RIS-aided OTFS Modulation

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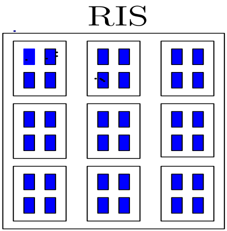
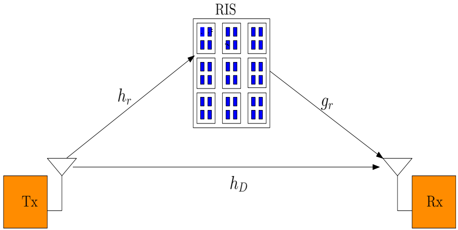
Overview

Reconfigurable intelligent surfaces (RIS)



- RIS is a planar array consisting of large number of passive low cost reflecting elements.
- Changes the reflection characteristics of incident electromagnetic wave by inducing a phase shift at every element.
- Phases at RIS are chosen in such a way that desired parameters at the receiver are optimized.

RIS-aided transmission



- Grouping into sub-surfaces
  - A set of adjacent elements with highly correlated channels are grouped into a sub-surface.
  - L such sub-surfaces.
- Both transmitter (Tx) and receiver (Rx) have single antenna each.
- h_r: Channel gain between Tx and rth sub-surface of RIS.
  g_r : Channel gain between rth sub-surface of RIS and Rx.
  h_D : Direct link channel gain between Tx and Rx.

RIS-aided transmission

- The received signal at Rx

$$y = \sqrt{E_s}(h_D + \sum_{r=1}^{L} h_r e^{\phi_r} g_r)x + n \quad (1)$$

ϕ_r : adjustable phase introduced by the rth sub-surface of the RIS
x : transmitted symbol $\in \mathbb{A}$
n : additive white Gaussian noise

- In matrix form,

$$y = \mathbf{g}^T \mathbf{\Phi} \mathbf{h} x + n \quad (2)$$

$$\mathbf{h} = [h_1 \ h_2 \ \cdots \ h_L]^T, \ \mathbf{g} = [g_1 \ g_2 \ \cdots \ g_L]^T, \ \mathbf{\Phi} = ([e^{j\phi_1} \ e^{j\phi_2} \ \cdots \ e^{j\phi_L}])$$

- Model in (2) resembles that of a precoding/beamforming system
- This 'beamforming' happens in the medium (not at Tx or Rx)

RIS-aided transmission

- Define $h_r = \alpha_r e^{j\theta_r}$, $g_r = \beta_r e^{j\psi_r}$, and $h_D = \varepsilon e^{j\eta}$
- Instantaneous SNR at the receiver is

$$\text{SNR} = \frac{E_s \left| \sum_{r=1}^{L} \alpha_r \beta_r e^{j(\phi_r + \theta_r + \psi_r)} + \varepsilon e^{j\eta} \right|^2}{\sigma^2}$$

- RIS is assumed to be controlled by a smart controller having the knowledge of the phases of channel coefficients.
- SNR at the receiver can be maximized by adjusting the reflection phases at the RIS, $\phi_r = (-\theta_r - \psi_r + \eta)$.
- Detection at the receiver is carried out using ML detection.

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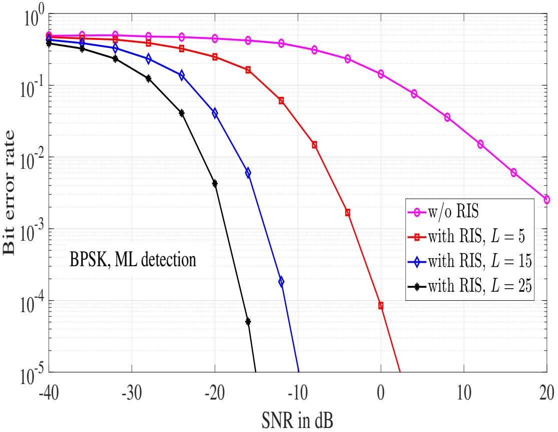
[1] L. Yang, F. Meng, M. O. Hasna, and E. Basar, "A novel RIS-assisted modulation scheme," *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1359–1363, Jun. 2021

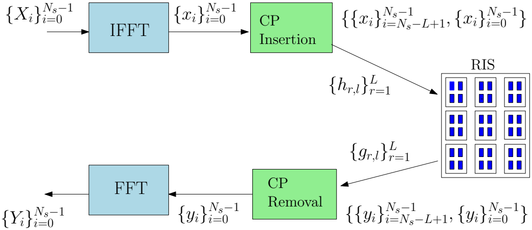
[2] E. Basar, M. D. Renzo, J. de Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753-116773, Aug. 2019.

BER performance of RIS-aided communication



- Performance improves with the aid of RIS.
- Performance improvement is more for large L.

RIS-aided OFDM



- Transmitted OFDM symbol in frequency domain $\mathbf{x} \triangleq [X_0, X_1, \cdots, X_{N_s-1}]^T$, N_s: no. of sub-carriers.
- $h_{r,l}$: lth tap channel gain of Tx-RIS link associated with rth sub-surface.
  $g_{r,l}$: lth tap channel gain of RIS-Rx link associated with rth sub-surface.
- Received OFDM symbol in frequency domain $\mathbf{y} \triangleq [Y_0, Y_1, ..., Y_{N_s-1}]^T$.

RIS-aided OFDM

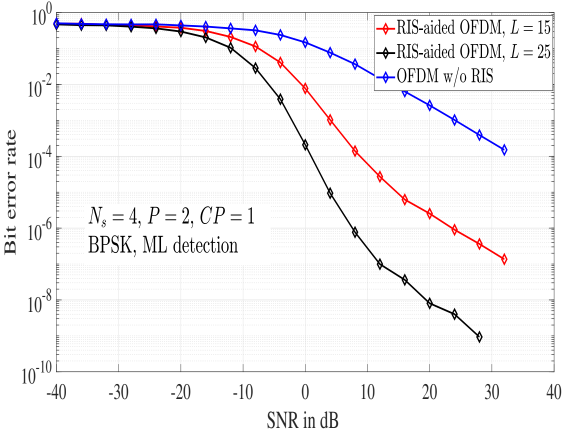
- End-to-end frequency domain input-output relation:

$$\mathbf{y} = \mathbf{X}\left(\sum_{r=1}^{L} \mathbf{q}_r \phi_r \odot \mathbf{b}_r\right) + \mathbf{n},$$

  where
  - $\mathbf{q}_r \in \mathbb{C}^{N_s \times 1}$: channel frequency response of Tx-RIS link associated with rth sub-surface.
  - $\mathbf{b}_r \in \mathbb{C}^{N_s \times 1}$: channel frequency response of RIS-Rx link associated with rth sub-surface.
  - $\odot$: Hadamard product.
  - $\mathbf{X} \triangleq \text{diag}(\mathbf{x})$.
- Reflection phases $(\phi_r,\ r = 1 \cdots, L)$ that maximize the rate are chosen.

[3] B. Zheng and R. Zhang, "Intelligent reflecting surface-enhanced OFDM: channel estimation and reflection optimization," *IEEE Wireless Commun. Lett.*, vol. 9, no. 4, pp. 518-522, Apr. 2020.

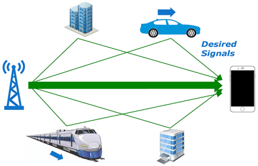
Performance of RIS-aided OFDM

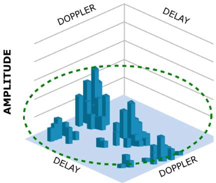


- Performance of OFDM improves with the aid of RIS.

Orthogonal Time Frequency Space (OTFS) modulation

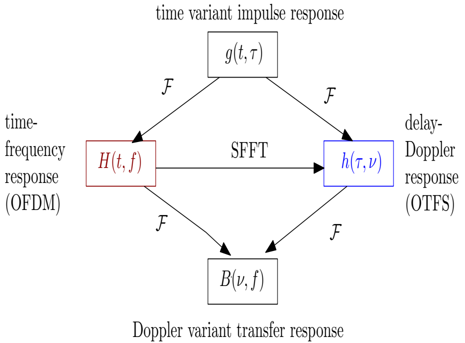
- A promising modulation scheme for doubly-selective channels
- Channel is viewed/represented in DD domain
- Information is multiplexed in the delay-Doppler (DD) domain
  - Map information from DD domain to time domain and transmit
  - Two-step transformation: DD domain → TF domain → time domain
- Superior performance compared to OFDM



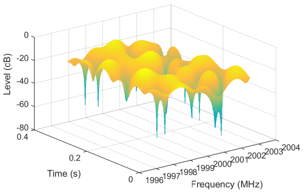


[5] R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch, and R. Calderbank, "Orthogonal time frequency space modulation," in *Proc. IEEE WCNC*, San Francisco, CA, USA, March 2017.

Channel representation in DD domain

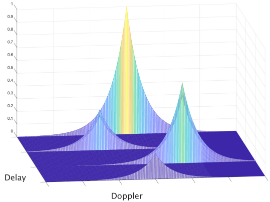


- $h(\tau,\nu)$ representation
  - τ: determined by relative distance
  - ν: determined by relative velocity
- τ,ν are time-invariant for long
- $h(\tau,\nu)$: slowly-varying, sparse
- $h(\tau,\nu)=\sum_{i=1}^{P} h_i\delta(\tau-\tau_i)\delta(\nu-\nu_i)$

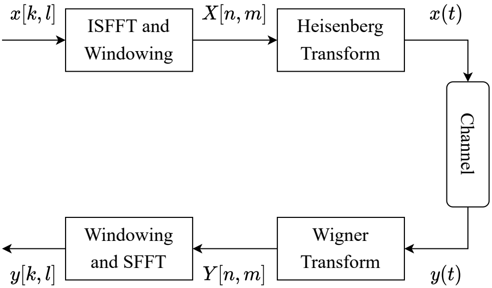


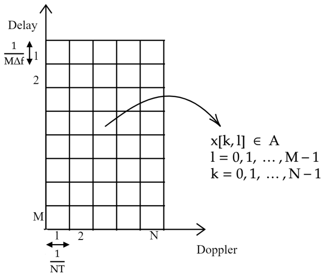
SFFT →

← ISFFT



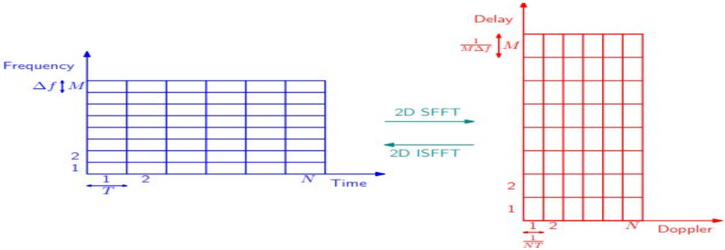
OTFS - Signaling in DD domain





Time-Frequency grid

Delay-Doppler grid



Input-output relation

- Received signal in DD domain (for $\tau_i \triangleq \frac{\alpha_i}{M\Delta f}$, $\nu_i \triangleq \frac{\beta_i}{NT}$, α_i, β_i: integers)

$$y[k,l] = \sum_{i=1}^{P} h'_i \, x[(k-\beta_i)_N, (l-\alpha_i)_M] + v[k,l]$$

where $h'_i = h_i e^{-j2\pi\nu_i\tau_i}$, $h_i \sim \mathcal{CN}(0, 1/P)$.

- The DD domain input-output relation can be vectorized as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{v},$$

where $x_{k+Nl} = x[k,l]$, $y_{k+Nl} = y[k,l]$, $v_{k+Nl} = v[k,l]$,

$\mathbf{H} \in \mathbb{C}^{MN\times MN}$: jth row ($j = k + Nl$) of $\mathbf{H}$ is

$$\mathbf{H}[j] = [\hat{h}((k-0)_N, (l-0)_M) \;\; \hat{h}((k-1)_N, (l-0)_M) \;\; \cdots \hat{h}((k-N-1)_N, (l-M-1)_M)],$$

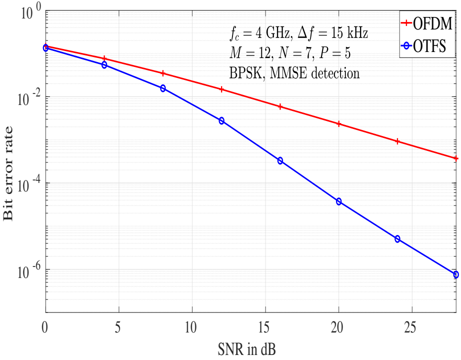
$$\hat{h}(k,l) = \begin{cases} h'_i & \text{if } k = \beta_i \ \& \ l = \alpha_i \text{ for some } i \in \{1, \cdots, P\} \\ 0 & \text{otherwise.} \end{cases}$$

  - $\mathbf{H}$ is block circulant with circulant blocks (P non-zeros in each row)

[6] P. Raviteja, K. T. Phan, and E. Viterbo, "Interference cancellation and iterative detection for orthogonal time frequency space modulation," *IEEE Trans. Wireless Commun.*, vol. 17, no. 10, pp. 6501-6515, Oct. 2018.

OTFS performance

- OTFS vs OFDM performance



Parameter	Value
Carrier frequency (GHz)	4
Subcarrier spacing (kHz)	15
Frame size (M, N)	$(12, 7)$
Number of paths (P)	5
Delay profile	Exponential
Maximum speed (km/h)	500
Maximum Doppler (Hz)	1875
Modulation scheme	BPSK

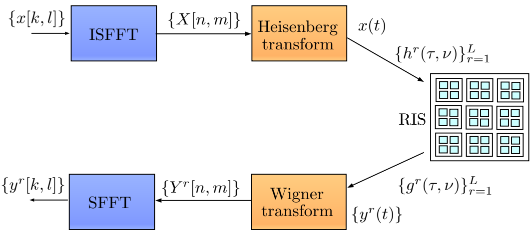
* Smallest resource block used in LTE: $M = 12$, $N = 7$

- MMSE detection

- OFDM performs poor due to Doppler-induced ICI
- OTFS performs significantly better than OFDM

[7] G. D. Surabhi, R. M. Augustine, and A. Chockalingam, "On the diversity of uncoded OTFS modulation in doubly-dispersive channels," *IEEE Trans. Wireless Commun.*, vol. 18, no. 6, pp. 3049-3063, Jun. 2019.

RIS-aided OTFS



- *DD domain to TF domain conversion using ISFFT :*

$$X[n,m] = \frac{1}{\sqrt{MN}} \sum_{k=0}^{N-1} \sum_{l=0}^{M-1} x[k,l] e^{j2\pi\left(\frac{nk}{N} - \frac{ml}{M}\right)}$$

- *Transmitted time-domain signal :*

$$x(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X[n,m] g_{tx}(t-nT) e^{j2\pi m\Delta f(t-nT)}$$

$g_{tx}(t)$: transmit pulse

RIS-aided OTFS

- Tx to RIS channel (associated with rth sub-surface)

$$h^r(\tau,\nu)=\sum_{p=1}^{P_1} h_p^r \delta(\tau-\tau_p^{r,1})\delta(\nu-\nu_p^{r,1})$$

- Signal received at rth sub-surface of RIS

$$z^r(t)=\int_\nu\int_\tau h^r(\tau,\nu)x(t-\tau)e^{j2\pi\nu(t-\tau)}d\tau d\nu$$

- Time-domain signal at Rx (reflected from rth sub-surface of RIS)

$$y^r(t)=\phi_r\int_{\nu_2}\int_{\tau_2} g^r(\tau_2,\nu_2)z^r(t-\tau_2)e^{j2\pi\nu_2(t-\tau_2)}d\tau_2 d\nu_2$$

- Here, $\phi_r=\gamma_r e^{j\theta_r}$ is the reflection coefficient
  - γ_r : reflection amplitude of rth sub-surface
  - θ_r : reflection phase of rth sub-surface

Demodulation at OTFS receiver

- *Wigner transform* : time domain to TF domain

$$Y^r(t,f) = \int_{t'} g^*_{rx}(t'-t) y^r(t') e^{-j2\pi f(t'-t)} dt'$$

$$Y^r[n,m] = Y^r(t,f)|_{t=nT, f=m\Delta f}$$

$g_{rx}(t)$: receive pulse.

- *TF domain input-output relation :*

$$Y^r[n,m] = \phi_r \sum_{n'=0}^{N-1} \sum_{m'=0}^{M-1} H^r_{n,m}[n',m'] X[n',m']$$

- In $H^r_{n,m}[n',m']$, a term of cross-ambiguity function $A_{g_{rx},g_{tx}}\Big((n-n')T - (\tau_1+\tau_2), (m-m')\Delta f - (\nu_1+\nu_2)\Big)$ is present.

$$A_{g_{rx},g_{tx}}(t,f) = \int_{t'} g^*_{rx}(t'-t) g_{tx}(t') e^{-j2\pi f(t'-t)} dt'$$

Demodulation at OTFS receiver

- For ideal pulses,

$$A_{g_{rx},g_{tx}}(t,f) = \begin{cases} 1, & n=0, m=0 \\ 0, & \text{otherwise}, \end{cases}$$

for $t \in (nT - \tau_{max}, nT + \tau_{max})$ and $f \in (m\Delta f - \nu_{max}, m\Delta f + \nu_{max})$

- Assuming ideal pulses, TF domain input-output relation :

$$Y^r[n,m] = \phi_r H^r_{n,m}[n,m]X[n,m]$$

- *SFFT*: TF domain to DD domain

$$y^r[k,l] = \frac{1}{\sqrt{MN}} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} Y^r[n,m] e^{-j2\pi(\frac{nk}{N} - \frac{ml}{M})}$$

DD domain input-output relation

- The derived input-output relation in DD domain:

$$y^r[k,l] = \phi_r \sum_{q=1}^{P_2} g_q^r e^{-j2\pi\nu_q^{r,2}\tau_q^{r,2}} \sum_{p=1}^{P_1} h_p^r e^{-j2\pi\nu_p^{r,1}(\tau_p^{r,1}+\tau_q^{r,2})}$$
$$x[[k-(\beta_p^{r,1}+\beta_q^{r,2})]_N, [l-(\alpha_p^{r,1}+\alpha_q^{r,2})]_M],$$

$\tau_p^{r,1} \triangleq \frac{\alpha_p^{r,1}}{M\Delta f}$, $\nu_p^{r,1} \triangleq \frac{\beta_p^{r,1}}{NT}$, $\tau_q^{r,2} \triangleq \frac{\alpha_q^{r,2}}{M\Delta f}$, and $\nu_q^{r,2} \triangleq \frac{\beta_q^{r,2}}{NT}$.

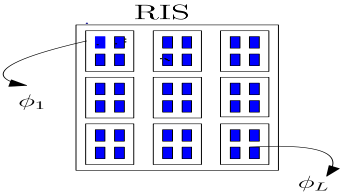
- $\alpha_p^{r,1}, \beta_p^{r,1}, \alpha_q^{r,2}$, and $\beta_q^{r,2}$ are assumed to be integers.
- *Vectorized input-output relation:*

$$\mathbf{y} = \sum_{r=1}^{L} \phi_r \mathbf{H}^r \mathbf{x} + \mathbf{v},$$

$\mathbf{y}, \mathbf{x} \in \mathbb{C}^{MN\times 1}$, the $(k+Nl)$th entry of $\mathbf{x}$, $x_{k+Nl} = x[k,l]$
$\mathbf{H}^r \in \mathbb{C}^{MN\times MN}$: effective cascaded channel matrix for rth sub-surface.

[8] G. Harshavardhan, V. S. Bhat, and A. Chockalingam, "RIS-aided OTFS modulation in high-Doppler channels," *accepted in IEEE PIMRC'2022,* Sep. 2022.

Reflection phase design



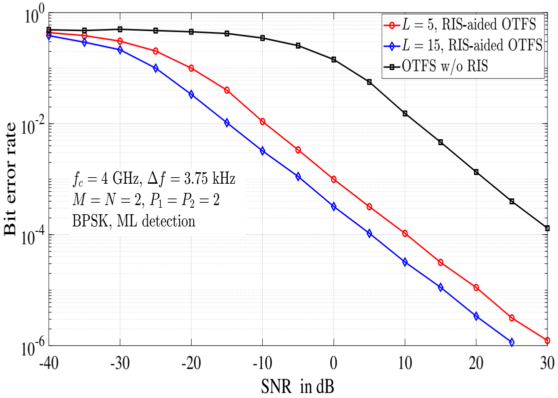
- We fix $\gamma_r = 1$, and choose $\theta_r \in [-\pi, \pi]$.
- We choose $\mathbf{\Theta} = [\theta_1\, \theta_2\, \cdots\, \theta_L]$ that maximizes $\| \sum_{r=1}^{L} e^{j\theta_r} \mathbf{H}^r \|^2$.
- *Approximate solution:*
  - Multiple random phase vector realizations are generated.
  - ith realization : $\mathbf{\Theta}^i = [\theta_1^i\, \theta_2^i\, \cdots\, \theta_L^i]$, θ_r^i : uniformly distributed in $[-\pi, \pi]$.
  - Choose $\mathbf{\Theta}^{i^*}$ where $i^* = \arg\max_i \{\| \sum_{r=1}^{L} e^{j\theta_r^i} \mathbf{H}^r \|^2\}$.

Simulation setting

Parameter	Value
Frame size (M, N)	(2, 2)
DD (τ_i, ν_i) profile for 2 paths	$(0,0)$, $(\frac{1}{M\Delta f}, \frac{1}{NT})$
DD (τ_i, ν_i) profile for 4 paths	$(0,0)$, $(0, \frac{1}{NT})$, $(\frac{1}{M\Delta f}, 0)$, $(\frac{1}{M\Delta f}, \frac{1}{NT})$
Maximum speed	506.25 km/h
Modulation	BPSK

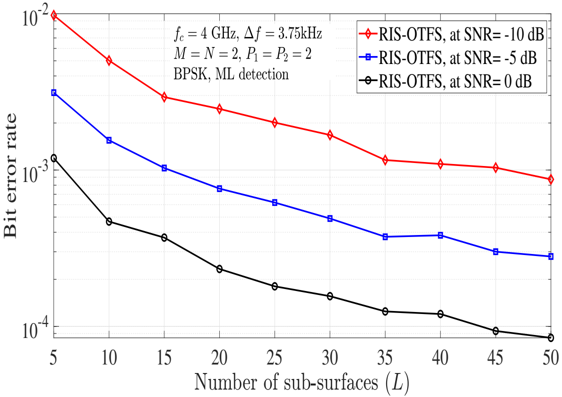
- Carrier frequency f_c : 4 GHz
- Maximum Doppler : 1.875 kHz
- Sub-carrier spacing : 3.75 kHz

Performance of OTFS w/o RIS and RIS-aided OTFS



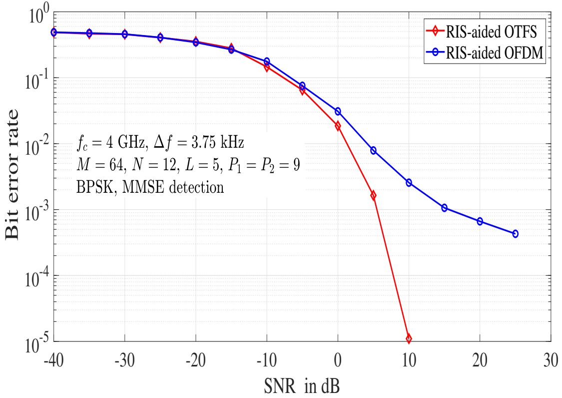
- OTFS performance improves with aid of RIS
- Increased performance gain with increased number of sub-surfaces

Effect of number of sub-surfaces L on BER



- Performance gain improves with increase in the number of sub-surfaces.

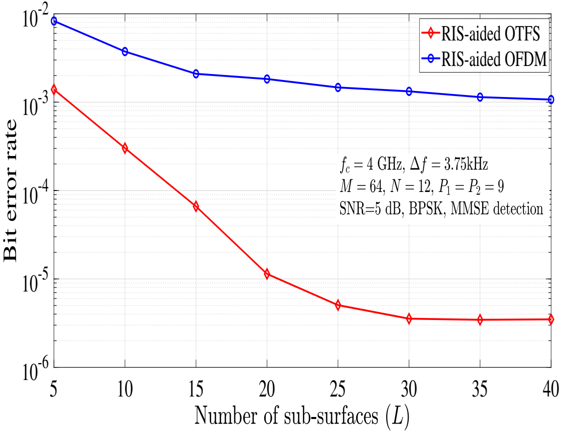
RIS-aided OTFS vs RIS-aided OFDM



- Power-delay profile : Extended vehicular A (EVA) model.
- ith path Doppler shift $(\nu_i) = \nu_{max} \cos\theta$, $\nu_{max} = 1.34$ KHz.

[9] *Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) Radio Transmission and Reception, Version 14.3.0, Release 14*, document TS 36.104, 3GPP, Apr. 2017.

Effect of number of sub-surfaces on BER



- BER performance gap between RIS-OTFS and RIS-OFDM at $L = 5$ is one order.
- At $L = 20$, it is three orders.

Concluding remarks

- RIS and OTFS are promising technologies for 6G and beyond
  - RIS $\rightarrow$ energy efficient communication
  - OTFS $\rightarrow$ high-mobility support and radar sensing
  - RIS-aided OTFS $\rightarrow$ offers the benefit of both
- RIS-OTFS research
  - in early stages and promising
  - derived end-to-end input-output relation can trigger algorithm development/performance evaluation related work for RIS-OTFS
  - phase design optimization, channel estimation can be studied
  - scope for more research

Thank you