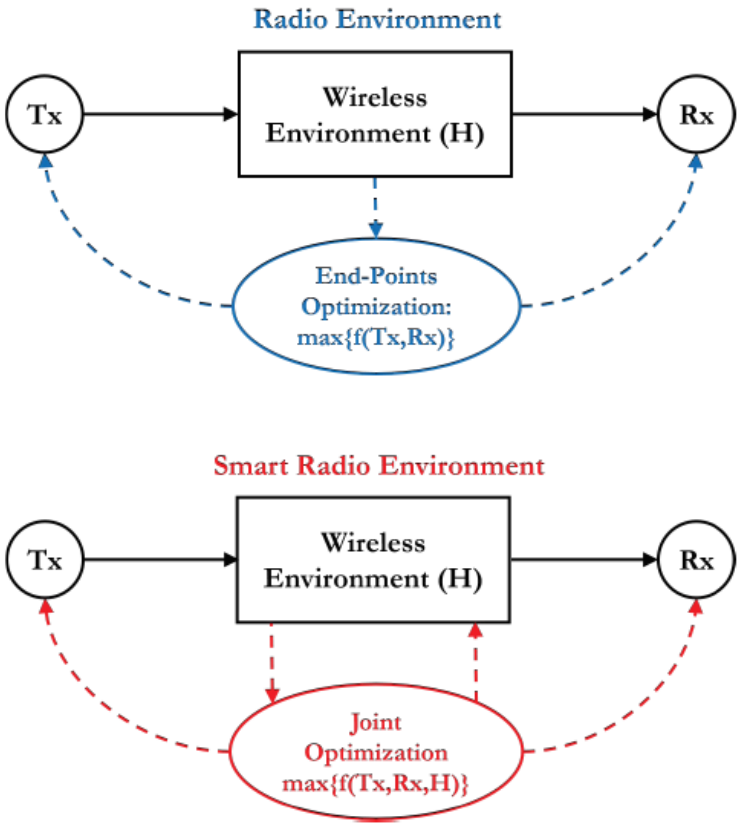
Reconfigurable Intelligent Surface (RIS)-Assisted Wireless Networks

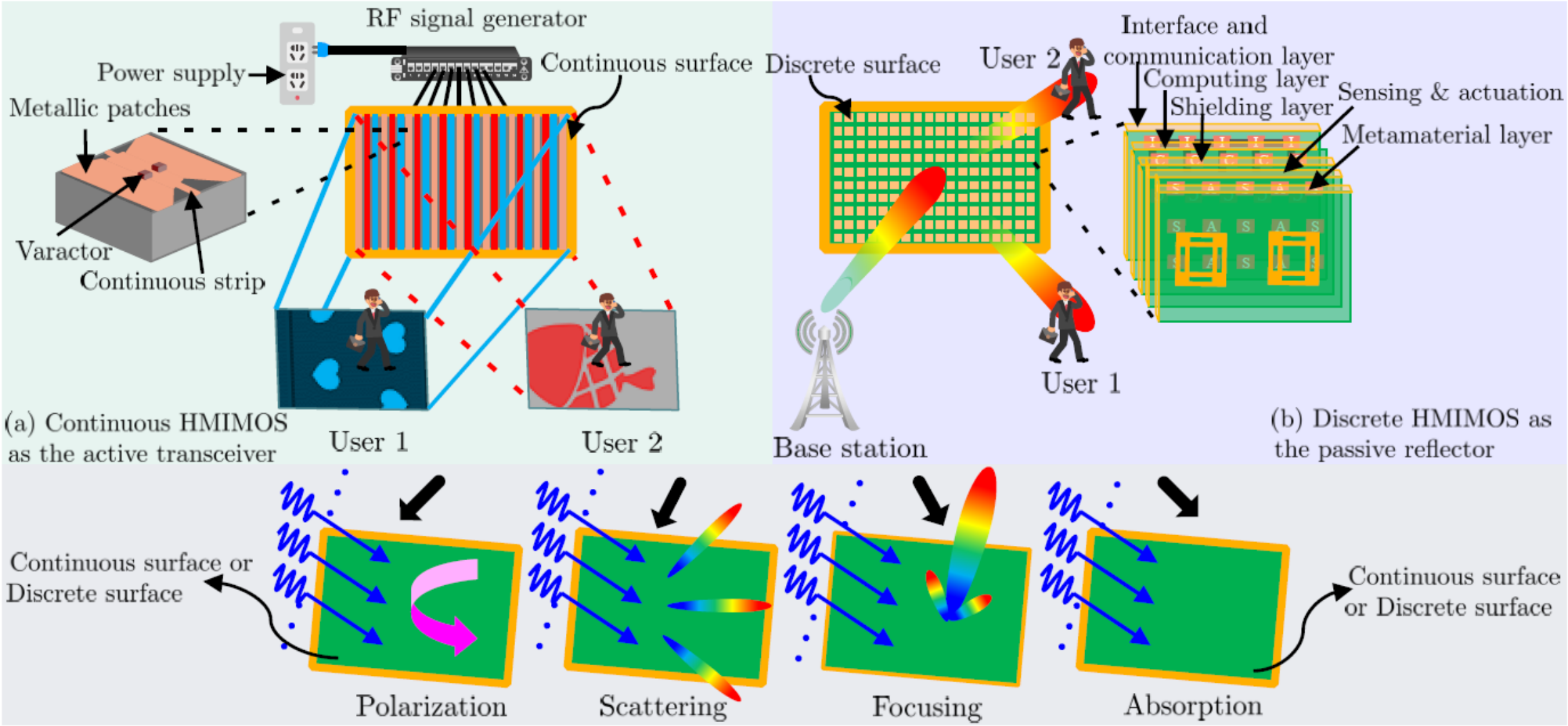
Assoc Prof Chau Yuen (Fellow IEEE)
Engineering Product Development
Singapore University of Technology and Design

Smart Radio Environment

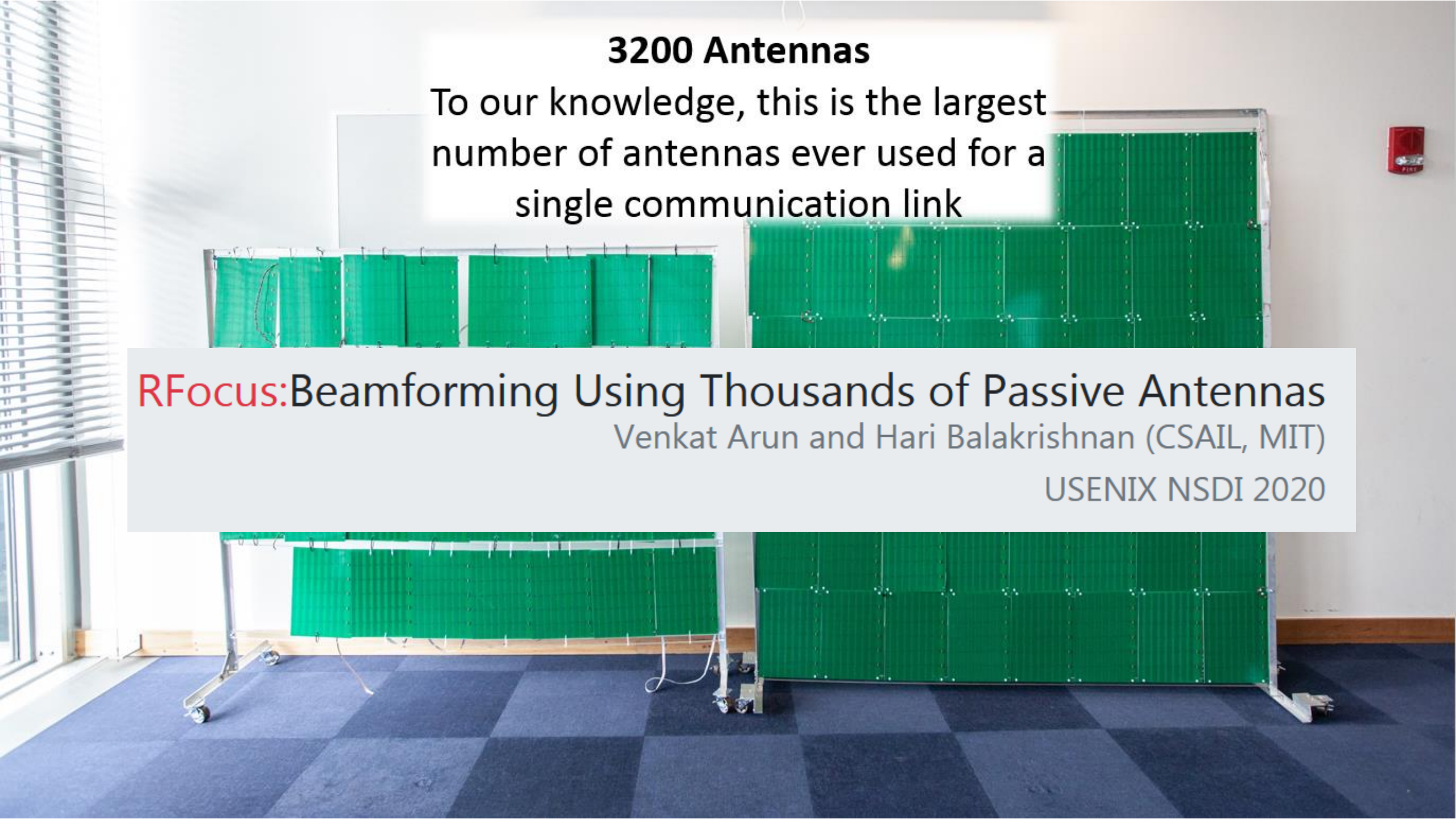


M. D. Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. d. Rosny, and S. Tretyakov, **Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How it Works, State of Research, and Road Ahead**, IEEE JSAC, vol. 38, Nov 2020, pp. 2450-2525

Reconfigurable Intelligent Surfaces (RIS)



C. Huang, S. Hu, G. C. Alexandropoulos, A. Zappone, C. Yuen, R. Zhang, M. D. Renzo, M. Debbah, **Holographic MIMO Surfaces for 6G Wireless Networks: Opportunities, Challenges, and Trends**, IEEE Wireless Communications, vol. 27, Oct. 2020, pp. 118 - 1250



3200 Antennas

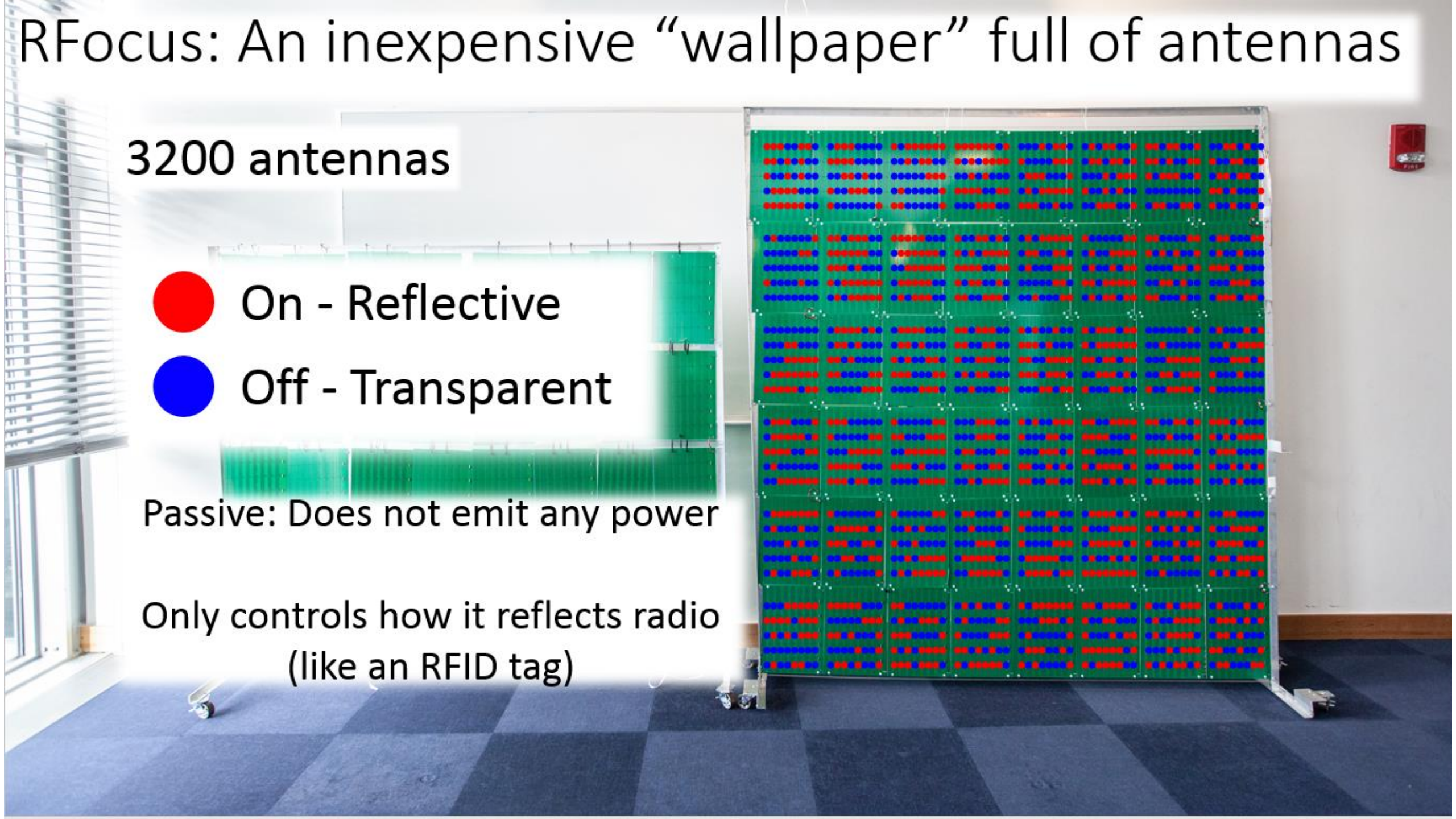
To our knowledge, this is the largest number of antennas ever used for a single communication link

RFocus:Beamforming Using Thousands of Passive Antennas

Venkat Arun and Hari Balakrishnan (CSAIL, MIT)

USENIX NSDI 2020

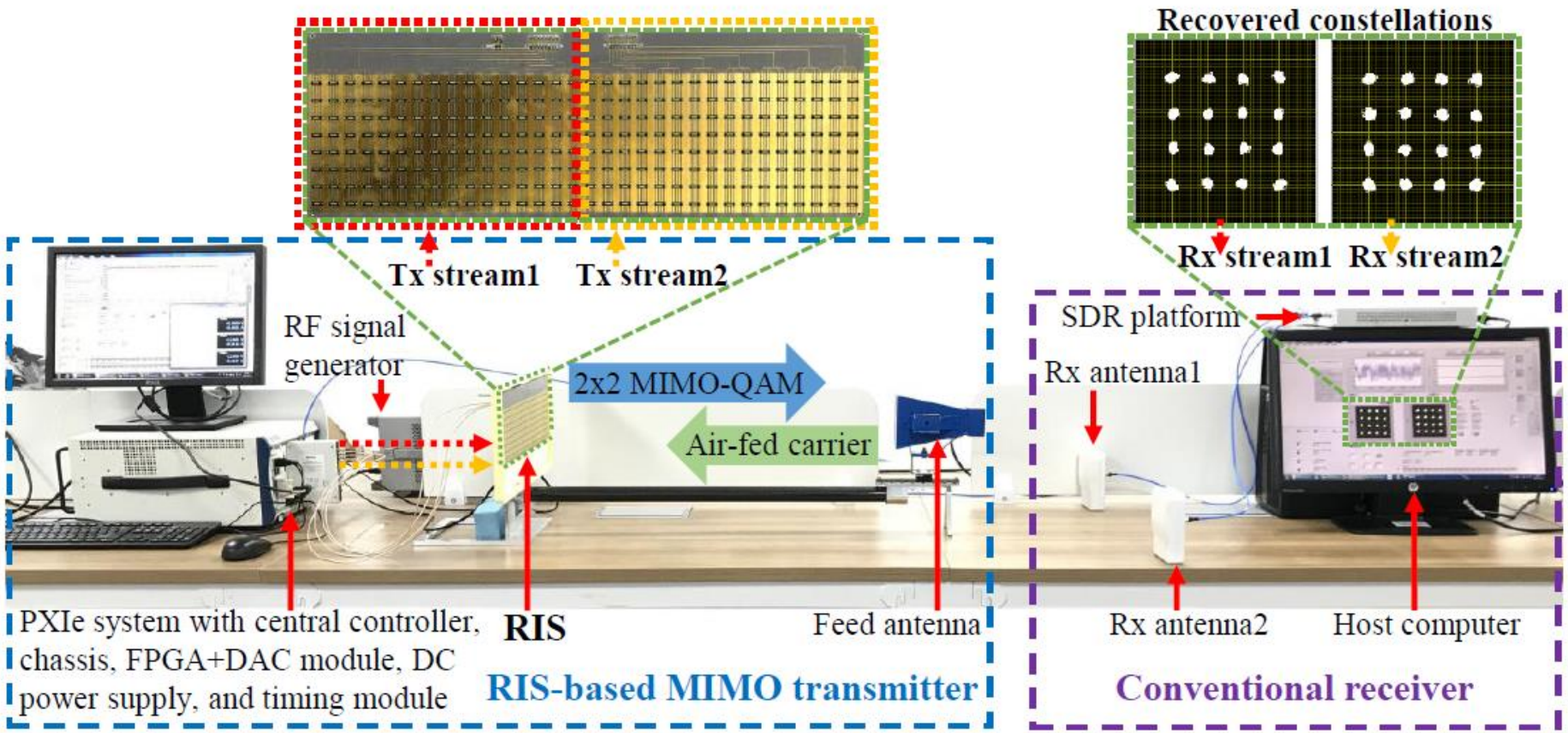
RFocus: An inexpensive “wallpaper” full of antennas



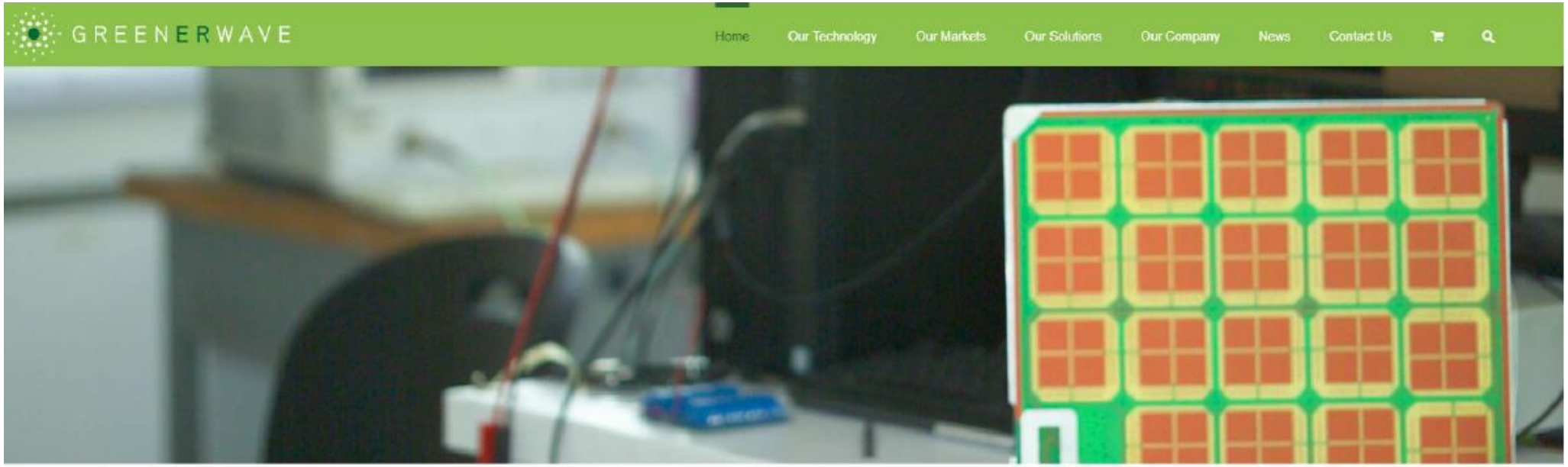
MIMO Transmission through Reconfigurable Intelligent Surface: System Design, Analysis, and Implementation

Wankai Tang, Jun Yan Dai, Ming Zheng Chen, Kai-Kit Wong,
Xiao Li, Xinsheng Zhao, Shi Jin, Qiang Cheng, and Tie Jun Cui

[JSAC Nov 2020]



Greenerwave



Our Technology – Shaping electromagnetic waves with metasurfaces

Greenerwave is a deeptech start-up from French CNRS.

Its breakthrough technology uses metasurfaces to shape electromagnetic waves and control them.

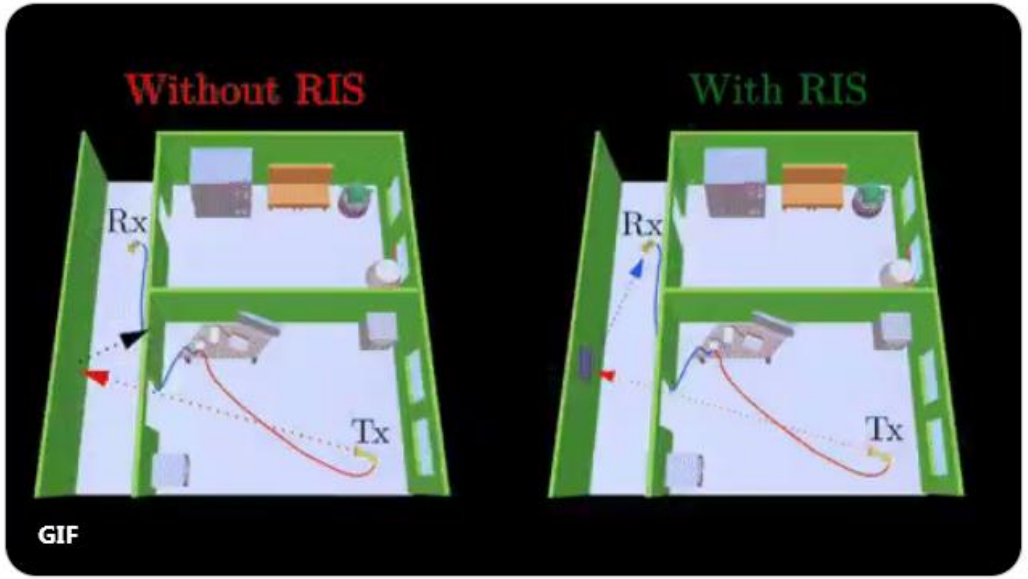
Compatible with all standards up to 100GHz (RFID, Satcom, mm radars, 5G ...),
potential for applications is tremendous.

Greenerwave

Greenerwave @greenerwave · Apr 29

Do you know that the metasurfaces we develop for our disruptive electronically steerable antennas Ka/Ku band can be used as Reconfigurable Intelligent Surfaces (#RIS)?

We're thrilled to pursue Greenerwave original mission, smart EM environments for 5G



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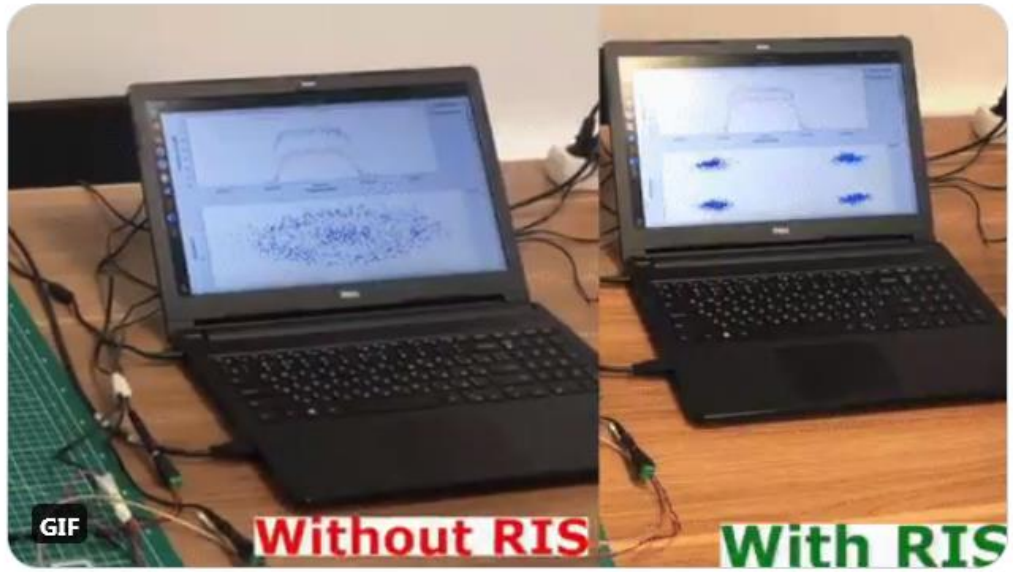
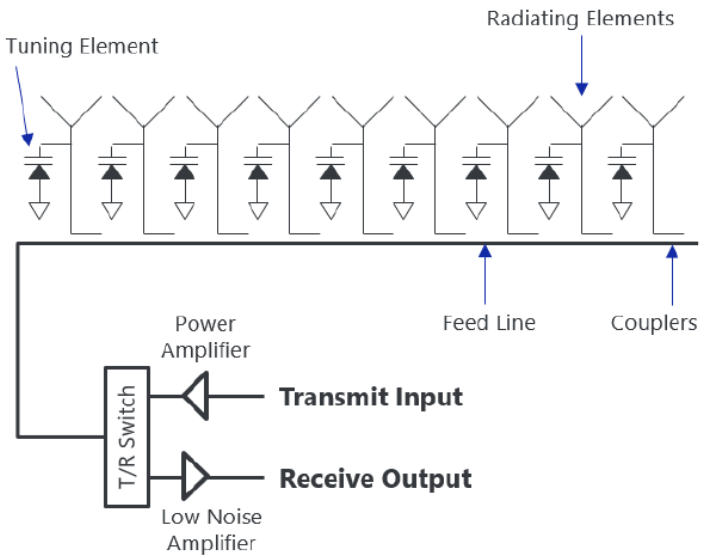


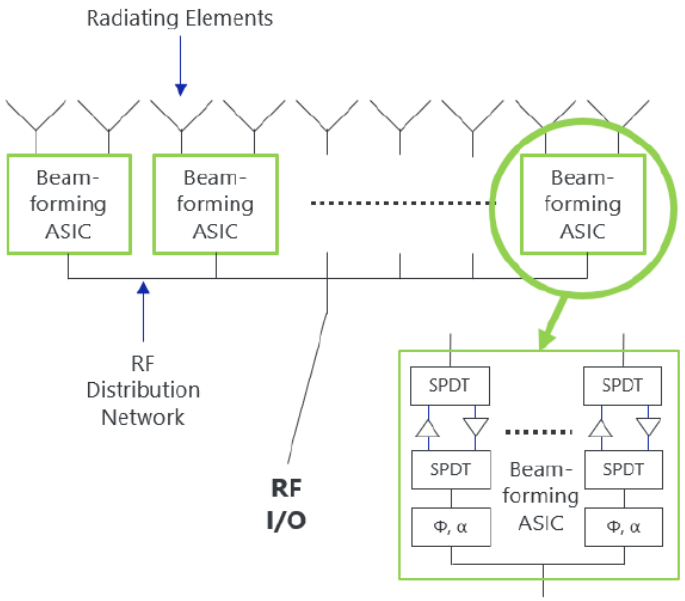
Pivotal Commware - Holographic Beam Forming

There are two key differences:

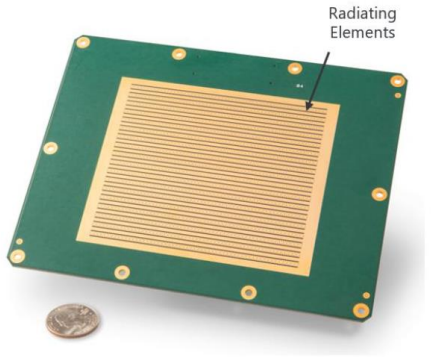
1) the method used to steer the signal, and
2) 2) the location of amplification



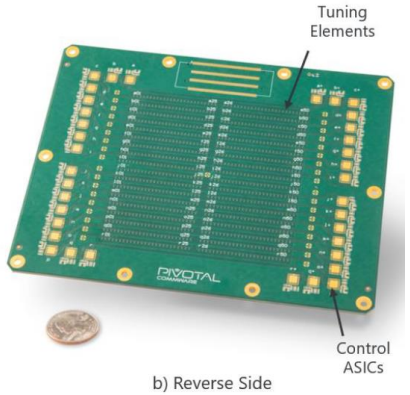
a) Holographic Beamforming Antenna Block Diagram (including external amplifiers and T/R switch)



b) Active Phased Array Antenna Block Diagram

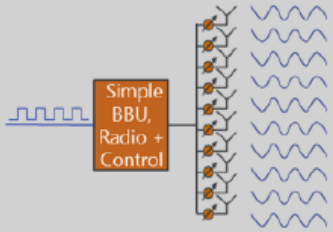
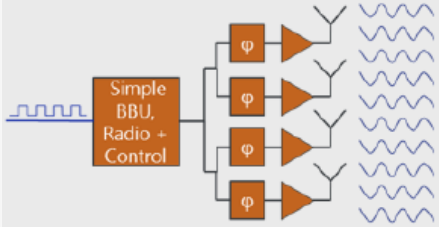
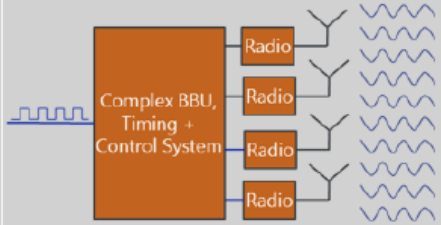


a) Free Space Side



b) Reverse Side

Pivotal Commware - Holographic Beam Forming

Architecture	Block Diagram	Cost	Size	Challenges
Holographic Beam Former		Super-sampled COTS design enables low price	Thin, Conformable	Single beam per polarization per sub-aperture.
Phased Array		Distributed phase shifters and amplifiers pushes moderate price	Trades cost for thickness. Thin is very expensive	Thermal challenges difficult due to distributed amplification. Multi-beam significantly increases cost (more phase shifters, distribution layers)
MIMO		Radios behind every element and complex BBU drives high price and power consumption	Usually thick but antenna thickness can be reduced by hiding BBU in baseband cabinet	No FDD Unworkable at mmW Spectral Efficiency vs. cost scales poorly

NTT Docomo and Metawave

December 04, 2018 10:13 AM Eastern Standard Time

PALO ALTO, Calif.--(BUSINESS WIRE)--NTT DOCOMO, Inc., in collaboration with Metawave Corporation, announced the demonstration of a 5G mobile communication system using 28GHz-band 5G, and the world's first meta-structure reflect-array technology. The world's first successful demonstration took place in the world in Koto-ku, Tokyo on November 29, 2018. Meta-structures are an artificial medium with optical characteristics developed by arranging structures that are sufficiently small with respect to wavelength in the form of an array. The meta-structure reflector will be exhibited at the "DOCOMO Open House 2018."

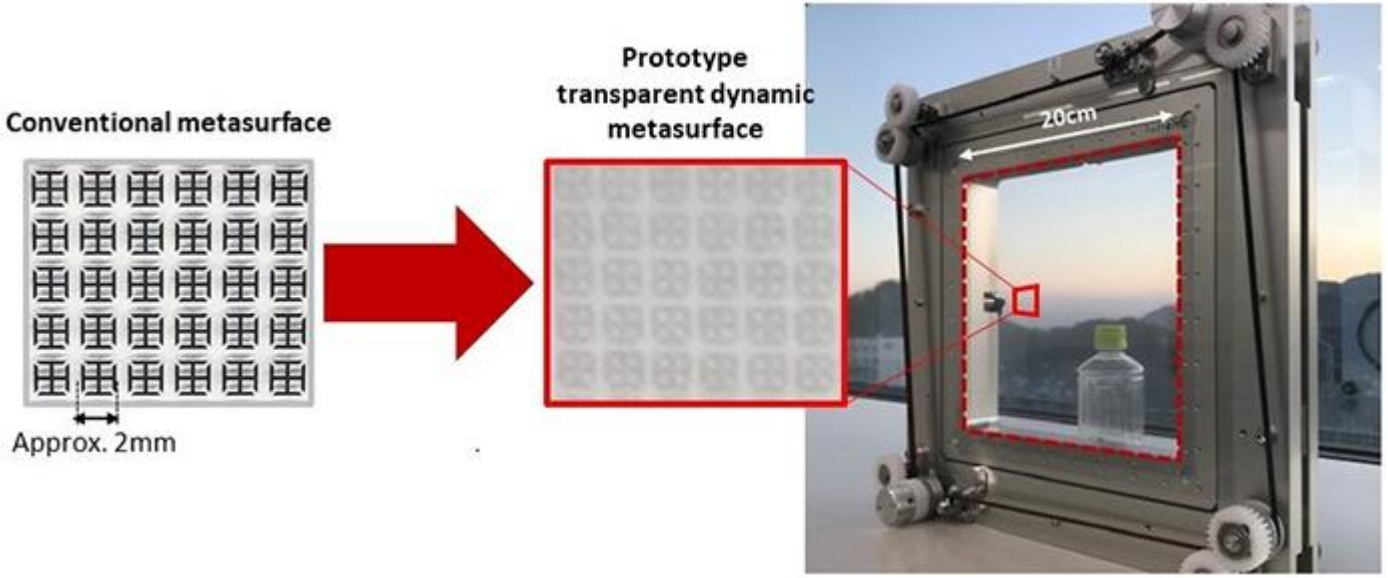
January 17, 2020

DOCOMO Conducts World's First Successful Trial of Transparent Dynamic Metasurface

— Dynamic wave manipulation and high transparency expected to optimize 5G network construction —

Print Like Tweet

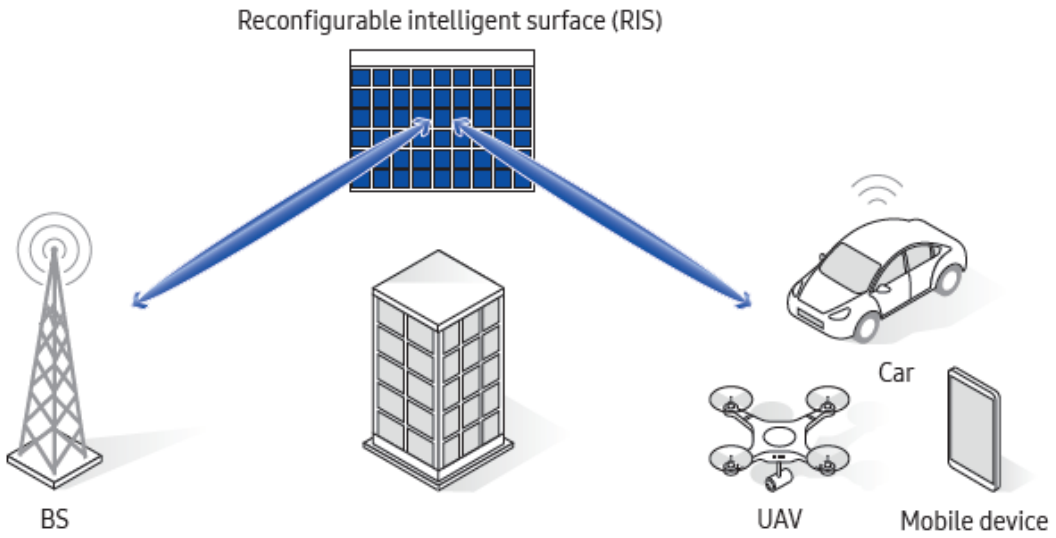
TOKYO, JAPAN, January 17, 2020 --- NTT DOCOMO, INC., working in collaboration with the global glass manufacturer AGC Inc., announced today that it has successfully conducted what is believed to be world's first trial of a prototype transparent dynamic metasurface using 28 GHz 5G radio signals. The new metasurface achieves dynamic manipulation of radio-wave reflection and penetration in a highly transparent package suitable for unobtrusive use in the windows of buildings and vehicles as well as on billboards.



– *Reconfigurable intelligent surface (RIS)* can be used to provide a propagation path where no LoS link exists [25]. An example of signal reflection via RIS is illustrated in Figure 12.

Figure 12

RIS-aided communication between a BS and a mobile user, where the LoS path is blocked.



[25] Chongwen Huang *et al.*, "Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication," IEEE Transactions on Wireless Communications, vol. 18, no. 8, pp. 4157-4170, Aug. 2019.

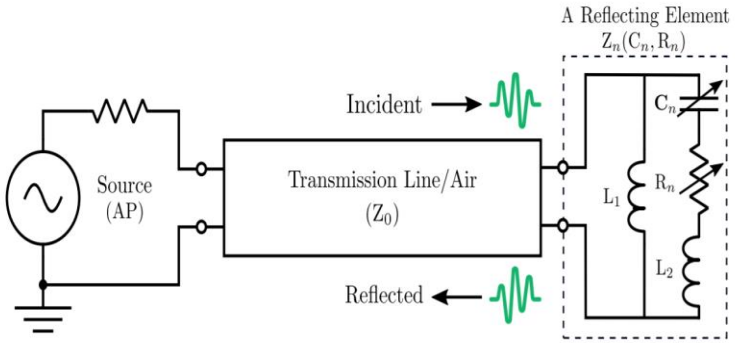
IEEE Marconi Prize Paper Award in Wireless Communications 2021

Outline

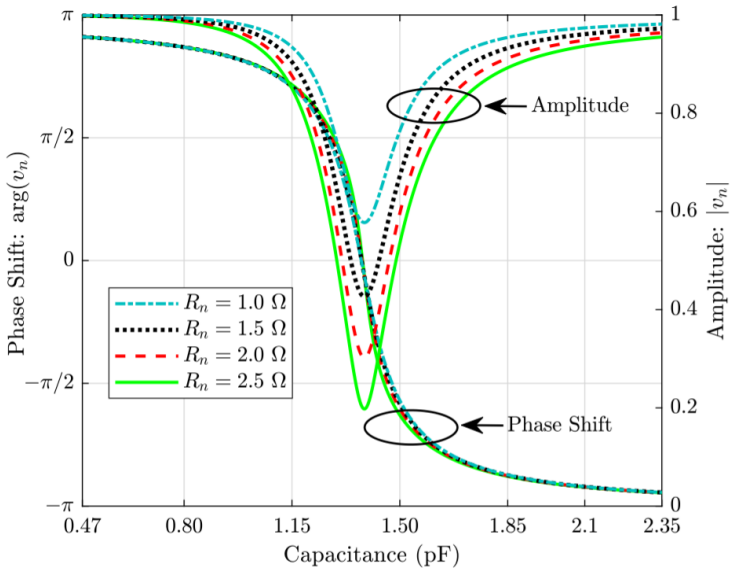
- RIS in Physical Layer
  - Practical Phase Shift Model
  - Channel Estimation
  - Hybrid Beamforming Architture
- RIS in MAC Layer
  - Multiple Uplink
  - Multi-Pair Communications
  - RIS with Spectrum Learning

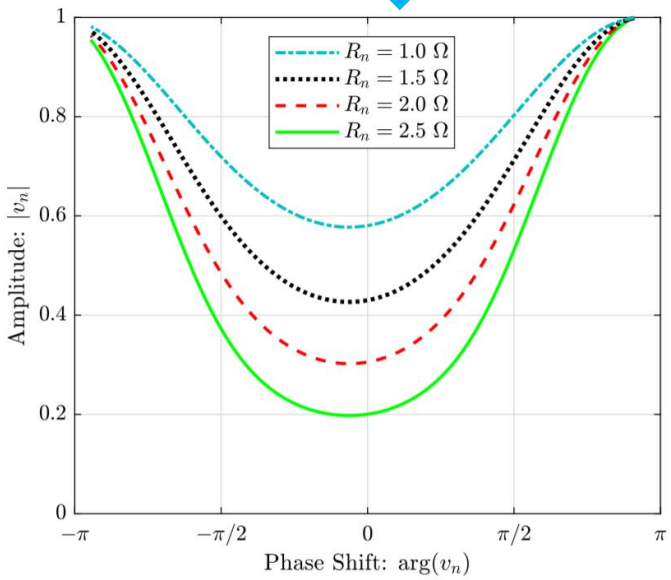
RIS Research in Physical Layer #1
Practical Phase Shift Model

Transmission line model of a reflecting element of the RIS



One element





- Reflection coefficient at each RIS element

this is always one (i.e., unity) in the ideal model

$$v_n = \boxed{\beta_n(\theta_n)} e^{j\theta_n} \qquad n = 1, \dots, N$$

where

phase shift: $\theta_n \in [-\pi, \pi)$

(our proposed model)

reflection amplitude: $\boxed{\beta_n(\theta_n)} = (1 - \beta_{\min}) \left(\frac{\sin(\theta_n - \phi) + 1}{2} \right)^k + \beta_{\min}$

S. Abeywickrama, R. Zhang, Q. Wu, and C. Yuen, "Intelligent reflecting surface: practical phase shift model and beamforming optimization," IEEE Transactions on Communications, vol. 68, no. 9, pp. 5849-5863, Sept. 2020.

RIS Research in Physical Layer #1
Practical Phase Shift Model

with ideal model (widely used in the literature)

$$\min_{\{\mathbf{w}_k\},\mathbf{v},\{\theta_n\}} \sum_{k=1}^{K} \|\mathbf{w}_k\|^2$$

$$\text{s.t.} \frac{|(\mathbf{v}^H\mathbf{\Phi}_k + \mathbf{h}_{d,k}^H)\mathbf{w}_k|^2}{\sum_{j\neq k}^{K} |(\mathbf{v}^H\mathbf{\Phi}_k + \mathbf{h}_{d,k}^H)\mathbf{w}_j|^2 + \sigma_k^2} \geq \gamma_k$$

$$v_n = e^{\jmath\theta_n}, n = 1, \ldots, N,$$

$$-\pi \leq \theta_n \leq \pi, n = 1, \ldots, N,$$

with practical model (our proposed)

$$\min_{\{\mathbf{w}_k\},\mathbf{v},\{\theta_n\}} \sum_{k=1}^{K} \|\mathbf{w}_k\|^2$$

$$\text{s.t.} \frac{|(\mathbf{v}^H\mathbf{\Phi}_k + \mathbf{h}_{d,k}^H)\mathbf{w}_k|^2}{\sum_{j\neq k}^{K} |(\mathbf{v}^H\mathbf{\Phi}_k + \mathbf{h}_{d,k}^H)\mathbf{w}_j|^2 + \sigma_k^2} \geq \gamma_k$$

$$v_n = \beta_n(\theta_n) e^{\jmath\theta_n}, n = 1, \ldots, N,$$

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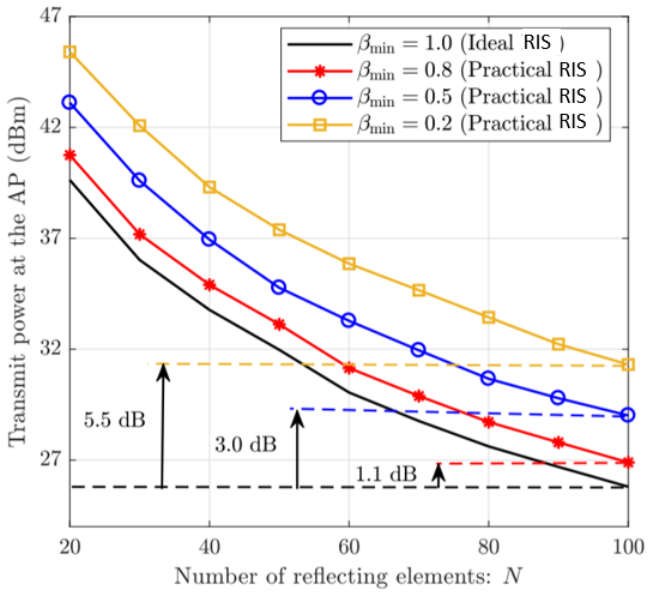


The **power loss is non-negligible,** implying that the consideration of RIS hardware imperfection is indeed crucial for the beamforming design and achievable performance in practical systems.

S. Abeywickrama, R. Zhang, Q. Wu, and C. Yuen, "Intelligent reflecting surface: practical phase shift model and beamforming optimization," IEEE Transactions on Communications, vol. 68, no. 9, pp. 5849-5863, Sept. 2020.

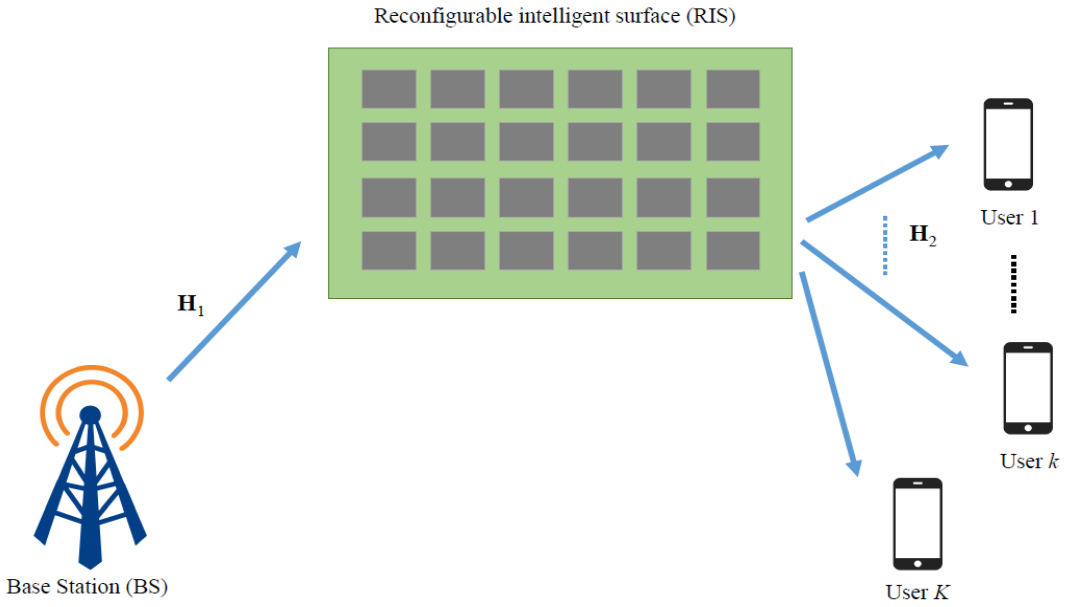
RIS Research in Physical Layer #2
Channel Estimation

Challenges

- Channel estimation in RIS-assisted multi-user communications is a challenging task due to the massive channel training overhead required.

Novelty

- This paper adopts PARAllel FACtor (PARAFAC) based channel estimation method and alternating least squares (ALS) algorithm to estimate all involved channels **individually** in a RIS-aided multi-user MISO system.
- The considered RIS-based multi-user MISO system consisting of a M-antenna base station simultaneously serving in the K single-antenna mobile users with N RIS elements.



L. Wei, C. Huang, G. C. Alexandropoulos, C. Yuen, Z. Zhang and M. Debbah, "Channel Estimation for RIS-Empowered Multi-User MISO Wireless Communications," in IEEE Transactions on Communications, pp. 1-14, 2021.

RIS Research in Physical Layer #2
Channel Estimation

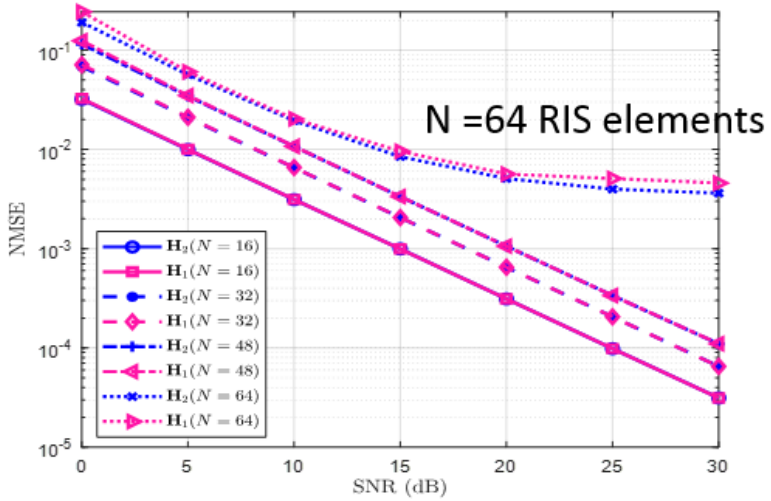
$$\mathbf{Y}_p \triangleq \mathbf{H}_2 D_p(\mathbf{\Phi})\mathbf{H}_1\mathbf{X} + \mathbf{W}_p$$

$$\widetilde{\mathbf{Z}}_p \triangleq \mathbf{Y}_p\mathbf{X}^H = \mathbf{Z}_p + \widetilde{\mathbf{W}}_p$$

Mode-1: $\mathbf{Z}_\alpha = (\mathbf{H}_1^T \circ \mathbf{\Phi})\mathbf{H}_2^T \in \mathbb{C}^{PM\times K}$,

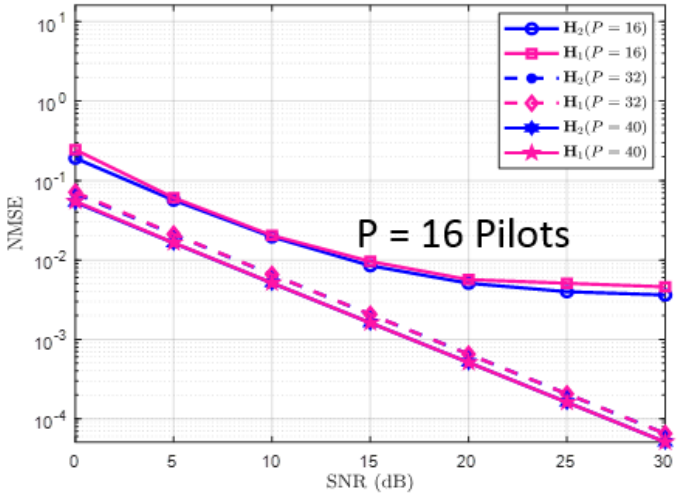
Mode-2: $\mathbf{Z}_\beta = (\mathbf{\Phi} \circ \mathbf{H}_2)\mathbf{H}_1 \in \mathbb{C}^{KP\times M}$,

Mode-3: $\mathbf{Z}_\gamma = (\mathbf{H}_2 \circ \mathbf{H}_1^T)\mathbf{\Phi}^T \in \mathbb{C}^{MK\times P}$.



NMSE performance of the proposed algorithm versus the SNR in dB for $M = K = T = 64$, $P = 16$, and various values of N.

The larger N reduces the performance (for fixed P)



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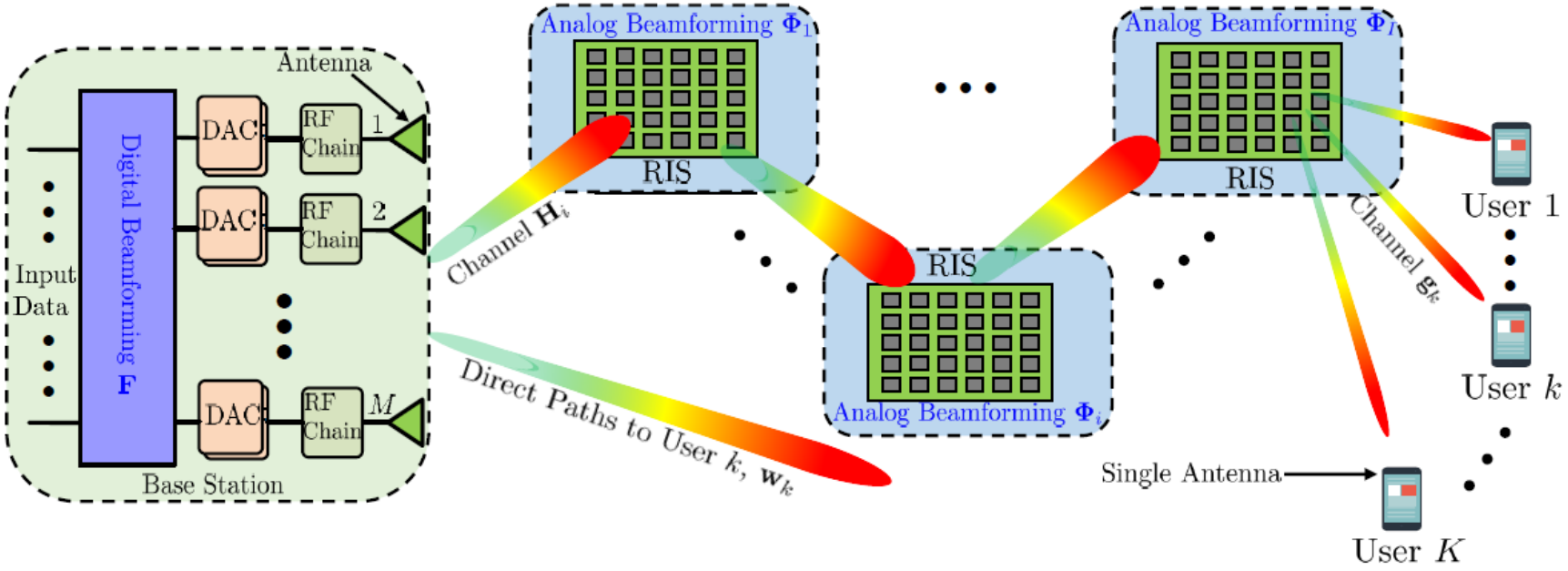
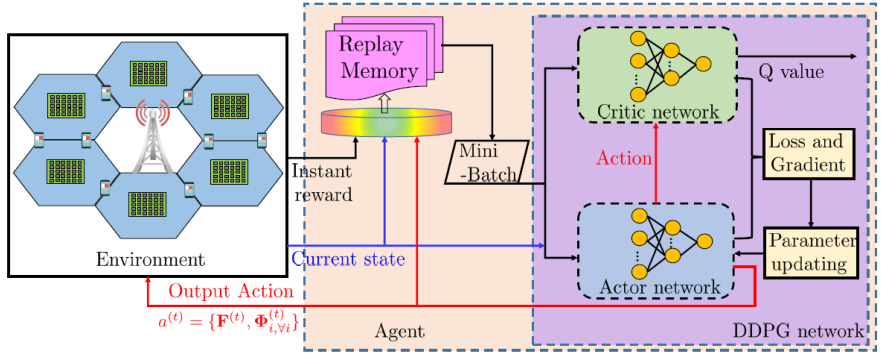
RIS Research in Physical Layer #3
Hybrid Beamforming Architecture

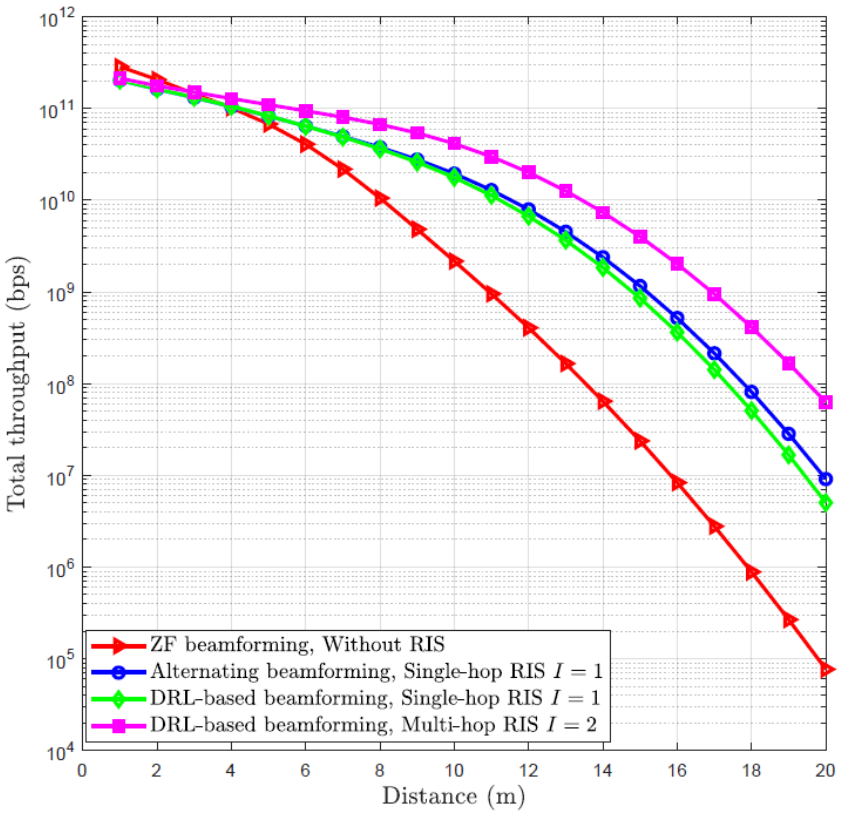


In contrast to the traditional beamforming architectures, a key novelty of this scheme is to take full advantage of RISs with the unique programmable feature **as an external and standalone analog beamforming**, which not only can remove internal analog beamforming at BS that simplifies the architecture and reduces cost, but also improve the beamforming performance of THz-band communication systems significantly.

C. Huang, Z. Yang, G. C. Alexandropoulos, K. Xiong, L. Wei, C. Yuen, Z. Zhang, M. Debbah, "Multi-hop RIS-Empowered Terahertz Communications: A DRL-based Hybrid Beamforming Design", IEEE JSAC, vol. 39, June 2021, pp. pp. 1663-1677.

RIS Research in Physical Layer #3
Hybrid Beamforming Architecture



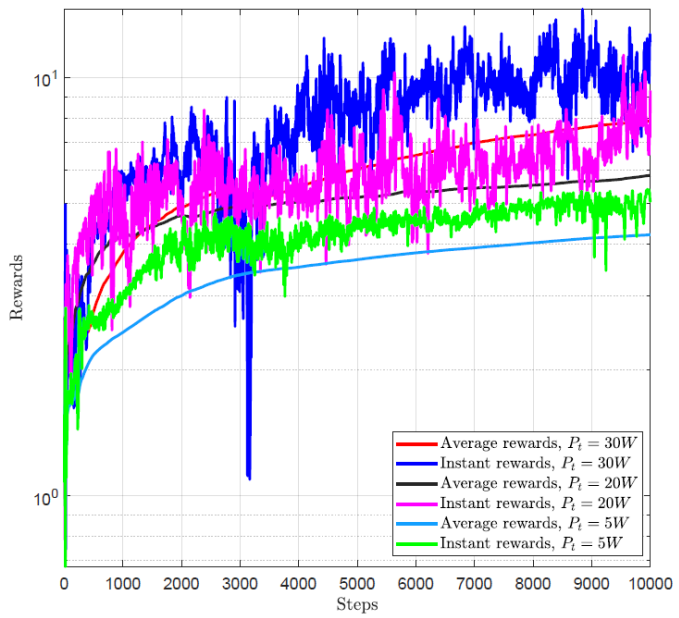


Total throughput versus transmission distance

Multi-hop (i.e. 2-hop) means that received signals are not only via the hop 2, but also hop 1 and direct path.

Single-hop means that received signals are via hop 1 and direct path

Without RIS: means that it just is the direct path signals.



Rewards versus steps at Pt = 5W, Pt = 20W, and Pt = 30W. Larger power, more fluctuation, lower convergence.

C. Huang, Z. Yang, G. C. Alexandropoulos, K. Xiong, L. Wei, C. Yuen, Z. Zhang, M. Debbah, "Multi-hop RIS-Empowered Terahertz Communications: A DRL-based Hybrid Beamforming Design", IEEE JSAC, vol. 39, June 2021, pp. pp. 1663-1677.

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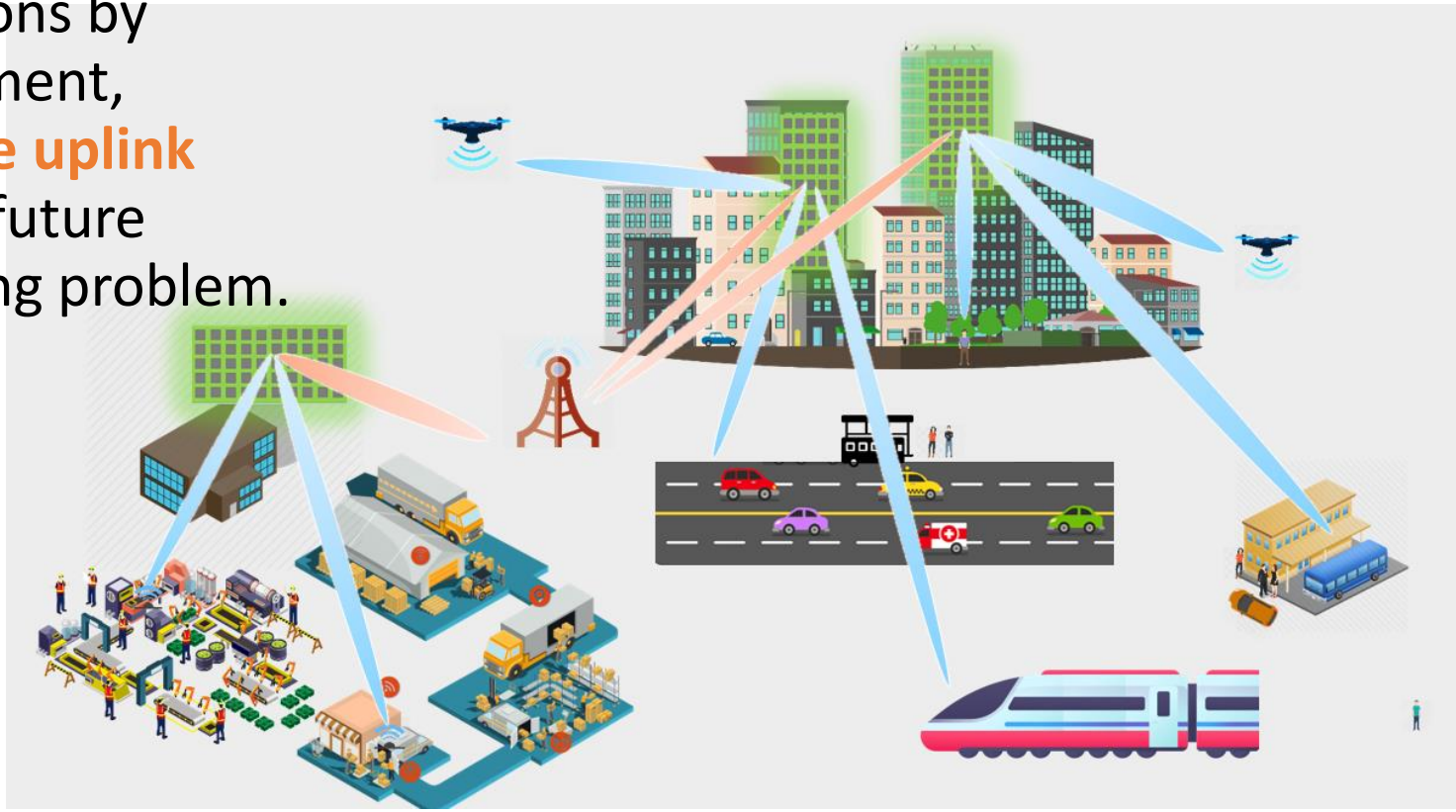
  - Channel Estimation
  - Hybrid Beamforming Architecture
- RIS in MAC Layer
  - Multiple Uplink
  - Multi-Pair Communications
  - RIS with Spectrum Learning

Motivation for MAC in RIS

Since RISs researches in the physical layer have witnessed the coverage enhancement, the achievable rate increment, and the energy efficiency improvement of wireless communications by reconfiguring the propagation environment, **enabling multiple devices to access the uplink channel with the assistance of RISs** in future wireless networks is a crucial challenging problem.



Motivated by this, we study the RIS-assisted MAC protocol for the multi-user uplink communication system.

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, Z. Han, D. Niyao, H. V. Poor, L. Hanzo, "AI-Assisted MAC for Reconfigurable Intelligent Surface-Aided Wireless Networks: Challenges and Opportunities," IEEE Communication Magazine, May 2021. (Accepted)

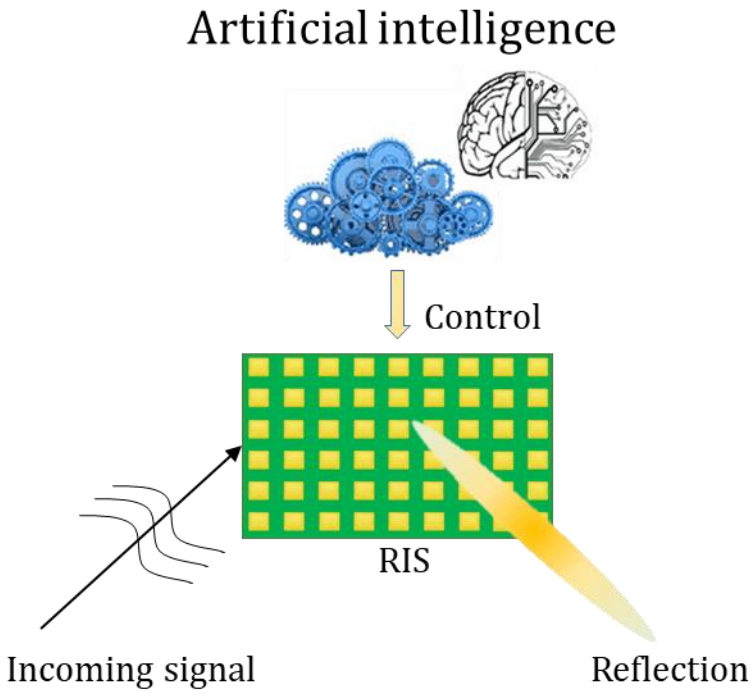
Research Challenges

Gap

- Several MAC-related works have been discussed for RIS-aided wireless networks following the recent breakthrough in the RIS physical layer technologies. However, most of them are centralized designs and lack distributed designs.

Challenges

- In our work, to achieve real-time configuration of RISs at low cost and improve the benefits of RISs, by designing various MAC protocols for RIS-aided wireless networks.



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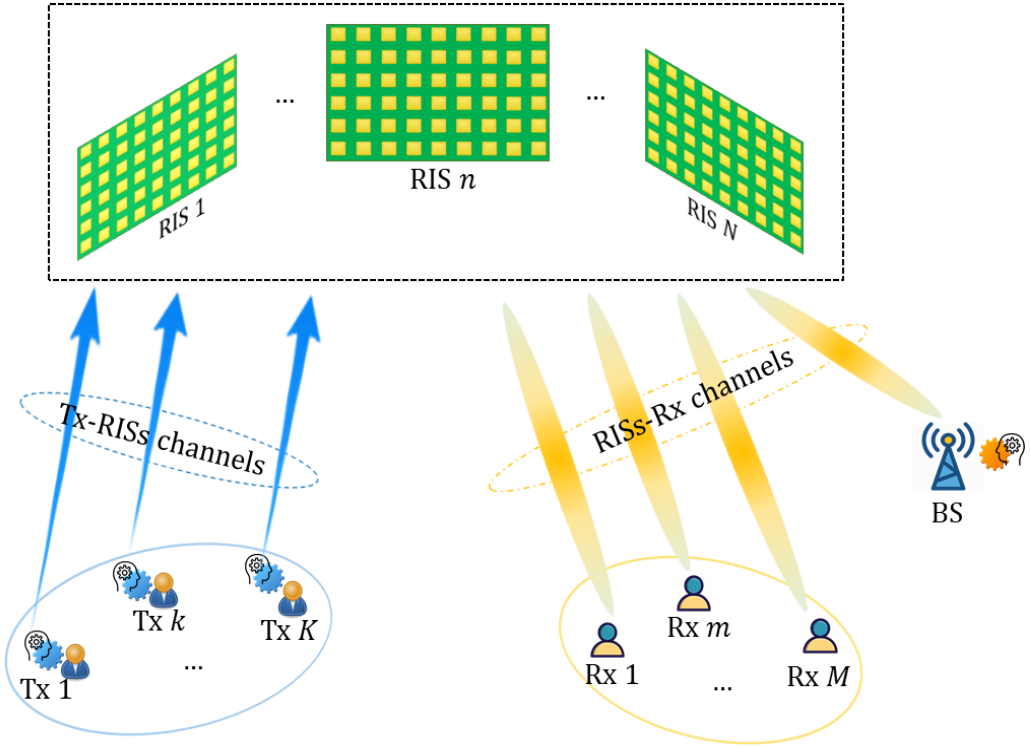
Scenarios

Four types

- **S1**: Single RIS-aided multiple-Tx single-Rx
- **S2**: Single RIS-aided multiple-Tx multiple-Rx
- **S3**: Multiple RIS-aided multiple-Tx single-Rx
- **S4**: Multiple RIS-aided multiple-Tx multiple-Rx



X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, Z. Han, D. Niyao, H. V. Poor, L. Hanzo, "AI-Assisted MAC for Reconfigurable Intelligent Surface-Aided Wireless Networks: Challenges and Opportunities," IEEE Communication Magazine, May 2021. (Accepted)

MAC Protocols

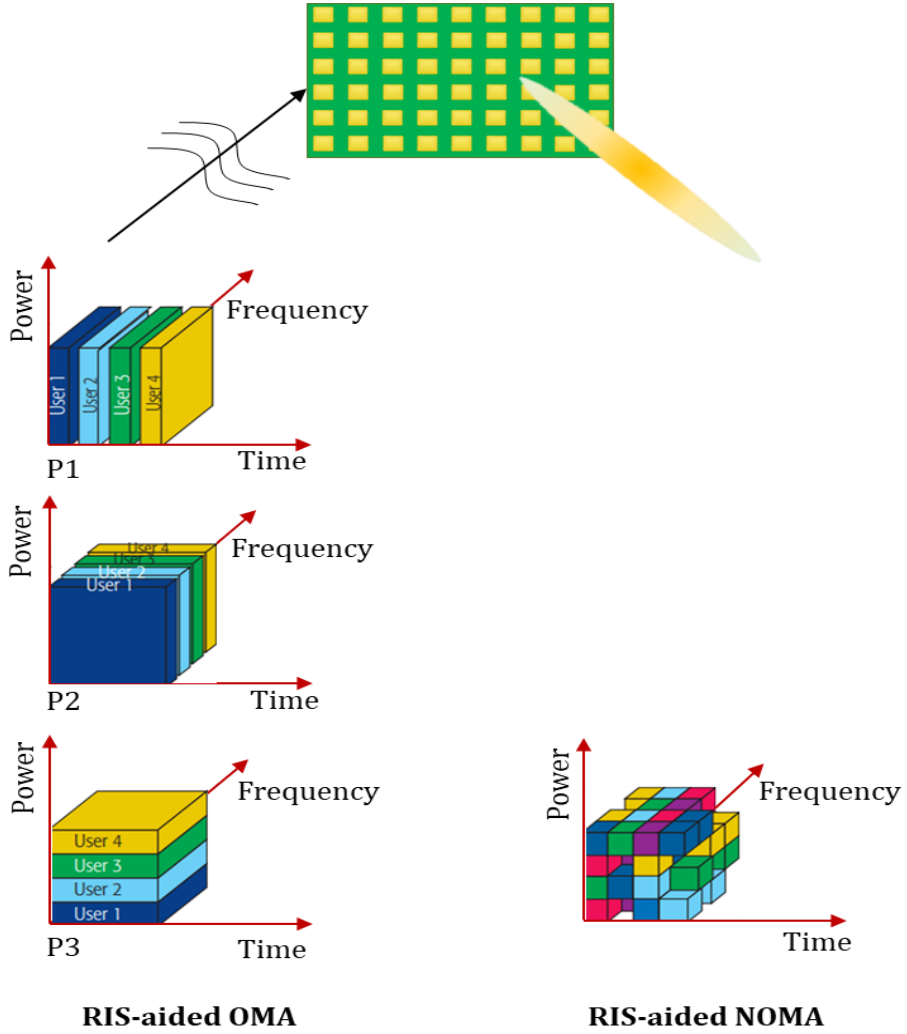
RIS-aided OMA

- **P1**: RIS-aided time division multiple access (TDMA)
- **P2:** RIS-aided frequency division multiple access (FDMA)
- **P3**: RIS-aided spatial division multiple access (SDMA)
- **P4**: RIS-aided carrier sensing multiple access (CSMA)

RIS-aided NOMA

Design Objects

- **O1**: System throughput
- **O2**: EE performance
- **O3**: Fairness
- **O4**: Overhead
- **O5**: Latency

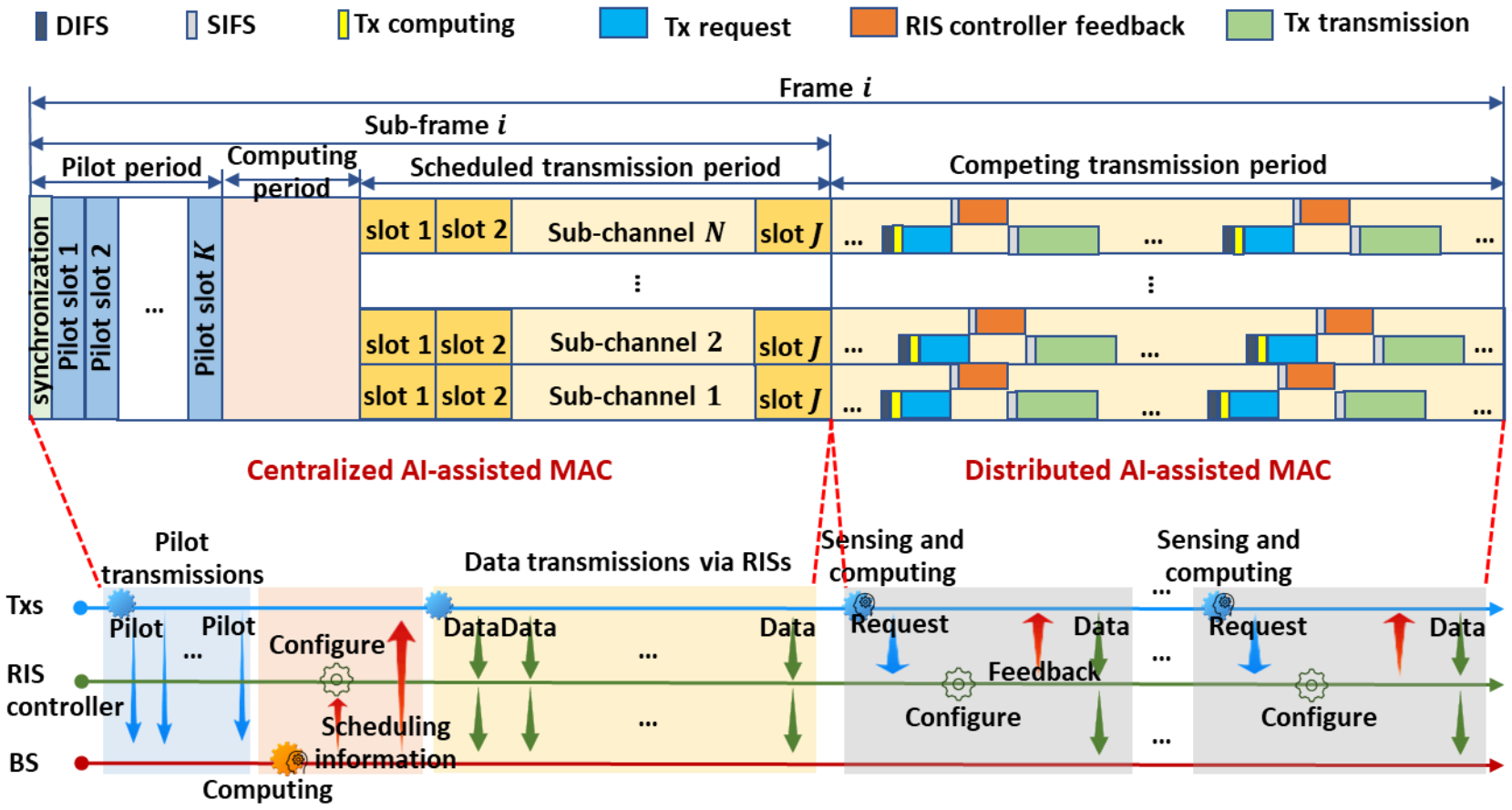


X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, Z. Han, D. Niyao, H. V. Poor, L. Hanzo, "AI-Assisted MAC for Reconfigurable Intelligent Surface-Aided Wireless Networks: Challenges and Opportunities," IEEE Communication Magazine, May 2021. (Accepted)

MAC Designs

Three AI-assisted MAC protocols for RIS-aided wireless networks:

- Centralized AI-assisted
- Distributed AI-assisted
- Hybrid AI-assisted



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Design Challenges

Rendezvous

For the distributed MAC design, how to joint improve the MAC efficiency and the RIS utilization by implementing an effective rendezvous among users.

RIS Computation Complexity

How to reduce the computation complexity of RIS configuration by designing a high effective MAC design in RIS-assisted wireless networks.

Spectrum Sensing

Designing a distributed MAC protocol, accurate spectrum sensing is quite critical for reducing collisions and interferences. Therefore, intelligent spectrum learning can be explored to improve sensing efficiency and accuracy.

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, Z. Han, D. Niyao, H. V. Poor, L. Hanzo, "AI-Assisted MAC for Reconfigurable Intelligent Surface-Aided Wireless Networks: Challenges and Opportunities," IEEE Communication Magazine, May 2021. (Accepted)

RIS MAC Outline

1. Reconfigurable Intelligent Surfaces (RISs)-Aided MAC for Multiple Uplink Communications
2. RIS-assisted Multi-Pair Aerial-Terrestrial Communications via Multi-task Learning
3. Intelligent Spectrum Learning for Wireless Networks with RIS

Research Challenges

Gap

- Unlike traditional MAC, configuration at RIS is required.
- The RIS-aided MAC explorations on the **distributed implementation** are very limited due to the complexity of **information exchange** and **competition**.

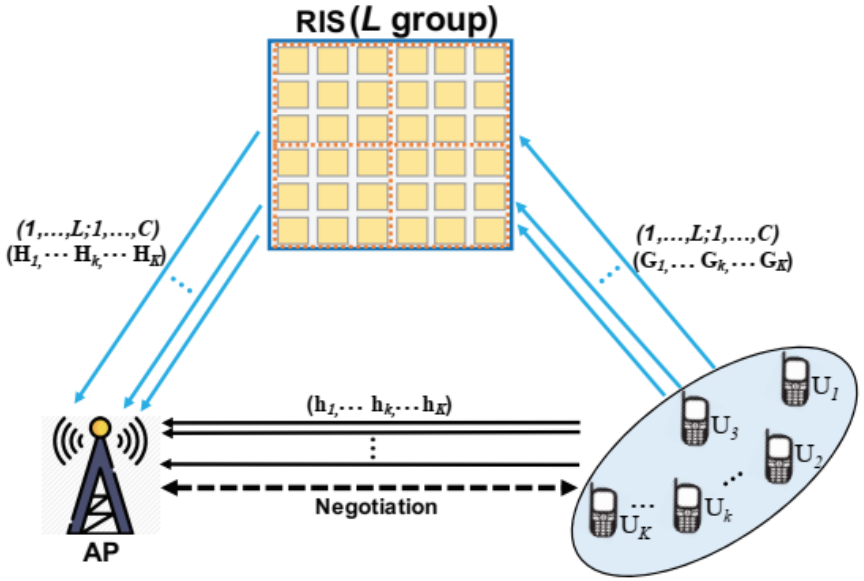
Challenges

- How to design the distributed RISs-aided MAC with low complexity?
- How to avoid transmission collisions when using RISs?
- How to jointly optimize the RIS configuration and MAC layer parameters?

X. Cao, B. Yang, H. Zhang, C. Huang, C. Yuen and Z. Han, "Reconfigurable Intelligent Surface-Assisted MAC for Wireless Networks: Protocol Design, Analysis, and Optimization," IEEE Internet of Things Journal, Mar. 2021. (Early access)

Contributions

- We design a distributed RIS-aided MAC protocol, where the information exchange and RIS-aided data transmissions are fit together in a **distributed way**. The information exchange is needed to realize the RIS allocation and reconfiguration.
- We propose the **multi-dimension reservation (MDR)** scheme based on information exchange to avoid RIS-aided transmission collisions, thus improving the RIS elements utilization.
- An **optimization problem** is formulated by considering RIS configuration, transmission power, and MAC parameters to maximize the system capacity.



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RIS-Aided MAC Design

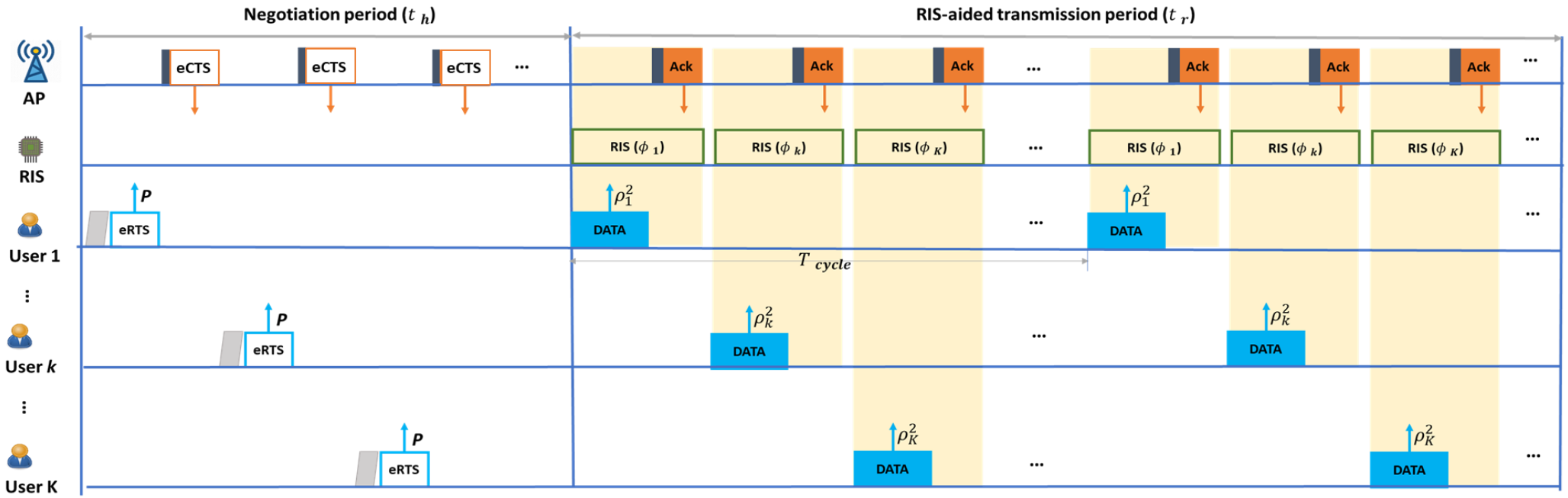
Multi-dimension	Operations
Time slot	User → AP → User
Frequency	User → AP → User
Power	AP → User
RIS phase	AP → RIS

<u>MDR Scheme</u>

MDR scheme means that each user can reserve the multiple dimensions before the data transmission, MDR includes **time zone, frequency zone , power zone , RIS coefficients zone.** Note that **one frequency zone corresponds to one RIS group**, i.e., the accordingly RIS group is reserved once the sub-channel is reserved.

X. Cao, B. Yang, H. Zhang, C. Huang, C. Yuen and Z. Han, "Reconfigurable Intelligent Surface-Assisted MAC for Wireless Networks: Protocol Design, Analysis, and Optimization," IEEE Internet of Things Journal, Mar. 2021. (Early access)

RIS-Aided MAC Design

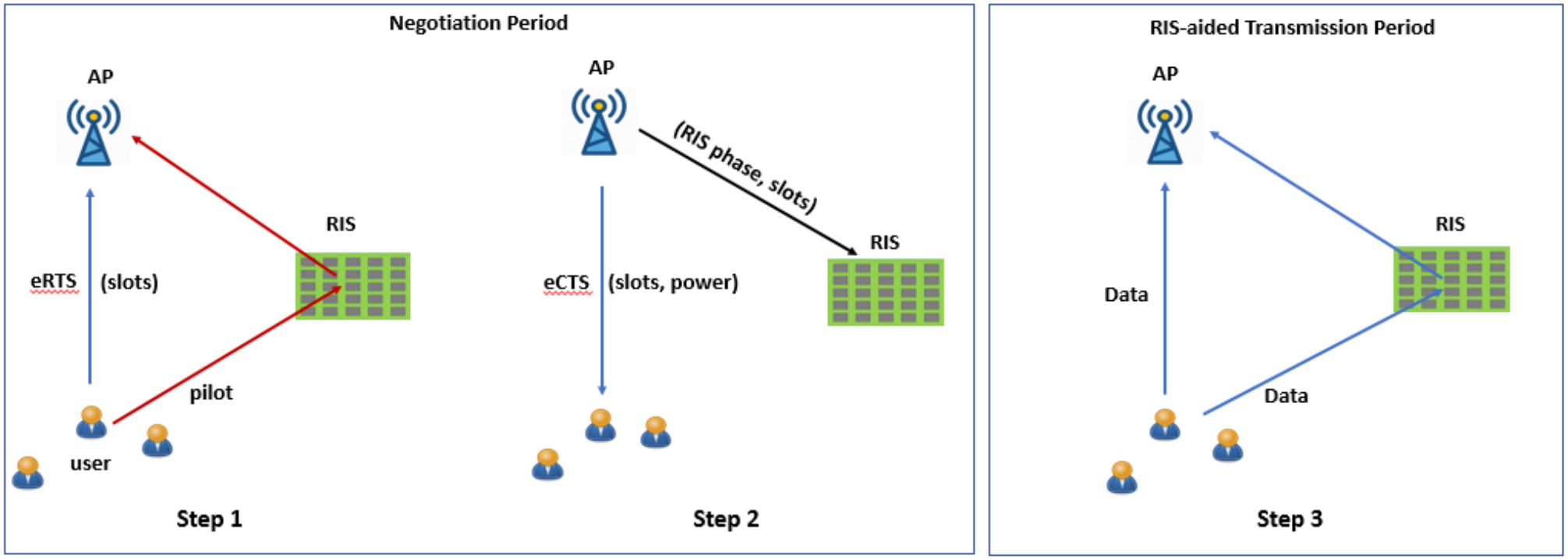


Frame Structure

- The time frame is separated into two phases: **the negotiation phase** and **the RIS-aided transmission phase**;
- In the negotiation phase, each user **competes for** the access privilege and **operates MDR**;
- In the RIS-aided transmission phase, the RIS controller controls the RIS elements **according to MDR information**.

X. Cao, B. Yang, H. Zhang, C. Huang, C. Yuen and Z. Han, "Reconfigurable Intelligent Surface-Assisted MAC for Wireless Networks: Protocol Design, Analysis, and Optimization," IEEE Internet of Things Journal, Mar. 2021. (Early access)

RIS-aided Single Channel Multi-User Communications (SCMU)



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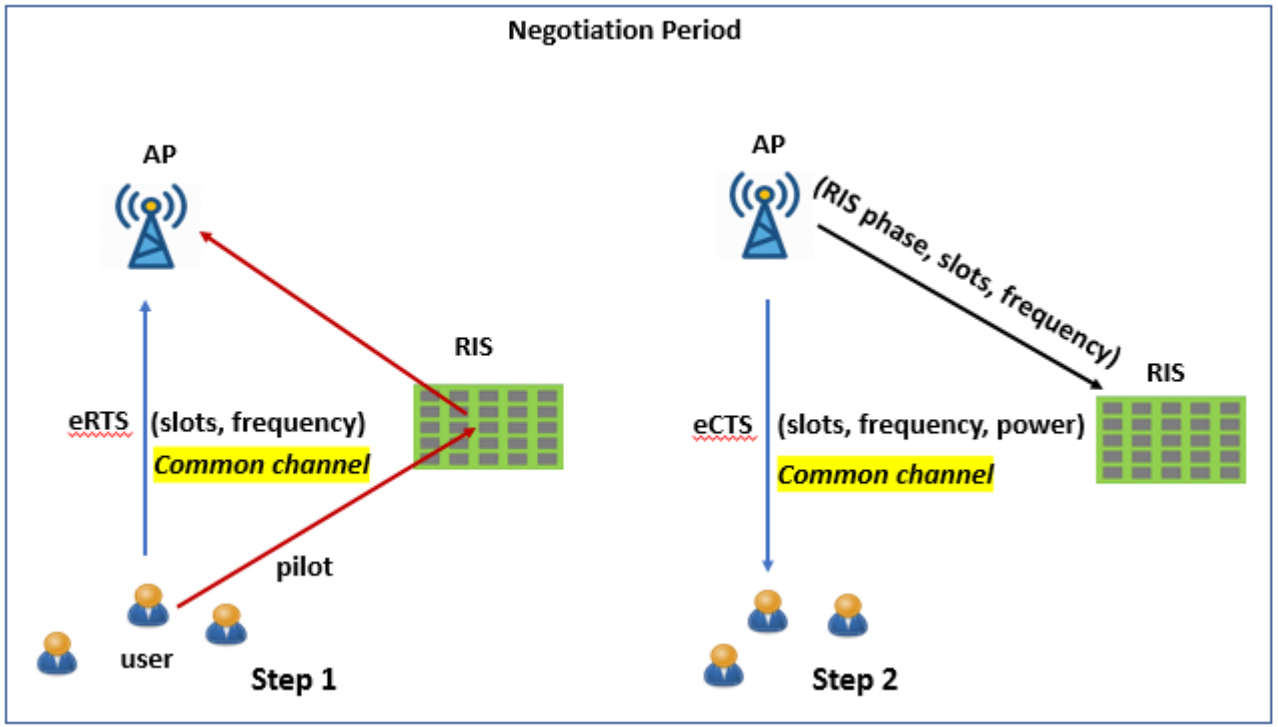
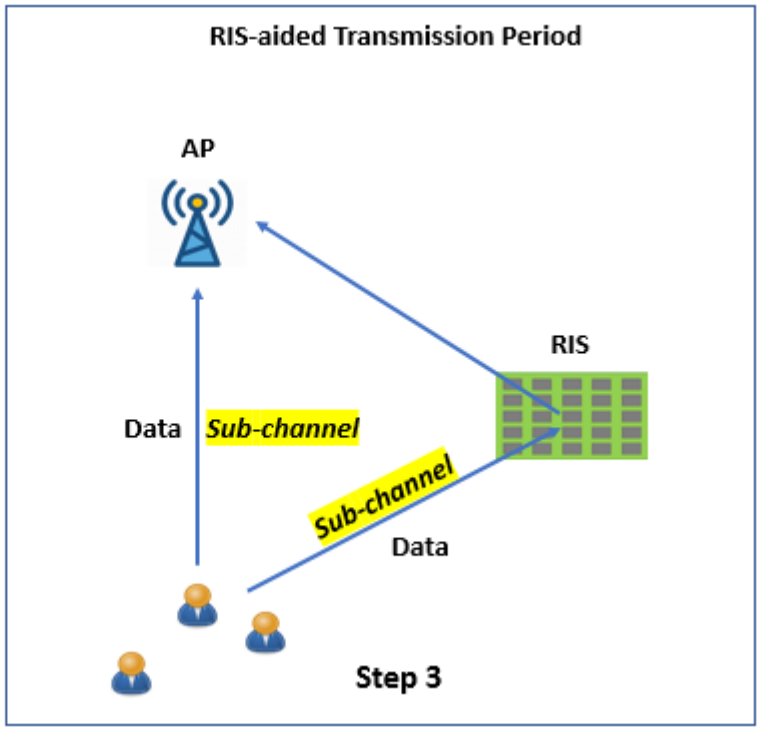
RIS-aided Multiple Channel Multi-User Communications (MCMU)





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Problem Formulation

Single Channel Problem

$$\Im_{Total}^{SCMU} = \frac{t_p t_h \zeta_s}{T t_s K} B \sum_{k=1}^{K} r_k \log_2\left(1 + \mathrm{SNR}_k^{SCMU}\right)$$

$$\mathbf{P1}: \max_{\rho_1{}^2,\ldots,\rho_K{}^2;\boldsymbol{\Theta}_1,\ldots,\boldsymbol{\Theta}_K;r_1\ldots,r_K} \Im_{Total}^{SCMU},$$

$$\text{s.t.} \quad \text{C1:} \quad 0 \le \rho_k^2 \le P - P_{RIS}, \ \forall k,$$

constrains the transmit power

$$\text{C2:} \quad |\phi_k^n| = 1, \quad \forall k, n,$$

$$\text{C3:} \quad \theta_k^n \in \Omega, \quad \forall k, n,$$

constrain RISs coefficients

$$\text{C4:} \quad t_h + t_r = T, \quad \forall k$$

$$\text{C5:} \quad \frac{t_p}{t_s} r_{max} \zeta_s \le \frac{t_r}{t_h}, \quad \forall k$$

constrain the negotiation period and the transmission period

$$\text{C6:} \quad 1 \le r_k \le r_{max}, \quad \forall k,$$

constrains the number of transmissions

Multi Channel Problem

$$\Im_{Total}^{MCMU} = \sum_{j=1}^{C} \sum_{k=1}^{K} \frac{t_p r_k}{T} \varepsilon_k^j \pi_j R_k^{MCMU}\left(\rho_k, \phi_k\right)$$

$$\mathbf{P3}: \max_{\rho_1{}^2,\ldots,\rho_K{}^2;\phi_1^{l(n)},\ldots,\phi_K^{l(n)}} \sum_{k=1}^{K} \log_2\left(1 + \mathrm{SNR}_k^{MCMU}\right)$$

$$\text{s.t.} \quad \text{C7:} \quad 0 \le \rho_k{}^2 \le P - \frac{1}{L} P_{RIS}, \ \forall k,$$

$$\text{C8:} \quad |\phi_k^{l(n)}| = 1, \ n \in l, \quad \forall k, l,$$

$$\text{C9:} \quad \theta_k^{l(n)} \in \boldsymbol{\Omega}, \ n \in l, \quad \forall k, l,$$

$$\text{C10:} \quad 1 \le l \le L, L = C,$$

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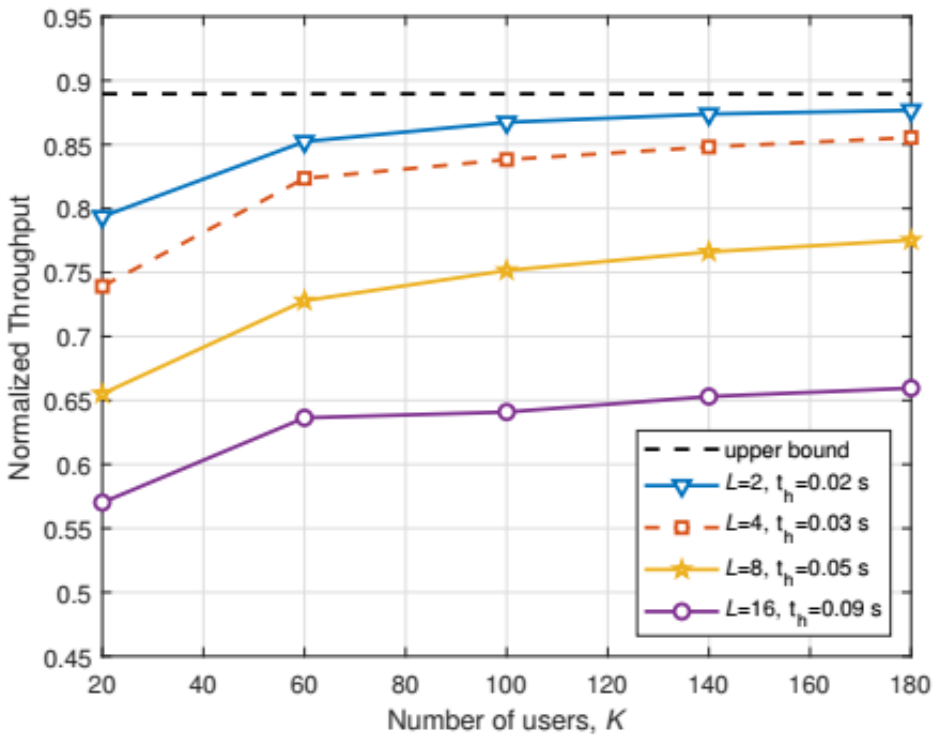
Simulation Results

In the RIS-aided multi-user communication system, the normalized throughput based on the proposed RIS-aided MAC are evaluated as follows:

- The fewer number of RIS group or the shorter negotiation period, the better throughput. There is a trade-off between the number of users and the negotiation period. As a large number of users needs a longer negotiation period.



The normalized throughput vs. the number of users

L = number of group, t_h = negotiation period

X. Cao, B. Yang, H. Zhang, C. Huang, C. Yuen and Z. Han, "Reconfigurable Intelligent Surface-Assisted MAC for Wireless Networks: Protocol Design, Analysis, and Optimization," IEEE Internet of Things Journal, Mar. 2021. (Early access)

Conclusions

- We investigate how to design the **distributed RIS-aided MAC protocol** to improve the system performance of **the RIS-aided multi-user uplink communications**.
- We propose the RIS-aided **multiple dimension reservation (MDR)** scheme. On this basis, RIS-aided Single Channel Multi-User / Multi Channel Multi-User communications are explored, respectively.
- The problem that joints MAC design and RIS configuration for **RIS-aided SCMU/MCMU communications** is formulated as an MINLP, which can be solved using alternative iterative method.

X. Cao, B. Yang, H. Zhang, C. Huang, C. Yuen and Z. Han, "Reconfigurable Intelligent Surface-Assisted MAC for Wireless Networks: Protocol Design, Analysis, and Optimization," IEEE Internet of Things Journal, Mar. 2021. (Early access)

RIS MAC Outline

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2. RIS-assisted Multi-Pair Aerial-Terrestrial Communications via Multi-task Learning
3. Intelligent Spectrum Learning for Wireless Networks with RIS

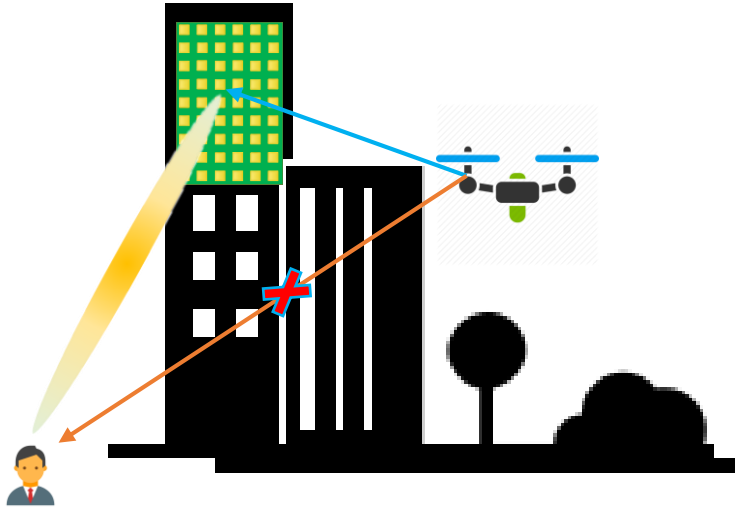
Comparison Work I and Work II

	Protocol Design	RIS Group	Problem Formulation	System Model	Power Control
Work I	Time frame, distributed, contention-based.	Fixed	MAC parameters and RIS reflection parameters joint optimization	Multi-user uplink to Single AP	Yes
Work II	Time frame, centralized, schedule-based.	Dynamical	RIS group allocation and RIS reflection parameters joint optimization	Multi-pair communications	No

Motivation

The aerial-terrestrial communication system constitutes an efficient paradigm for complementing terrestrial communications. However, the line-of-sight (LoS) transmissions in this system are prone to severe deterioration due to complex propagation environments in urban areas. The emerging technology of reconfigurable intelligent surfaces (RISs) has recently become a potential solution to mitigate propagation-induced impairments at a low cost.

Motivated by this, we investigate the RIS-assisted Aerial-Terrestrial Communications via Multi-task Learning.



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Research Challenges

Gaps

- Several existed works have been explored in an RIS-assisted UAV communication system to improve energy efficiency. However, in such a system, designing a transmission protocol and developing a transmission strategy are also important to improve link performance and coverage.

Challenges

- How to design an RIS-assisted transmission protocol for an aerial-terrestrial system?
- How to design an RIS-assisted transmission strategy?
- How to allocate the RIS elements and configure the RIS coefficients at a low cost?

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

Contributions

- We design an adaptive RIS-assisted transmission protocol, which is a frame-based periodic structure, where channel estimation, transmission strategy, and data transmissions are alternately executed in a frame.

- We propose an RIS-assisted transmission strategy to allocate the RIS elements and configure the RIS coefficients. By executing this strategy, the RIS controller decides for UAVs whether to communicate via the RIS.

- We introduce a deep neural network-based machine learning model, called multi-task learning, to infer the optimal transmission strategy accurately in near-real-time. We then evaluate the proposed protocol and solution methods.

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

System Model

- Channel Links

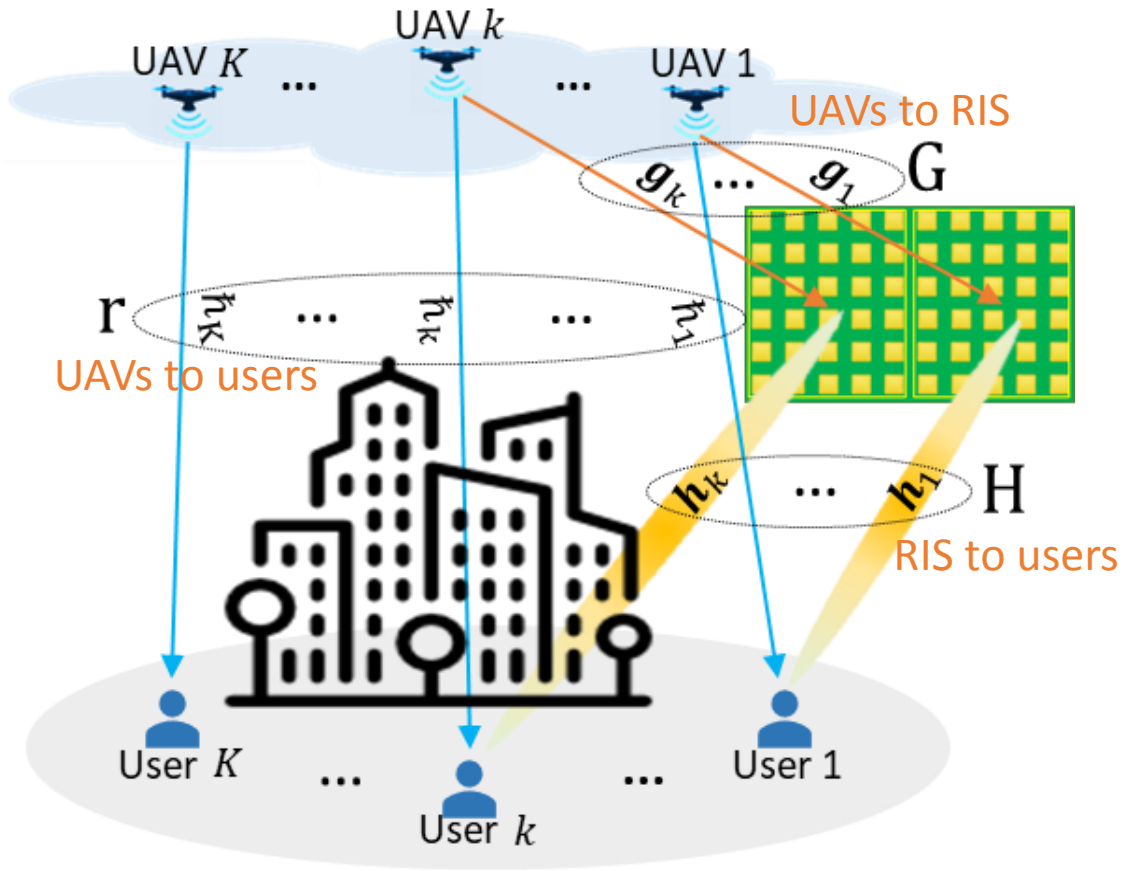
$$\mathbf{G} = \{\mathbf{g}_1, \mathbf{g}_2, \ldots, \mathbf{g}_K\}$$
$$\mathbf{H} = \{\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_K\}$$
$$\mathbf{r} = \{\hbar_1, \hbar_2, \ldots, \hbar_K\}$$

- Received signal at k-th user

The signal of from UAV k

$$y_k = \underbrace{\hbar_k s_k}_{\text{direct path}} + \underbrace{\mathbf{h}_k \mathbf{\Theta}_k \mathbf{g}_k s_k}_{\text{reflect paths}} + w_k$$

Noise signal



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RIS-Assisted Transmission Strategy Design

- Strategy for UAV *k*

Phase shift vector of allocated RIS group for UAV k

$$\mathcal{D}_k = \{u_k, \boldsymbol{\theta}_k\}$$

RIS group allocation for UAV k

where

The label of RIS group l

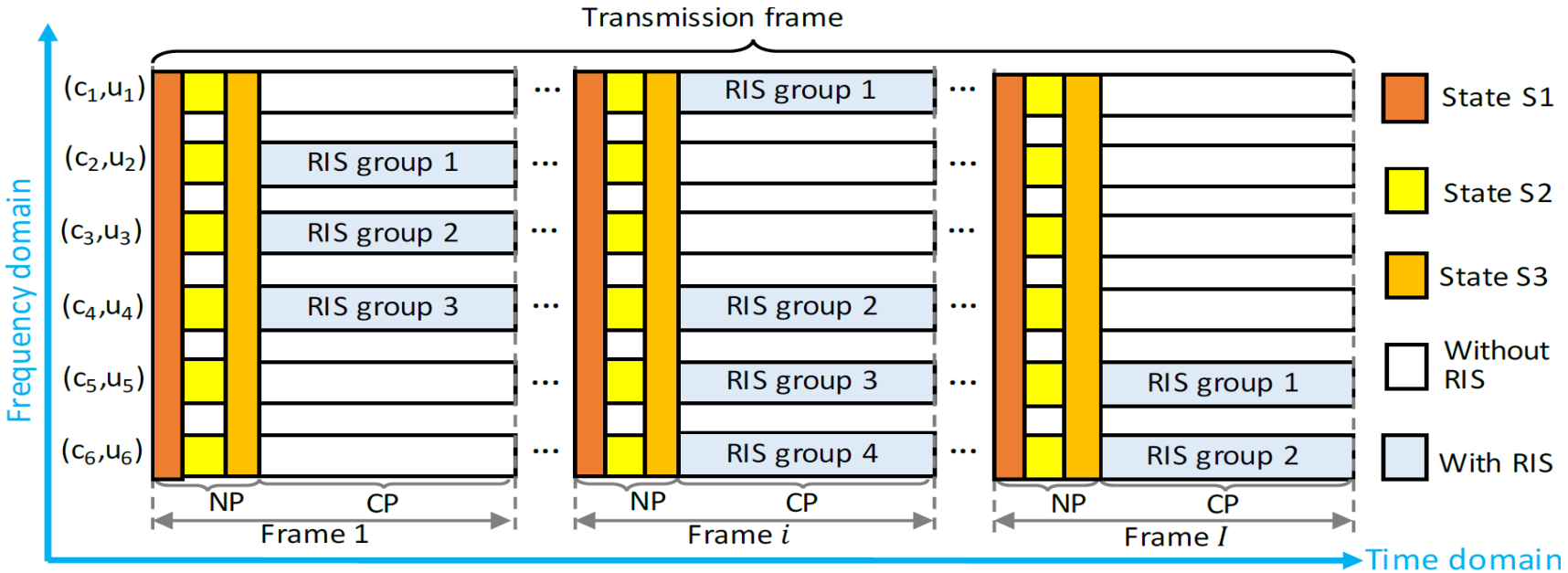
$$u_k = \begin{cases} l, & \text{if UAV } k \text{ transmits via RIS group } l, \\ 0, & \text{if UAV } k \text{ transmits without the RIS.} \end{cases}$$

$$f(u_k) = \begin{cases} 1, & u_k \neq 0, \\ 0, & u_k = 0. \end{cases}$$

Whether an RIS group is assigned to UAV k

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

RIS-Aided Transmission Protocol Design

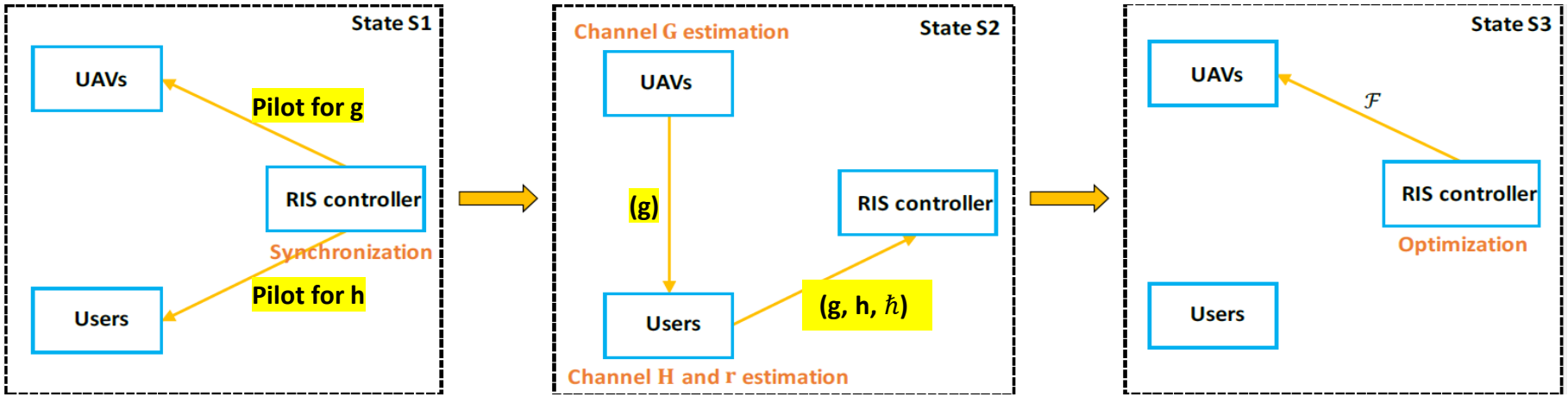


Protocol Design

- In the frequency domain, each UAV-user pair occupies a sub-carrier.
- In the time domain, the transmission frame can be divided into I frames. Each frame consists of two phases: the negotiation phase (NP) and the communication phase (CP). Furthermore, each NP consists of three states: synchronization (state S1), channel estimation (state S2), and optimization (state S3).

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

RIS-Aided Transmission Protocol Design



<u>Three states</u>

- At state S1, the RIS controller sends the pilots across the whole frequency band for synchronization and channel estimation.
- At state S2, channel information $\mathbf{g}$, $\mathbf{h}$ and $\hbar$ are estimated and are fed back to the RIS controller.
- At state S3, the RIS controller optimizes the transmission strategy and initiates the transmissions of K UAV-user pairs.

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

Problem Formulation

Overall system capacity optimization at the RIS controller：

P1 (Original problem) :

$$\max_{\mathcal{U},\mathbf{\Psi}} \quad R_{oveall}$$

Problem **P1** can be solved by using alternative iterative algorithm.

$$\text{s.t.}\quad \begin{aligned}
&\text{C1:}\ \ u_k \in \{0, l\}, && \forall k \in \mathcal{K}, l \in \mathcal{L} \\
&\text{C2:}\ \ u_k \neq u_{k'}, && \exists u_k \neq 0, u'_k \neq 0, \forall k, k' \in \mathcal{K}, \\
&\text{C3:}\ \ f(u_k) \in \{0, 1\}, && \forall k \in \mathcal{K}, \\
&\text{C4:}\ \ \sum_{k=1}^{K} f(u_k) = L, && \forall k \in \mathcal{K}, \\
&\text{C5:}\ \ L \leq L_{max}, && \\
&\text{C6:}\ \ P_o \leq P_{max}, && \forall k \in \mathcal{K}, \\
&\text{C7:}\ \ p_k = \{0, \frac{1}{\sum_{k=1}^{K} f(u_k)}\}, && \forall k \in \mathcal{K}, \\
&\text{C8:}\ \ |\ \phi_k^{l_n}| = 1, && \forall k \in \mathcal{K},\ \forall l \in \mathcal{L}, \\
&\text{C9:}\ \ \theta_k^{l_n} \in [0, 2\pi), && \forall k \in \mathcal{K},\ \forall l \in \mathcal{L}.
\end{aligned}$$

RIS-assisted transmission strategy constrains

Power constrain

RIS group constrains

RIS phase reflection coefficients constrains

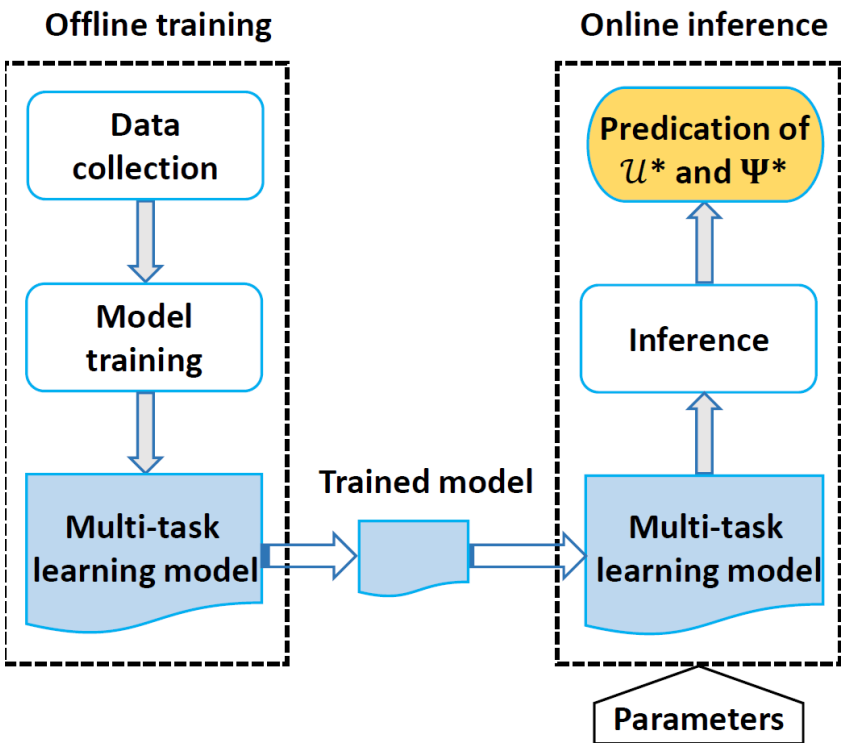
X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

AI-based Solution

The real-time RIS strategy are costly in practice. Also, conventional optimization methods need large number of iterations, and the solution is often sub-optimal. An AI-based method is used to solve problem.

Multi-Task Learning

- Deep neural networks can be designed and trained offline to obtain a multi-task learning model.
- By feeding the parameters (such as the number of UAV-user pairs, RIS size, and channel conditions) into the trained multi-task learning model, the optimal transmission strategy of each UAV-user pair can be inferred online.
- By moving the complexity of online computation to offline training, the complexity of solving problem P1 can be significantly decreased to $\mathcal{O}(1)$.



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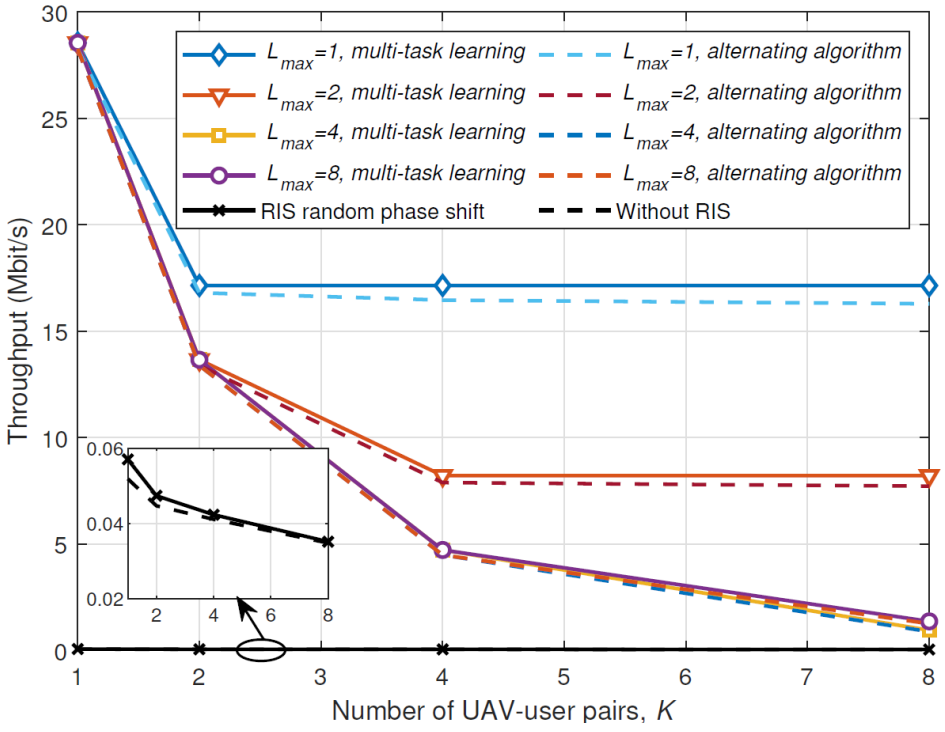
Simulation Results

In an RIS-assisted aerial-terrestrial communication system, *the system throughput* are evaluated as follows:

- With the assistance of RIS, the larger number of RIS groups, the larger number of UAV links can be improved.
- The system throughput significantly improves via the RIS.
- Multi-task learning is slightly better than an alternating algorithm.



The system throughput vs. the number of UAV-user pairs

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Conclusions

- RISs are investigated to enhance the aerial-terrestrial communication system, especially for its coverage and the link performance.
- Based on the proposed transmission strategy, a frame-based RIS-assisted transmission protocol is designed to adaptive to aerial-terrestrial communications.
- The formulated joint optimization of RIS group allocation and RIS configuration can be speed up by using multi-task learning model instead of conventional mathematical methods.

X. Cao, B. Yang, C. Huang, C. Yuen, M. D. Renzo, D. Niyao, Z. Han, "Reconfigurable Intelligent Surface-assisted Aerial-Terrestrial Communications via Multi-task Learning", IEEE Journal on Selected Areas in Communications, Apr 2021. (To appear)

RIS MAC Outline

1. Reconfigurable Intelligent Surfaces (RISs)-Aided MAC for Multiple Uplink Communications
2. RIS-assisted Multi-Pair Aerial-Terrestrial Communications via Multi-task Learning
3. Intelligent Spectrum Learning for Wireless Networks with RIS

Motivation

Naturally, the interfering signals tend to dynamically fluctuate and a conventional RIS 'blindly' reflects both the desired and interfering signals, as shown in Fig. 1.

Motivated by this, we study the spectrum learning-aided RIS framework through learning the inherent features of the incident RF signals at the RIS controller.

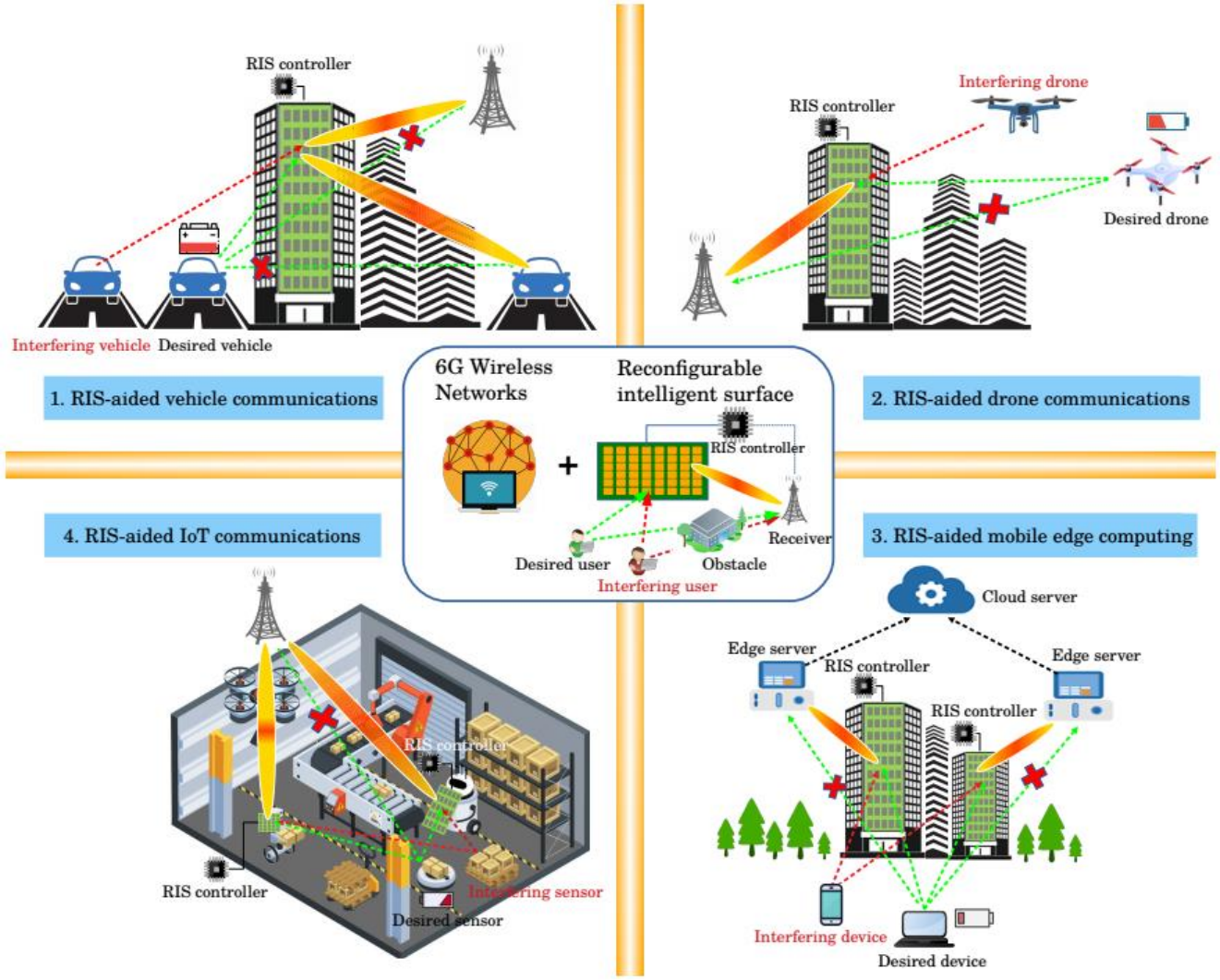

Fig. 1 RISs-empowered applications

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

Research Challenges

Gap

- In reality, the SINR at the receiver might even be degraded compared to a system dispensing with RISs, as illustrated in Fig. 2.
- However, it is not trivial to estimate the dynamically fluctuating interference since conventional RISs are nearly passive surfaces with no active sensing capabilities.

Challenges

- Due to the unpredictable nature of interference, how to detect the incident RF signals and avoid the undesired reflections become a critical challenge.

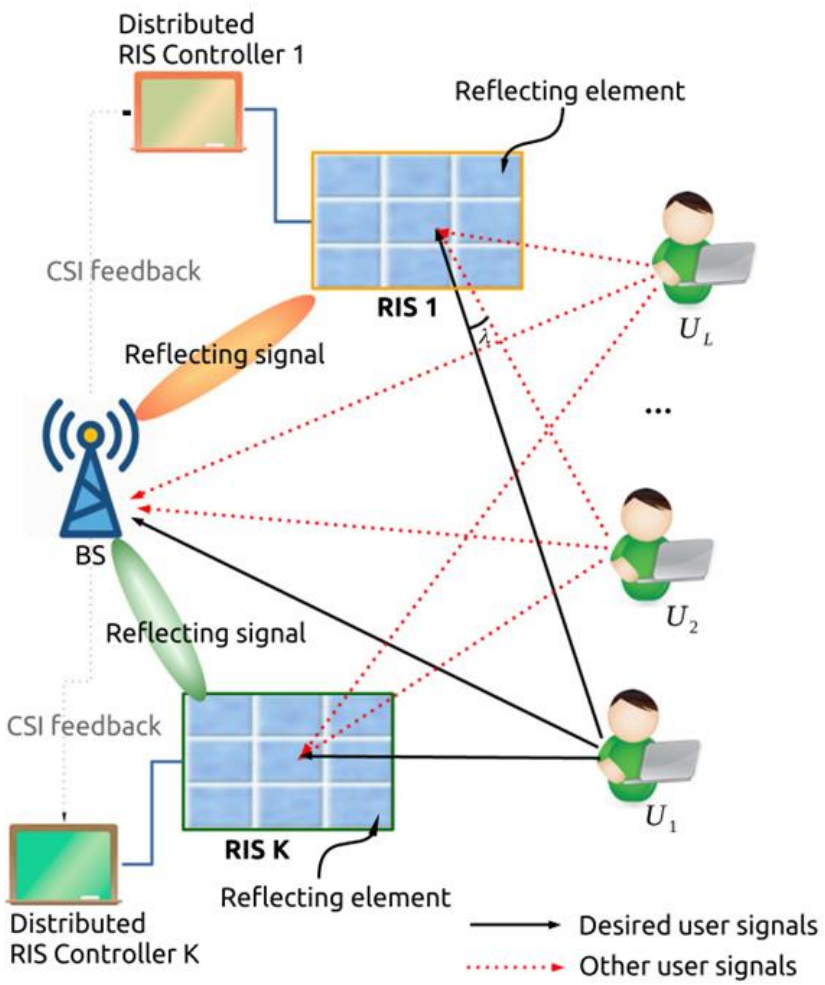

Fig. 2 System model

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

Contributions

- We empower a conventional RIS-assisted wireless system with spectrum learning (SL) capabilities, by leveraging appropriately trained CNN at the RIS controller in order to predict/estimate the interfering devices from the incident signals.
- We further propose a SL-aided ON-OFF RIS control mechanism for maximizing the received SINR at the destination BS, as illustrated in Fig. 3. Note that the ON-OFF status is referred to having the entire set of elements of the RIS to be ON or OFF.
- This is a distributed scheme. Each RIS makes their own decision, by comparing the achievable SINR obtained by reflecting and the SINR of the direct link. If the reflected SINR is larger than that of direct link, then RIS is "ON", and vice versa. It is assumed that perfect CSI can be achieved at the BS and feedback to each RIS controller.

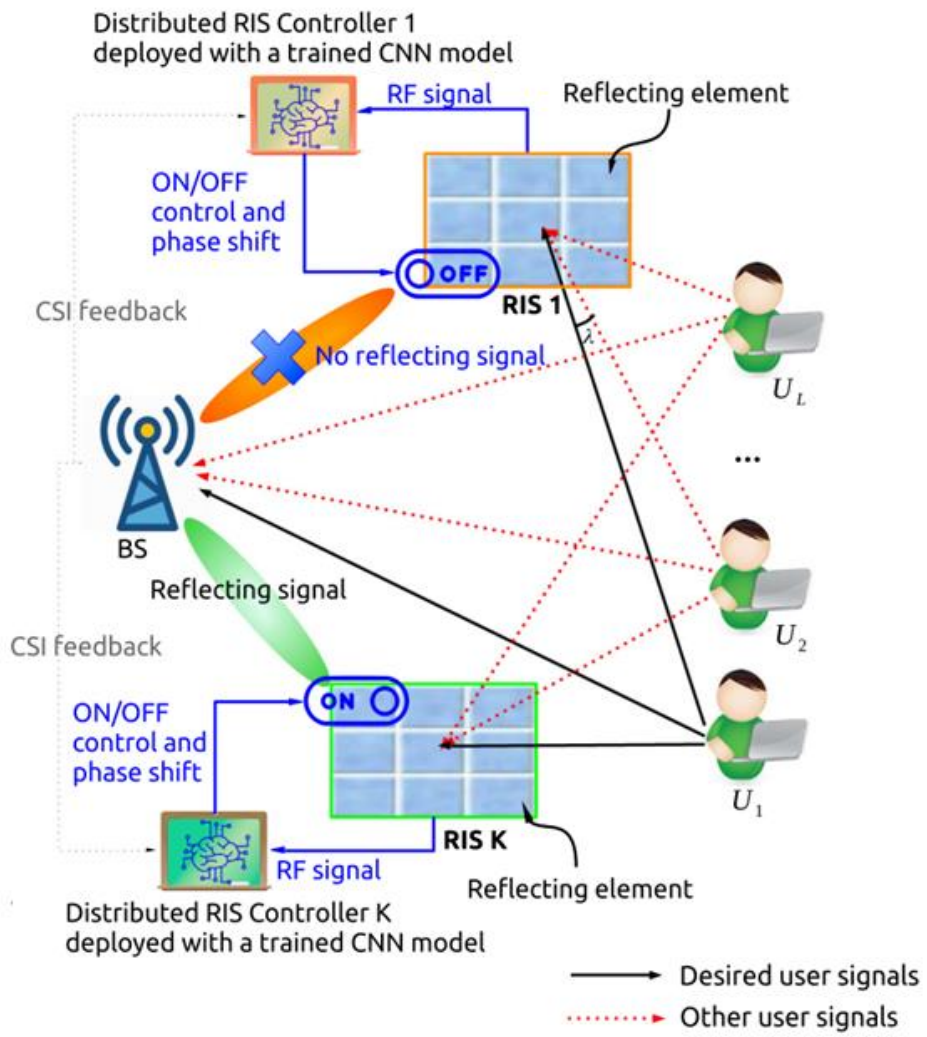

Fig. 3 An example of ISL

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

SL-Aided RIS Design

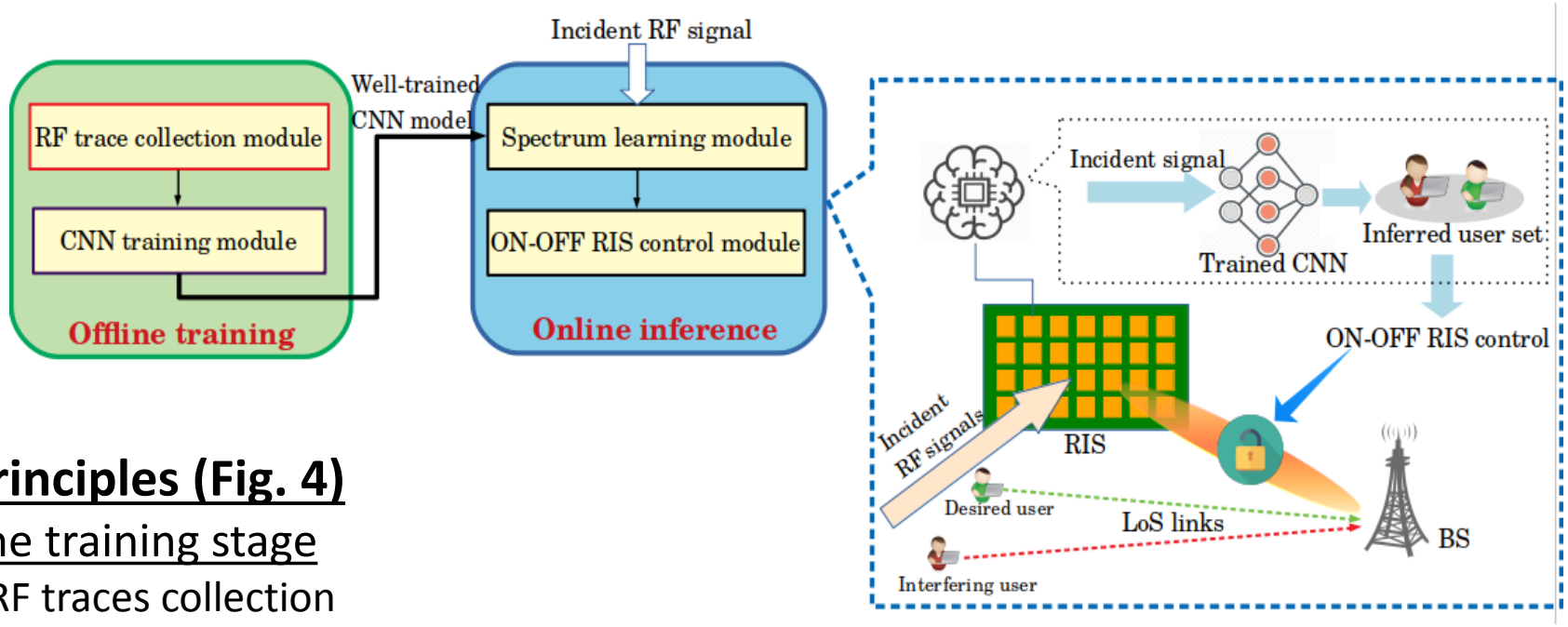

Fig. 4 SL-aided RIS design

Design Principles (Fig. 4)

- Offline training stage
  - RF traces collection
  - CNN training
- Online inference stage
  - Spectrum learning
  - ON-OFF RIS control

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

Offline Training

RF traces collection

- We collected RF traces by building a universal software radio peripheral (USRP2) based testbed, which is wired connected to a host computer, as shown in Fig. 5.
- **Tx**: baseband processing, up-conversion, D/A conversion; **Rx**: A/D conversion, down-conversion, baseband processing.
- The RF traces are collected at the Rx as an Inphase and Quadrature (I/Q) file.

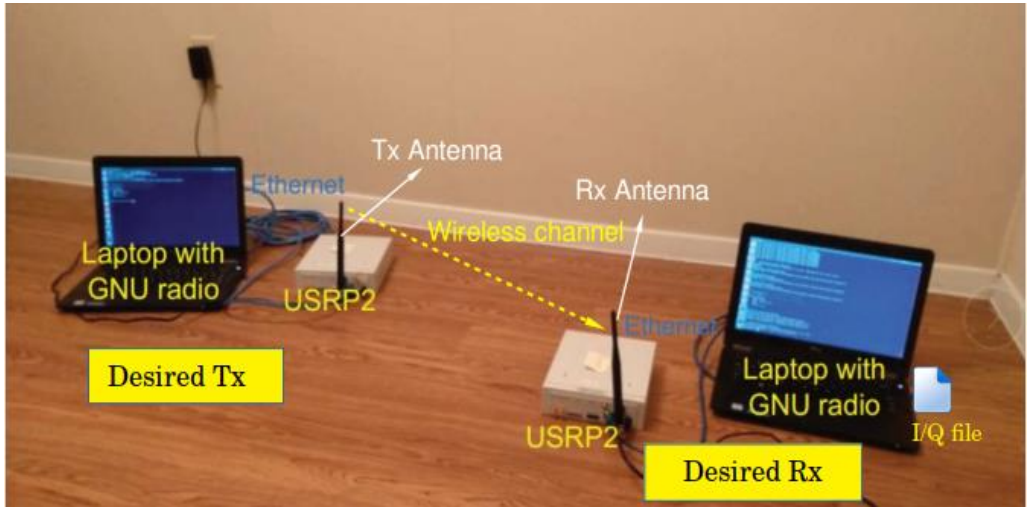

Fig. 5 RF traces collection

CNN training for signal classification

- Input: I/Q sequences; Output: the users set.
- The well-trained CNN model is employed at the RIS controller, consisting of two convolutional layers relying on the ReLU activation functions, followed by a pair of dense fully-connected layers and the output layer with a Softmax activation, as shown in Fig. 6.

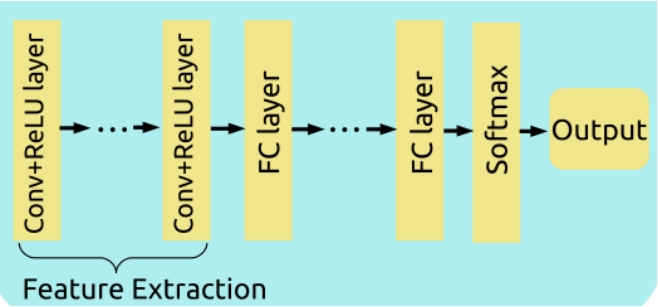

Fig. 6 CNN training

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

Online Inference

Spectrum learning

- We arrange for having only a few active RIS elements for the baseband processing of the incident signal at the RIS controller at a low overhead

  (*A. Taha, et al., "Enabling Large Intelligent Surfaces With Compressive Sensing and Deep Learning," IEEE Access, Mar. 2021*).
- The I/Q sequence is fed into the trained CNN model for inferring the desired and interfering users, as shown in Fig. 7. The CNN inference result under two-user case is shown in Table 1.

ON-OFF RIS Control

- The entire RIS will be 'turned OFF', if the received SINR at the destination BS achieved by RIS-aided transmission is lower than that obtained by the direct link, and vice versa.

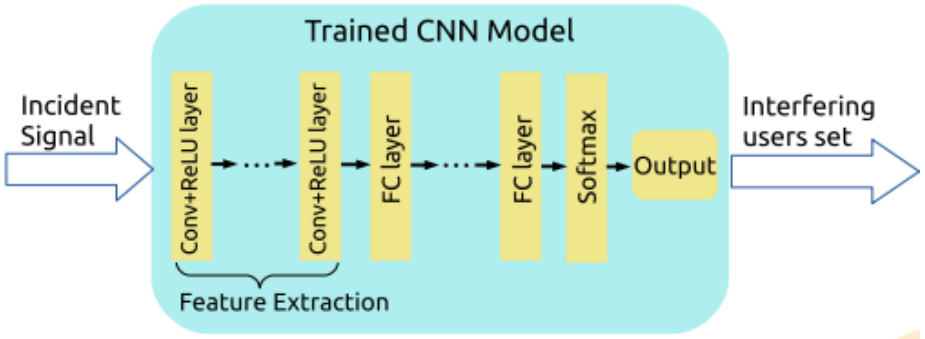

Fig. 7 CNN inference

Table 1 An example with two users

Inferred Class	Description
Class-1: Idle	The collected RF traces include only the noise
Class-2: Only U_1	The collected RF traces include only U_1
Class-3: Only U_2	The collected RF traces include only U_2
Class-4: U_1+U_2	The collected RF traces include both U_1 and U_2

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

CNN Testing Results

- We trained the CNN with the 80% of the collected RF data set which contains about 800 million I and Q samples (training set), we validated it by using 10% of the dataset (validation set), and we tested it by using 10% of the dataset (testing set) each corresponding to about 100 million of the I and Q samples.

- The CNN testing result with two users is shown in Table 2. It is observed that the inference accuracy is relatively high (larger than 95%).

Table 2 CNN testing result

Scenarios	$w = 32$	$w = 128$	$w = 512$
Idle	100.00%	100.00%	100.00%
Only U_1	98.35%	98.04%	96.21%
Only U_2	96.09%	96.12%	95.64%
$U_1 + U_2$	99.66%	99.76%	99.93%

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

Simulation Settings

- We suppose that there exists an interfering user (U_I) whose signal causes interference to the desired user (U_D) 's transmission at the BS, as shown in Fig. 8. There exist K RISs, the angle of incidence between U_I and U_D at the RIS is ϑ.
- We assume that the RISs are equally spaced by 5 m in the vertical direction, each having 256 elements. The amplitude reflection coefficient is 1 and the impact of interference is inversely proportional to ϑ. The RIS_1-U_D, RIS_1-U_I, and RIS_1-BS distances are 60 m, 10 m, and 80 m, respectively.
- We evaluate a pair of benchmark schemes:
  1) RIS always ON, and 2) RIS always OFF.

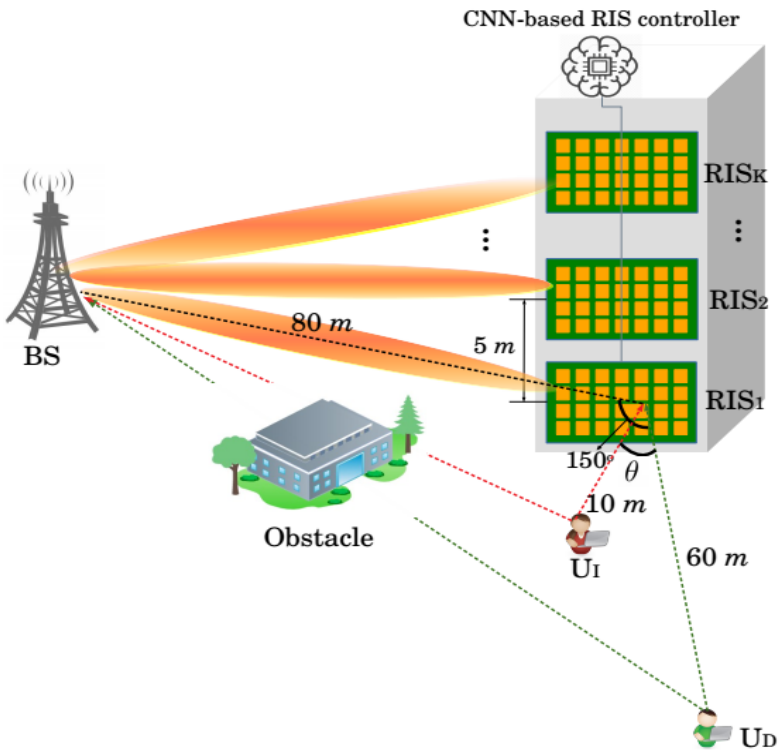

Fig. 8 Simulation scenario

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Simulation Results

The achievable SINR versus the incident angle (ϑ)

- In Fig. 9, as ϑ increases, the interference contaminating the desired receiver by reflection is reduced. Therefore, the SINR of the 'RIS always ON' scheme is increasing. The achievable SINR of the 'RIS always OFF' scheme reduces with ϑ due to the reduction of the distance between U_I and BS.
- SL-aided RIS achieve the best among the two.

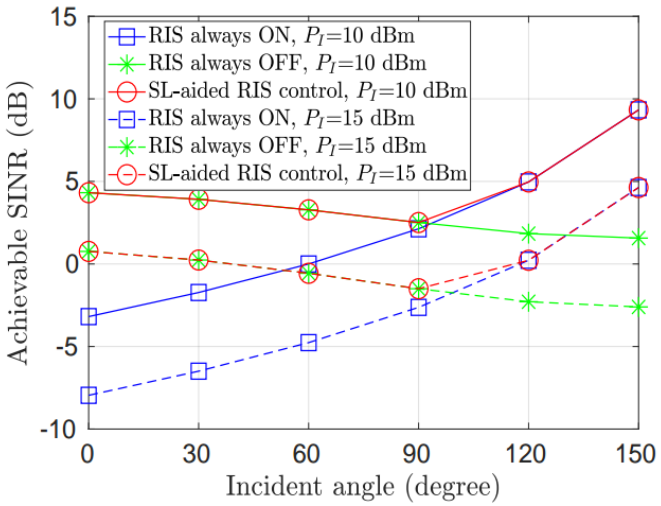

Fig. 9 SINR vs. incident angle, where K=1.

The achievable SINR versus the number of RISs (K)

- The SINR achieved by the 'RIS always OFF' remains unchanged, while that of the other two schemes increases with the number of RISs.
- Compared to the 'RIS always OFF' and 'RIS always ON' benchmarks, our proposed solution improves the received SINR from about 4.8 dB and 2.9 dB to 6.3 dB for K = 5.

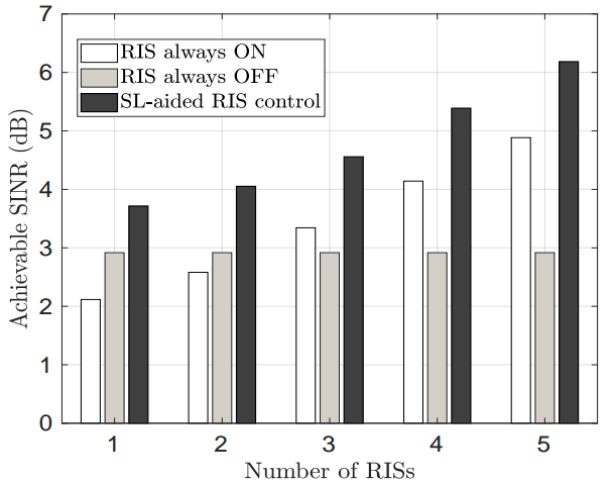

Fig. 10 SINR vs. number of RISs, where P_I = 10 dBm and ϑ is randomly selected from [30°; 120°].

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

Conclusions

- We investigate the potential of spectrum learning (SL) in addressing the critical challenges of RIS solutions.
- We proposed a SL-aided RIS framework and an ON-OFF RIS control scheme for dynamically configuring the binary status of RIS elements.
- The beneficial role of SL was validated by exemplifying the achievable SINR and compared to a pair of benchmarks.

B. Yang, X. Cao, C. Huang, C. Yuen, L. Qian and M. D. Renzo, "Intelligent Spectrum Learning for Wireless Networks With Reconfigurable Intelligent Surfaces," IEEE Transactions on Vehicular Technology, vol. 70, no. 4, pp. 3920-3925, April 2021.

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Recruitment of Postdoc

- Multiple postdoc positions available in the area of RIS for a 3-year theoretical research project.
- Candidate with PhD degree or going to graduate soon, welcome to apply: yuenchau@sutd.edu.sg

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