# Integrated Communications and Sensing with Hybrid Reconfigurable Intelligent Surfaces

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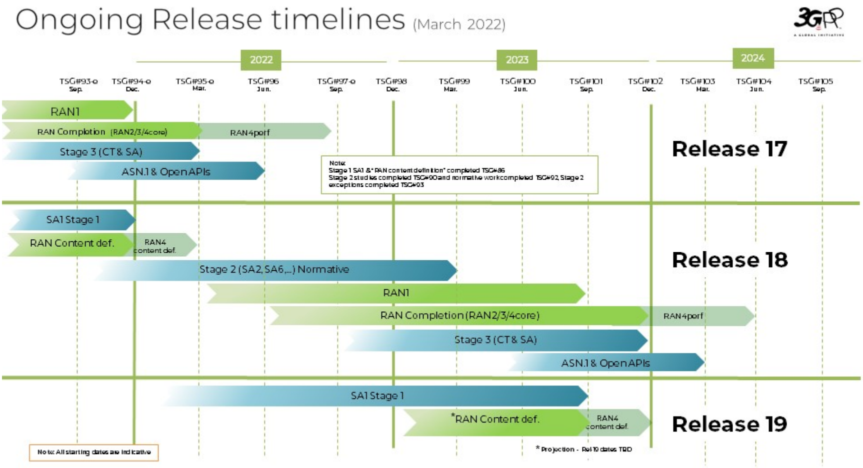
# 3GPP Release Timelines




- R17 frozen in March 2022; R18 (5G-Advanced) is now the focus.

# Content of 3GPP Release 18

3GPP A GLOBAL INITIATIVE — Release 18 — 5G ADVANCED

## TSG SA priorities*

**SA2 led - System Architecture and Services**

- XR (Extended Reality) & media services
- Edge Computing Phase 2
- System Support for AI/ML-based Services
- Enablers for Network Automation for 5G Phase 3
- Enh. support of Non-Public Networks Phase 2
- Network Slicing Phase 3
- 5GC LoCation Services Phase 3
- 5G multicast-broadcast services Phase 2
- Satellite access Phase 2
- 5G System with Satellite Backhaul
- 5G Timing Resiliency and TSC & URLLC enh.
- Evolution of IMS multimedia telephony service
- Personal IoT Networks
- Vehicle Mounted Relays
- Access Traffic Steering, Switching & Splitting support in the 5G system architecture Phase 3
- Proximity-based Services in 5GS Phase 2
- UPF enh. for Exposure & SBA
- Ranging based services & sidelink positioning
- Generic group management, exposure & communication enh.
- 5G UE Policy Phase 2
- UAS, UAV & UAM Phase 2
- 5G AM Policy Phase 2
- RedCap Phase 2
- Support for 5WWC Phase 2
- System Enabler for Service Function Chaining
- Extensions to TSC Framework to support DetNet
- Seamless UE context recovery
- MPS when access to EPC/5GC is WLAN

**SA3 led - Security and Privacy**

- Privacy of identifiers over radio access
- SECAM and SCAS for 3GPP virtualized network products and Management Function (MnF)
- Mission critical security enhancements Phase 3
- Security and privacy aspects of RAN & SA features

**SA4 led - Multimedia Codecs, Systems and Services**

Systems & Media Architecture:
- 5G Media, Service Enablers
- Split-Rendering
- 5G AR Experiences Architecture

Media:
- Video codec for 5G
- Media Capabilities for Augmented Reality Glasses
- AI / ML Study

Real-Time Communications:
- XR conversational services
- WebRTC-based services and collaboration models

Immersive Voice & Audio:
- EVS Codec Extension for Immersive Voice and Audio Services (IVAS_Codec)
- Terminal Audio quality performance and Test methods for Immersive Audio Services (ATIAS)

Streaming & Broadcast services:
- 5GMS Enh. (Network slicing, Low latency, Background traffic, 5GMS Uplink)
- Further MBS Enh. (Free to air, Hybrid unicast/broadcast)

**SA5 led - Management, Orchestration and Charging**

Operations, Administration, Maintenance and Provisioning (OAM&P):
- Intelligence and Automation: Self-Configuration of RAN NEs, Enh. autonomous network levels, Evaluation of autonomous network levels, Enh. intent driven management services for mobile networks, AI/ ML management, Enh. of the management aspects related to NWDAF
- Management Architecture and Mechanisms: Network slicing provisioning rules, Enh. service based management architecture
- Support of New Services: Enh. Energy Efficiency for 5G Phase 2, New aspects of Energy Efficiency for 5G networks Phase 2, Enh. management of Non-Public Networks, Network and Service Operations for Energy Utilities, Key Quality Indicators(KQIs)for 5G service experience, Deterministic Communication Service Assurance

Charging:
- Charging Aspects for Enh. Support of Non-Public Networks

**SA6 led - Application Enablement & Critical Communication Applications**

Critical Communications:
- MCX Enhancements – MC over 5GS (5MBS, ProSe) Adhoc group comm., MCPTT Enh.
- Railways - Gateway UE, Interworking

Service Frameworks:
- Edge App Architecture Enh., SEAL Enh., Subscriber-Aware API (CAPIF Enh.)
- Fused location, Application Data Analytics, App Layer NW Slicing

Enablers for Vertical Applications:
- Enhancements to V2X, UAS application-enablement
- Future Factories, Personal IoT networks, Capability exposure for IoT platforms

*These are preliminary lists (As at SA#94-e)

## TSG RAN priorities*

**RAN1 led - Radio Layer 1 (Physical layer)**

- NR-MIMO Evolution
- AI/ML - Air Interface
- Evolution of duplex operation
- NR Sidelink Evolution
- Positioning Evolution
- RedCap Evolution
- Network energy savings
- Further UL coverage enhancement
- Smart Repeater
- DSS
- Low power WUS
- CA enhancements

**RAN2 led - Radio layer 2 & layer 3 Radio Resource Control**

- Mobility Enhancements
- Enhancements for XR
- Sidelink Relay Enhancements
- NTN (Non-Terrestrial Networks) evolution - NR
- NTN (Non-Terrestrial Networks) evolution - IoT
- UAV (Uncrewed Aerial Vehicle)
- Multiple SIM (MUSIM) Enhancements
- In-Device Co-existence (IDC) Enhancements
- Small data
- MBS

**RAN3 led - UTRAN/E-UTRAN/NG-RAN architecture & related network interfaces**

- Additional topological improvements – IAB/VMR
- AI/ML for NG-RAN WI
- AI/ML for NG-RAN SI
- SON/MDT Enhancements
- QoE Enhancements
- Resiliency of gNB-CU-CP

**RAN4 led - Radio Performance and Protocol Aspects**

- RAN4-led spectrum items
- <5MHz in dedicated spectrum

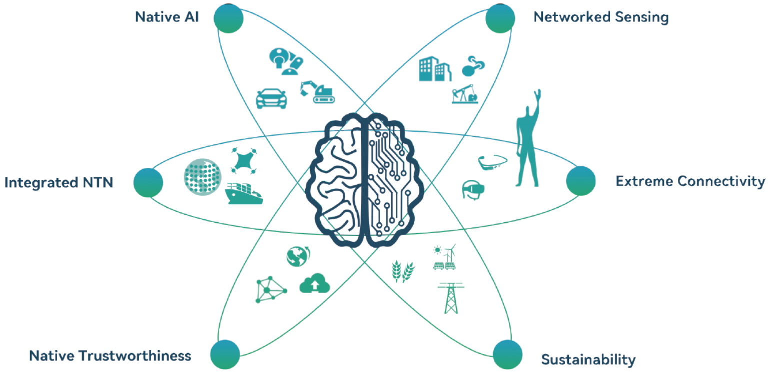
Rel-18 Workplan for TSG CT

CT will work on Stage 3 completion and ASN.1 code and OpenAPI freeze of Rel-17 until June 2022 (TSG#96).
Work Item discussion on Rel-18 Stage 2 / Stage 3 (under CT) from June 2022.

*Source: RP-213697 (RAN#94-e)

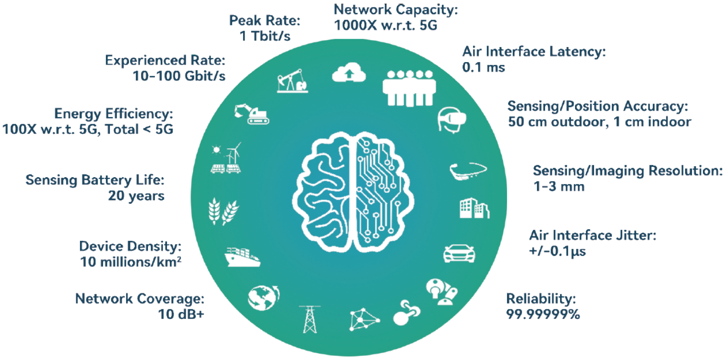
See the 3GPP Work Plan for full details, as Release 18 develops: www.3gpp.org/specifications/work-plan

# 6G Key Capabilities



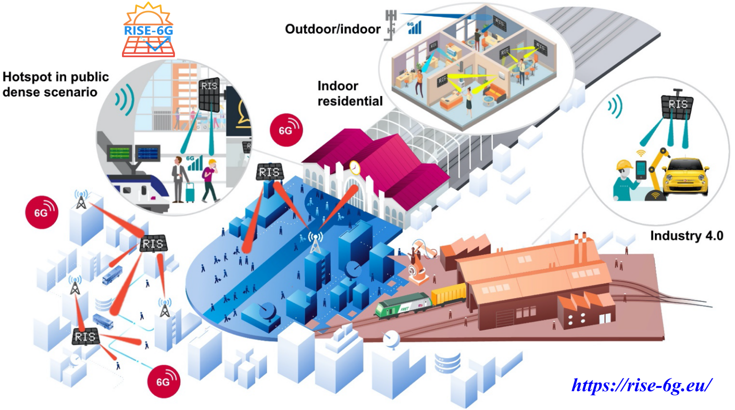

Huawei Technologies, Co. Ltd., "6G: The Next Horizon," *White Paper*, Sep. 2021.

# 6G RAN KPIs




Huawei Technologies, Co. Ltd., "6G: The Next Horizon," *White Paper*, Sep. 2021.

# Smart Wireless Environments




E. Calvanese Strinati, G. C. Alexandropoulos *et al.*, "Wireless environment as a service enabled by reconfigurable intelligent surfaces: The RISE-6G perspective," *Joint EuCNC & 6G Summit*, 2021.

E. Calvanese Strinati, G. C. Alexandropoulos *et al.*, "Reconfigurable, intelligent, and sustainable wireless environments for 6G smart connectivity," *IEEE COMMAG*, 2021.

G. C. Alexandropoulos *et al.*, "Smart wireless environments enabled by RISs: Deployment scenarios and two key challenges," *Joint EuCNC & 6G Summit*, 2022.

# Reconfigurable Intelligent Surfaces (RISs)

- A metamaterial (or meta-atom) is usually constructed by arranging multiple tunable elements (PIN diodes, varactor diodes, etc.) in repeating patterns, at scales that are smaller than the wavelengths.
- Its precise shape, geometry, size, orientation, and arrangement enable smart properties capable of manipulating electromagnetic waves, e.g., blocking, absorbing, enhancing, or bending waves, to achieve benefits that go beyond what is possible with conventional materials.
- Each meta-atom can be controlled independently to achieve desirable characteristics of the electromagnetic waves, such as the direction of propagation and reflection.

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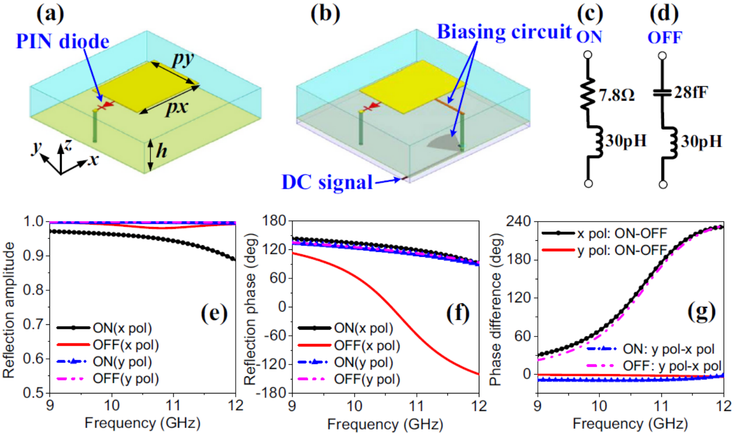
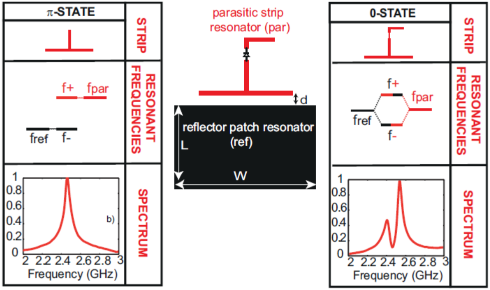
RISs are also know as intelligent reflective surfaces, programmable hypersurfaces, or simply as metasurfaces in the wireless communications' literature.

# A PIN-based Unit Cell @11.1GHz




H. Yang, X. Cao, F. Yang, J. Gao, S. Xu, M. Li, X. Chen, Y. Zhao, Y. Zheng, and S. Li, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Scientific Reports*, 2016.

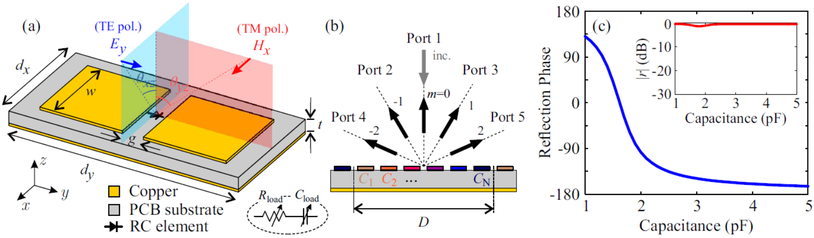
# A 0.4m$^2$ RIS with 102 Cells @2.47GHz




- Each unit cell consists of a rectangular patch coupled to a parasitic resonator, and is controlled by a PIN diode.
- The parasitic resonator reflects the impinging EM wave with 0 or $\pi$ phase shifts; *reflective* beamforming.

N. Kaina, M. Dupre, G. Lerosey, and M. Fink, "Shaping complex microwave fields in reverberating media with binary tunable metasurfaces," *Scientific Reports*, 2014.

# Variable Capacitance via Tunable Lumped Elements




O. Tsilipakos, F. Liu, A. Pitilakis, A. C. Tasolamprou, D.-H. Kwon, M. S. Mirmoosa, N. V. Kantartzis, E. N. Economou, M. Kafesaki, C. M. Soukoulis, and S. A. Tretyakov, "Tunable perfect anomalous reflection in metasurfaces with capacitive lumped elements," *Metamaterials*, 2018.

# The Cascaded Channel Model

The baseband received signal at RX can be expressed as (in the case of the absence of a direct TX-RX link):

$$y_{\mathrm{RX}} = \mathbf{h}_2 \mathbf{\Phi} \underbrace{\mathbf{h}_1 s}_{\triangleq \mathbf{y}_{\mathrm{RIS}}} + w = \left( \mathbf{h}_2 \circ \mathbf{h}_1^T \right) \boldsymbol{\phi} s + w$$

- $\mathbf{y}_{\mathrm{RIS}} \in \mathbb{C}^{N \times 1}$ is the baseband equivalent of the signal impinging on the RIS unit elements, which is processed in the RF domain without actually being received from any dedicated RF chain (this would insert reception thermal noise).
- For example, the signal reaching the $n$-th $(n = 1, 2, \ldots, N)$ RIS unit element is $[\mathbf{h}_1]_n s$, which gets reflected becoming $[\boldsymbol{\phi}]_n [\mathbf{h}_1]_n s$.

# Physics-Based End-to-End Channel Modeling

In general, the baseband received signal at RX needs to be of the form:

$$y_{\mathrm{RX}} = \bar{h}(\mathbf{\Phi})s + w$$

- The cascaded channel model is actually an oversimplification of the above expression that is valid only for highly specular channels, although widely used up to date.
- PhysFad incorporates the notions of space and causality, dispersion, frequency selectivity, and the intertwinement of each RIS element's phase and amplitude response, as well as any arising mutual coupling effects including long-range mesoscopic correlations.

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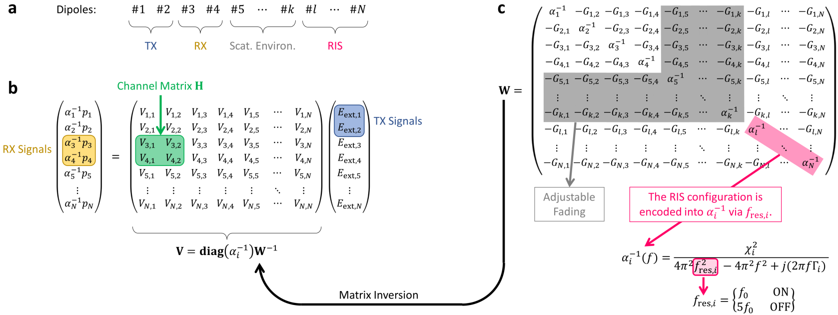
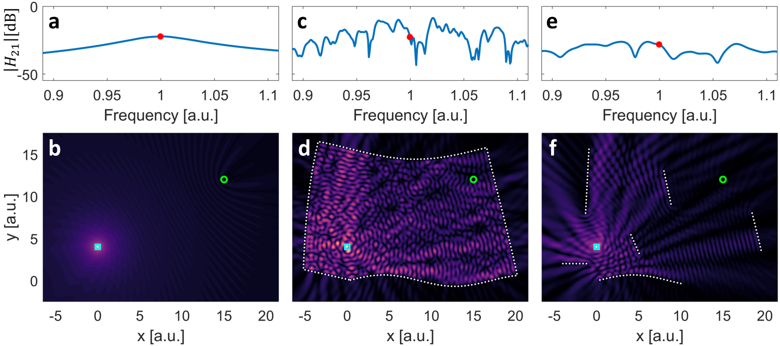
R. Faqiri, C. Saigre-Tardif, G. C. Alexandropoulos, N. Shlezinger, M. F. Imani, and P. del Hougne, "PhysFad: Physics-based end-to-end channel modeling of RIS-parametrized environments with adjustable fading," under revision, 2022; [Online] https://arxiv.org/abs/2202.02673.

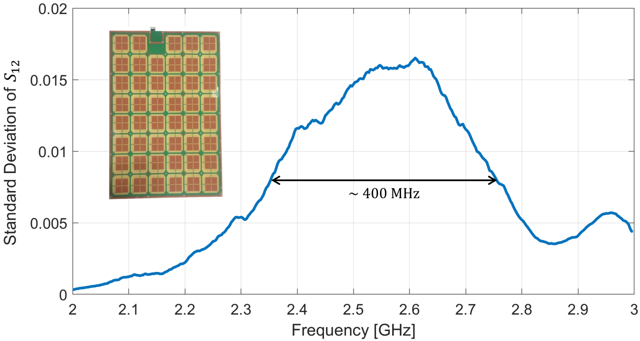



R. Faqiri, C. Saigre-Tardif, G. C. Alexandropoulos, N. Shlezinger, M. F. Imani, and P. del Hougne, "PhysFad: Physics-based end-to-end channel modeling of RIS-parametrized environments with adjustable fading," under revision, 2022; [Online] https://arxiv.org/abs/2202.02673.




R. Faqiri, C. Saigre-Tardif, G. C. Alexandropoulos, N. Shlezinger, M. F. Imani, and P. del Hougne, "PhysFad: Physics-based end-to-end channel modeling of RIS-parametrized environments with adjustable fading," under revision, 2022; [Online] https://arxiv.org/abs/2202.02673.

# Passive RISs - Bandwidth of Influence

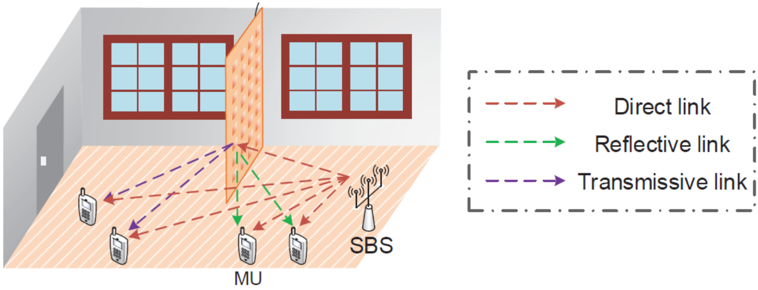



N. Kaina, M. Dupre, G. Lerosey, and M. Fink, "Shaping complex microwave fields in reverberating media with binary tunable metasurfaces," *Scientific Reports*, 2014.

G. C. Alexandropoulos, N. Shlezinger, and P. del Hougne, "Reconfigurable intelligent surfaces for rich scattering wireless communications: Recent experiments, challenges, and opportunities," *IEEE COMMAG*, 2021.

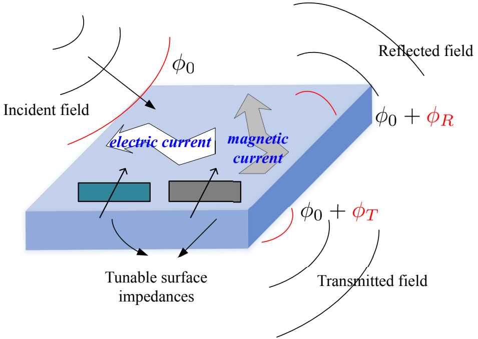
G. C. Alexandropoulos *et al.*, "Smart wireless environments enabled by RISs: Deployment scenarios and two key challenges," *Joint EuCNC & 6G Summit*, 2022.

# Reflective-Transmissive RISs




S. Zhang, H. Zhang, B. Di, Y. Tan, Z. Han, and L. Song, "Reflective-transmissive metasurface aided communications for full-dimensional coverage extension," *IEEE TVT*, 2020.

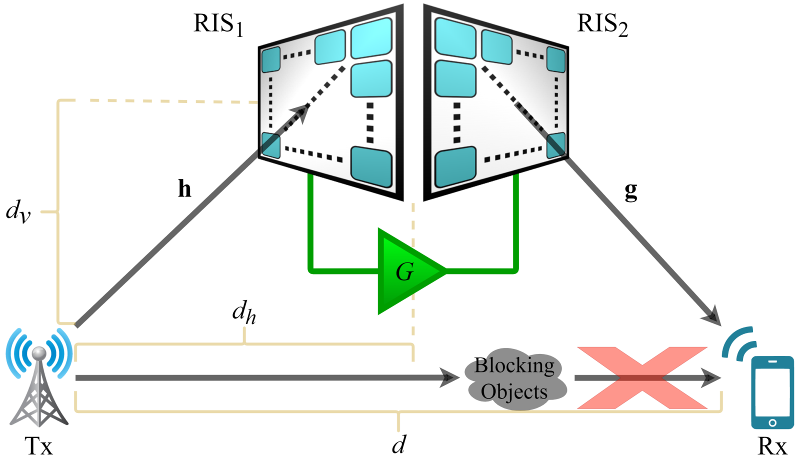
# Simultaneously Transmitting and Reflecting RISs




J. Xu, Y. Liu, X. Mu, O. A. Dobre, "STAR-RISs: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces," *IEEE COML*, 2021.

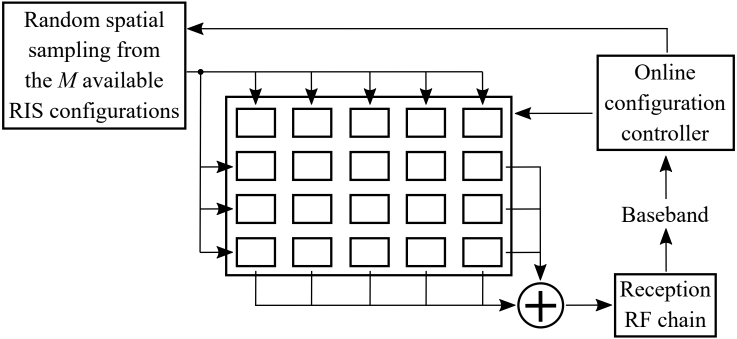
S. Zhang, H. Zhang, B. Di, Y. Tan, M. Di Renzo, Z. Han, H. V. Poor, L. Song, "Intelligent omni-surfaces: Ubiquitous wireless transmission by reflective-refractive metasurfaces," *IEEE TWC*, 2021.

# RISs with Reflection Amplification



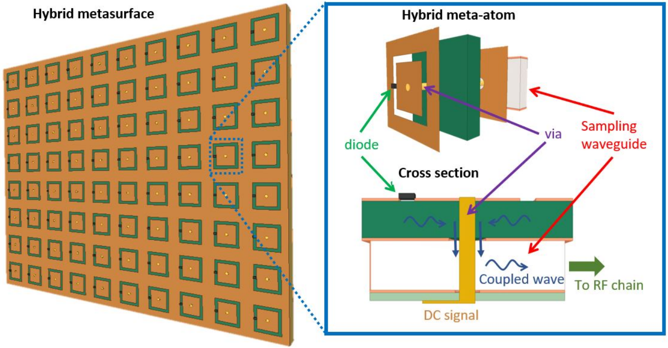

R. Akif Tasci, F. Kilinc, E. Basar, and G. C. Alexandropoulos, "A new RIS architecture with a single power amplifier: Energy efficiency and error performance analysis," *IEEE Access*, 2022.

# RISs with RX RF Chains




G. C. Alexandropoulos and E. Vlachos, "A hardware architecture for reconfigurable intelligent surfaces with minimal active elements for explicit channel estimation," *IEEE ICASSP*, 2020.

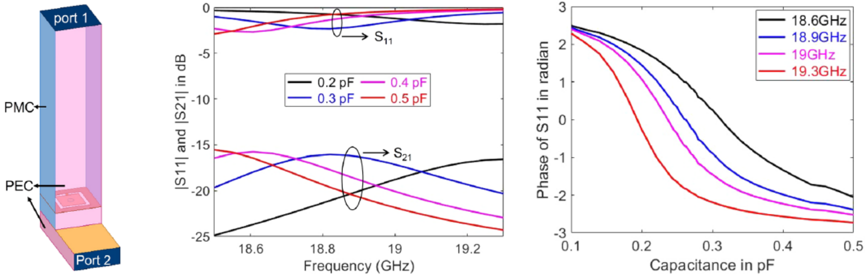
# RISs for Simultaneous Tunable Reflections and Sensing




G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang, and Y. C. Eldar, "Hybrid reconfigurable intelligent metasurfaces: Enabling simultaneous tunable reflections and sensing for 6G wireless communications," under revision, 2022; [Online] https://arxiv.org/pdf/2104.04690.

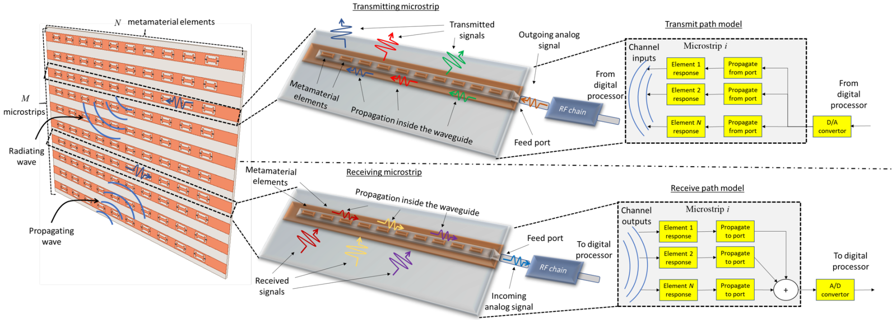
I. Alamzadeh, G. C. Alexandropoulos, N. Shlezinger, and M. F. Imani, "A reconfigurable intelligent surface with integrated sensing capability," *Scientific Reports*, 2021.

# Simulated Reflection and Coupling Coefficients



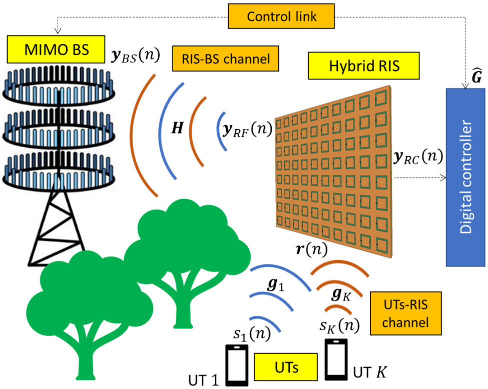

I. Alamzadeh, G. C. Alexandropoulos, N. Shlezinger, and M. F. Imani, "A reconfigurable intelligent surface with integrated sensing capability," *Scientific Reports*, 2021.

# Metasurface-Based Holographic MIMO




N. Shlezinger, G. C. Alexandropoulos, M. F. Imani, Y. C. Eldar, and D. R. Smith, "Dynamic metasurface antennas for 6G extreme massive MIMO communications," *IEEE WCOM*, 2021.

# Channel Estimation with HRISs

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H. Zhang, N. Shlezinger, I. Alamzadeh, G. C. Alexandropoulos, M. F. Imani, and Y. C. Eldar, "Channel estimation with simultaneous reflecting and sensing reconfigurable intelligent metasurfaces," *IEEE SPAWC*, 2021.

H. Zhang, N. Shlezinger, G. C. Alexandropoulos, A. Shultzman, I. Alamzadeh, M. F. Imani, and Y. C. Eldar, "Channel estimation with hybrid reconfigurable intelligent metasurfaces," under review, 2022; [Online] https://arxiv.org/abs/2206.03913.

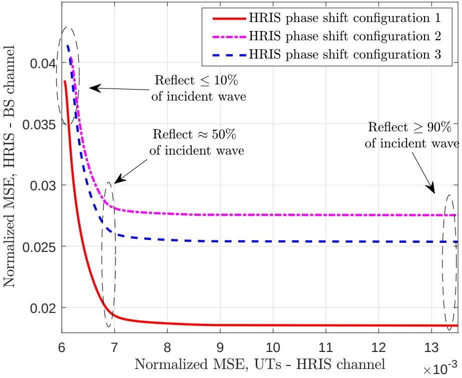
# Individual Channels' Estimation Formulation

$$\min_{\{\rho(b),\psi(b),\phi(b)\}} \quad \mathcal{E}_{\mathbf{H}}\left(\{\boldsymbol{\rho}\left(b\right),\boldsymbol{\psi}\left(b\right),\boldsymbol{\phi}\left(b\right)\}\right)+\mathcal{E}_{\mathbf{G}}\left(\{\boldsymbol{\rho}(b),\boldsymbol{\phi}(b)\}\right)$$
$$\text{s.t.} \quad [\rho(b)]_p \in [0,1],\ [\psi(b)]_p \in [0,2\pi],\ [\phi(b)]_q \in [0,2\pi],$$
$$b=1,2,\ldots,B,\ p=1,2,\ldots,N,\ q=1,2,\ldots,N\times N_r$$

- The UTs-HRIS channel is estimated at the HRIS side **G** and then shared via the HRIS controller to the BS.
- The HRIS-BS channel is then estimated at the BS using the latter shared estimation for **G**.

H. Zhang, N. Shlezinger, G. C. Alexandropoulos, A. Shultzman, I. Alamzadeh, M. F. Imani, and Y. C. Eldar, "Channel estimation with hybrid reconfigurable intelligent metasurfaces," under review, 2022; [Online] https://arxiv.org/abs/2206.03913.

# The Role of the Power Splitting Factor




- 16-Antenna BS, 8 UTs, 64-element HRIS with 8 RF chains.

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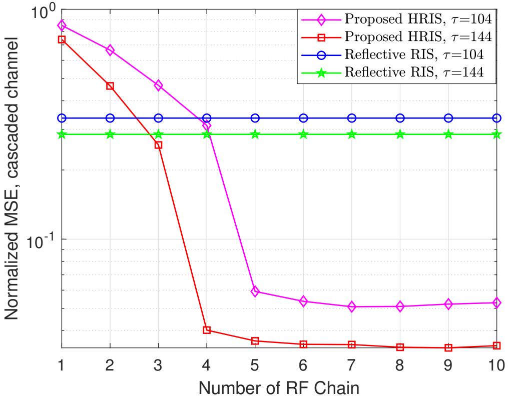
G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang, and Y. C. Eldar, "Hybrid reconfigurable intelligent metasurfaces: Enabling simultaneous tunable reflections and sensing for 6G wireless communications," under revision, 2021; [Online] https://arxiv.org/abs/2104.04690.

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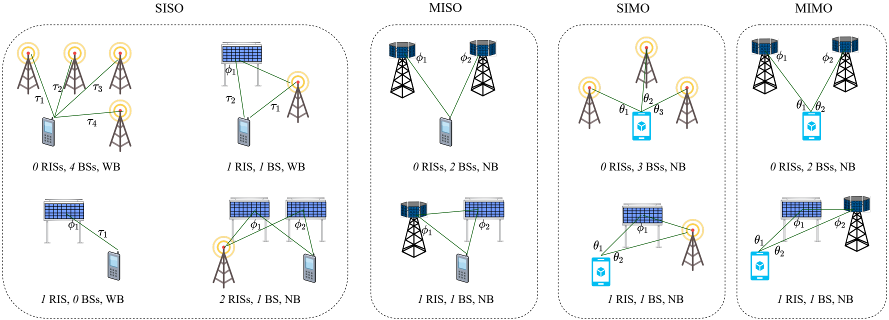
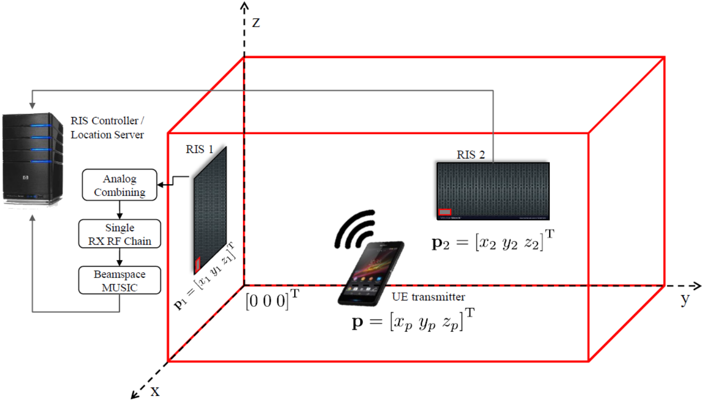
# Enabling 3D Localization with Passive RISs



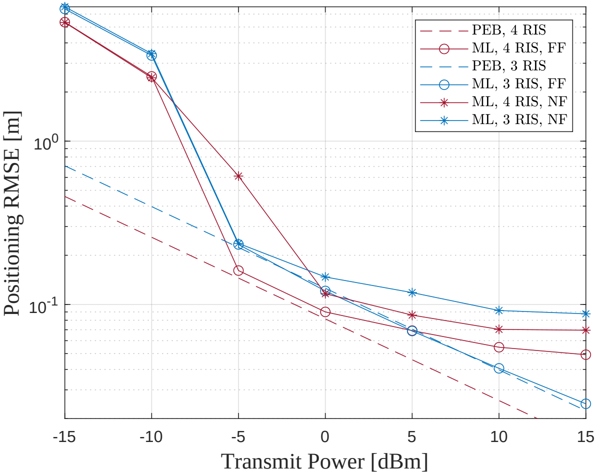

K. Keykhosravi, B. Denis, G. C. Alexandropoulos, Z. S. He, A. Albanese, V. Sciancalepore, and H. Wymeersch, "Leveraging RIS-enabled smart signal propagation for solving infeasible localization problems," under review, 2022; [Online] https://arxiv.org/pdf/2204.11538.

# 3D Localization with Single-RX-RF HRISs



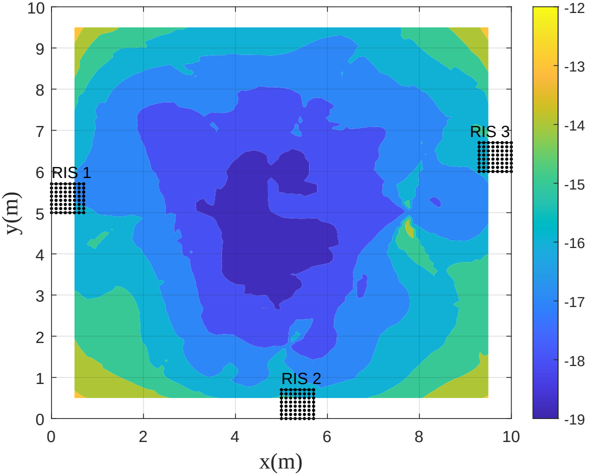

G. C. Alexandropoulos, I. Vinieratou, and H. Wymeersch, "Localization via multiple reconfigurable intelligent surfaces equipped with single receive RF chains," *IEEE WCL*, 2022.

# Positioning RMSE for Near- and Far-Field



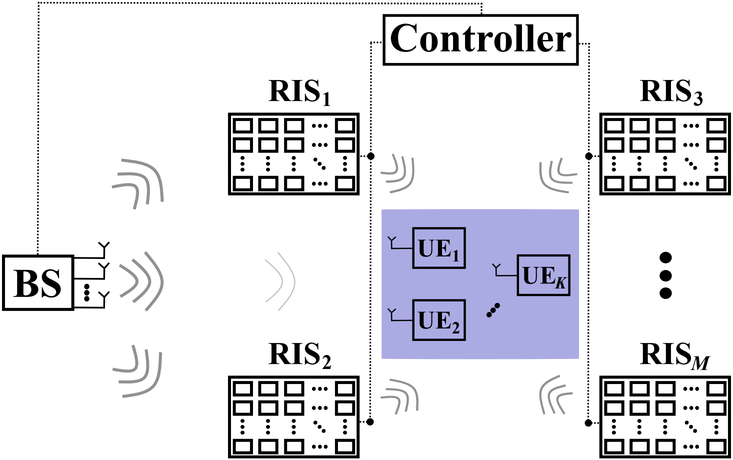

G. C. Alexandropoulos, I. Vinieratou, and H. Wymeersch, "Localization via multiple reconfigurable intelligent surfaces equipped with single receive RF chains," *IEEE WCL*, 2022.

# PEB with 3 Single-RX-RF HRISs and 1-bit Elements




G. C. Alexandropoulos, I. Vinieratou, and H. Wymeersch, "Localization via multiple reconfigurable intelligent surfaces equipped with single receive RF chains," *IEEE WCL*, 2022.

# Environmental AI




G. C. Alexandropoulos, K. Stylianopoulos, C. Huang, C. Yuen, M. Bennis, and M. Debbah, “Pervasive machine learning for smart radio environments enabled by reconfigurable intelligent surfaces,” *Proc. IEEE*, to appear, 2022; [Online] https://arxiv.org/pdf/2205.03793.pdf

The goal is to find a policy that maximizes the expected sum of rewards:

- **State:**

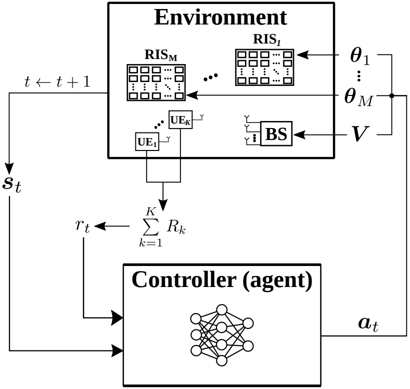
$$\mathbf{s}_t \triangleq [\mathrm{vec}(\mathbf{H}_1), \mathrm{vec}(\mathbf{H}_2), \ldots, \mathrm{vec}(\mathbf{H}_M), \mathbf{g}_{1,1}^T, \mathbf{g}_{1,2}^T, \ldots, \mathbf{g}_{1,K}^T, \ldots, \mathbf{g}_{M,1}^T, \mathbf{g}_{M,2}^T, \ldots, \mathbf{g}_{M,K}^T]^T$$

- **Action:**

$$\mathbf{a}_t \triangleq [\mathrm{vec}(\mathbf{V}), \vartheta^T]^T$$

- **Reward:**

$$r_t \triangleq \sum_{k=1}^{K} R_k$$

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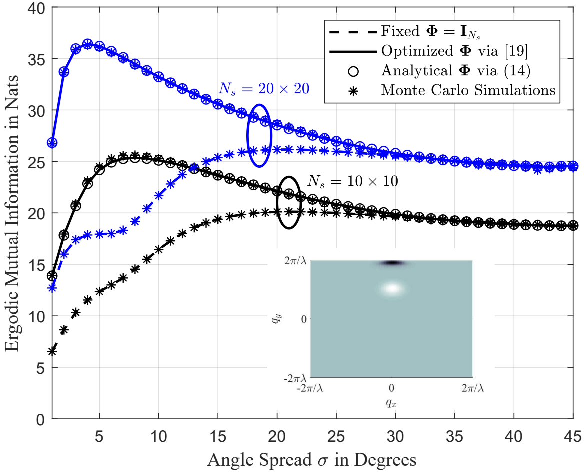
# Conclusion and Research Directions

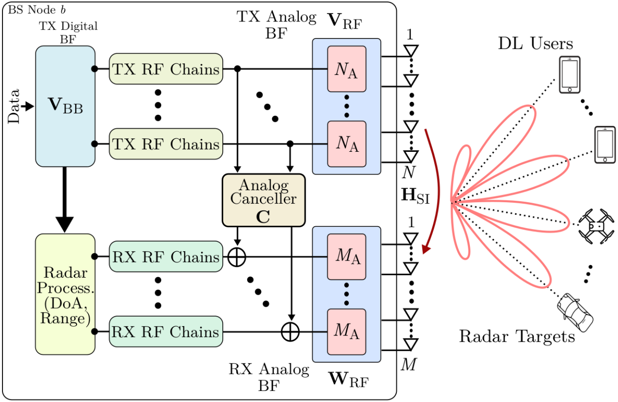
- HRISs can boost the performance and/or enable various wireless applications in cost- and energy-efficient manners, similar to what passive RISs were envisioned to do, but with an embedded mechanism that enables its efficient reconfiguration.
- The HRIS operation supports integrated communications and sensing in an autonomous manner, facilitating large-scale RF sensing (e.g., localization, direction estimation, and radio mapping) that can offer environmental AI.
- Physics-driven characterization of HRISs is required to characterize the coupling between its parameters (i.e., power splitting and phase shifting coefficients) as well as between different elements.
- Proof-of-concepts realizing such metasurfaces for wireless communications still requires a large body of experimental efforts and hardware designs, from low up to THz frequencies.

# Understanding (H)RIS Optimization




A. L. Moustakas, G. C. Alexandropoulos, and M. Debbah, "Capacity optimization using reconfigurable intelligent surfaces: A large system approach," *IEEE GLOBECOM*, 2021.

# Holographic MIMO with Full Duplex Radios




M. A. Islam, G. C. Alexandropoulos, and B. Smida, "Simultaneous multi-user MIMO communications and multi-target tracking with full duplex radios," under review 2021; [Online] https://arxiv.org/abs/2205.08402.

# Thank you for your attention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