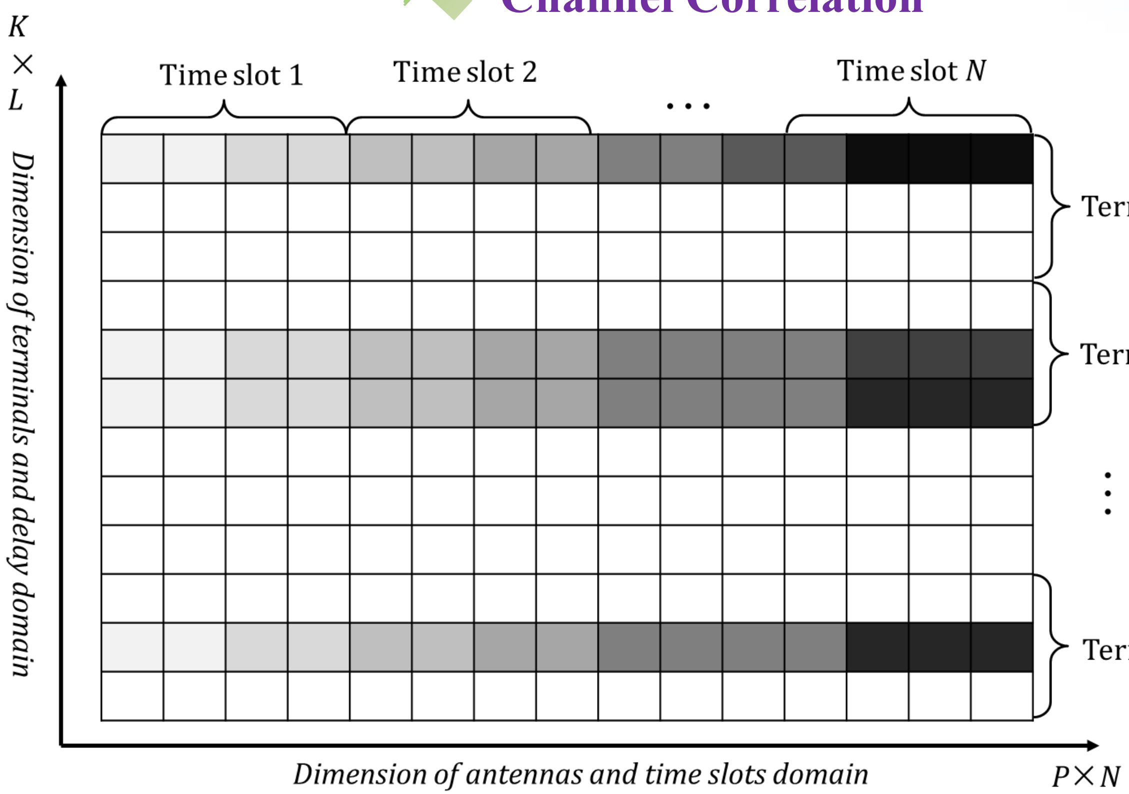
Outline

CS-based Sparse Channel Vectors Recovery

- **Structured Sparsity** [Tropp'05]
  - Channel matrix shows sparsity in terminal and delay dimensions and common sparsity in antenna and time slot dimensions

Channel Correlation

Sporadic Traffic and Inherent Sparsity of TSL channel



For the joint sparse signal recovery under the framework of compressive sensing, the state-of-the-art simultaneous orthogonal matching pursuit (SOMP) can be used

Active User Detection

- **Results of SOMP**
  - **Recovered sparse channel vectors:** $\tilde{\mathbf{H}}^{e}_{\mathrm{TS}}$
  - **Index of support set :** $\mathcal{I}$
  - **Index of support set associated with the *k*-th terminal :**

$$\Omega_k = \{\omega_k | \omega_k \in \mathcal{I}, (k-1)L \leq \omega_k < kL\}$$

- **Active User Detection**

$$\hat{\alpha}_k = \begin{cases} 1 & \text{if } \Omega_k \neq \emptyset \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

  - **Active terminal set:** $\hat{\mathcal{A}} = \{k | \hat{\alpha}_k = 1, 1 \leq k \leq K\}$

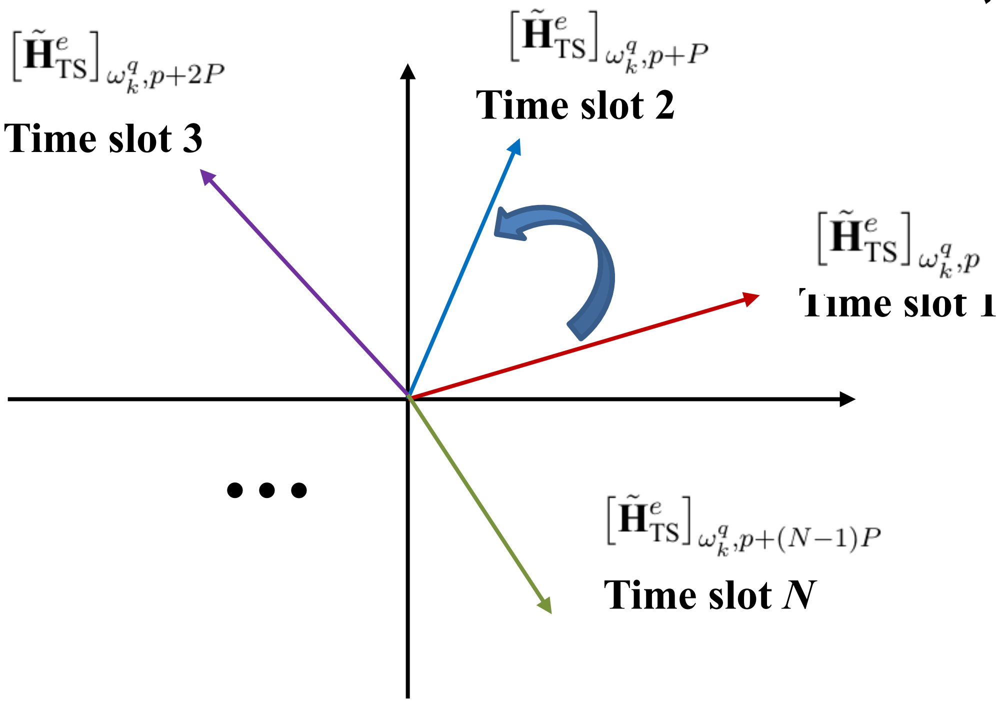
- **Estimate of relative time of arrival:**

$$\hat{\ell}^q_k = \omega^q_k - (k-1)L$$

  - $\omega^q_k \ (1 \leq q \leq |\Omega_k|)$ **is the *q*-th element of** Ω_k

Channel Estimation

- **TLS-ESPRIT Based Doppler Shift Estimation** [Roy'89]
  - **Estimate signal parameters via rotational invariance (ESPRIT) is an array signal processing algorithm, which uses subspace rotational invariance to solve signal parameters**
  - **There are phase rotations on the channel coefficients of different time slots:**



✓ **The coefficients of the front N-1 time slots, and the back differs from a phase rotation matrix Φ :**

$$\mathbf{X}_1 = \mathbf{A}_1\mathbf{S} \tag{7}$$

$$\mathbf{X}_2 = \mathbf{A}_2\mathbf{S} = \mathbf{A}_1\mathbf{\Phi}\mathbf{S} \tag{8}$$

✓ **Phase rotation matrix are determined by the Doppler shift**

$$\Phi = \mathrm{diag}(e^{j\omega_1}, e^{j\omega_2}, \ldots, e^{j\omega_m}) \tag{9}$$

✓ **Their eigenvectors have the following relationship:**

$$\mathbf{U}_2 = \mathbf{U}_1\mathbf{T}^{-1}\mathbf{\Phi}\mathbf{T} = \mathbf{U}_1\mathbf{\Psi} \tag{10}$$

Parametric Approach

- The channel coefficients can be calculated **mathematically** with the estimated **delay and Doppler shift**:

$$\hat{\mathbf{h}}_p^{\mathrm{eff},i} = \mathbf{\Psi}_{\mathcal{I}}^{\dagger} \sum_{k\in\mathcal{A}} \mathbf{\Delta}_k \psi_k \mathbf{h}_{\mathrm{TS},k,p}^{i}(\ell_k+1) + \underbrace{(\mathbf{\Psi}_{\mathcal{I}}^{\mathrm{H}}\mathbf{\Psi}_{\mathcal{I}})^{-1}\mathbf{\Psi}_{\mathcal{I}}^{\mathrm{H}}\mathbf{w}_{\mathrm{TS},p}^{i}}_{\text{noise}}$$

$$\approx \overbrace{\mathbf{\Psi}_{\mathcal{I}}^{\dagger}\left[\mathbf{\Delta}_{k_1}\psi_{k_1}, \mathbf{\Delta}_{k_2}\psi_{k_2}, \ldots, \mathbf{\Delta}_{k_{K_a}}\psi_{k_{K_a}}\right]}^{\mathbf{\Gamma}} \left[\mathbf{h}_{\mathrm{TS},k_1,p}^{i}(\ell_{k_1}+1), \mathbf{h}_{\mathrm{TS},k_2,p}^{i}(\ell_{k_2}+1), \ldots, \mathbf{h}_{\mathrm{TS},k_{K_a},p}^{i}(\ell_{k_{K_a}}+1)\right]^{\mathrm{T}}$$

$$= \mathbf{\Gamma} \underbrace{\left[e^{j2\pi\upsilon_{k_1}\frac{L-M_t+i(M+M_t)-\ell_{k_1}}{N(M+M_t)}}, e^{j2\pi\upsilon_{k_2}\frac{L-M_t+i(M+M_t)-\ell_{k_2}}{N(M+M_t)}}, \ldots, e^{j2\pi\upsilon_{k_{K_a}}\frac{L-M_t+i(M+M_t)-\ell_{k_{K_a}}}{N(M+M_t)}}\right]^{\mathrm{T}}}_{\boldsymbol{\eta}^i}$$

$$\odot \left[g_{k_1,p}^{\mathrm{eff}}, g_{k_2,p}^{\mathrm{eff}}, \ldots, g_{k_{K_a},p}^{\mathrm{eff}}\right]^{\mathrm{T}}$$

$$\hat{\mathbf{h}}_k^{\mathrm{eff},i} = \mathbf{\Gamma}\boldsymbol{\eta}^i \odot \mathbf{g}_p^{\mathrm{eff}} + (\mathbf{\Psi}_{\mathcal{I}}^{\mathrm{H}}\mathbf{\Psi}_{\mathcal{I}})^{-1}\mathbf{\Psi}_{\mathcal{I}}^{\mathrm{H}}\mathbf{w}_{\mathrm{TS},p}^{i}$$

- Reconstruct the CIR in **time-delay** domain and **delay-Doppler** domain:

$$\hat{h}_{k,p}[\kappa,\ell] = \sum_{q=1}^{|\Omega_k|} \hat{g}_{k,p}^{\mathrm{eff},q} e^{j2\pi\frac{\hat{\upsilon}_k^q(\kappa-\hat{\ell}_k^q)}{N(M+M_t)}} \cdot \delta[\ell-\hat{\ell}_k^q] \quad (11)$$

$$\hat{h}_{k,p}^{\mathrm{DD}}[\kappa,\ell] = \sum_{q=1}^{|\Omega_k|} \hat{g}_{k,p}^{\mathrm{eff},q} e^{-j2\pi\hat{\upsilon}_k^q\hat{\ell}_k^q} \frac{1}{NM}\left[e^{-j(N-1)\pi\frac{\kappa-\kappa_{\hat{\upsilon}_k^q}}{N}} \frac{\sin(\pi(\kappa-\kappa_{\hat{\upsilon}_k^q}))}{\sin(\frac{\pi(\kappa-\kappa_{\hat{\upsilon}_k^q})}{N})}\right]\left[e^{-j(M-1)\pi\frac{\ell-\ell_{\hat{\ell}_k^q}}{M}} \frac{\sin(\pi(\ell-\ell_{\hat{\ell}_k^q}))}{\sin(\frac{\pi(\ell-\ell_{\hat{\ell}_k^q})}{M})}\right] \quad (12)$$

Outline

Simulation Setup

- **Simulation Parameters**

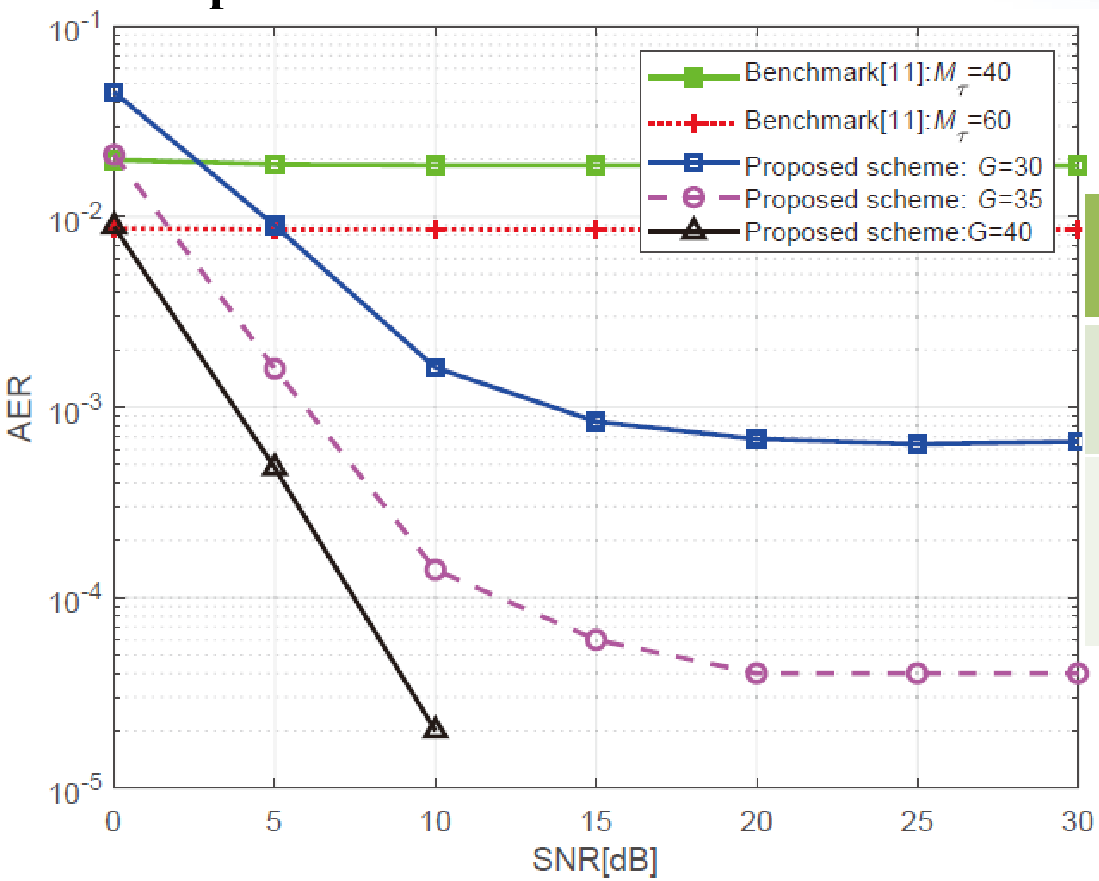
Contents	Parameters	Values
System	Carrier frequency (GHz)	10
	Subcarrier spacing (kHz)	480
	Bandwidth (MHz)	122.88
	Size of OTFS frame (M,N)	(256,8)
	Number of BS antennas (P_x,P_y)	(10,10)
TSL channel	LEO satellite velocity (km/s)	7.58
	IoT terminal velocity (m/s)	$0 \sim 100$
	Propagation delay (ms)	$0 \sim 0.067$
	Doppler shift (kHz)	$0 \sim 178.2$

- **Key Performance Indicators**
  - **Activity Error Rate of AUD:** $\mathrm{AER} = \frac{1}{K}\sum_{k=1}^{K} |\hat{\alpha}_k - \alpha_k|$
  - **Normalized Mean Square Error (NMSE) of CE**

$$\mathrm{NMSE} = \frac{\sum_{k,p,\kappa,\ell} ||\hat{\alpha}_k \hat{h}_{k,p}[\kappa,\ell] - \alpha_k h_{k,p}[\kappa,\ell]||_2^2}{\sum_{k,p,\kappa,\ell} ||\alpha_k h_{k,p}[\kappa,\ell]||_2^2}$$

Performance of AUD

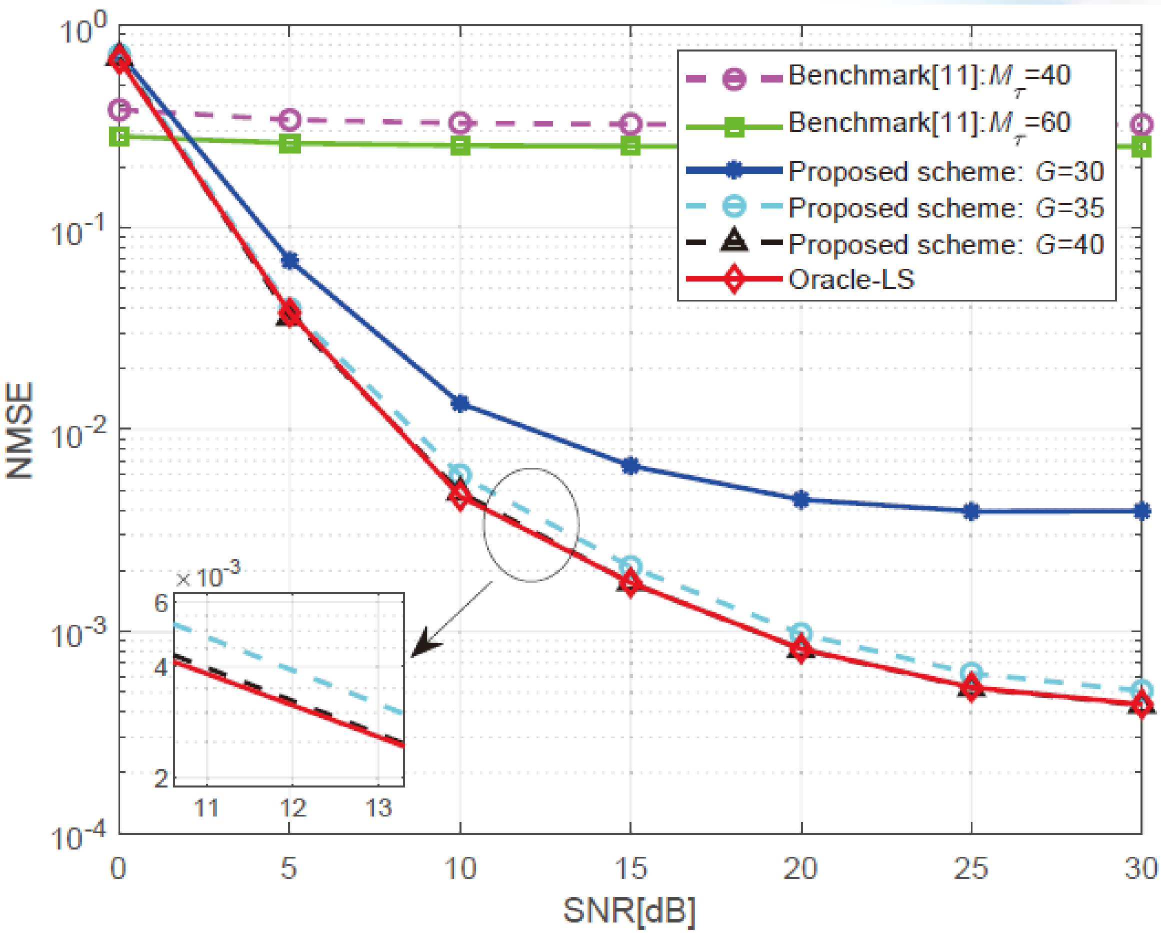
- **Access Parameters: Active IoT terminals and potential terminals are fixed as $K_a = 10$ and $K = 100$**
- **Benchmark: The embedded DD domain pilots and guard symbols are used to perform AUD and CE.**



	Benchmark	Proposed
Effective pilots	$(N, M_\tau) > (8,60)$	$(N, G) \le (8,40)$
Guard symbols	CP+$(N_g, M_g) = (0, L)$	ISI-contaminated region

Performance of CE

- **Benchmark** [Shen'19]



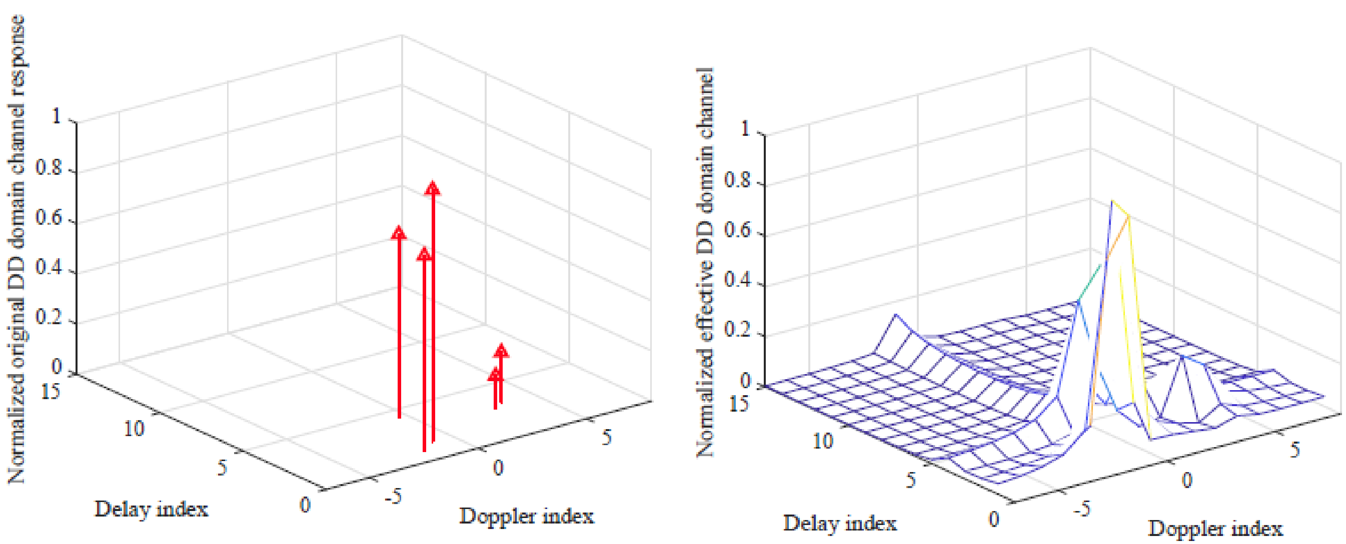
	Benchmark	Proposed
AUD	>-20dB	<-40dB
CE	>-10dB	<-30dB

The scheme which performs AUD and CE in DD domain completely fails in satellite-enabled communication environment, which also confirms that it suffers from serious performance degradation under severe Doppler shift environment.

[Shen'19] W. Shen, L. Dai, J. An, P. Fan and R. W. Heath, "Channel Estimation for Orthogonal Time Frequency Space (OTFS) Massive MIMO," ***IEEE Trans. Signal Process.***, vol. 67, no. 16, pp. 4204–4217, Aug. 2019.

Analysis

- **The Reduced Pilot Symbols Overhead**
  - Exploit the sporadic traffic and inherent sparsity of TSL channel
  - Overcome the sparsity deterioration due to the low resolution of Doppler domain
  - Make full use of multiple measurements of multiple time slots and antennas
- **The Better Performance**
  - Parametric method is used to realize super-resolution Doppler estimation



Challenges and Future Research Direction

- **The mathematic proof of the validation of the assumption and the results;**
- **The development of robust signal detection methods;**
- **The study of the more practical system;**
- **The study of the technique to reduce the peak-to-average ratio (PAPR) of OTFS.**
- **…….**

Reference

[Sanctis'16] M. De Sanctis, E. Cianca, G. Araniti, I. Bisio, and R. Prasad, "Satellite communications supporting Internet of remote things," *IEEE Internet Things J.*, vol. 3, no. 1, pp. 113–123, Feb. 2016.

[Liu'21] S. Liu, Z. Gao, Y. Wu, D. W. K. Ng, X. Gao, K. Wong, S. Chatzinotas, and B. Ottersten, "LEO satellite constellations for 5G and beyond: How will they reshape vertical domains?", *to appear in IEEE Commun. Mag.*.

[Zhang'20] Z. Zhang et al., "User Activity Detection and Channel Estimation for Grant-Free Random Access in LEO Satellite-Enabled Internet of Things," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8811-8825, Sept. 2020.

[Hadani'17] R. Hadani et al., "Orthogonal time frequency space modulation," in *Proc. IEEE Wireless Commun. Netw. Conf.,* Mar. 2017, pp. 1–6.

[Zhang'16] Z. Zhang, X. Wang, Y. Zhang, and Y. Chen, "Grant-free rateless multiple access: A novel massive access scheme for Internet of Things," *IEEE Commun. Lett.*, vol. 20, no. 10, pp. 2019–2022, Oct. 2016.

[Shen'16] W. Shen, L. Dai, J. An, P. Fan and R. W. Heath, "Channel Estimation for Orthogonal Time Frequency Space (OTFS) Massive MIMO," *IEEE Trans. Signal Process.,* vol. 67, no. 16, pp. 4204–4217, Aug. 2019.

[Roy'89] R. Roy and T. Kailath,"Esprit-estimation of signal parameters via rotational invariance techniques", *IEEE Trans. Acoust. Speech Signal Process.,* vol. ASSP-37, no. 7, pp. 984-995, Jul. 1989.

[Tropp'05] J. A. Tropp, A. C. Gilbert, and M. J. Strauss, "Simultaneous sparse approximation via greedy pursuit," in *Proc. Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, Philadelphia, PA, USA, Mar. 2005, pp. 721–724.

THANKS!