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Reconfigurable intelligent surfaces for 6G: applications, challenges, and solutions

Key words: 6G; Reconfigurable intelligent surface (RIS); Cascade channel decoupling; RIS regulatory constraint; RIS system architecture; True time delay

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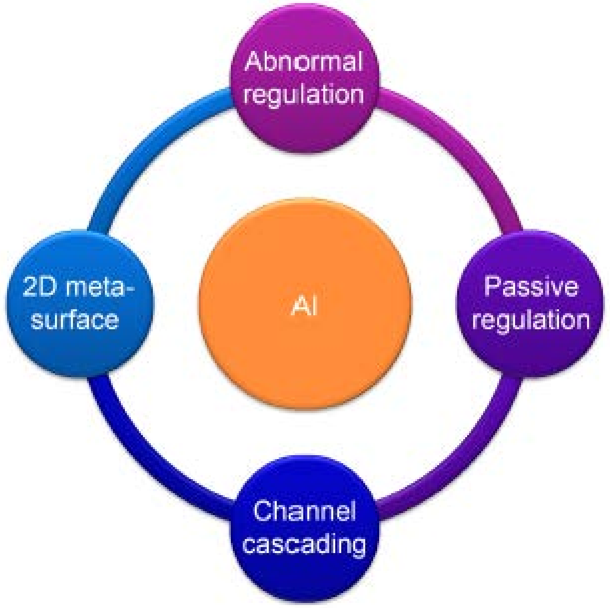
Introduction

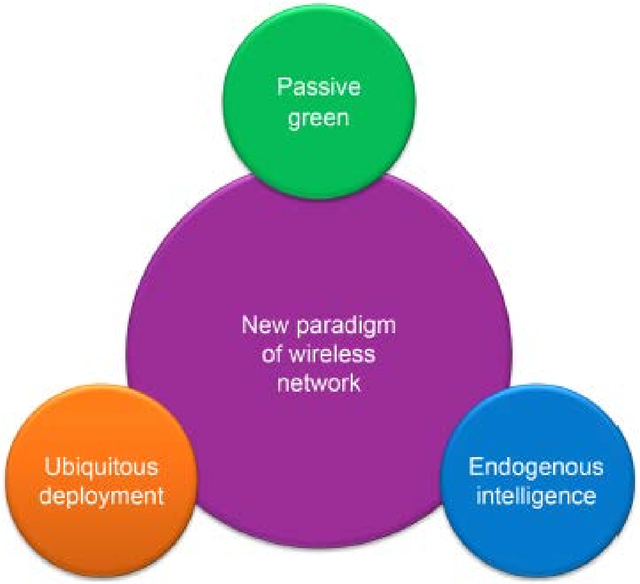
- This article provides an overview of reconfigurable intelligent surface (RIS) engineering applications, focusing primarily on their typical features, classifications, and deployment scenarios.
- We systematically and comprehensively analyze the challenges faced by RIS and propose potential solutions. These include addressing
  - Beamforming through cascade channel decoupling
  - Resolutions of regulatory constraints
  - Network-controlled mode for RIS system architecture
  - Examining integrated channel regulation and information modulation
  - True time delay (TTD) mechanism for RIS
  - RIS-assisted non-orthogonal multiple access (NOMA)
  - RIS-based transmitter
- This article also discusses future trends and challenges in this field.

Overview on engineering applications of RIS

- Main technical features of RIS
  - A reconfigurable artificial two-dimensional meta-surface
  - Passivity regulation
  - Abnormal regulation
  - Channel cascading
  - AI driven



- RIS highlights its main advantages, including the ability to support abnormal regulation, low power consumption, low cost, simple structure, and easy deployment.
- These advantages pave the way for widespread deployment of RIS in wireless networks and enable the establishment of intelligent and controllable wireless environments.
- Three key technical advantages essentially promise a new paradigm for future wireless networks: ubiquitous deployment, passive green, and endogenous intelligence.



Overview on engineering applications of RIS

- With the advancement of RIS engineering research, diverse technical characteristics and variations of RIS have emerged in the industry. Here, various types of RIS reported in the literature have been summarized and classified.

Feature	Type
Refraction/Reflection	Refractive RIS
	Reflective RIS
	Simultaneously transmitting and reflecting RIS (STAR-RIS)
Regulation functions	Spatial modulation, RIS-based transmitter
	Radio channel regulation, intelligent reconfiguration of wireless channels
	RIS-based novel phased array antenna
	RIS-based simultaneous wireless information and power transfer
Regulation mechanisms	PIN diode tube, varactor diode, MEMS, liquid crystal, graphene
Frequency band	Sub-6 GHz, millimeter-Wave band, terahertz band, optical band
Active or passive	Passive RIS, active RIS
Dynamicity	Static state, semi-static regulation, dynamic regulation
Measurement/Sensing	Consisting of passive elements only
	Including passive elements and some active elements with measuring/sensing ability
Deployment Mode	Network-controlled
	Standalone

Overview on Engineering Applications of RIS

- Four types of RIS deployment scenarios, including typical deployment variations and their respective key points.

Deployment scenario	Variation	Key points
Deployment mode	(1) Network-controlled mode (2) Standalone mode	(1) Control link (2) Measurement and control signaling
Coexistence and sharing	(1) Multi-operator network coexistence (2) Single- user access and multi-user access (3) Multi-RIS deployment (4) Spectrum properties, such as licensed spectrum or unlicensed spectrum	(1) Identification and collaboration of multiple RISs (2) Interference and coordination of coexistence and sharing in networks
Increasing rank and coverage	(1) Deployment near Node B (NB) (2) Deployment at the cell edge (3) Deployment in the middle of the cell (4) Ubiquitous deployment	(1) Increasing rank (2) Covering Enhancement (3) Near field/far field
Coverage area	(1) Remote area (2) Urban indoor/outdoor (3) NTN, UAV	(1) Wide area: semi-dynamic/static adjustment, which is used to improve capacity and coverage (2) Local area: dynamic and accurate channel regulation (3) Challenges of power supply and control link deployment

Technical challenges and solutions

Beamforming of cascade channels: channel decoupling

- **Challenges:** the cascade channels formed with the introduction of RIS present significant challenges in designing the RIS beamforming matrix.
- **Basic technical ideas**
  - The regulation of incident electromagnetic wave by RIS can be further divided into two sub-processes that can be respectively named as the response of the receiving sub-process to the incident electromagnetic wave and the regulation response of the outgoing sub-process.
  - Therefore, the RIS regulation matrix used for incident electromagnetic waves can be decomposed into two regulation matrix components corresponding to the above two sub-response processes, namely, the reception response matrix and the reflection regulation matrix .
  - The incident response of RIS to electromagnetic waves is similar to the response of the reception matrix of analog beamforming in the massive MIMO hybrid beamforming.
- The RIS regulation matrix $\boldsymbol{\Phi}$ is decomposed into two matrix components $\boldsymbol{\Phi}_1$ and $\boldsymbol{\Phi}_2$, such that the solution of RIS regulation matrix $\boldsymbol{\Phi}$ is transformed into the optimization of two independent components $\boldsymbol{\Phi}_1$ and $\boldsymbol{\Phi}_2$.

$$\boldsymbol{H}_{\mathrm{DL}} = \boldsymbol{H}_{\mathrm{ris-ue}} \boldsymbol{\Phi}_2 \boldsymbol{\Phi}_1 \boldsymbol{G}_{\mathrm{nb-ris}}.$$

$$\boldsymbol{\Phi} = \boldsymbol{\Phi}_2 \boldsymbol{\Phi}_1$$

Technical challenges and solutions

■ RIS regulation constraints

- **System model of RIS network**: The cascade channel, which includes both the NB and RIS, resembles a mix of digital and analog phased arrays, akin to the structure of conventional massive MIMO with hybrid beamforming. In this context, the NB's precoding is analogous to digital beamforming, and the RIS's array regulation is comparable to analog beamforming.
- **Influences of RIS regulatory constraints**
  - RIS, equipped with tuning capabilities, uses a uniform weighting coefficient matrix to adjust signals across a broader frequency band. As a result, current RIS systems struggle to optimally align with multiple sub-band channels at once, potentially causing substantial network coexistence issues and hindering effective support for multi-user access via orthogonal frequency-division multiple access.

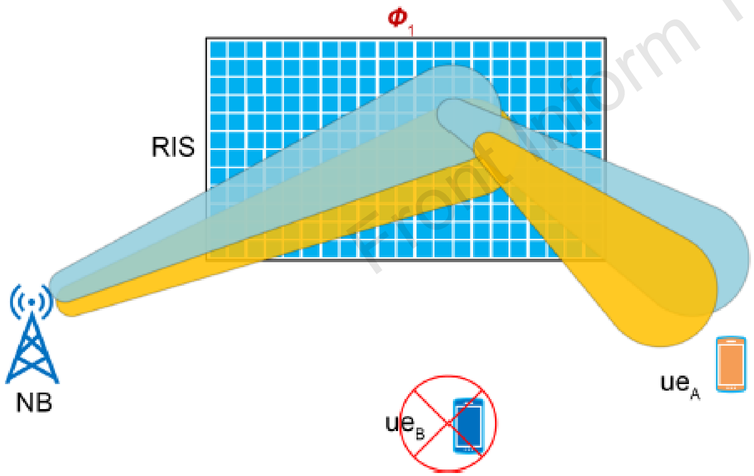


Fig. 3 Impacts on multi-user access

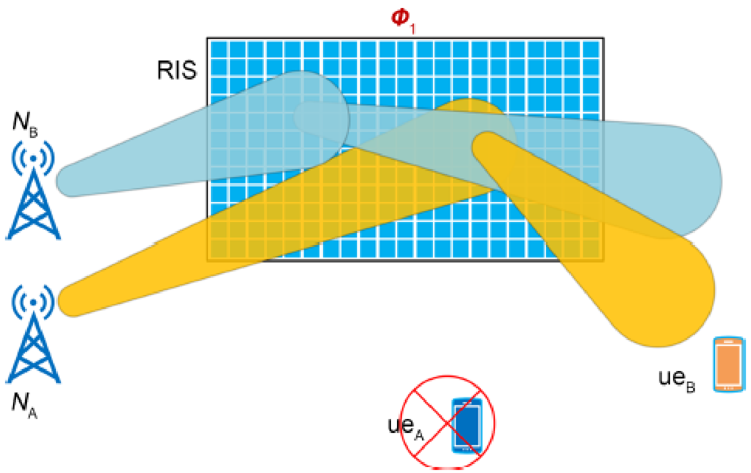


Fig. 4 Impacts on multi-network coexistence

Technical Challenges and Solutions

■ RIS regulation constraints

- **Solutions**
  - Two novel RIS design mechanisms, including a novel multi-layer RIS structure with an out-of-band filter and a RIS blocking mechanism, are further explored.

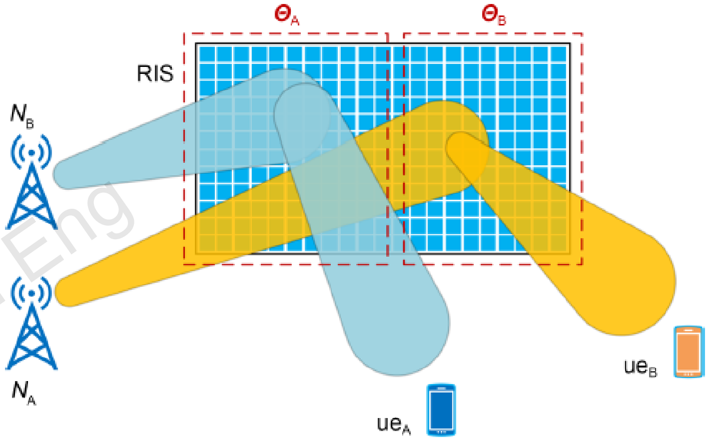


Fig. 5 Tuning incident signals on a sub-block by using an independent coefficient matrix separately

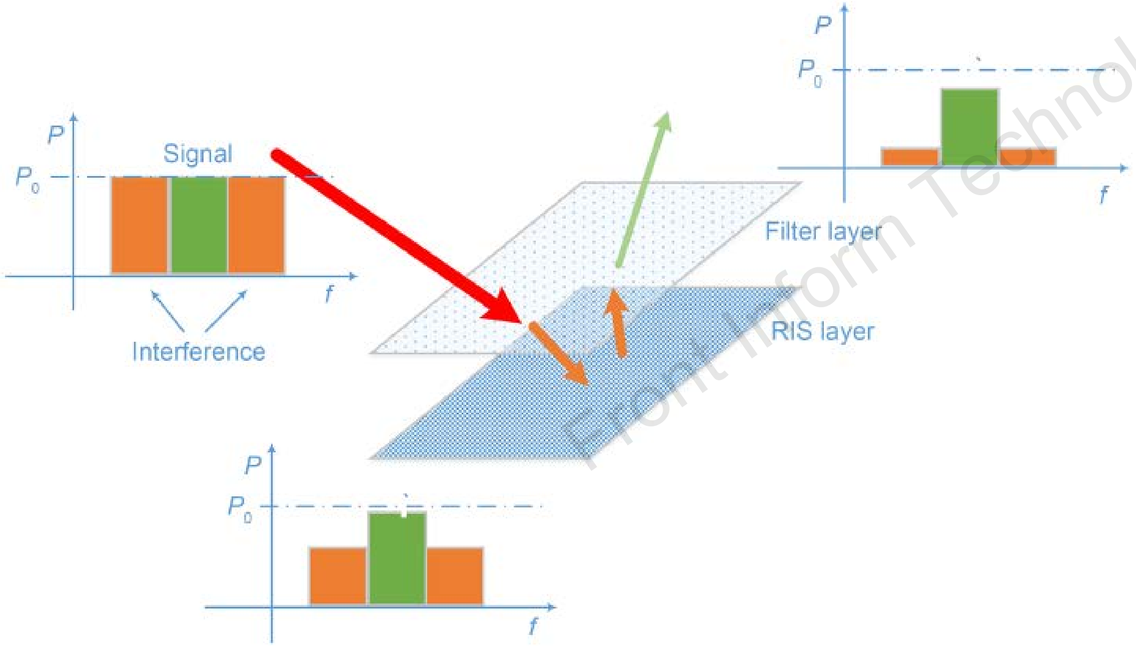


Fig. 7 Out-of-band filtering using a RIS with a double-layer structure (reflecting the RIS)

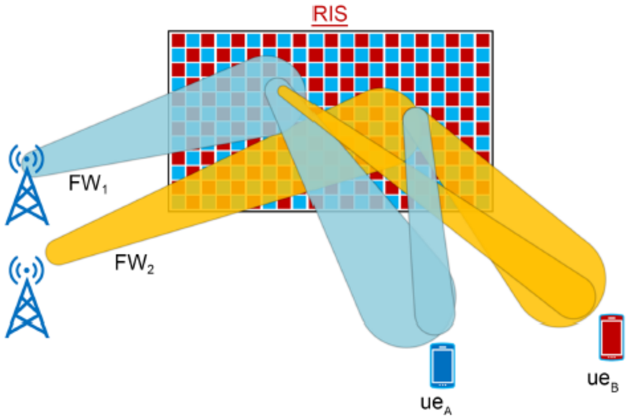


Fig. 6 Blocking of the RIS antenna array elements based on interval decimation for grouping

Technical challenges and solutions

RIS system architecture of network controlled mode

- The deployment mode where RIS is controlled by the network is referred to as "network-controlled mode," and the mode where RIS is self-controlled is referred to as "standalone mode."

Type	Advantage	Challenge
Network-controlled mode	(1) Support multi-network collaboration (2) Support multi-user access (3) Better meet the coexistence requirements of wireless networks deployed on licensed spectrum	(1) Network deployment is relatively complicated (2) Network control link needs to be deployed (3) It is necessary to design an interactive flow of control and measurement signaling
Standalone mode	(1) No network control link is required (2) The network is simple and easy to deploy (3) Suitable for unlicensed spectrum with low coexistence requirements	(1) Hard to overcome the interference of multiple networks (2) May cause serious inter-cell interference (3) Cannot support multi-user access well

Table 4 Advantages and challenges of network-controlled mode and standalone mode

Item	Requirement	Potential solution
Feedback of CSI and scheduling of beamforming	(1) The large number of antenna elements in the (2) ultra-large antenna array results in significant (3) pilot and channel information feedback overhead (4) Real-time demand of channel measurement and feedback	(1) Utilize channel sparsity, adopt compression sensing and other mechanisms to reduce overhead (2) Using statistical channel information (3) Using the dual time scale property of cascade channels (4) Beam scanning and codebook quantization
Network control link	The control link needs to be specially deployed, resulting in the complexity, and cost of deployment. Especially in remote areas, complexity and cost are very big problems	Flexible choice of wired or wireless links
Interactive flow of control and measurement signaling	The protocol standardization of interactive flow of control and measurement signaling is necessary	The related protocol flow can be standardized in the future 5G-A or 6G standards

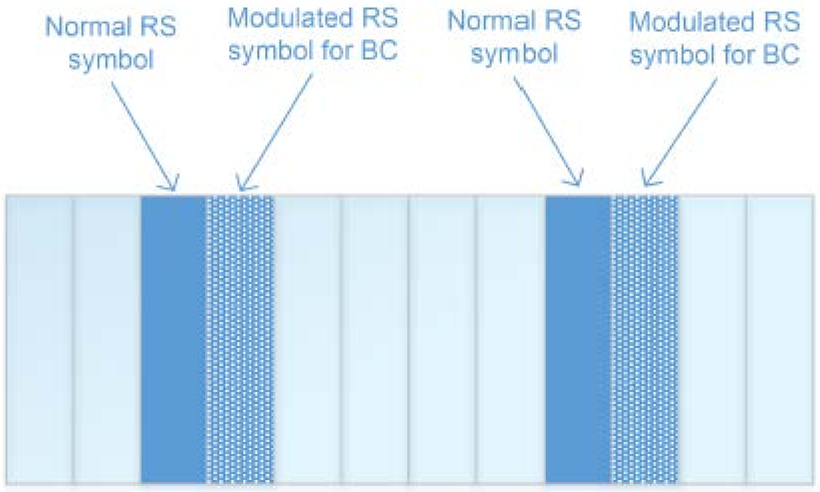
Table 5 Requirements and potential solutions of network-controlled mode

Technical challenges and solutions

■ Integrated channel regulation and information modulation

- **Requirements and challenges**
  - There is currently a lack of literature investigating information modulation and transmission based on RIS to facilitate the electromagnetic wave regulation function of RIS itself, particularly supporting the interaction of control and measurement information between RIS–NB and RIS–UE.
  - **Challenges:** (1) When RIS is used as a backscatter for information modulation, it introduces additional noise that causes random fluctuations in the regulation coefficient originally used for channel regulation. (2) The receiver in backscatter communication (BC) often experiences strong interference from the direct link signal. (3) It may lead to lower information rates and increased delays. (4) It may lead to performance degradation of the primary system, particularly in high-frequency narrow-beam scenarios. (5) The utilization of RIS as a backscatter device (BD) can have a significant impact on the communication of the primary system, particularly due to its large antenna aperture and deployment on the main propagation path of the primary system.

- **Solution: a novel frame structure**
  - A novel frame structure is provided to realize that RIS supports channel regulation and information modulation simultaneously.



Technical challenges and solutions

■ True time delay (TTD) schemes for RIS

- **Concepts of TTD scheme**
  - The TTD mechanism achieves precise phase adjustment across various sub-bands using delay. By modifying the delay differences, it allows for independent phase tuning for each sub-band.
- **RIS using TTD to support frequency-dependent beamforming for multiple-user access with OFDMA**
  - TTD mechanism is flexible in phase adjustment of different sub-bands; in other words, it increases phase freedom in the frequency domain, leading to scheduling performance gains.
  - The delay difference corresponding to the phase difference can be calculated by the following equation, wherein the time delay difference is inversely calculated according to the phase difference.

$$w_{m,n} = \alpha_n \exp\left(-\mathrm{j}\left(2\pi\left(f_m - f_{\mathrm{c}}\right)\tau_n + \varphi_n\right)\right).$$

  - The TTD coefficient matrix of m^{th} sub-carrier is

$$\boldsymbol{W}_m = \mathrm{diag}\left(\boldsymbol{w}_m\right), \text{ where } \boldsymbol{w}_m = \left[w_{m,1}, w_{m,2}, \dots, w_{m,N}\right].$$

Technical challenges and solutions

■ RIS-assisted NOMA

- The synergy between RIS and NOMA creates a mutually beneficial approach. NOMA enhances the multi-access capacity of the RIS-assisted multi-user system, allowing for flexible resource distribution. Simultaneously, RIS aids in reconstructing wireless channels to support NOMA pairing, thereby boosting the system's overall efficiency.

■ RIS-based transmitter

- RIS-based transmitter offers advantages of low cost and a simple structure without the need for radio frequency (RF) components like antenna arrays, filters, and mixers required by traditional methods.
- These transmitters can be understood in the context of three traditional concepts: information modulation technology, backscattering technology (or symbiotic communication technology), and information metamaterial technology.
- RIS can modulate information similar to information modulation technology by regulating electromagnetic waves and offer stronger capabilities for novel RIS-based transmitters.
- However, there are still engineering implementation challenges that need to be addressed for this novel transmitter system architecture, requiring further in-depth research to resolve them. Practical engineering applications can only be achieved once these engineering challenges are resolved.

Future trends and challenges

A new structure of RIS: RIS integrated with photovoltaic panels

- RIS itself is a plate-like structure with low power consumption, making it a natural idea to consider integrating RIS with photovoltaic panels, especially in outdoor scenarios, to address power requirements.
- The low power consumption feature of RIS passive regulation coupled with the use of green energy such as photovoltaic will truly achieve the goal of future green communication.

Complexity of RIS network deployment and optimization

- RIS will be likely to lead to pose the complexity issues pertaining to network deployment and optimization, including: RIS sharing, collaborative scheduling, control link, RIS network topology planning and optimization, station-site selection and power supply, and different scenarios requiring different types of RIS.

Engineering errors

- The engineering implementation of RIS may introduce errors due to cost and complexity constraints, including: (1) regulation phase quantization error, (2) deviation calibration, and (3) CSI feedback quantization error and time delay.

Standard and protocol design

- The standardization design of RIS involves mainly the following aspects, including: the access procedure of UE, resource management and scheduling procedure, the impact of the introduction of RIS on the handover procedure, and side control information interaction between NB and RIS.

Conclusions

- This paper focuses on the practical engineering applications of RIS.
- It outlines RIS’s engineering applications, explores technical challenges, and suggests possible solutions.
- Additionally, it delves into future trends and challenges in RIS engineering.
- In conclusion, despite the challenges in RIS engineering applications, feasible solutions are available.

Yajun ZHAO holds Bachelor's, Master's, and Doctoral degrees. Since 2010, he has assumed the role of Chief Engineer within the Wireless and Computing Product R&D Institute at ZTE Corp. Prior to this, he contributed to wireless technology research within the Wireless Research Department at Huawei. Currently, his primary focus centers on 5G standardization technology and the advancement of future mobile communication technology, particularly 6G. His research pursuits encompass a broad spectrum, including reconfigurable intelligent surfaces (RIS), spectrum sharing, flexible duplex, CoMP, and interference mitigation. He has played an instrumental role in founding the RIS Tech Alliance (RISTA) and currently holds the position of Deputy Secretary General within the organization. Additionally, he is a founding member of the RIS task group under the purview of the China IMT-2030 (6G) Promotion Group, where he serves as the Deputy Leader.