Multi-RIS-Assisted High-Speed Communication System with Doppler Mitigation and Hardware Impairments

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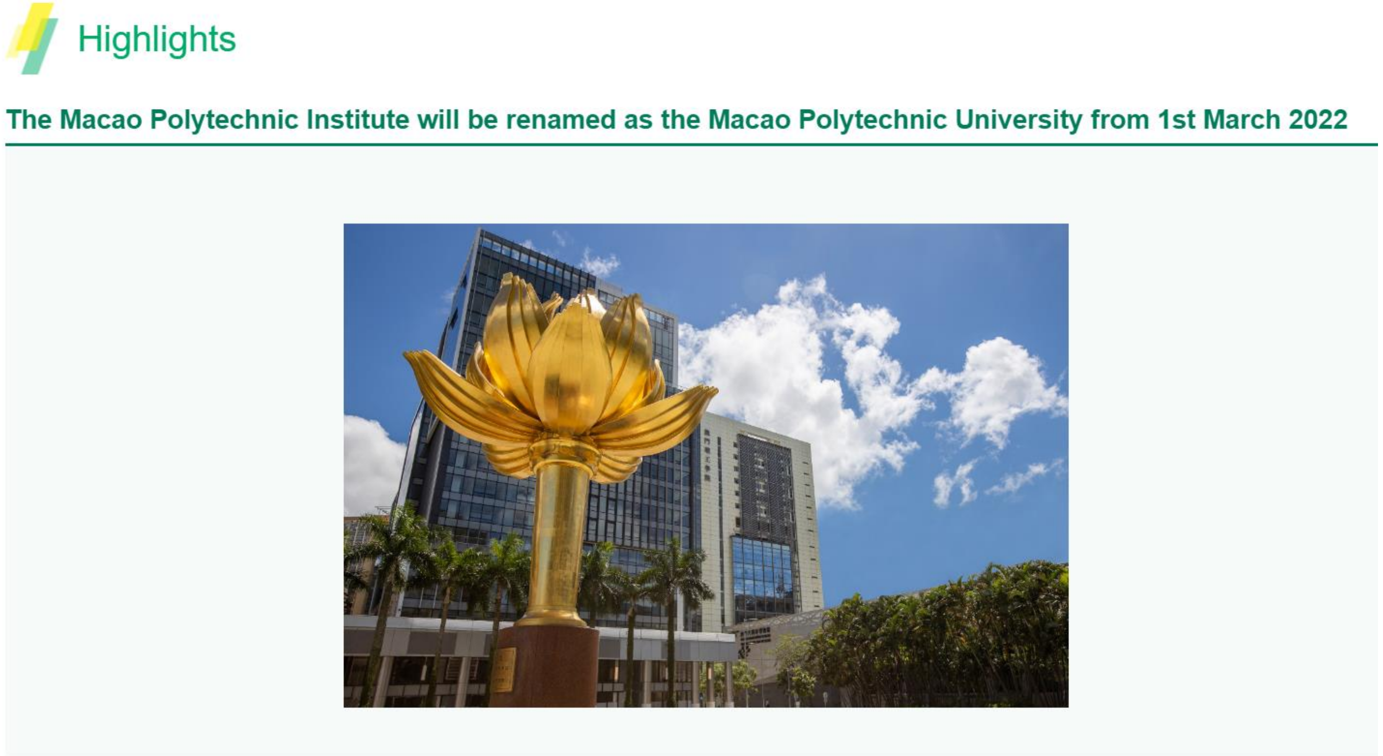

Highlights

The Macao Polytechnic Institute will be renamed as the Macao Polytechnic University from 1st March 2022

Macao Polytechnic Institute → Macao Polytechnic University

School of Applied Sciences → Faculty of Applied Sciences

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Outline

☐ Part 1: Introduction and Motivation

- ➢ Introduction of Reconfigurable Intelligent Surfaces (RIS)
- ➢ Motivation of Using RIS in High-Speed Communication

☐ Part 2: Multi-RIS-Assisted High-Speed Communication

- ➢ Abstract and System Model
- ➢ Doppler Mitigation, Phase Optimization, and Deployment
- ➢ Spectral and Energy Efficiency
- ➢ Simulation Results

☐ Part 3: Conclusions and Future Research Directions

Part 1

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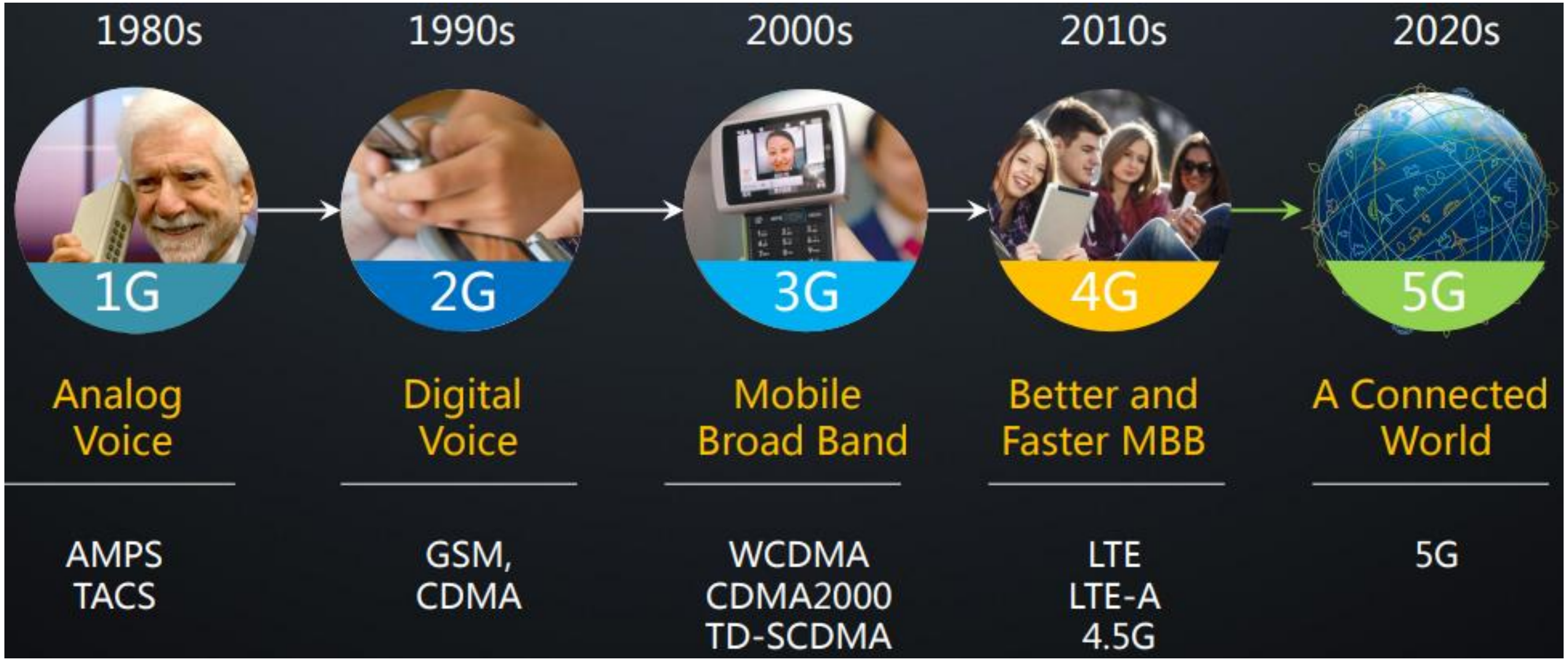
5G Era is Coming



[1]

☐ Ultra-Dense Network (UDN).
☐ Multiple-Input Multiple-Output (MIMO).
☐ millimeter Wave (mmWave).
☐ …

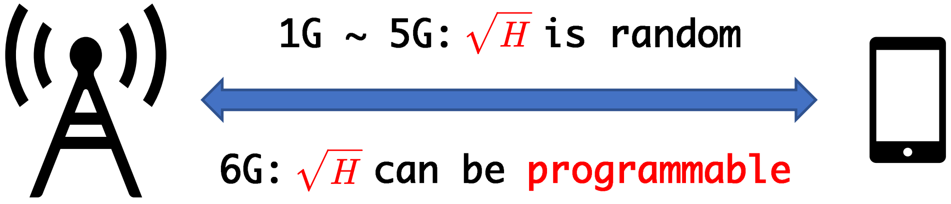
[2]

☐ Energy Consumptions.
☐ Hardware Costs.
☐ …

What is New in 6G?

- Promising 6G Paradigm: Smart Radio Environments (SRE).
- SRE: An electromagnetic environment that is generated by nature but is programmable and controllable by our design.

$$C=\log_2\left(1+\frac{(\sqrt{H})^2 P}{\sigma^2}\right)$$



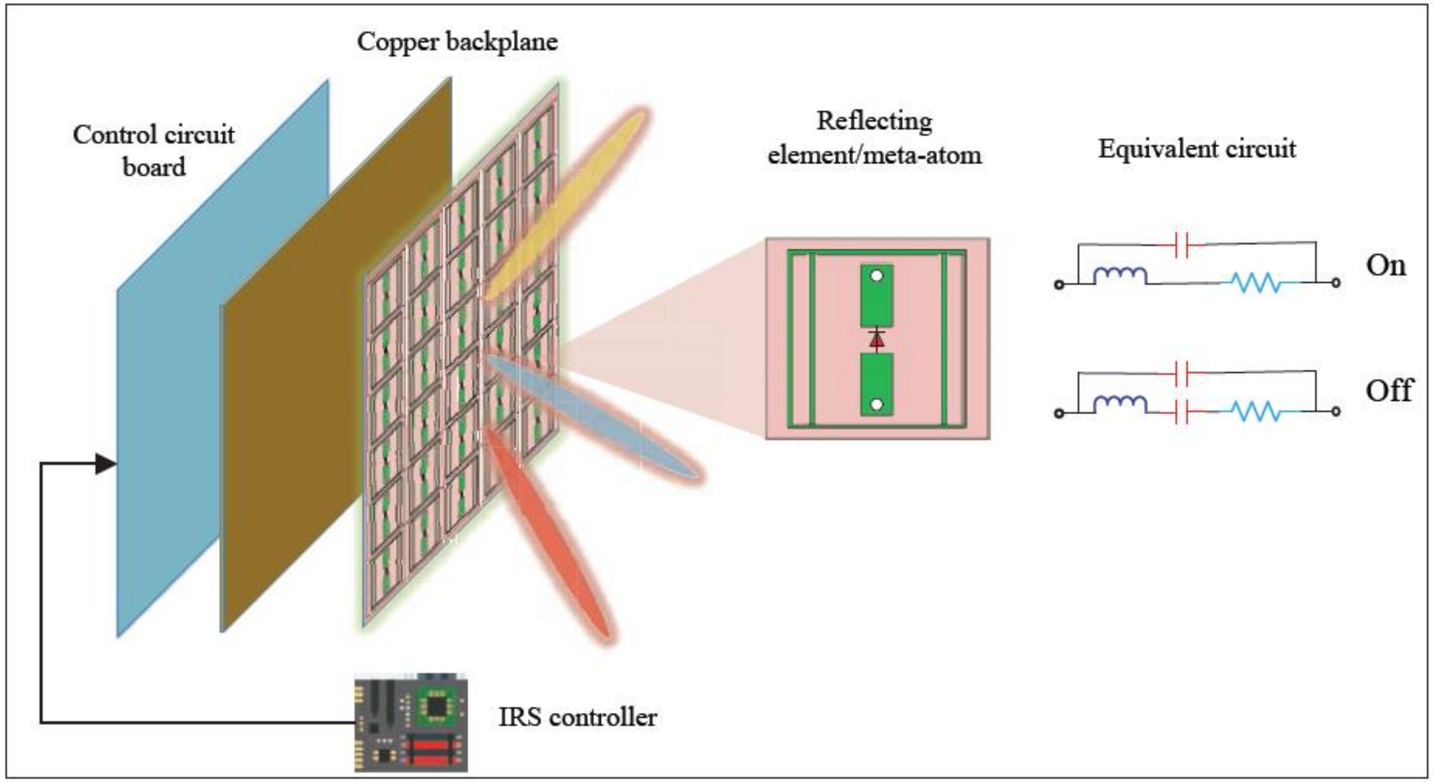
1G ~ 5G: $\sqrt{H}$ is random

6G: $\sqrt{H}$ can be programmable

[3]

- Key Technology: Reconfigurable Intelligent Surfaces (RIS).
  - Reconfigurable: can be redesigned.
  - Intelligent: inexpensive adaptive.
  - Surfaces: not necessarily planar.

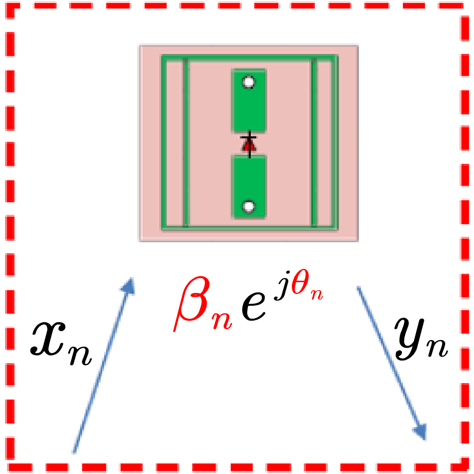
What is RIS?



[4]

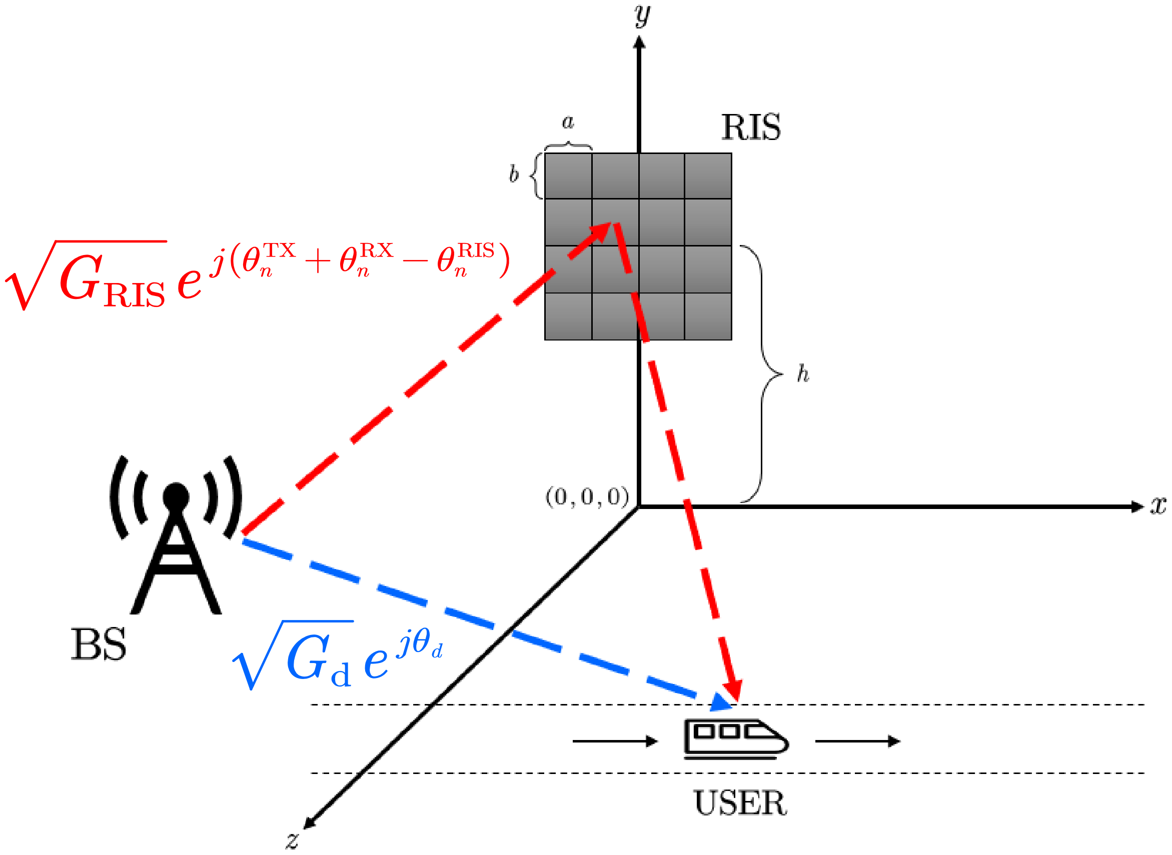
$$y_n = x_n \overbrace{\beta_n e^{j\theta_n}}^{\text{We can control } \sqrt{H}}$$

Where $\beta_n \in [0,1]$, $\theta_n \in [0,2\pi]$,
and $n = 1, \ldots, N$.



- RIS is a kind of metal surface that is made up of many sub-wavelength passive reflecting elements, each of which can cause amplitude and/or phase shift on the incident signal, in real-time, independently.

An RIS-Assisted Communication Model



$$\overbrace{y = \Big(\underbrace{\sqrt{G_{\mathrm{d}}}\,e^{j\theta_d}}_{\text{Dirct path}} + \overbrace{\sum_{n=1}^{N} \sqrt{G_{\mathrm{RIS}}}\,e^{j(\theta_n^{\mathrm{TX}}+\theta_n^{\mathrm{RX}}-\theta_n^{\mathrm{RIS}})}}^{\text{RIS(Cascaded)path}} \Big)}^{\sqrt{H}} x + w$$

$$\Downarrow$$

$$\mathrm{SNR} = \frac{P}{\sigma^2}\left|\sqrt{G_{\mathrm{d}}}\,e^{j\theta_d} + \sum_{n=1}^{N}\sqrt{G_{\mathrm{RIS}}}\,e^{j(\theta_n^{\mathrm{TX}}+\theta_n^{\mathrm{RX}}-\theta_n^{\mathrm{RIS}})}\right|^2$$

$$\leq \frac{P}{\sigma^2}\left|\sqrt{G_{\mathrm{d}}} + N\sqrt{G_{\mathrm{RIS}}}\right|^2$$

$$\Downarrow$$

We need to set $\theta_d = \theta_n^{\mathrm{TX}} + \theta_n^{\mathrm{RX}} - \underbrace{\theta_n^{\mathrm{RIS}}}_{\text{We can control!}}$,

i.e., $\theta_n^{\mathrm{RIS}} = \theta_n^{\mathrm{TX}} + \theta_n^{\mathrm{RX}} - \theta_d$

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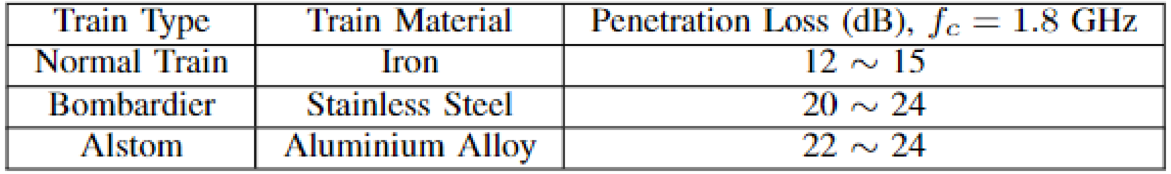
Main Issues of High-Speed Communications

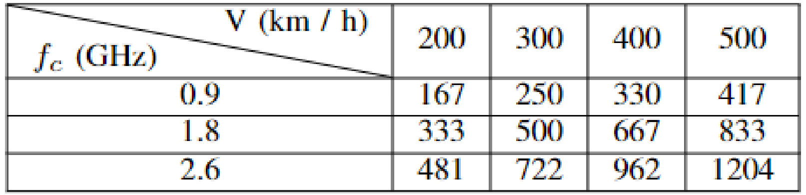
☐ Significant Signal Penetration Losses.
☐ Time-Varying Channel Modeling.
☐ Time-Varying Channel Estimation.
☐ Doppler Effect Compensation.
☐ Blockages of LoS Channel.
☐ …

Table. 1 The penetration loss (dB) of typical high-speed trains [5]



Train Type	Train Material	Penetration Loss (dB), $f_c = 1.8$ GHz
Normal Train	Iron	$12 \sim 15$
Bombardier	Stainless Steel	$20 \sim 24$
Alstom	Aluminium Alloy	$22 \sim 24$

Table. 2 Maximum Doppler shift (Hz) at different carrier frequency and speeds [6]

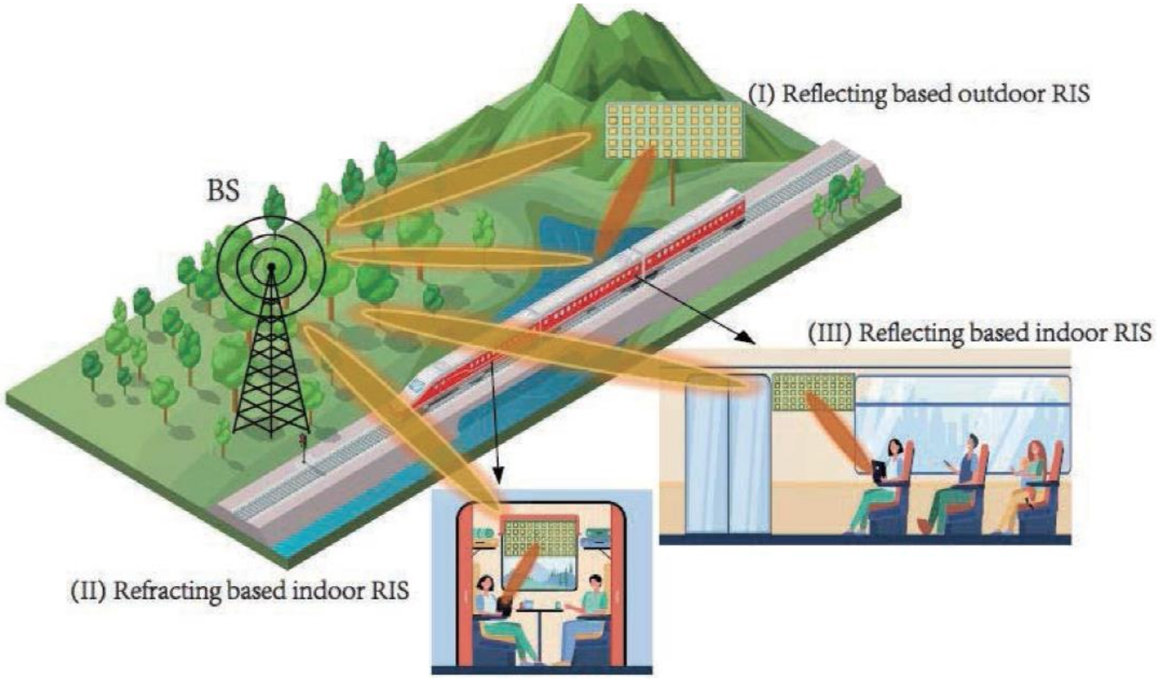


V (km / h) f_c (GHz)	200	300	400	500
0.9	167	250	330	417
1.8	333	500	667	833
2.6	481	722	962	1204

Alstom high-speed train on the Gotthard railway [7]

RIS Can Help High-Speed Communications

- ☐ Increase signal gain and reduce the penetration loss.
- ☐ Combat the blockage of communications.
- ☐ Solve the Doppler effect and multipath fading problems.
- ☐ Bring high energy efficiency.
- ☐ …



[8]

Hardware Impairments in RIS-Assisted High-Speed Communications

- The 1st kind: RIS Hardware Impairments (intrinsic hardware imperfection, imperfect CSI, quantization error, etc.).

- The 2nd kind: Transceivers Hardware Impairments (additive distortion noise, phase drift, amplified thermal noise, etc.).

- The 3rd Kind: Hardware Aging (time-related hardware degradation).

- …

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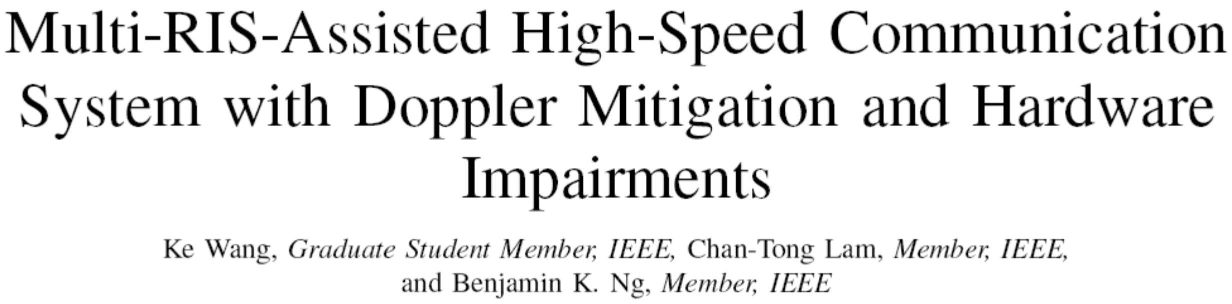
Abstract



Multi-RIS-Assisted High-Speed Communication System with Doppler Mitigation and Hardware Impairments

Ke Wang, *Graduate Student Member, IEEE,* Chan-Tong Lam, *Member, IEEE,*
and Benjamin K. Ng, *Member, IEEE*

Submitted to IEEE Transaction on Vehicular Technology, under view.

- The main concept of this paper is that we use multiple RISs to explore their potential for Doppler mitigation and spectral/energy efficiency enhancement.
  - We present a general multi-RIS-assisted system model for HSC with HWI;
  - We obtain a phase shift set that can maximize SE, remove Doppler spread, and keep delay spread at a very low level;
  - We derive a closed-form expression of SE and obtain an optimal transmit power that can maximize energy efficiency;
  - We compare performances of the single and multiple RISs.

System Model(1/4): General Setting

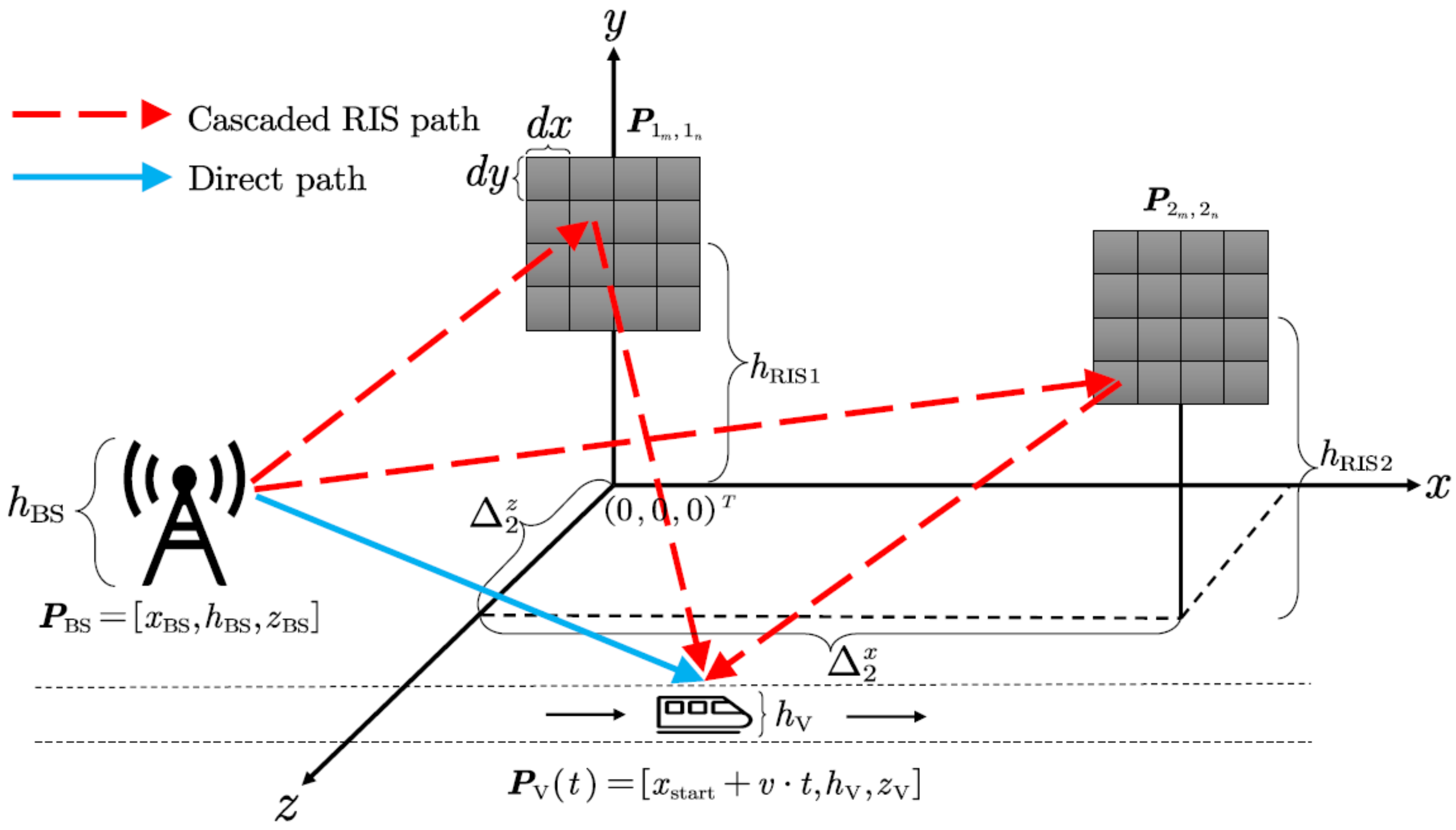
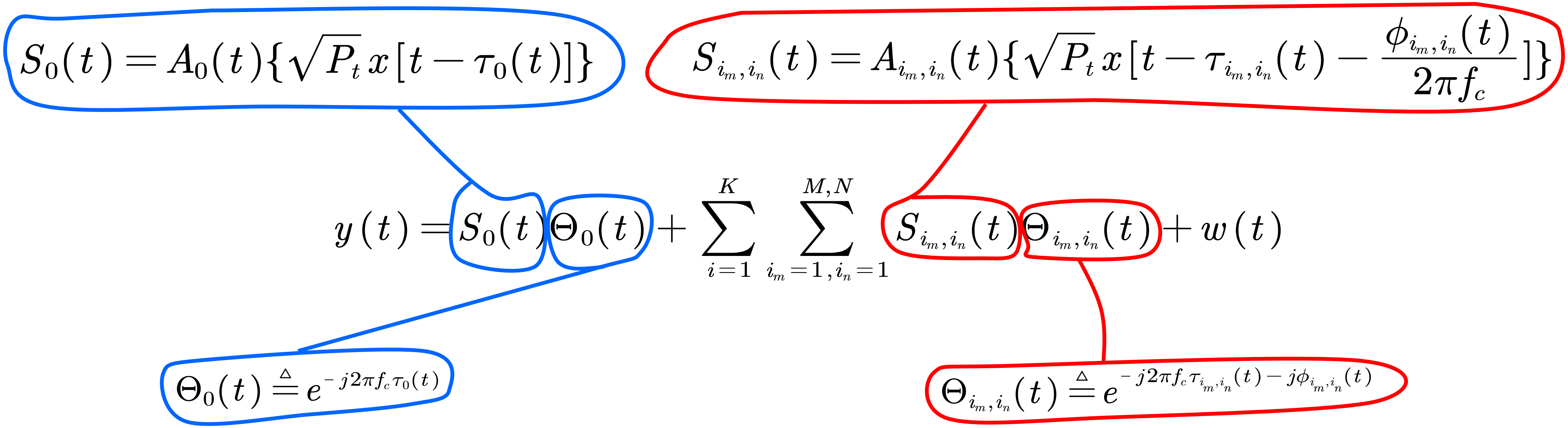


Fig. 1. A multi-RIS-assisted high-speed communication system. $K = 2$.

System Model (2/4): without HWI



$$S_0(t)=A_0(t)\{\sqrt{P_t}\,x[t-\tau_0(t)]\}$$

$$S_{i_m,i_n}(t)=A_{i_m,i_n}(t)\{\sqrt{P_t}\,x[t-\tau_{i_m,i_n}(t)-\frac{\phi_{i_m,i_n}(t)}{2\pi f_c}]\}$$

$$y(t)=S_0(t)\Theta_0(t)+\sum_{i=1}^{K}\sum_{i_m=1,i_n=1}^{M,N}S_{i_m,i_n}(t)\Theta_{i_m,i_n}(t)+w(t)$$

$$\Theta_0(t)\triangleq e^{-j2\pi f_c\tau_0(t)}$$

$$\Theta_{i_m,i_n}(t)\triangleq e^{-j2\pi f_c\tau_{i_m,i_n}(t)-j\phi_{i_m,i_n}(t)}$$

○ Direct Link

○ Cascaded Link

System Model (3/4): Two Kinds of HWIs

☐ RIS Hardware Impairments (intrinsic hardware imperfection, imperfect CSI, quantization error, etc.)

$$\Lambda_{i_m,i_n}(t) \triangleq e^{j\gamma_{i_m,i_n}(t)} \quad \text{where} \quad \gamma_{i_m,i_n}(t) \sim \mathcal{U}[-a_{\mathrm{HWI}}, a_{\mathrm{HWI}}]$$

☐ Transceivers Hardware Impairments (additive distortion noise, amplified thermal noise, etc.)

$$\eta_t(t) \sim \mathcal{CN}(0, \Upsilon_t), \qquad \eta_r(t) \sim \mathcal{CN}(0, V_r),$$

where Υ_t is the transmit power. where V_r is the received power.

System Model (4/4): with HWI

$$S_0^{\text{HWI}}(t) = A_0(t)\{\sqrt{P_t}\,x[t-\tau_0(t)] + \eta_t(t)\}$$

$$\Theta_0(t) \triangleq e^{-j2\pi f_c \tau_0(t)}$$

$$\Lambda_{i_m,i_n}(t) \triangleq e^{j\gamma_{i_m,i_n}(t)}$$

$$y^{\text{HWI}}(t) = S_0^{\text{HWI}}(t)\Theta_0(t) + \sum_{i=1}^{K}\sum_{i_m=1,i_n=1}^{M,N} S_{i_m,i_n}^{\text{HWI}}(t)\Theta_{i_m,i_n}(t)\Lambda_{i_m,i_n}(t) + \eta_r(t) + w(t)$$

$$\Theta_{i_m,i_n}(t) \triangleq e^{-j2\pi f_c \tau_{i_m,i_n}(t) - j\phi_{i_m,i_n}(t)}$$

$$S_{i_m,i_n}^{\text{HWI}}(t) = A_{i_m,i_n}(t)\{\sqrt{P_t}\,x[t-\tau_{i_m,i_n}(t) - \frac{\phi_{i_m,i_n}(t) - \gamma_{i_m,i_n}(t)}{2\pi f_c}] + \eta_t(t)\}$$

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Delay Spread

- The delay spread of the i-th RIS is the maximum difference in propagation time overall the two significant transmission paths, i.e.,

$$T_i(t) = \max\{T_{0i}(t), T_{\mathrm{RIS}i}(t)\},$$

where $T_{0i}(t) = \max\limits_{i_m, i_n}\{\tau_{i_m,i_n}(t) + \frac{\phi_{i_m,i_n}(t) - \gamma_{i_m,i_n}(t)}{2\pi f_c}\} - \tau_0(t)$ and

$$T_{\mathrm{RIS}i}(t) = \max_{i_m, i_n}\{\tau_{i_m,i_n}(t) + \frac{\phi_{i_m,i_n}(t) - \gamma_{i_m,i_n}(t)}{2\pi f_c}\} - \min_{i_{m'}, i_{n'}}\{\tau_{i_{m'},i_{n'}}(t) + \frac{\phi_{i_{m'},i_{n'}}(t) - \gamma_{i_{m'},i_{n'}}(t)}{2\pi f_c}\}.$$

- Therefore, at time t, the delay spread for the K RISs is

$$T(t) = \max_i\{T_i(t)\}, \quad i = 1, 2, \ldots, K.$$

Doppler Spread

- The Doppler spread of the i-th RIS is the maximum difference in instantaneous frequency overall the two significant transmission paths, i.e.,

$$D_i(t) = \max\{D_{0i}(t), D_{\mathrm{RIS}\,i}(t)\},$$

where $D_{0i}(t) = f_c \max_{i_m, i_n} \left| \frac{d}{dt}\left(\tau_{i_m,i_n}(t) + \frac{\phi_{i_m,i_n}(t) - \gamma_{i_m,i_n}(t)}{2\pi f_c}\right) - \frac{d}{dt}\tau_0(t) \right|$ and

$$D_{\mathrm{RIS}\,i}(t) = f_c \max_{i_m, i_n, i_{m'}, i_{n'}} \left| \frac{d}{dt}\left(\tau_{i_m,i_n}(t) + \frac{\phi_{i_m,i_n}(t) - \gamma_{i_m,i_n}(t)}{2\pi f_c}\right) - \frac{d}{dt}\left(\tau_{i_{m'},i_{n'}}(t) + \frac{\phi_{i_{m'},i_{n'}}(t) - \gamma_{i_{m'},i_{n'}}(t)}{2\pi f_c}\right) \right|.$$

- Therefore, at time t, the Doppler spread for the K RISs is

$$D(t) = \max_i \{D_i(t)\}, i = 1, 2, \ldots, K.$$

Doppler Shift

- The Doppler shift for the direct link is

$$DS_0(t) = -f_c \frac{d}{dt}\{\tau_0(t)\}.$$

- The Doppler shift for the i-th RIS link is

$$DS_i(t) = -\max_i\{|DS_{i_{m,n}}(t)|\}, \quad i = 1, 2, \ldots, K,$$

where $DS_{i_{m,n}}(t) = -f_c \frac{d}{dt}\{\tau_{i_m,i_n}(t) + \frac{\phi_{i_m,i_n}(t) - \gamma_{i_m,i_n}(t)}{2\pi f_c}\}.$

- Therefore, at time t, the Doppler shift for the K RISs is

$$DS(t) = -\max_i\{|DS_0(t)|, |DS_i(t)|\}, \quad i = 1, 2, \ldots, K.$$

Phase Optimization (1/4)

- The optimal phase shift should be designed to align the phases of direct and cascaded link, then we have

$$\phi_{i_m,i_n}(t) = 2\pi f_c(\tau_0(t) - \tau_{i_m,i_n}(t)) + 2\pi k_{i_m,i_n}(t),$$

where $k_{i_m,i_n}(t)$ is additional full carrier signal period delay in the m,n-th element on the i-th RIS.

- If $k_{i_m,i_n}(t) \geq \lceil f_c(\tau_{i_m,i_n}(t) - \tau_0(t)) \rceil$ and $k_{i_m,i_n}(t) \in \mathbb{Z}_0^+$, the received power can be maximized.

- Also, the Doppler spread will be removed.

Phase Optimization (2/4)

- ☐ However, the delay spread would be obtained as

$$T(t)=\max_{i}\{T_i(t)\}, i=1,2,\ldots,K,$$

where $T_i(t)=\max_{i_m,i_n}\{\tau_{i_m,i_n}(t)+\frac{k_{i_m,i_n}(t)}{f_c}-\frac{\gamma_{i_m,i_n}(t)}{2\pi f_c}\}-\tau_0(t).$

- ☐ Therefore, $T(t)$ can be affected by $k_{i_m,i_n}(t)$ and $\gamma_{i_m,i_n}(t)$.
- ☐ In other words, the phase shift set and the hardware impairment of the RIS can increase the delay spread.
- ☐ So $k_{i_m,i_n}(t)$ should be as small as possible, i.e.,

$$k_{i_m,i_n}(t)=\lceil f_c(\tau_{i_m,i_n}(t)-\tau_0(t))\rceil$$

- ☐ $\gamma_{i_m,i_n}(t)$ cannot be removed, i.e., HWI increases the delay spread.

Phase Optimization(3/4)

☐ The Doppler shift of the m,n-th element of the i-th RIS after RIS phase optimization is

$$DS_{i_{m,n}}(t) = -f_c \frac{d}{dt}\{\tau_0(t) + \frac{k_{i_m,i_n}(t)}{f_c} - \frac{\gamma_{i_m,i_n}(t)}{2\pi f_c}\}.$$

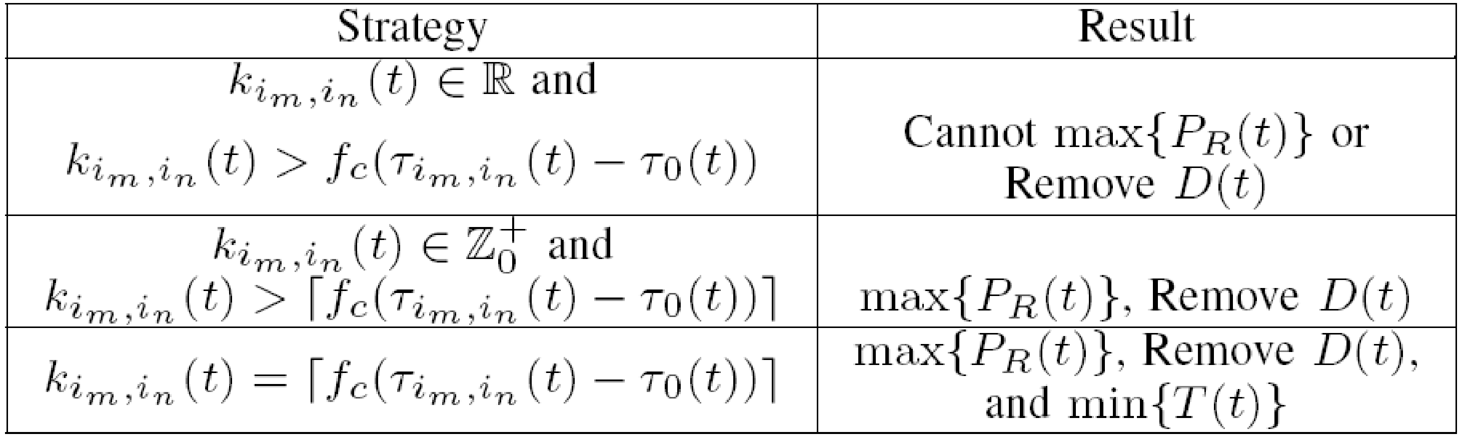
☐ Therefore, RIS cannot remove Doppler shift if direct link exists.

☐ In other words, if the system only has the cascaded link, then the Doppler shift is zero.

Phase Optimization(4/4)

- ☐ Comparison between different phase shift set

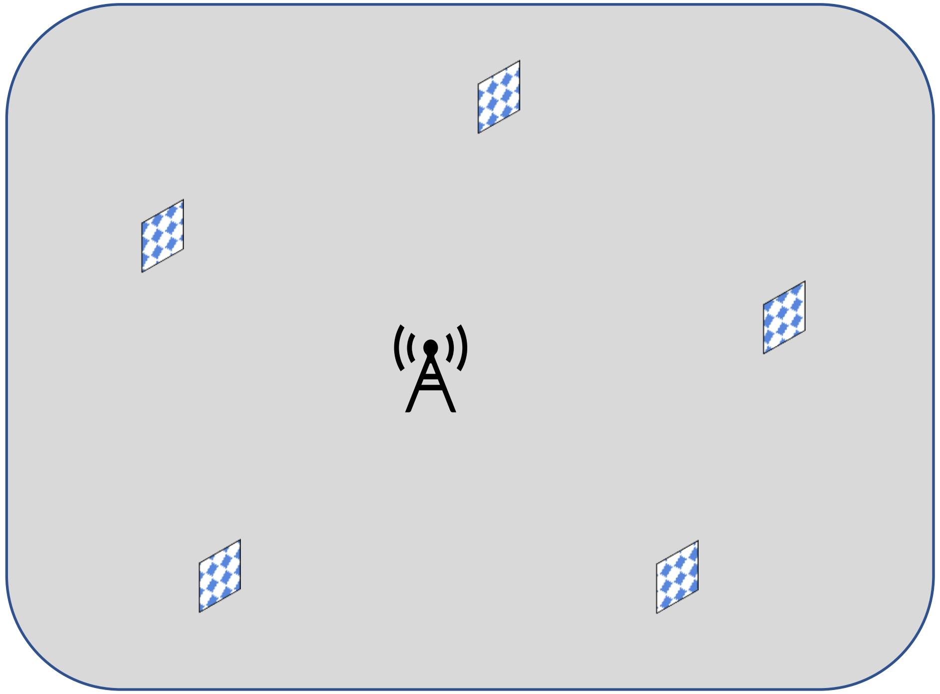
$$\phi_{i_m,i_n}(t) = 2\pi f_c(\tau_0(t) - \tau_{i_m,i_n}(t)) + 2\pi k_{i_m,i_n}(t),$$ and

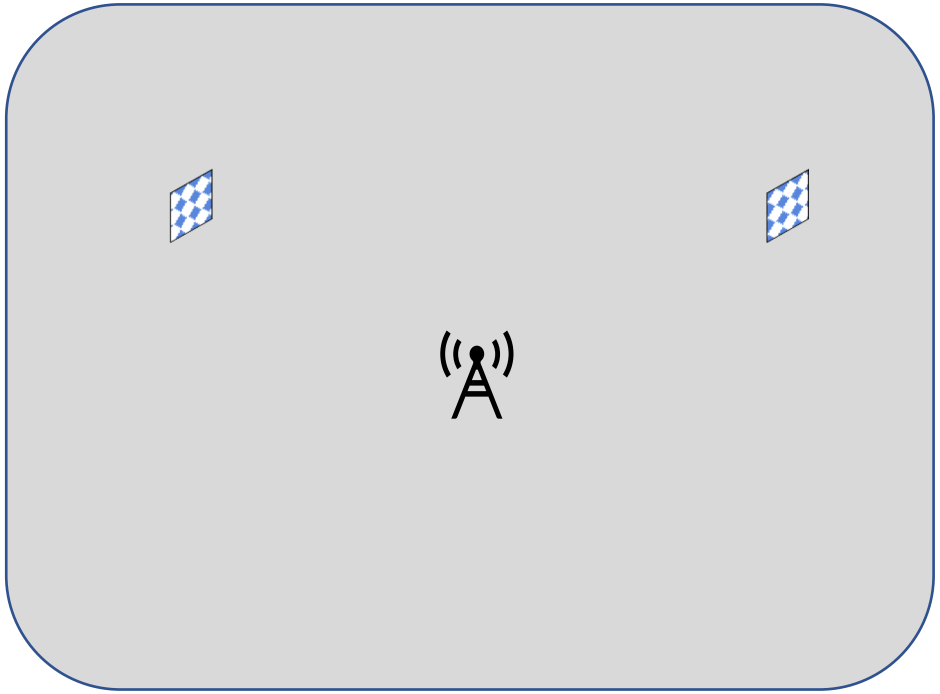


Strategy	Result
$k_{i_m,i_n}(t) \in \mathbb{R}$ and $k_{i_m,i_n}(t) > f_c(\tau_{i_m,i_n}(t) - \tau_0(t))$	Cannot $\max\{P_R(t)\}$ or Remove $D(t)$
$k_{i_m,i_n}(t) \in \mathbb{Z}_0^+$ and $k_{i_m,i_n}(t) > \lceil f_c(\tau_{i_m,i_n}(t) - \tau_0(t)) \rceil$	$\max\{P_R(t)\}$, Remove $D(t)$
$k_{i_m,i_n}(t) = \lceil f_c(\tau_{i_m,i_n}(t) - \tau_0(t)) \rceil$	$\max\{P_R(t)\}$, Remove $D(t)$, and $\min\{T(t)\}$

Deployment Strategy and Delay Spread

- ☐ The delay spread is the smallest if the distance of cascaded link is the smallest.
- ☐ The delay spread of the system with the K RISs only depends on the RIS that is the farthest to the BS.





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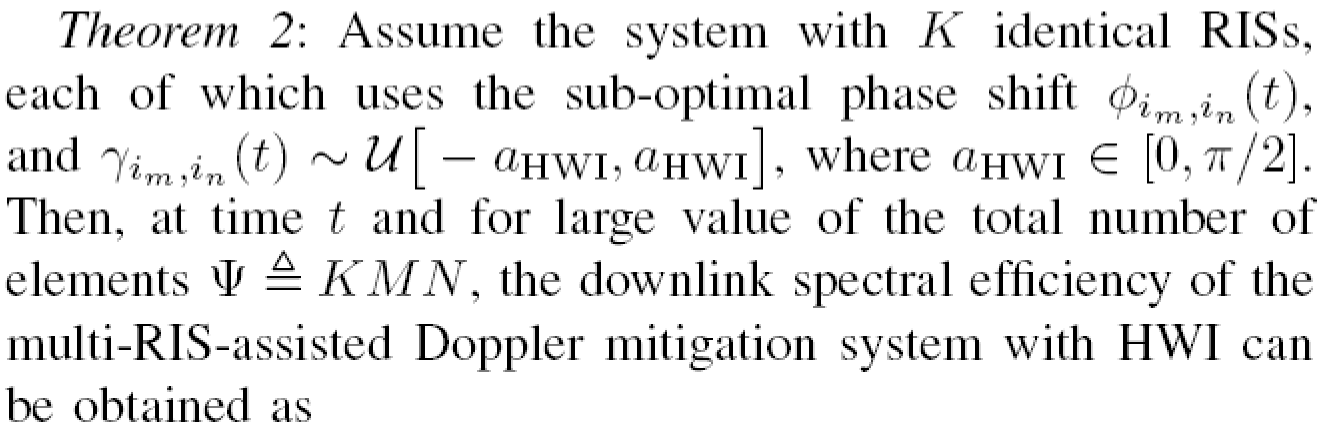
Spectral Efficiency



Theorem 2: Assume the system with K identical RISs, each of which uses the sub-optimal phase shift $\phi_{i_m,i_n}(t)$, and $\gamma_{i_m,i_n}(t) \sim \mathcal{U}\big[-a_{\mathrm{HWI}}, a_{\mathrm{HWI}}\big]$, where $a_{\mathrm{HWI}} \in [0, \pi/2]$. Then, at time t and for large value of the total number of elements $\Psi \triangleq KMN$, the downlink spectral efficiency of the multi-RIS-assisted Doppler mitigation system with HWI can be obtained as

$$\mathrm{SE}(t) \xrightarrow{a.s.} \log_2\Big\{1 + \frac{\mathcal{Q}(t)}{(\kappa_t + \kappa_r)\mathcal{Q}(t) + N_0}\Big\},$$ where

$$\mathcal{Q}(t) \xrightarrow{a.s.} P_t\Big\{A_0^2(t) + \mathrm{sinc}^2(a_{\mathrm{HWI}})A^\star(t) + \sum_{i=1}^{K}\sum_{i_m=1,i_n=1}^{M,N} A_{i_m,i_n}^2(t) + 2A_0(t)\mathrm{sinc}(a_{\mathrm{HWI}})\sum_{i=1}^{K}\sum_{i_m=1,i_n=1}^{M,N} A_{i_m,i_n}(t)\Big\},$$ and

$$A^\star(t) = A_1(t)\sum_{j\neq 1}^{\Psi} A_j(t) + A_2(t)\sum_{j\neq 2}^{\Psi} A_j(t) + \cdots + A_\Psi(t)\sum_{j\neq \Psi}^{\Psi} A_j(t)$$

Energy Efficiency

$$\mathcal{P}_{\text{total}}(t, P_t, \Psi) \triangleq \frac{P_t}{\nu} + P_{\text{V}} + P_{\text{BS}} + P_{\text{RIS}}$$

$$= \frac{P_t}{\nu} + P_{\text{V}} + P_{\text{BS}} + \Psi P_e$$

⇨

$$\eta_{\text{EE}}(t) = \frac{B \cdot \text{SE}(t, P_t)}{\mathcal{P}_{\text{total}}(P_t)}.$$

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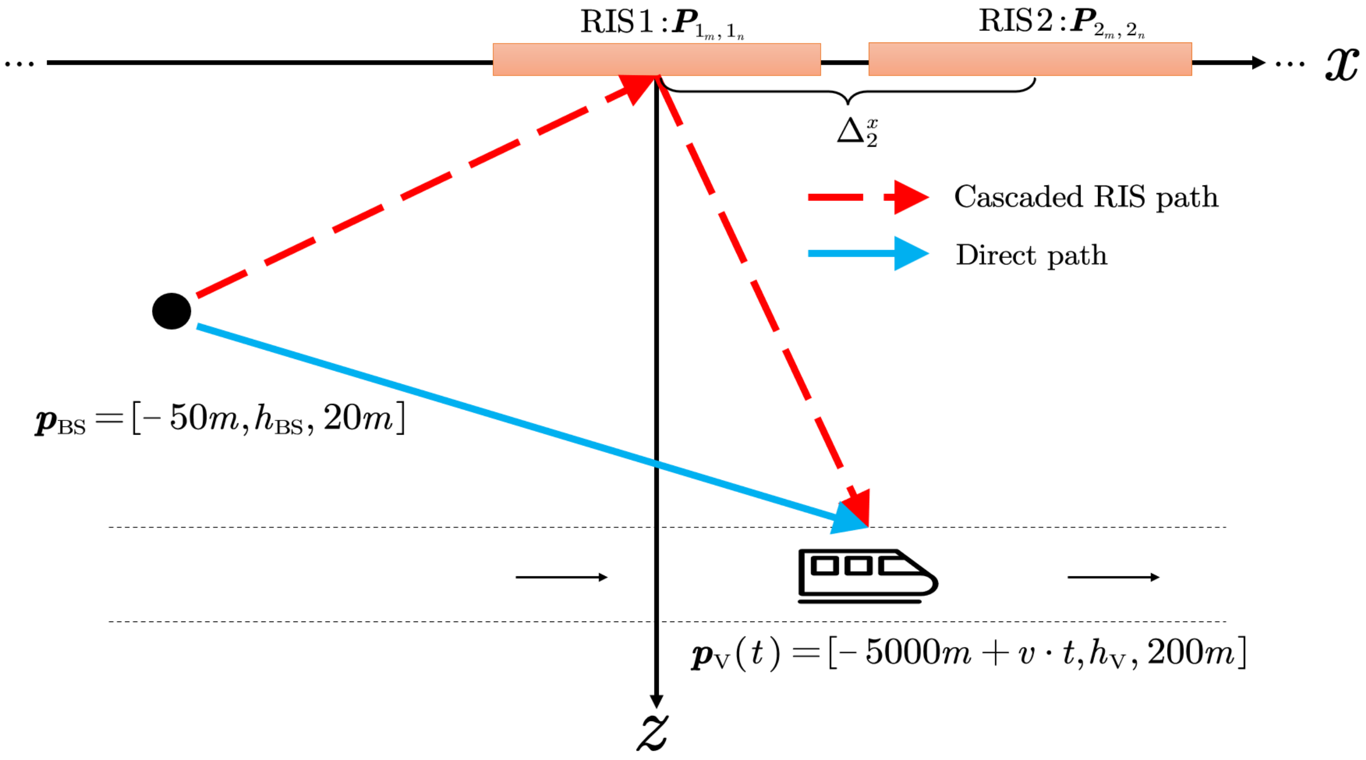
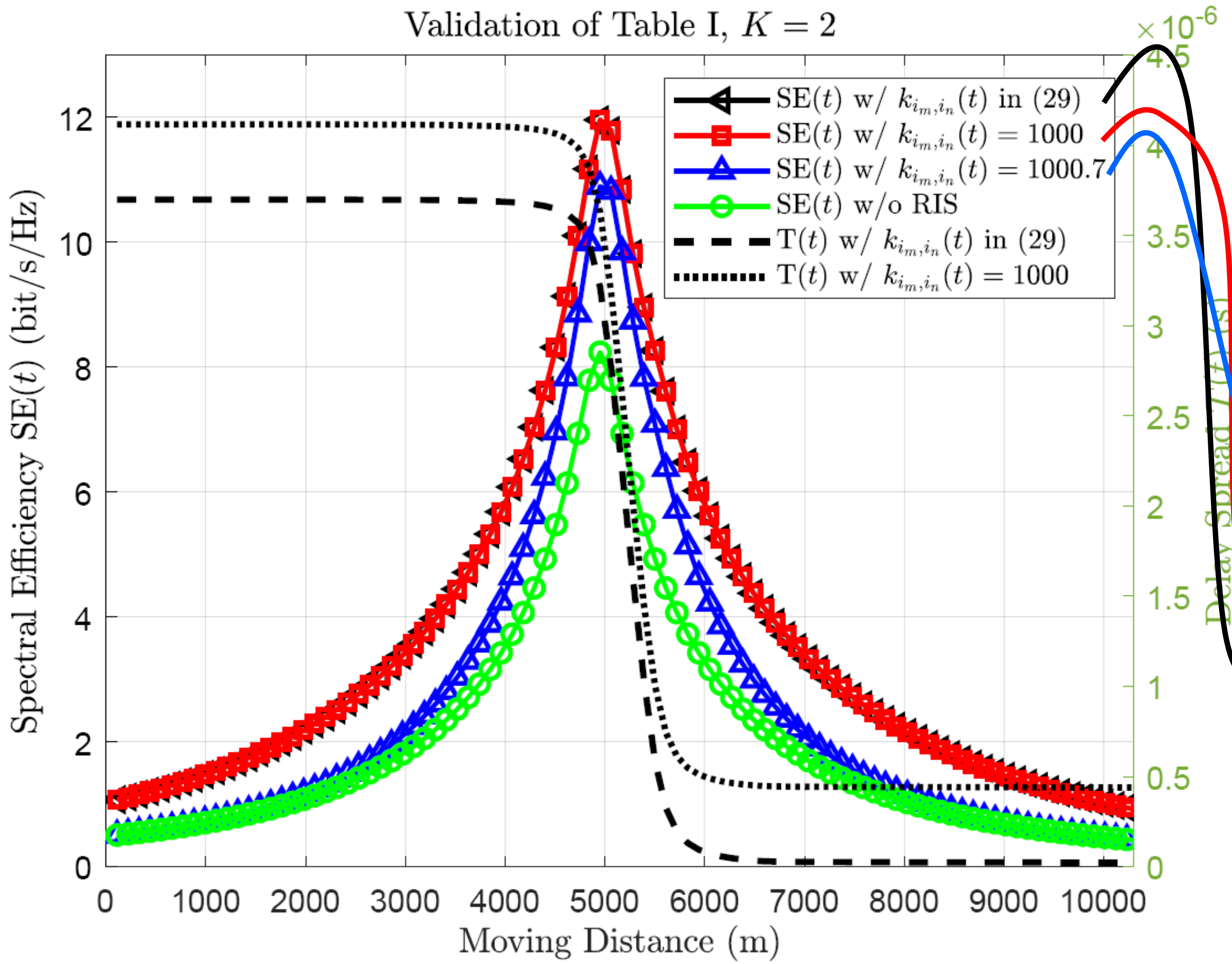
Parameter Setting



In this section, numerical examples are provided to validate the results in Section III and IV. Based on Fig.2, assuming the BS is located at [-50 m, h_{BS} m, 20 m], and the vehicle is located at [$x_{\mathrm{start}} + v \cdot t$ m, h_{V} m, 200 m] where $t \in \mathbb{Z}_0^+$ and its range is from 1 s to 100 s. Without loss of generality, we assume all RISs are with zero z coordinate, i.e., $\Delta_i^z = 0$.

Parameters	**Values**
BS height (h_{BS})	20 m
RIS height (h_{RIS})	15 m
Vehicle height (h_{V})	1.5 m
Speed of the vehicle (v)	110 m/s
Start point of the vehicle (x_{start})	-5000 m
Total time for one vehicle pass	100 s
Transmit power (P_t)	30 dBm
Power spectral density (N_0)	-80 dBm/Hz
Carrier frequency (f_c)	2.4 GHz
Coherence Bandwidth (B)	180 KHz
Transmit power amplifier efficiency (ν)	0.5
Vehicle hardware static power consumption (P_{V})	5 dBm
BS hardware static power consumption (P_{BS})	5 dBm
Each element hardware static power consumption (P_{e})	0.8 dBm
Rectangular grid spacing of the RIS (dx, dy)	$\lambda/2$, $\lambda/2$
Spacing of two inter-RISs	500 m
The x coordinate of the center of RIS1 (Δ_1^x)	0 m

Performance for Different Phase Shift Sets

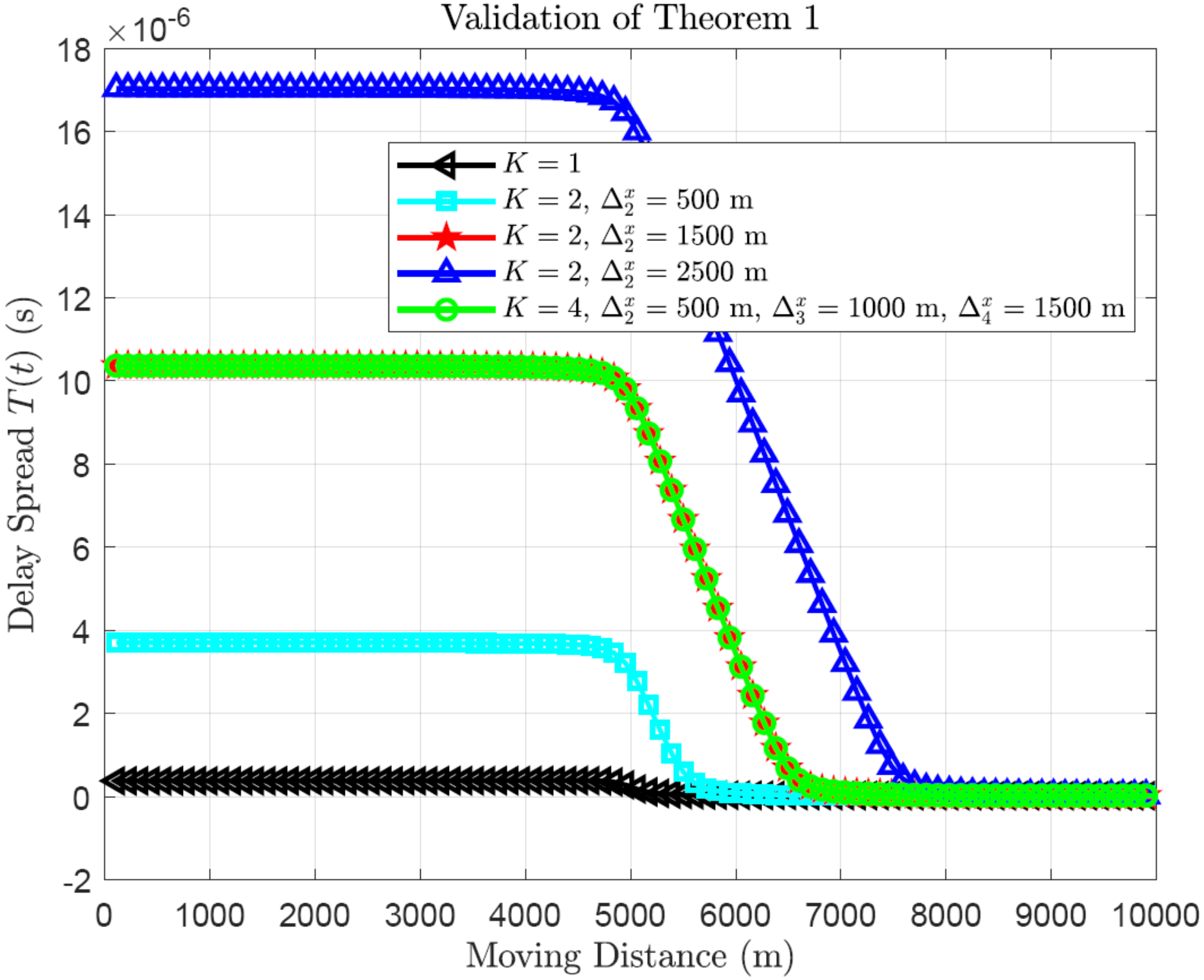


$$\phi_{i_m,i_n}(t) = 2\pi f_c\big(\tau_0(t) - \tau_{i_m,i_n}(t)\big) + 2\pi k_{i_m,i_n}(t)$$
$$= 2\pi\Big\{ f_c\big(\tau_0(t) - \tau_{i_m,i_n}(t)\big) + k_{i_m,i_n}(t)\Big\}, \quad (29)$$

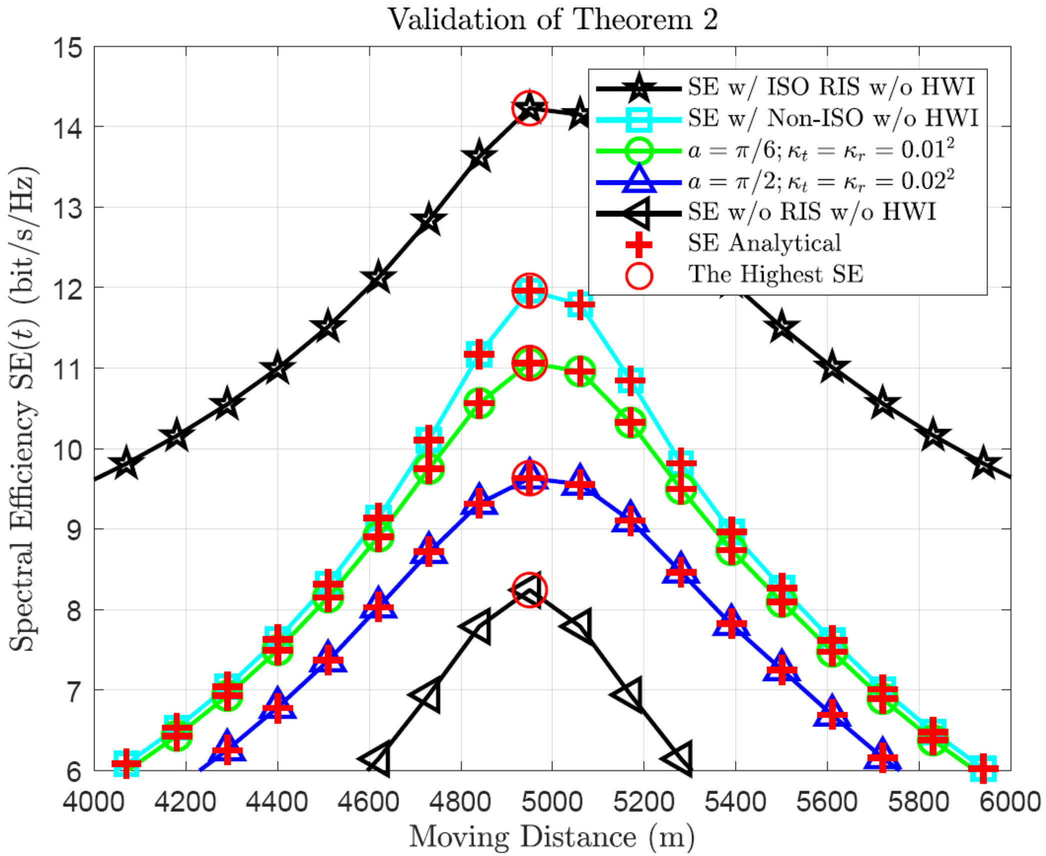
where $k_{i_m,i_n}(t) = \lceil f_c(\tau_{i_m,i_n}(t) - \tau_0(t))\rceil$ and $\lceil\cdot\rceil$ denotes the ceiling of the argument.

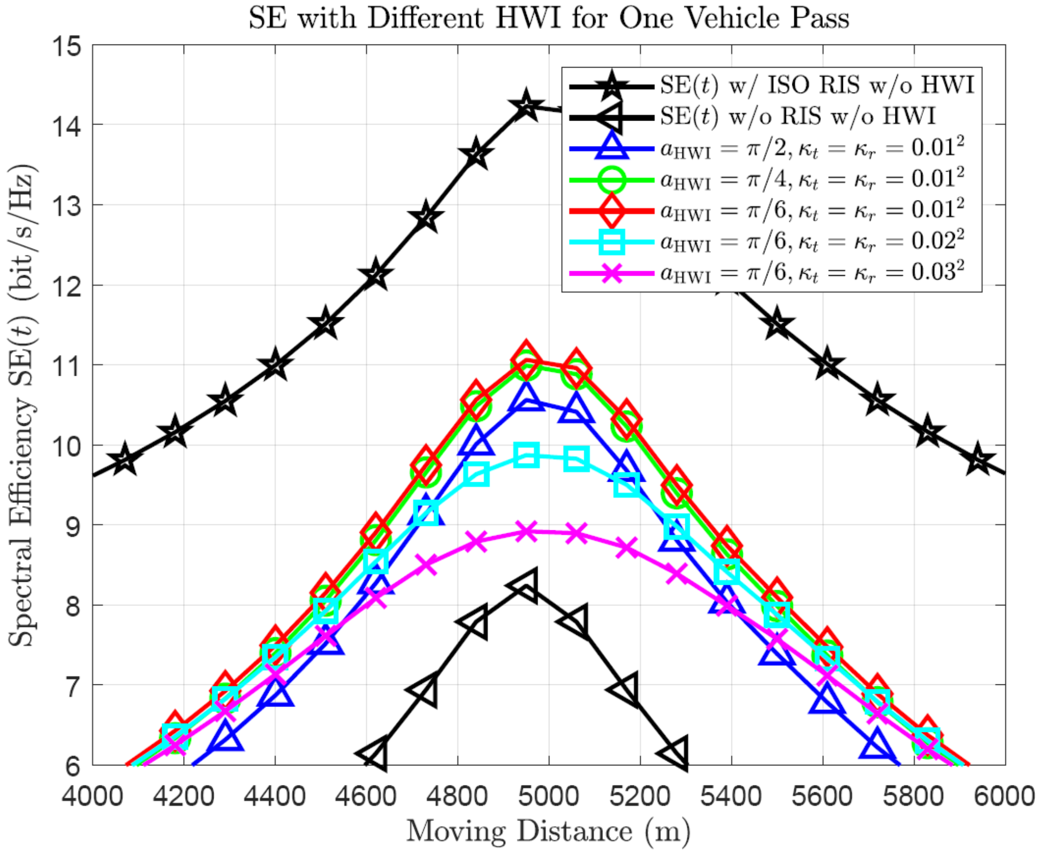
Strategy	Result
$k_{i_m,i_n}(t) \in \mathbb{R}$ and $k_{i_m,i_n}(t) > f_c(\tau_{i_m,i_n}(t) - \tau_0(t))$	Cannot max$\{P_R(t)\}$ or Remove $D(t)$
$k_{i_m,i_n}(t) \in \mathbb{Z}_0^+$ and $k_{i_m,i_n}(t) > \lceil f_c(\tau_{i_m,i_n}(t) - \tau_0(t))\rceil$	max$\{P_R(t)\}$, Remove $D(t)$
$k_{i_m,i_n}(t) = \lceil f_c(\tau_{i_m,i_n}(t) - \tau_0(t))\rceil$	max$\{P_R(t)\}$, Remove $D(t)$, and min$\{T(t)\}$

Delay Spread for Different Numbers of RIS

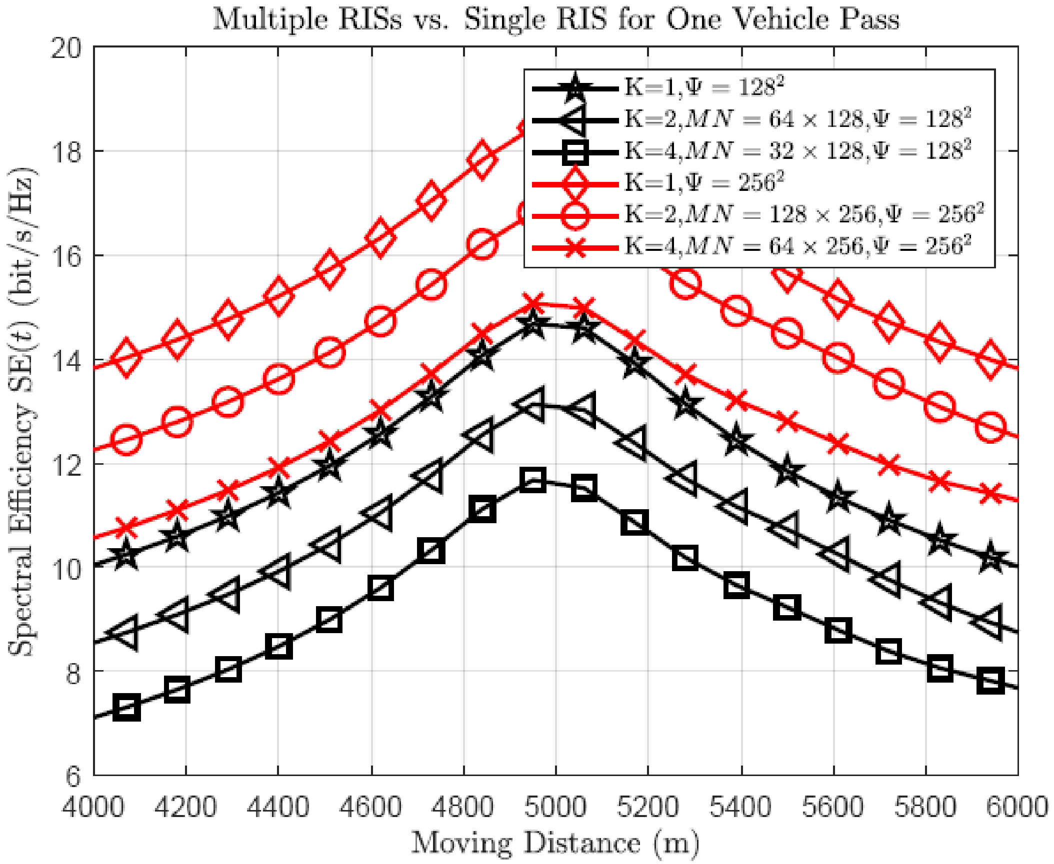


Spectral Efficiency for multi-RIS System with HWI



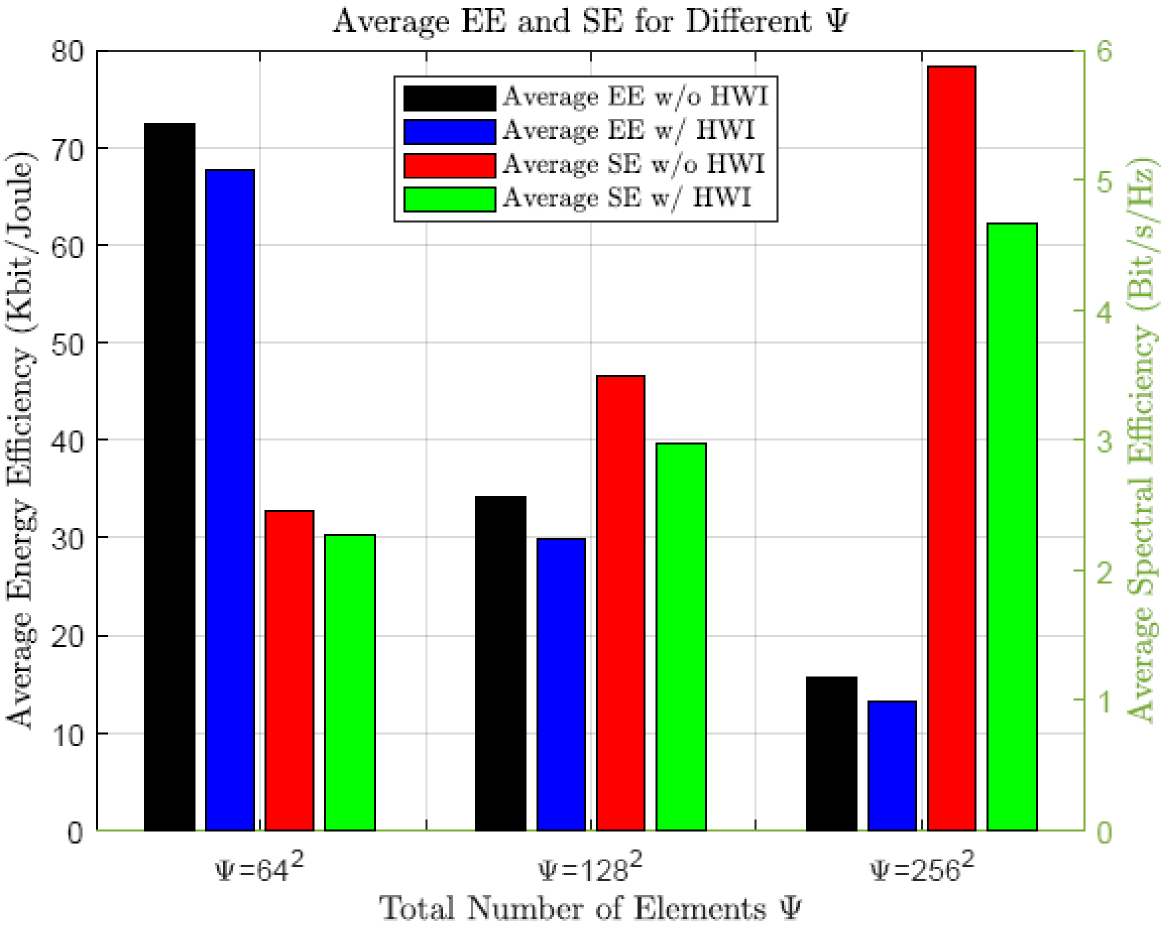


Multiple RISs vs. Single RIS for One Vehicle Pass



- When the total number of elements is fixed, single-RIS near the BS is the best deployment strategy.
- When the total number of elements increases, the SE increases.
- Single-RIS cannot be too large.

Average Spectral and Energy Efficiency



☐ The RIS with more elements, a higher SE but a lower EE would be obtained.

☐ In order to achieve a balance between SE and EE, we should choose the total number of elements carefully.

Part 3

- ☐ Part 1: Introduction and Motivation
  - ➢ Introduction of Reconfigurable Intelligent Surfaces (RIS)
  - ➢ Motivation of Using RIS in High-Speed Communication

- ☐ Part 2: Multi-RIS-Assisted High-Speed Communication
  - ➢ Abstract and System Model
  - ➢ Doppler Mitigation and Phase Optimization
  - ➢ Spectral and Energy Efficiency
  - ➢ Simulation Results

- ☐ Part 3: Conclusion and Future Research Directions

Conclusion

- RIS can benefit from high-speed communication (SE/EE enhancement, Doppler spread elimination, etc.).
- HWI increases the delay spread and decreases the SE/EE.
- The delay spread of the system with the K RISs only depends on the RIS that is the farthest to the BS.
- The multiple RISs system is with a higher SE but a more serious delay spread.

Future Research Directions

- ☐ Hardware Aging of RIS-Assisted System.
- ☐ Doppler Diversity Generation using RIS.
- ☐ Cell-Free Massive MIMO Networks with RIS.
- ☐ Practical RIS-Assisted System Model.
- ☐ …

Thanks, QA?

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