Wireless 2.0: Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces

(How it Works, State of Research, and the Road Ahead)

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The Main Takes of this Talk

- **Smart Radio Environments**
- **Smart Surfaces: "Tiny" Antennas vs. Metasurfaces**
- **Surface Electromagnetics: Modeling Metasurfaces**
- **Uses, Applications, Prototypes of Smart Surfaces**
- **Advantages and Limitations of Smart Surfaces**
- **Recent Research Activities**
  - **Path-Loss Modeling of Metasurfaces [new]**
  - **Joint Encoding, Performance Evaluation, Training Overhead**
- **What's Next ?**

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- **What's Next ?**
- **WTC-SIG "RISE" & other IEEE-COMSOC activities**

Smart Radio Environments & Reconf. Metasurfaces

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EURASIP Journal on Wireless Communications and Networking

REVIEW Open Access

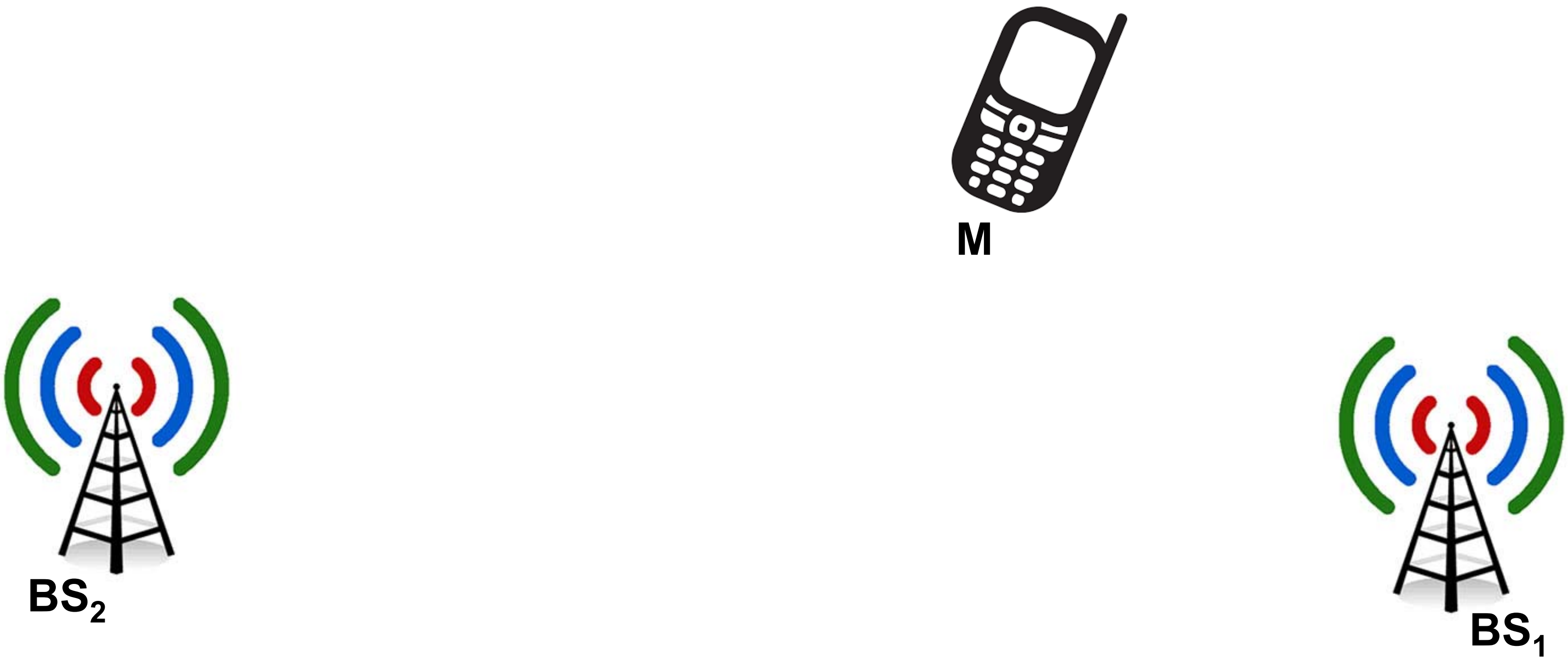
Smart radio environments empowered by reconfigurable AI meta-surfaces: an idea whose time has come

Marco Di Renzo[1*], Merouane Debbah[2], Dinh-Thuy Phan-Huy[3], Alessio Zappone[4], Mohamed-Slim Alouini[5], Chau Yuen[6], Vincenzo Sciancalepore[7], George C. Alexandropoulos[8], Jakob Hoydis[9], Haris Gacanin[10], Julien de Rosny, Ahcene Bounceur[12], Geoffroy Lerosey[13] and Mathias Fink[11]

Abstract

Future wireless networks are expected to constitute a distributed intelligent wireless communications, sensing, and computing platform, which will have the challenging requirement of interconnecting the physical and digital worlds in a seamless and sustainable manner. Currently, two main factors prevent wireless network operators from building such networks: (1) the lack of control of the wireless environment, whose impact on the radio waves cannot be customized, and (2) the current operation of wireless radios, which consume a lot of power because new signals are generated whenever data has to be transmitted. In this paper, we challenge the usual "more data needs more power and emission of radio waves" status quo, and motivate that future wireless networks necessitate a smart radio environment: a transformative wireless concept, where the environmental objects are coated with artificial thin films of electromagnetic and reconfigurable material (that are referred to as reconfigurable intelligent meta-surfaces), which are capable of sensing the environment and of applying customized transformations to the radio waves. Smart radio environments have the potential to provide future wireless networks with uninterrupted wireless connectivity,

Current Wireless Networks



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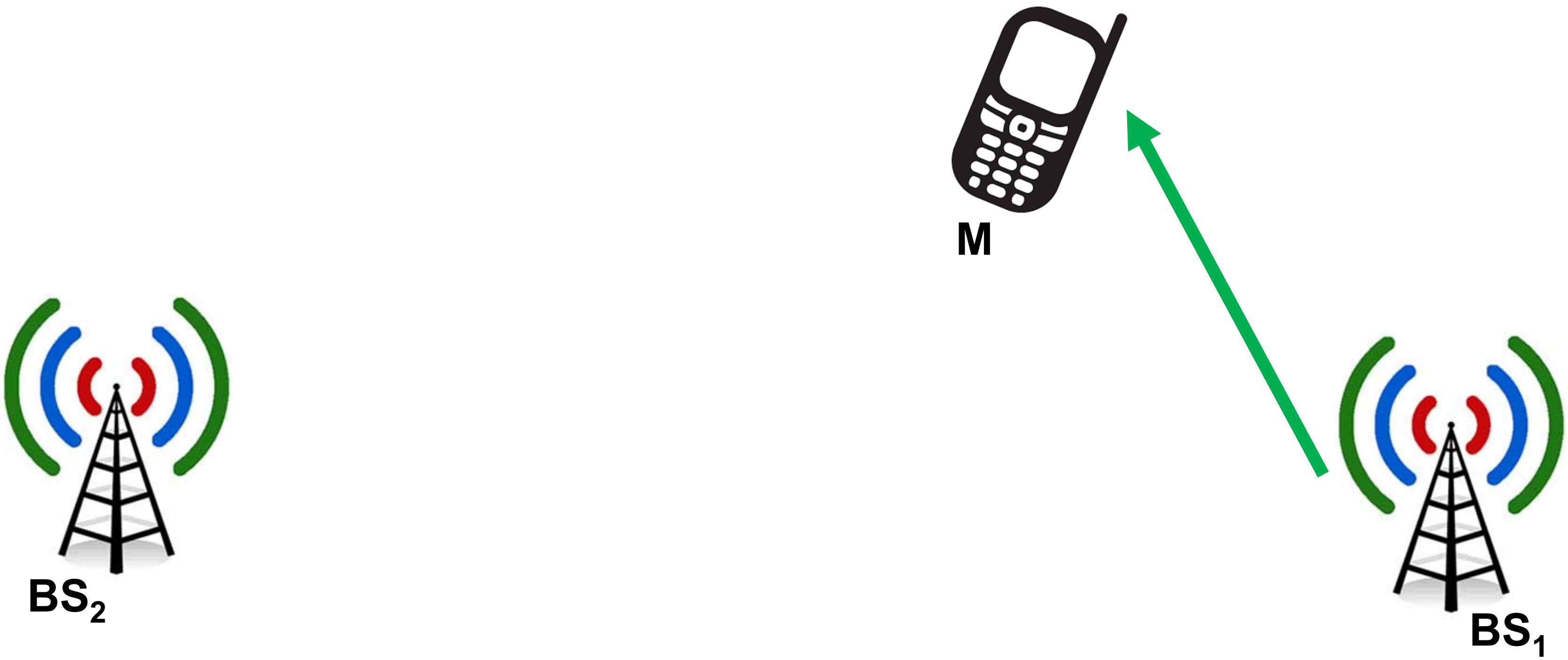

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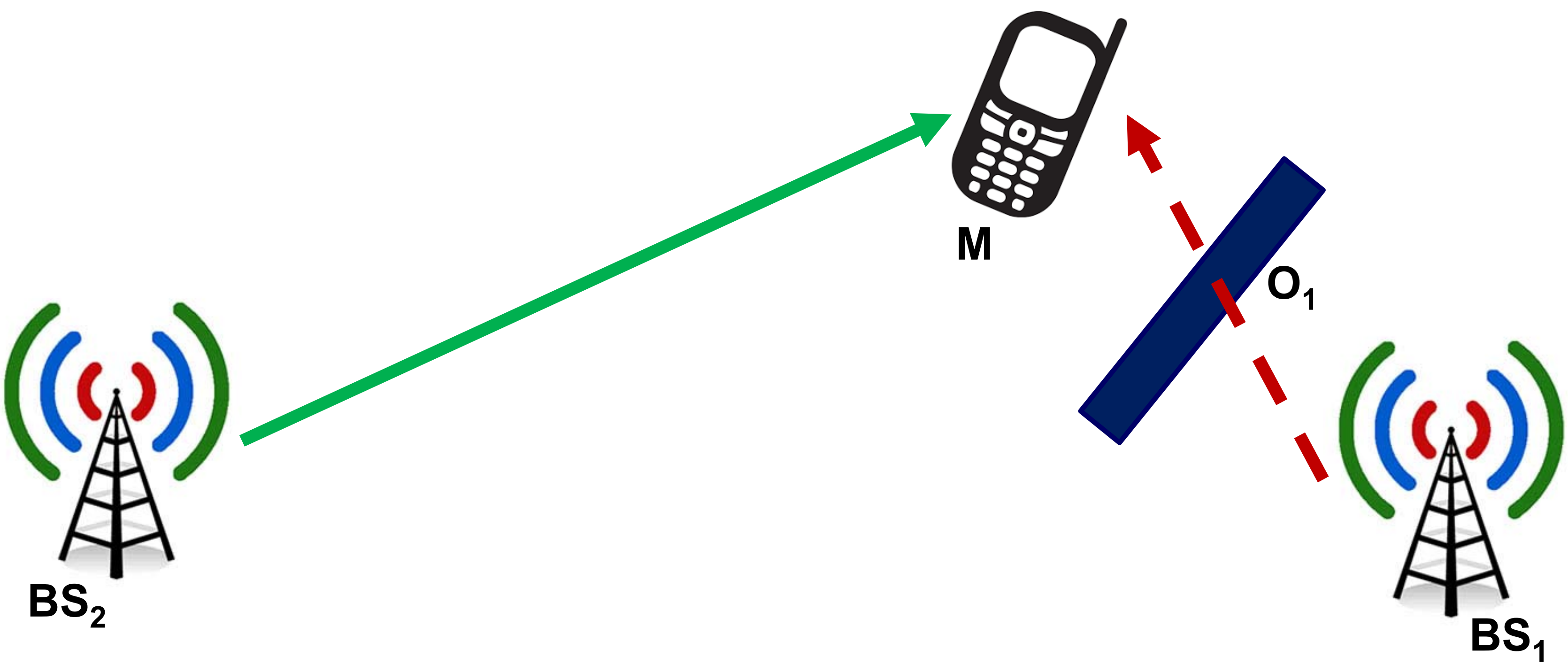

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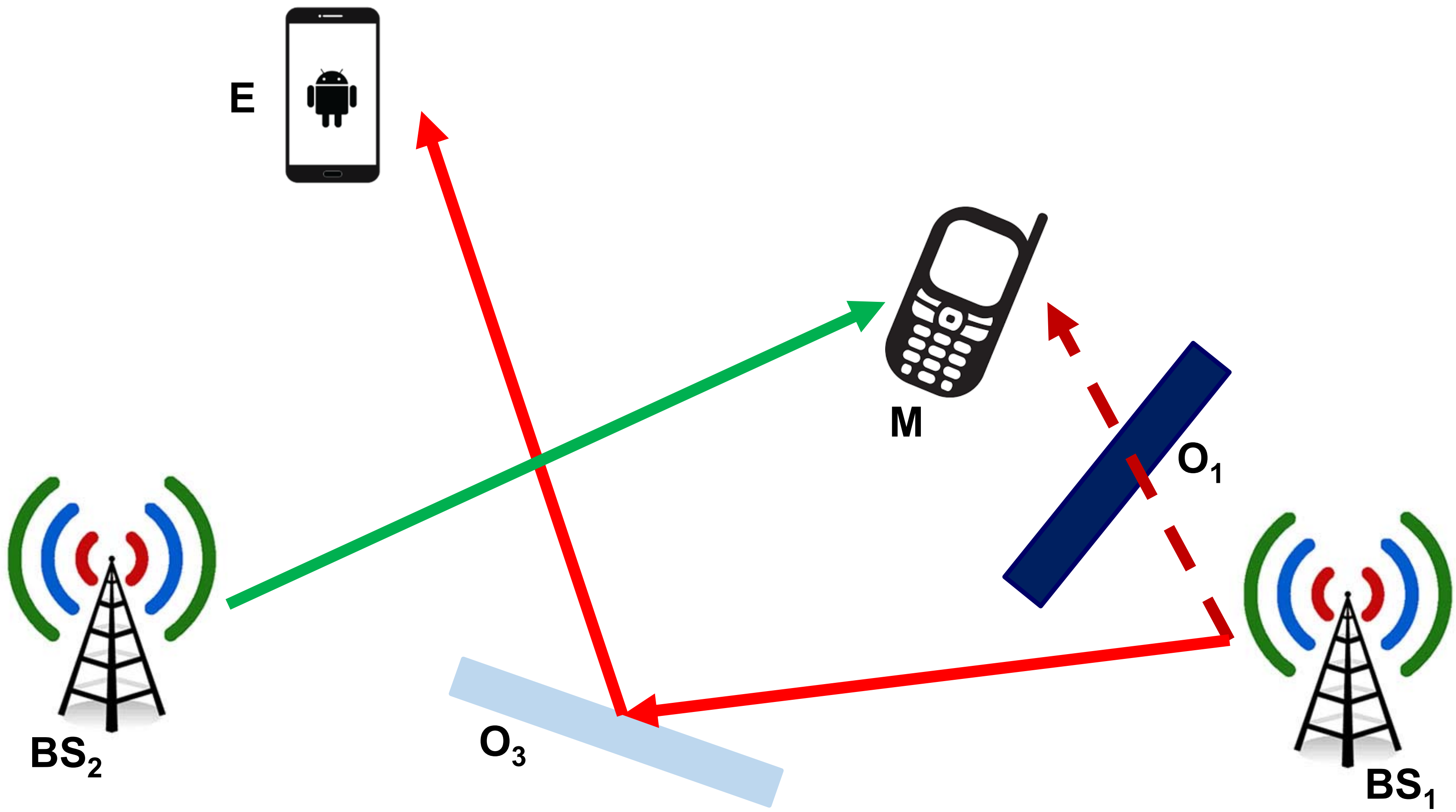

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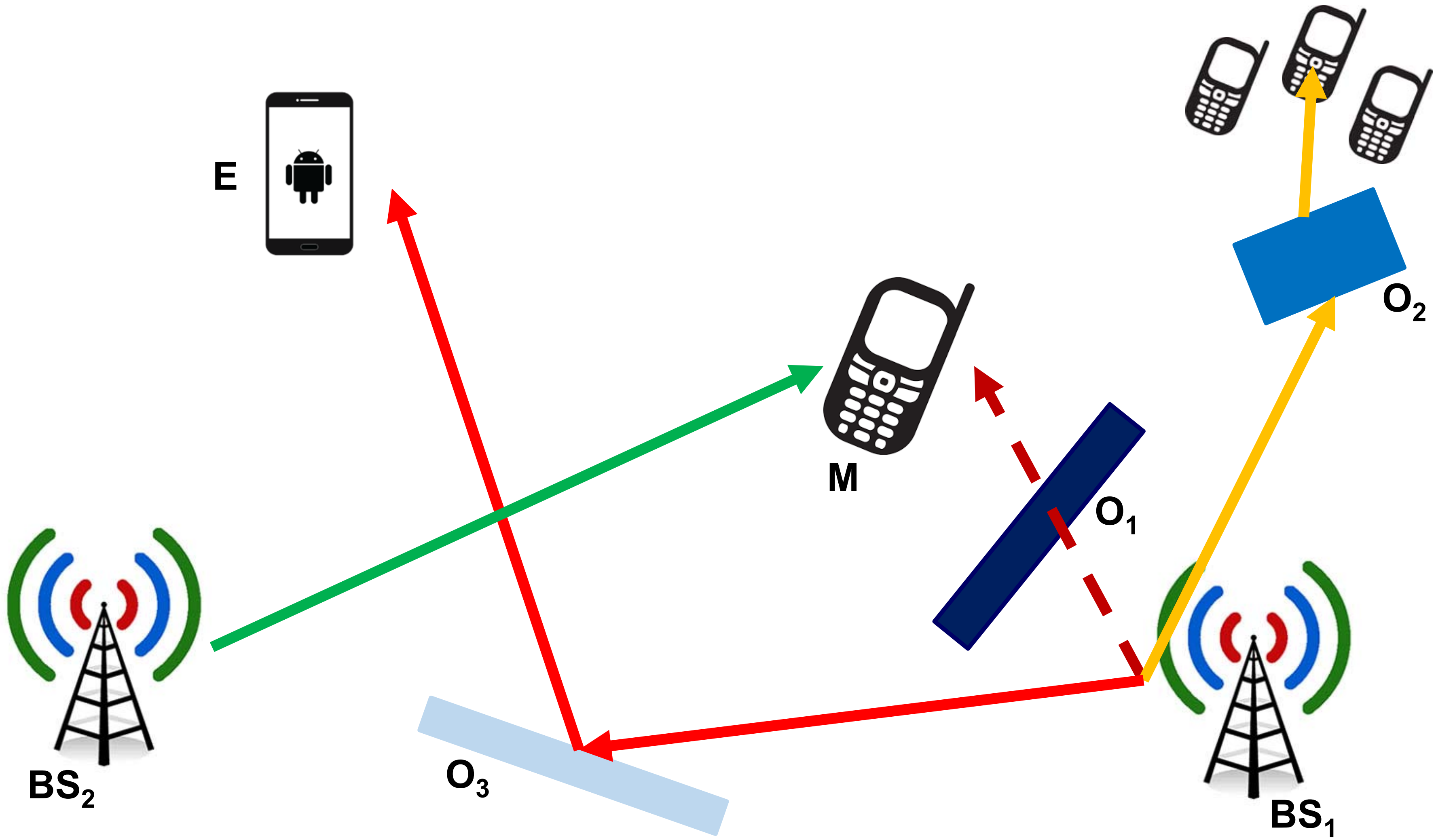
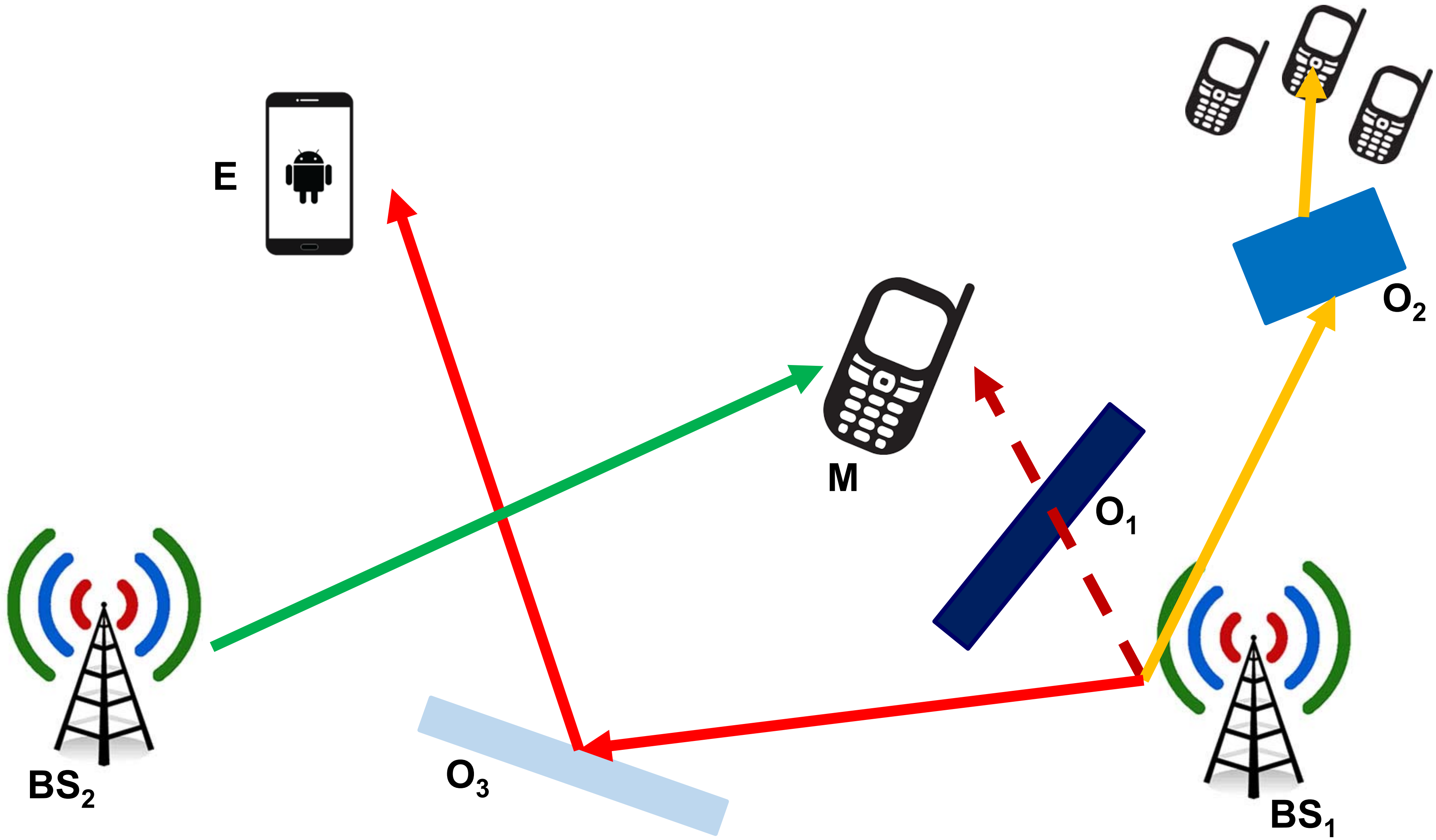


Current Wireless Networks: No Control of Radio Waves



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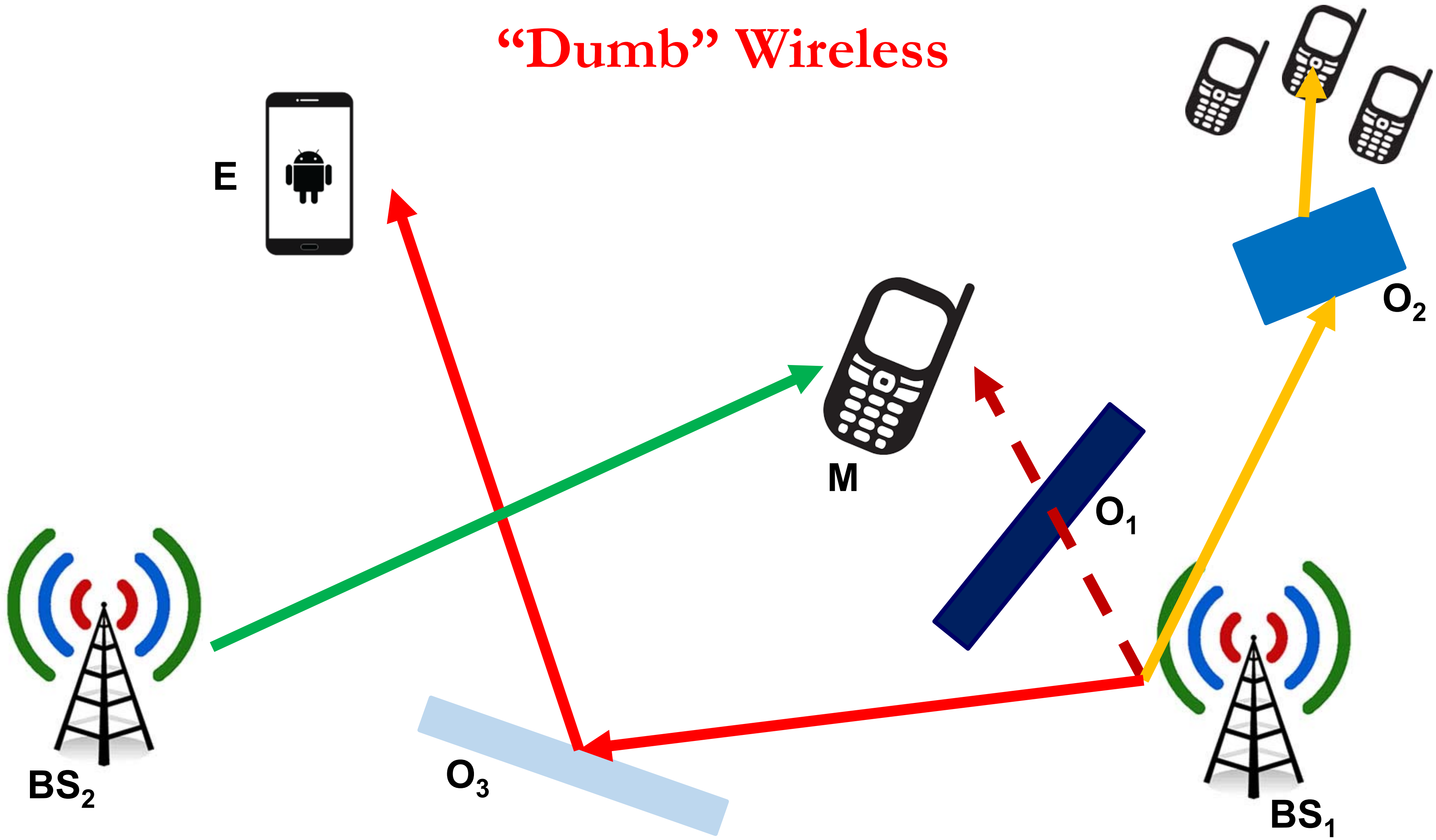

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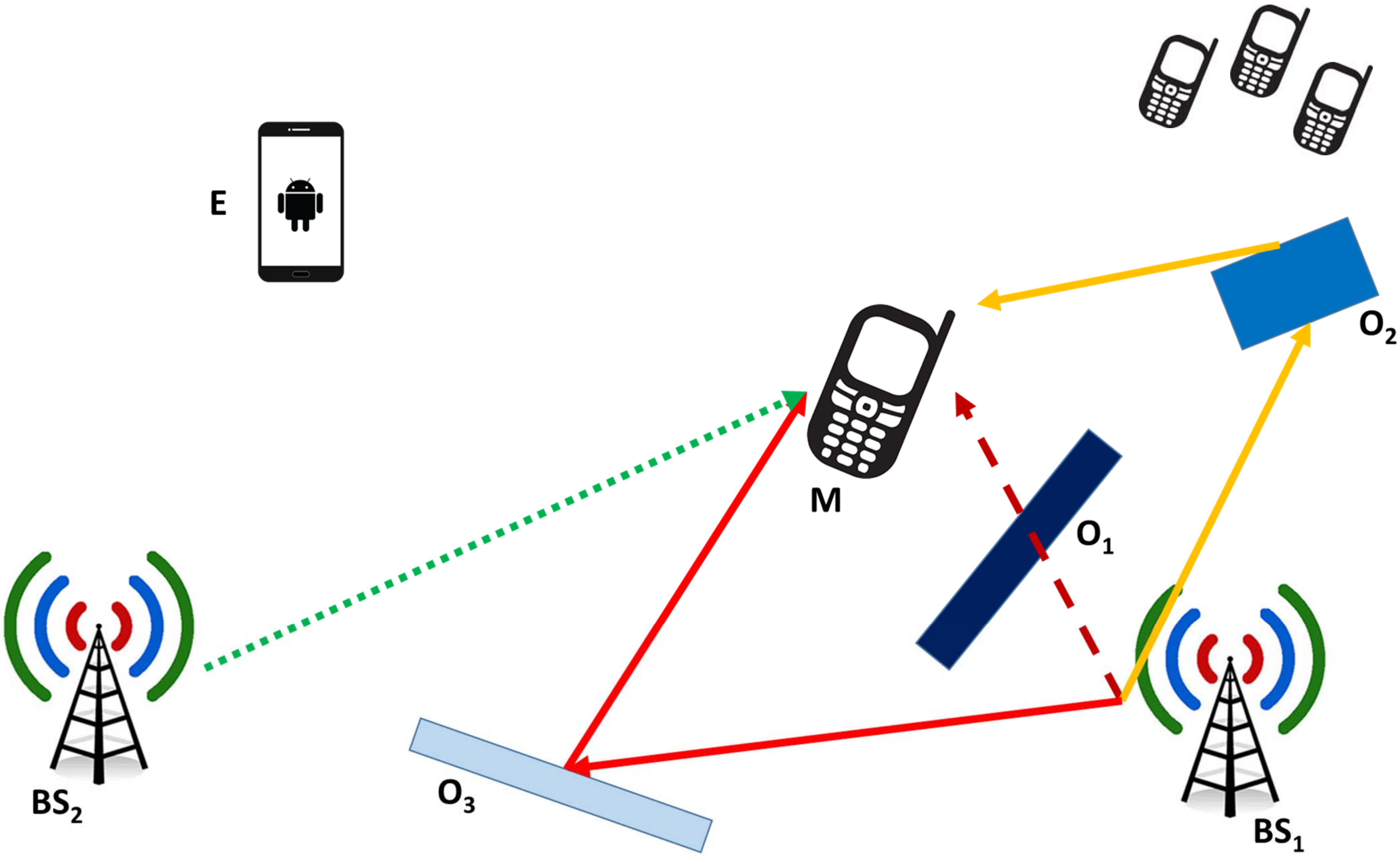
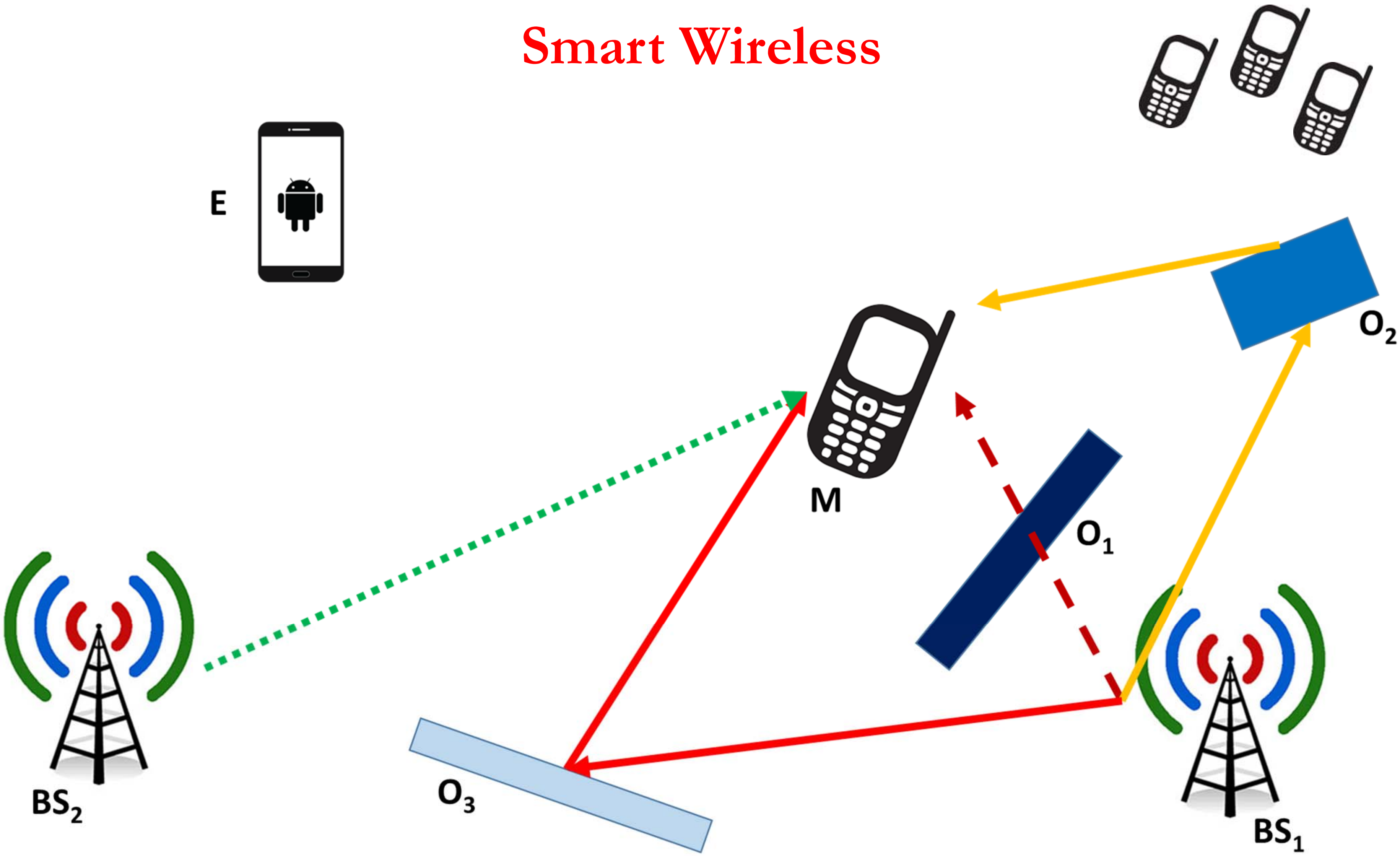
… WHAT IF …

Smart Radio Environments

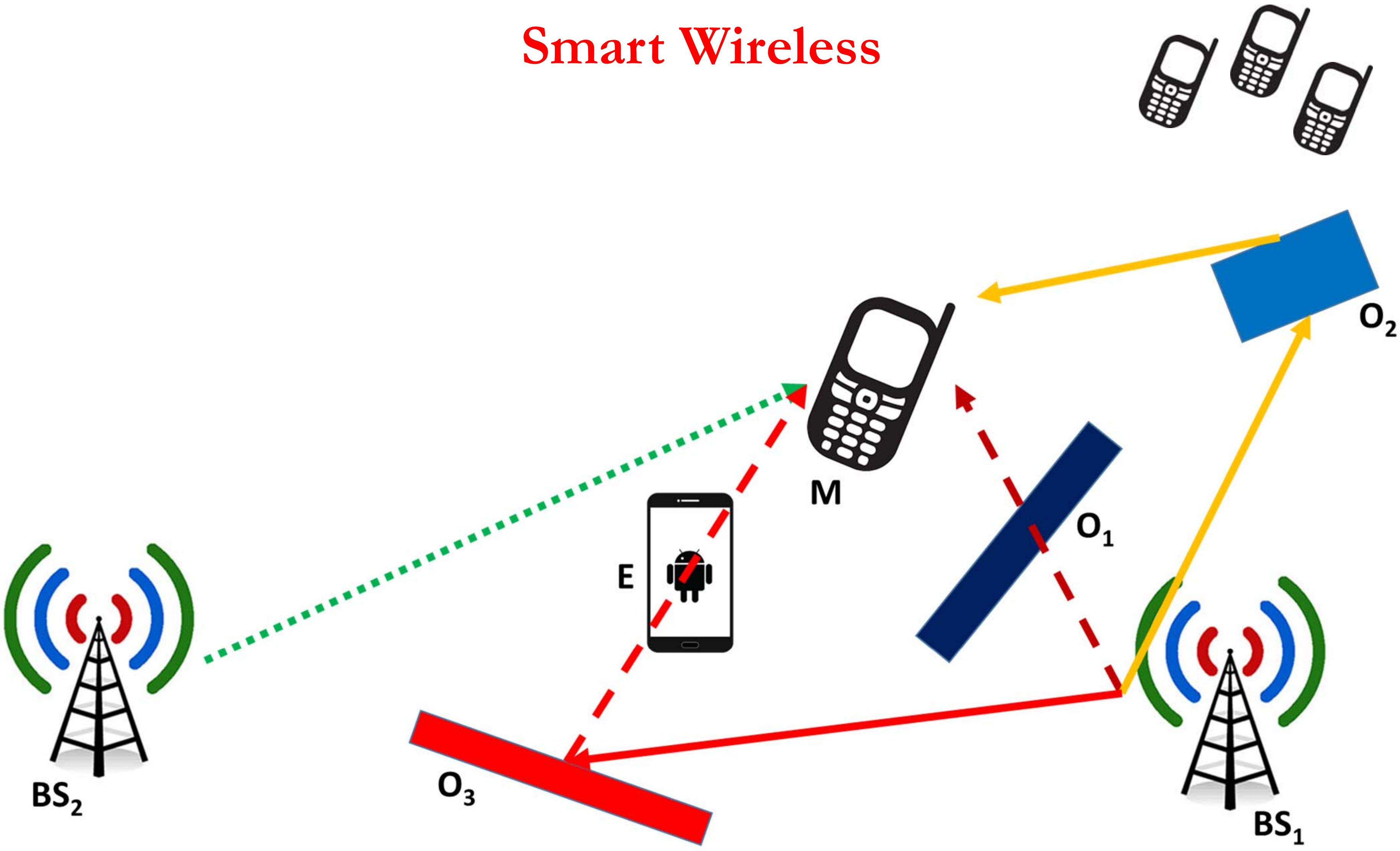


Smart Radio Environments

Smart Wireless



Smart Wireless



Smart Wireless

… from adaptation to …

Control & Programmability

Adaptation: End-Points Optimization

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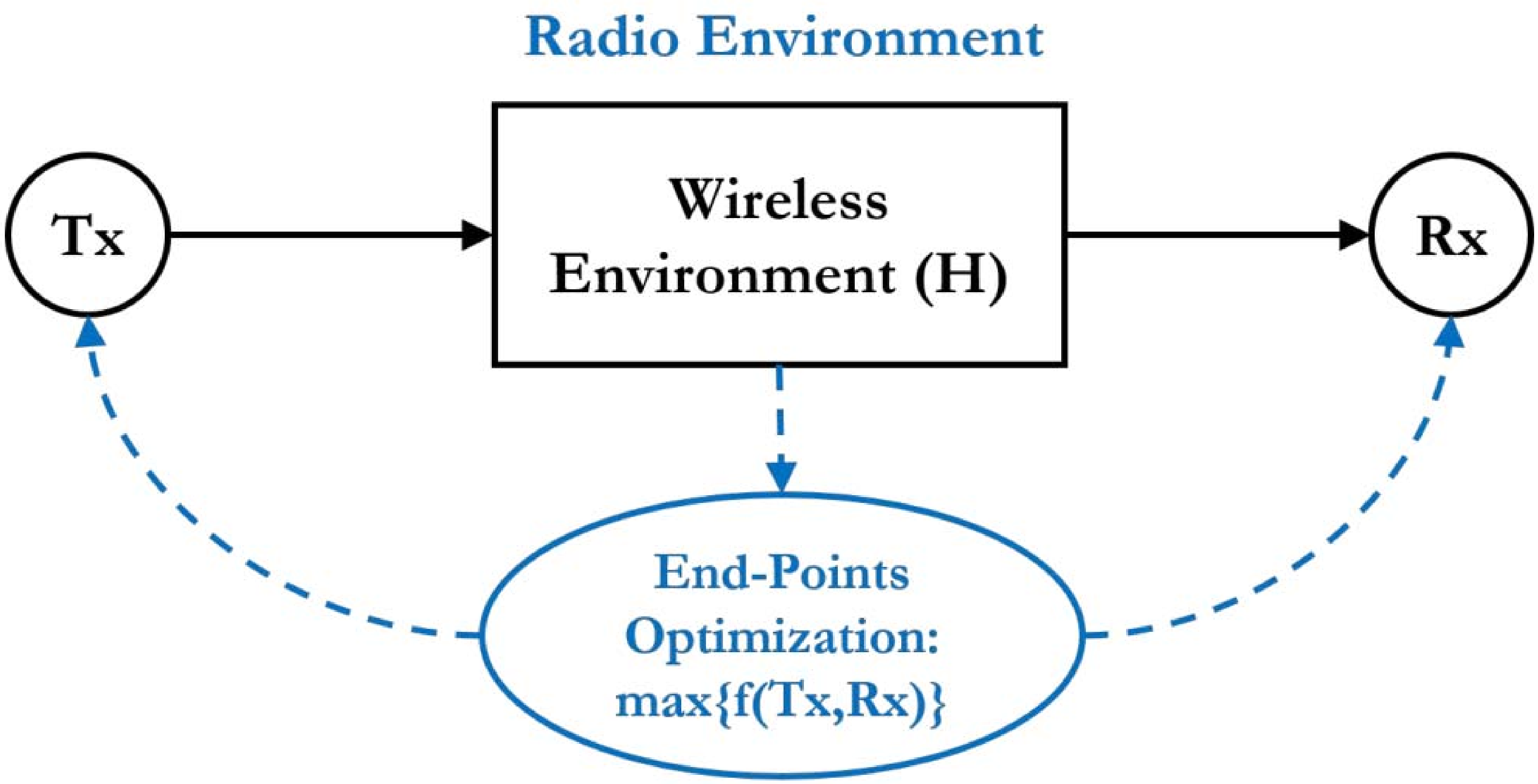

Control & Programmability: Joint Optimization

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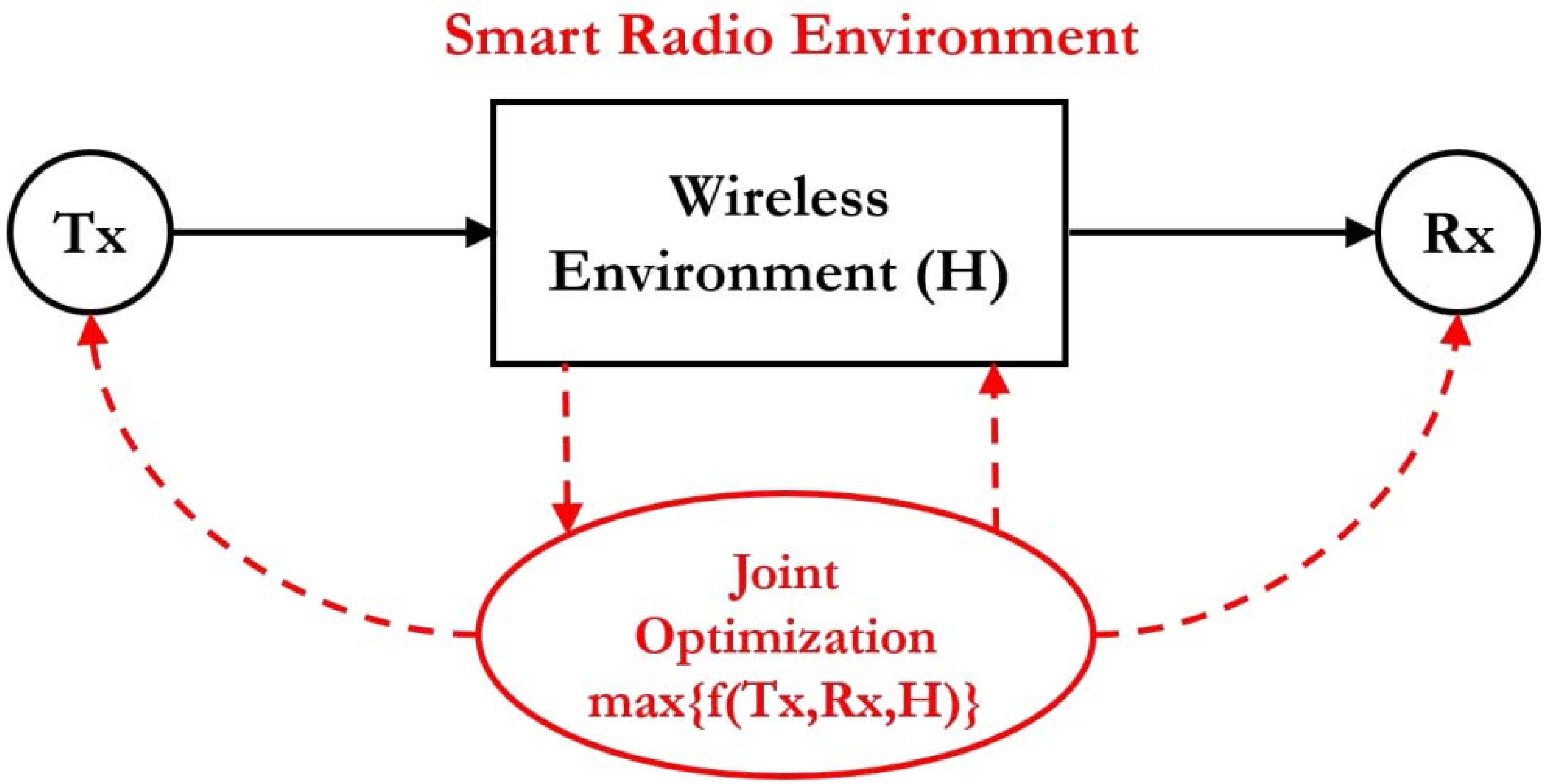

How Can We Design Smart Radio Environments ?

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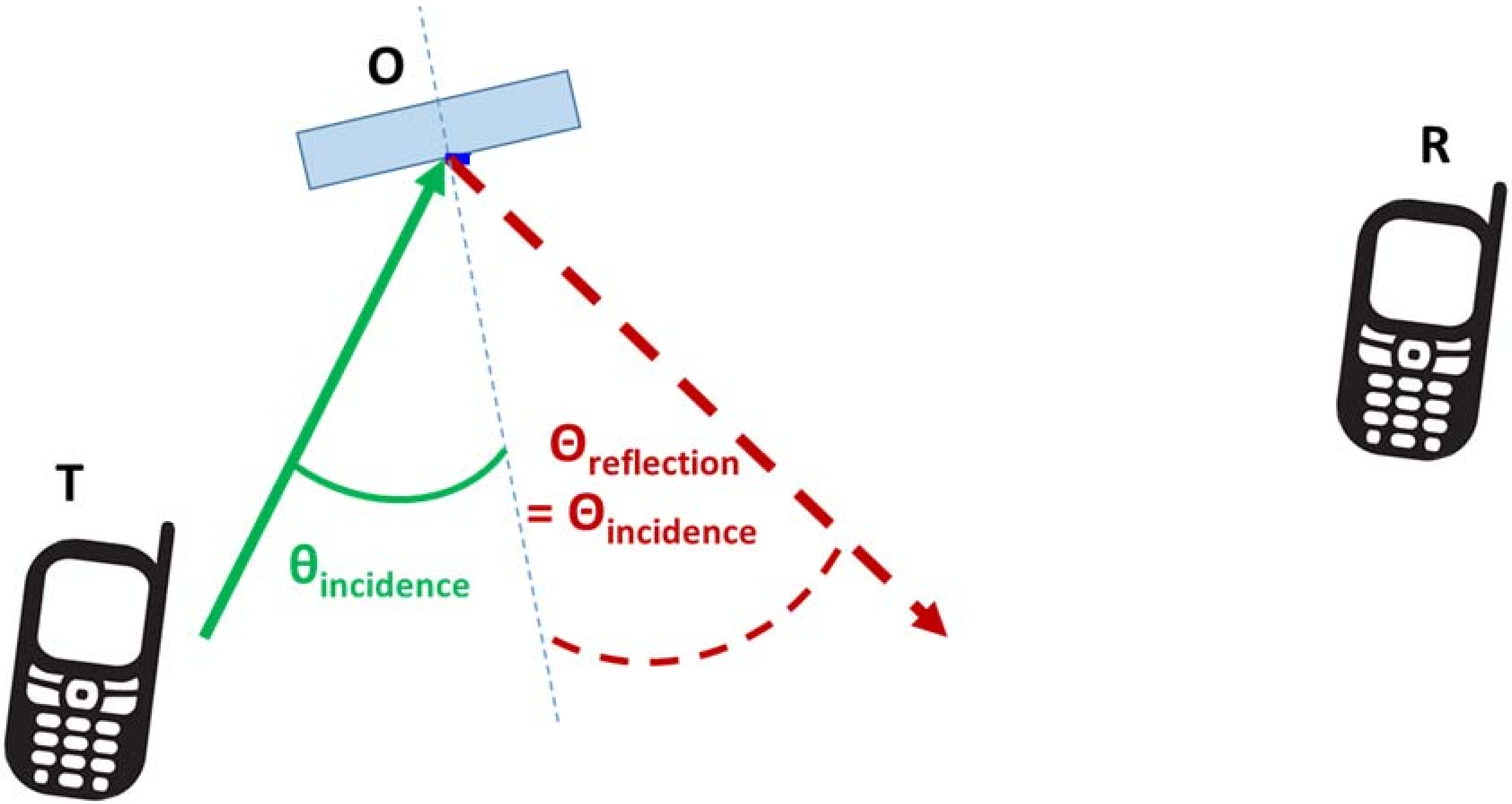
Reconfigurable Intelligent Surfaces (RISs)

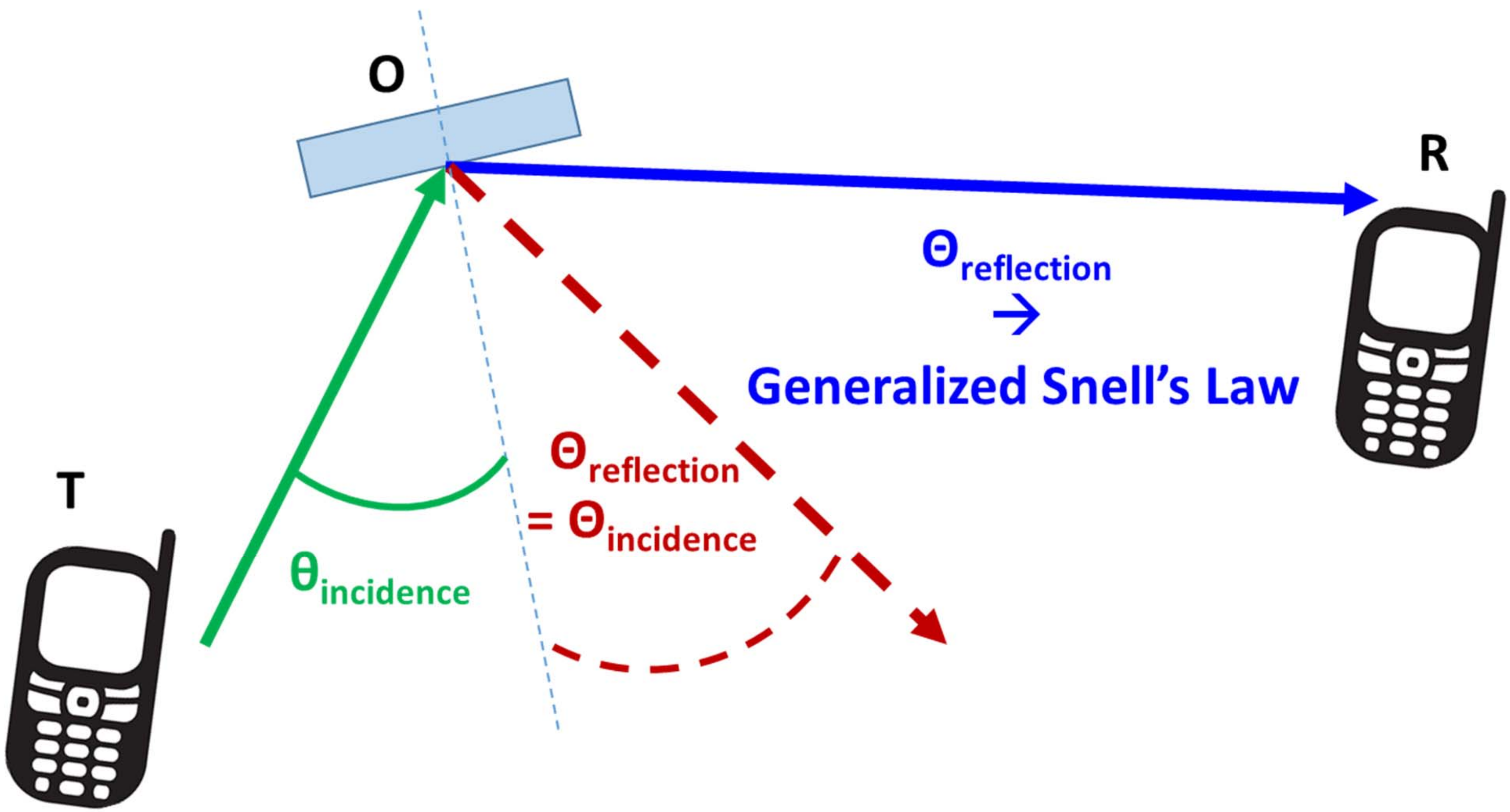
How Can We Design Smart Radio Environments ?

Without an RIS: From Reflections …



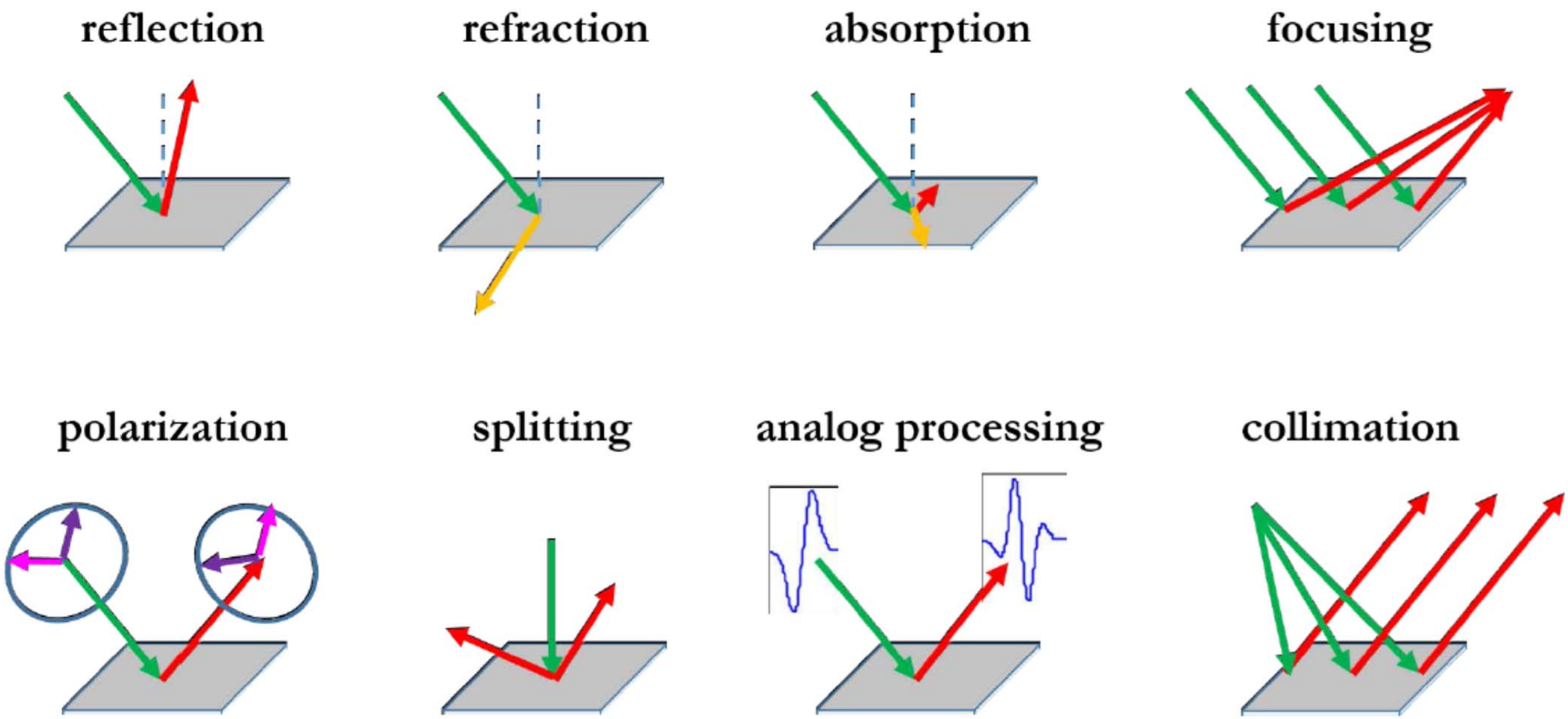
How Can We Design Smart Radio Environments ?

With an RIS: To Smart Reflections …



How Can We Design Smart Radio Environments ?

… RISs are more than just "smart reflections" …



RISs for Wireless Communications

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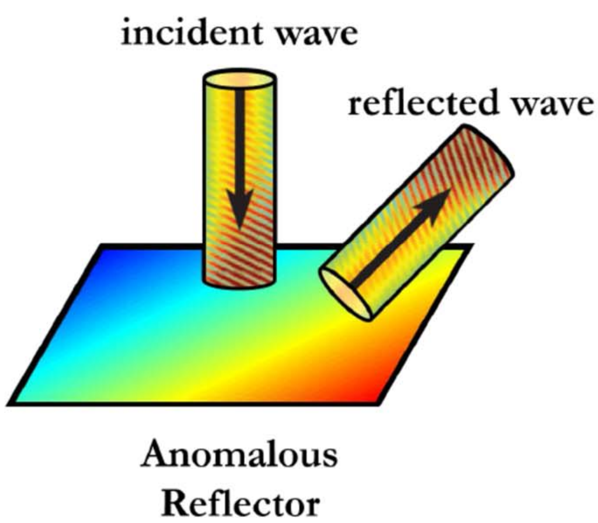
RISs for Wireless Communications



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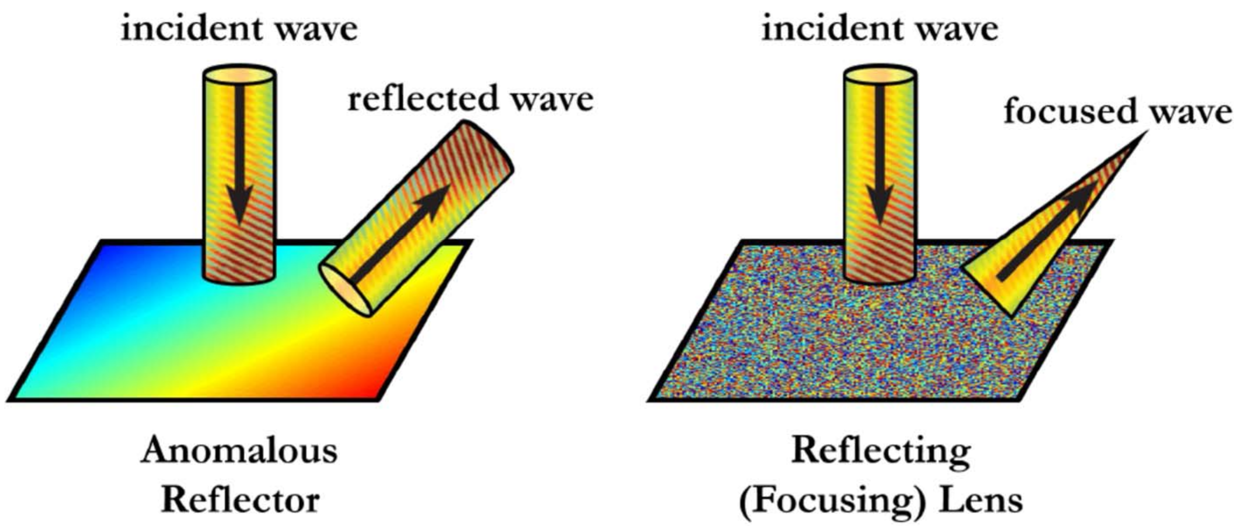

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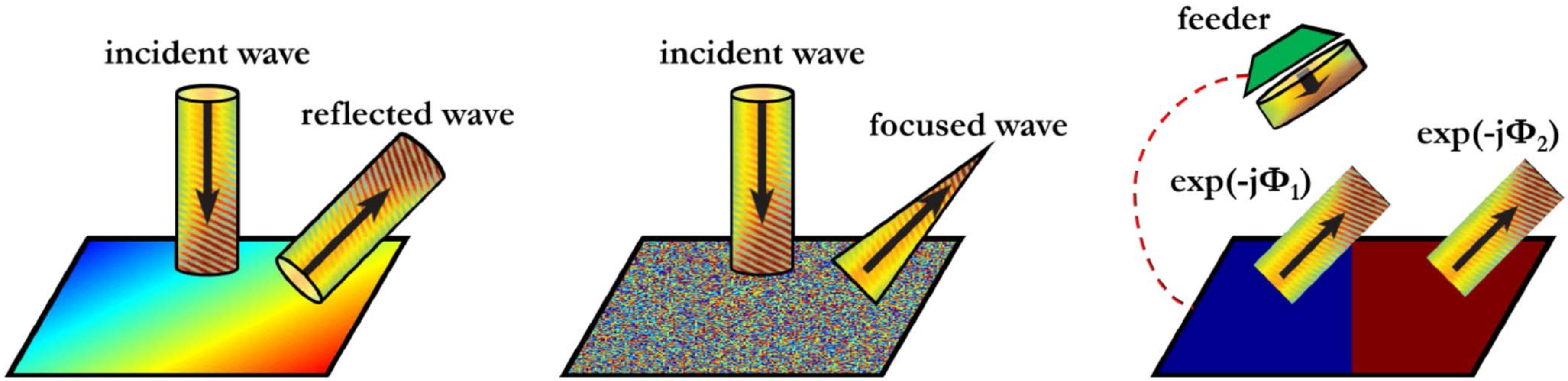
RISs for Wireless Communications



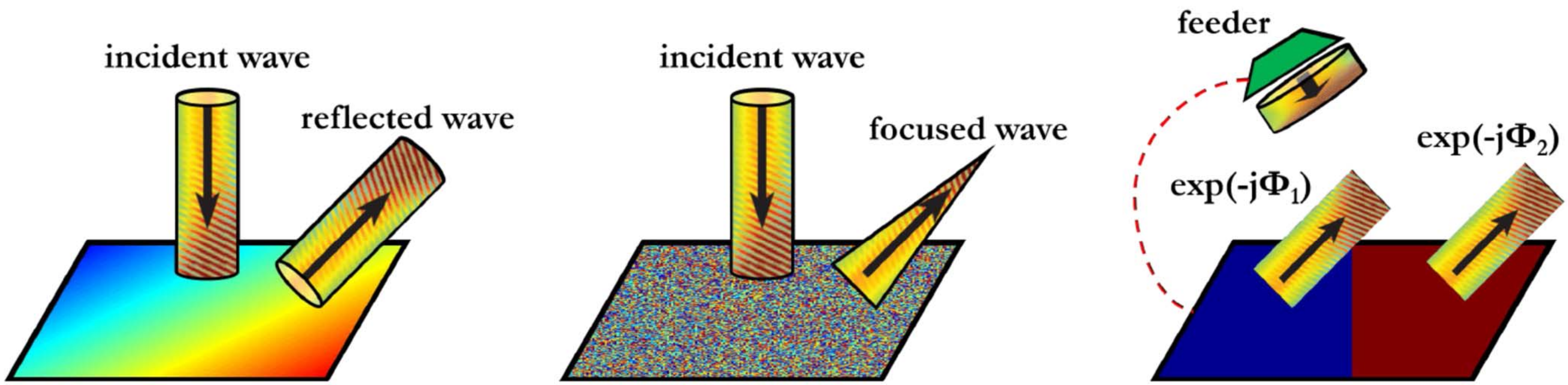
Anomalous Reflector

Reflecting (Focusing) Lens

Joint Encoding & Single-RF Transmitter

How Can We Design Smart Radio Environments ?

RISs for Wireless Communications



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Joint Encoding & Single-RF Transmitter

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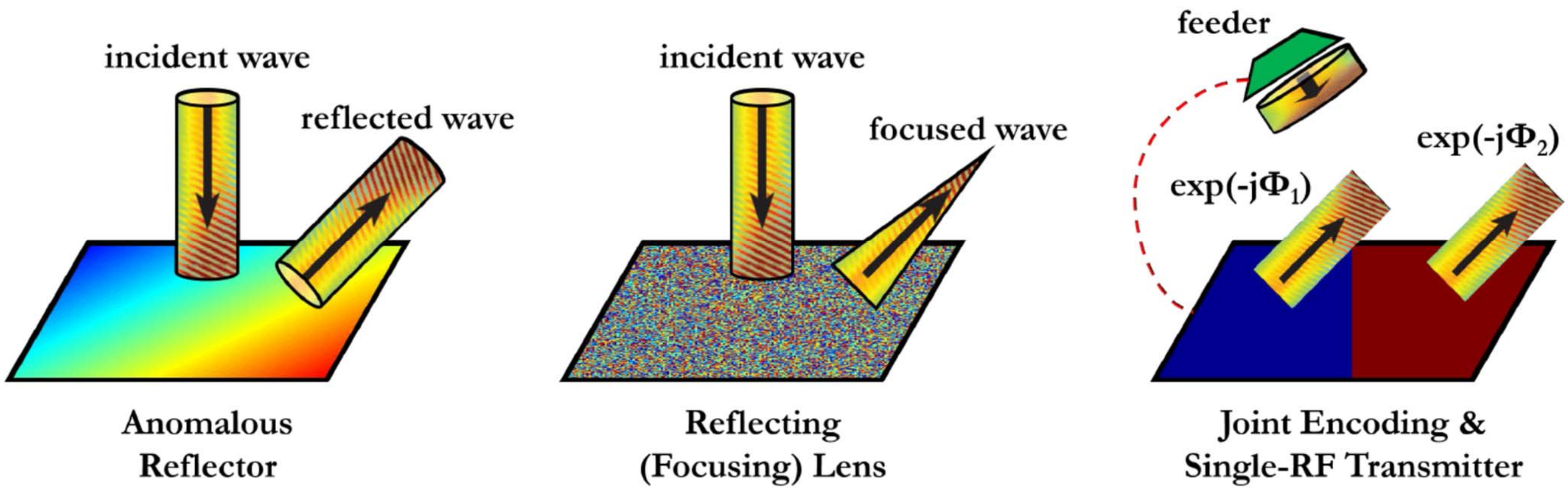
RISs for Wireless Communications



$$E^{(\text{scattered})}(S) \propto E^{(\text{incident})}(S)\left[A(S)\cdot\exp\left(j\Phi(S)\right)\right]$$

$$\Downarrow$$

$$E^{(\text{scattered})}(V) \propto \text{Surface Equivalent Theorem}\left\{E^{(\text{scattered})}(S)\right\}$$

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  - **Implementations based on large arrays of inexpensive antennas that are usually spaced half of the wavelength apart**
  - **Metamaterial-based planar or conformal large surfaces whose scattering elements have sizes and inter-distances much smaller than the wavelength**

How Can We Design Smart Radio Environments ?

RISs: Tiny Antennas Spaced ~λ/2

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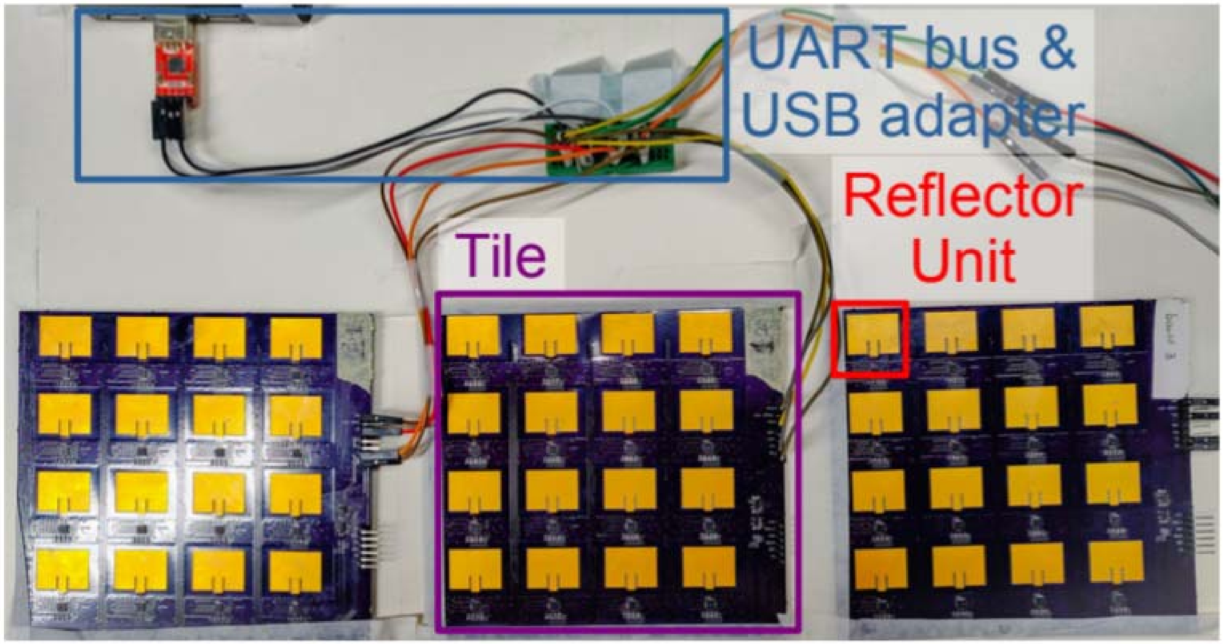
RISs: Tiny Antennas Spaced ~λ/2 (e.g., ScatterMIMO)

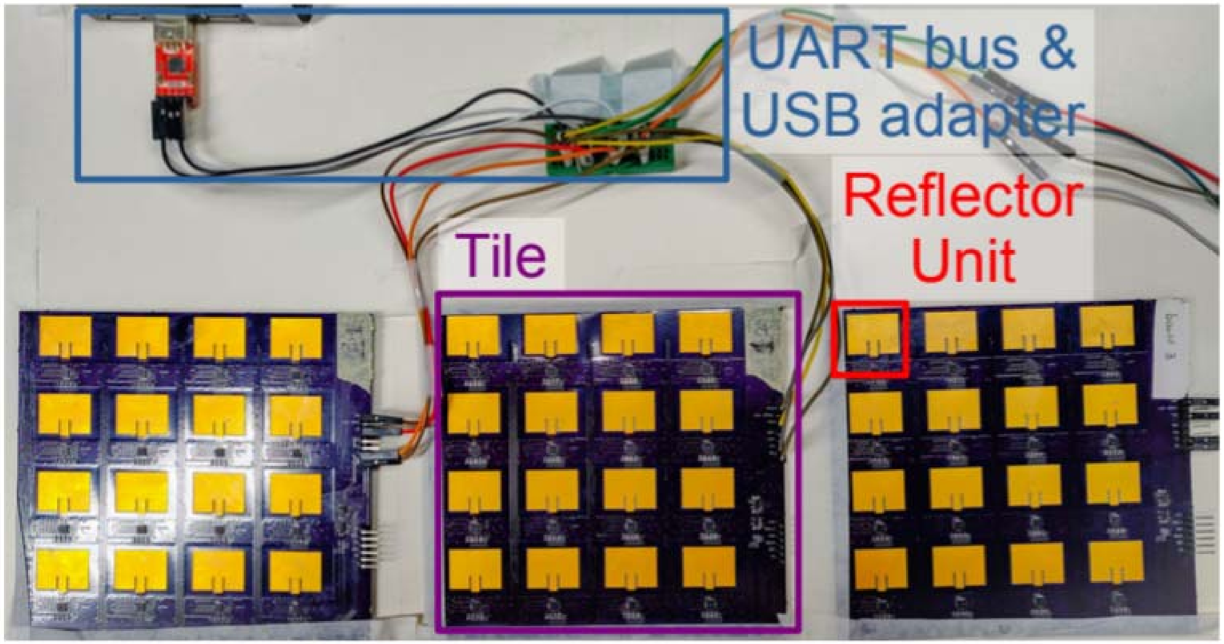


Univ. California
San Diego
MobiCom 2020

Properties	ScatterMIMO
# antenna elements	48
Algorithm Latency	3 packets
Coverage	upto 45m

How Can We Design Smart Radio Environments ?

RISs: Tiny Antennas Spaced ~λ/2 (e.g., ScatterMIMO)



Univ. California
San Diego
MobiCom 2020

Properties	ScatterMIMO	LAIA [30]	RFocus [9]
# antenna elements	48	36	3720
Algorithm Latency	3 packets	72 packets	4000 packets
Coverage	upto 45m	8 m	30 m

How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < λ/2

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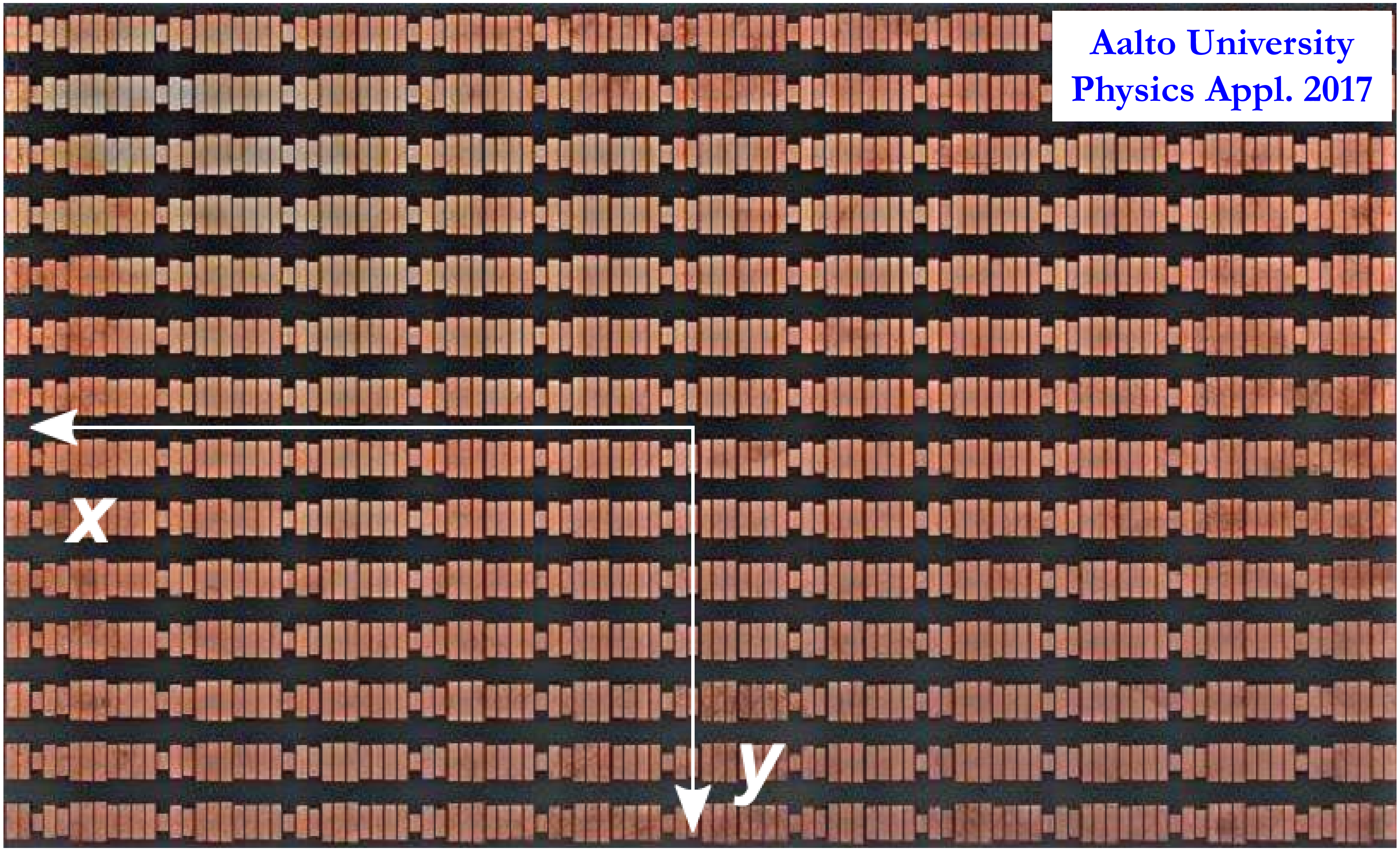
(e.g., Perfect Anomalous Reflection)



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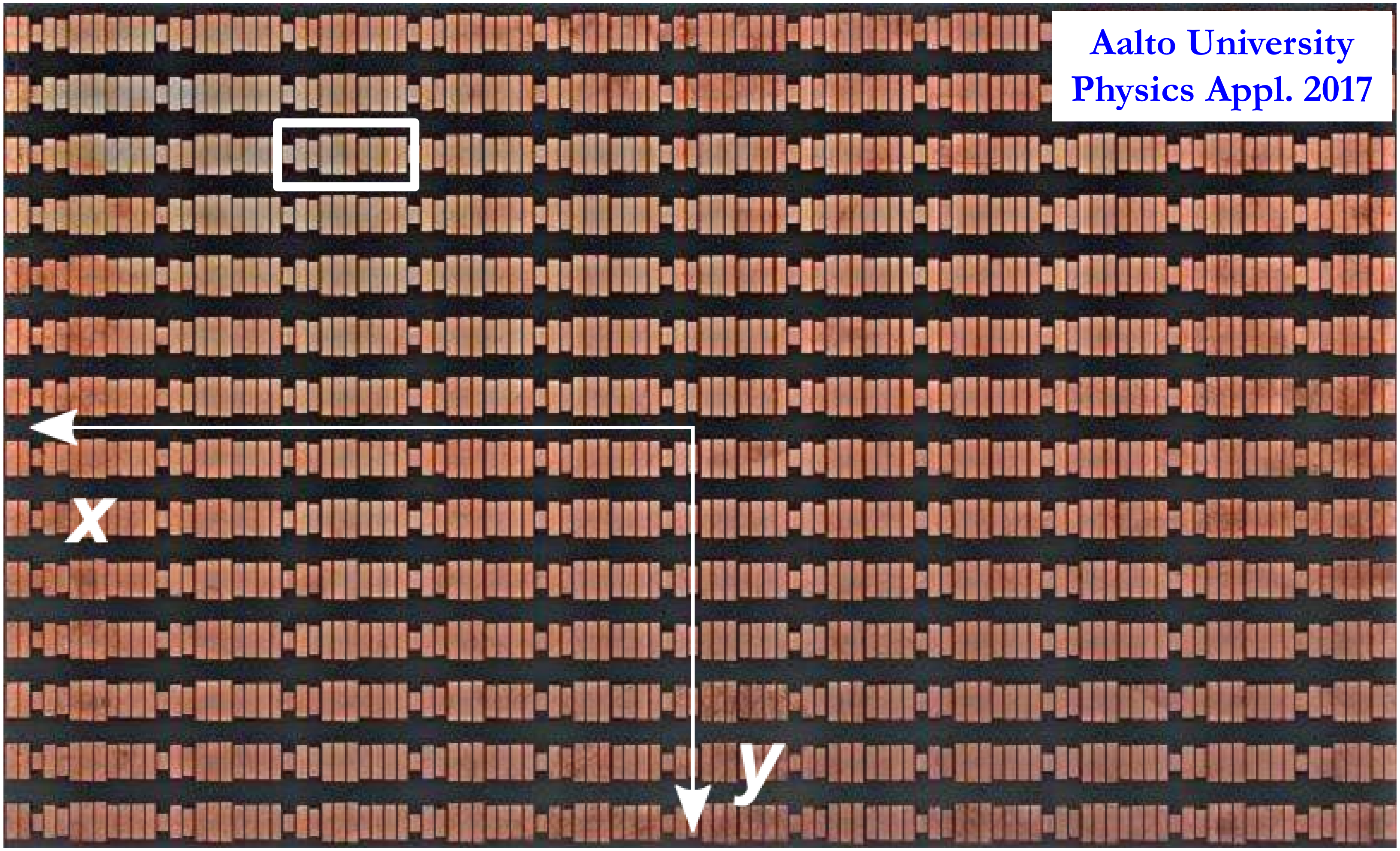

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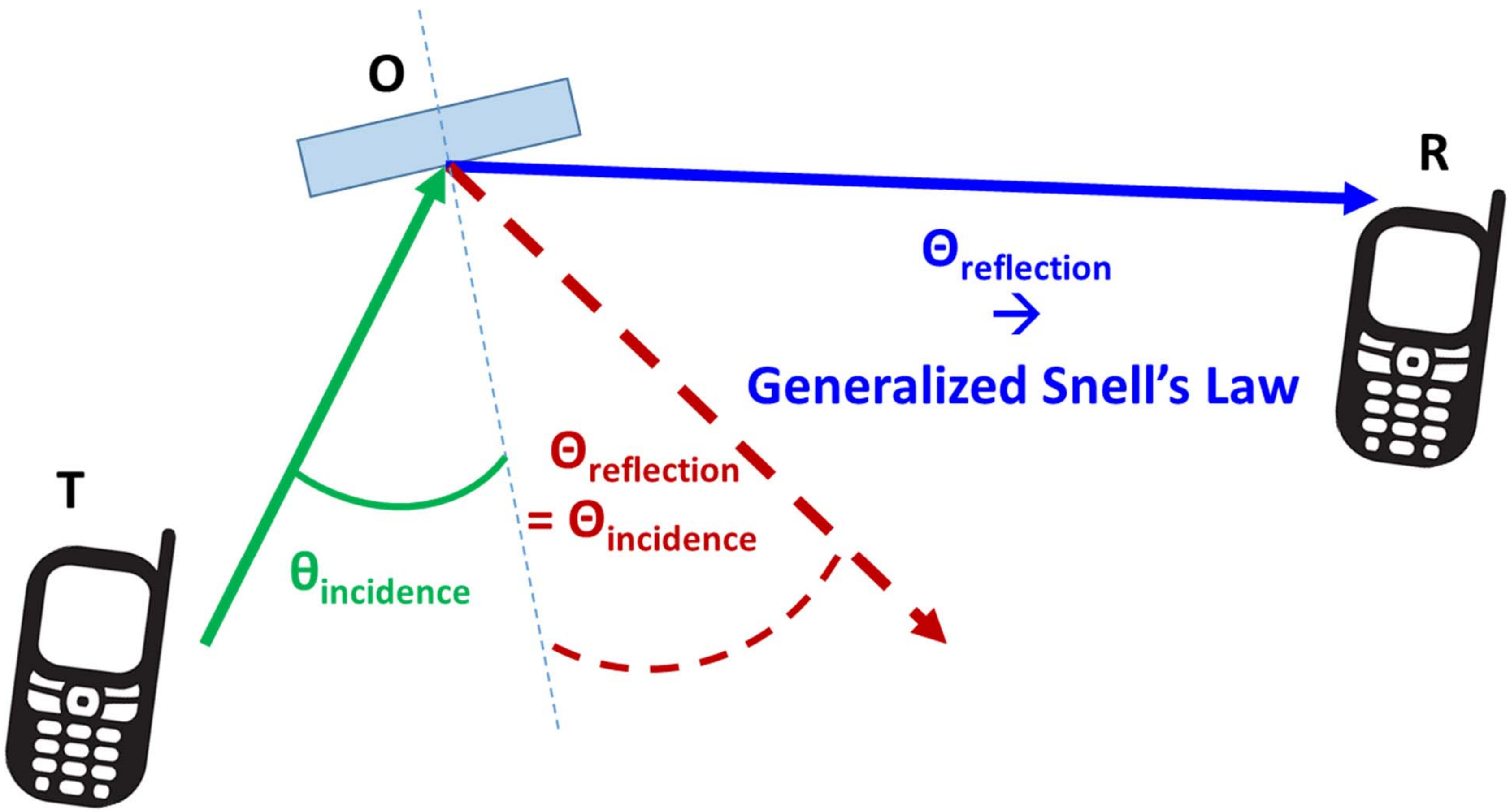

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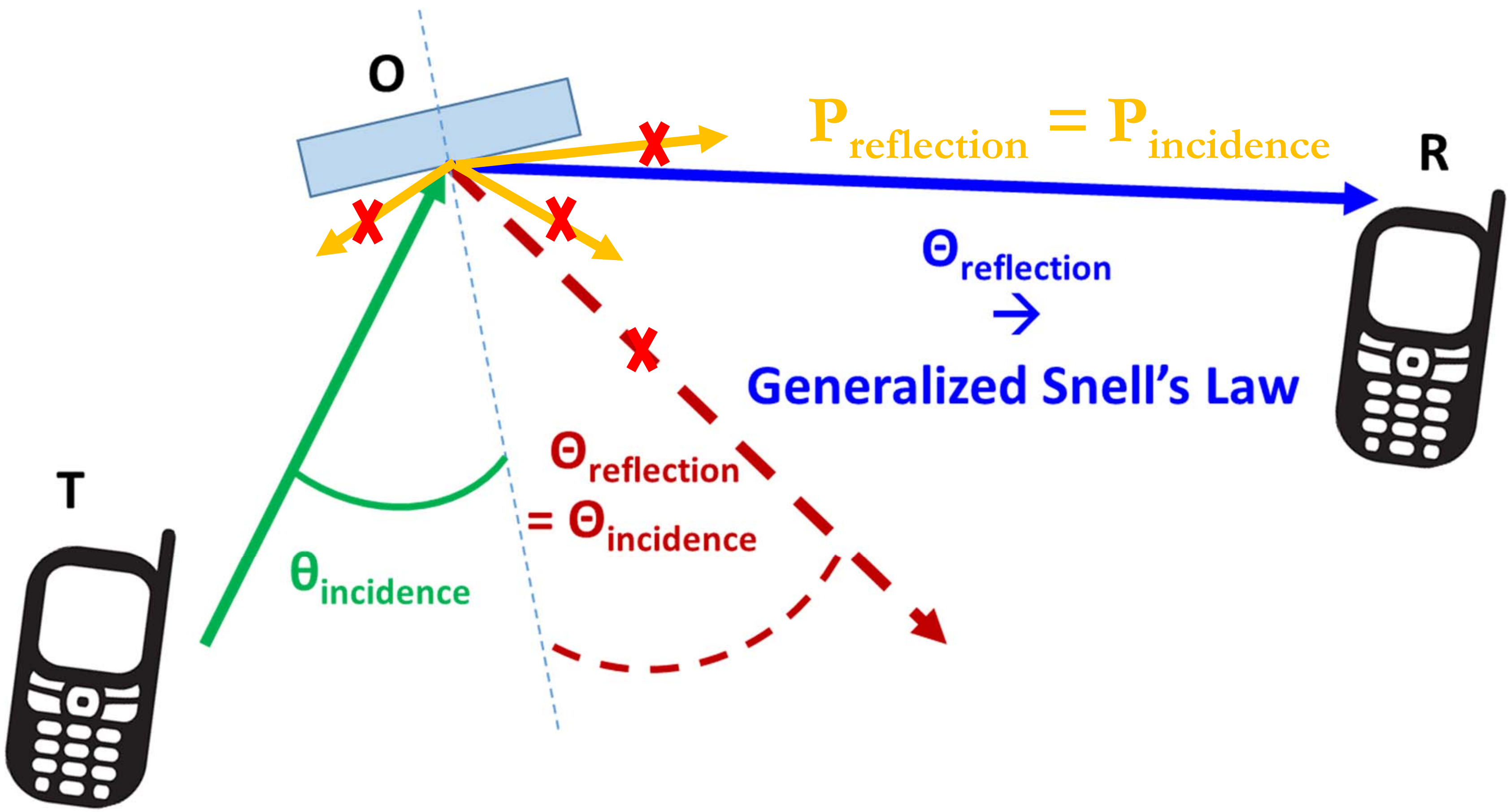

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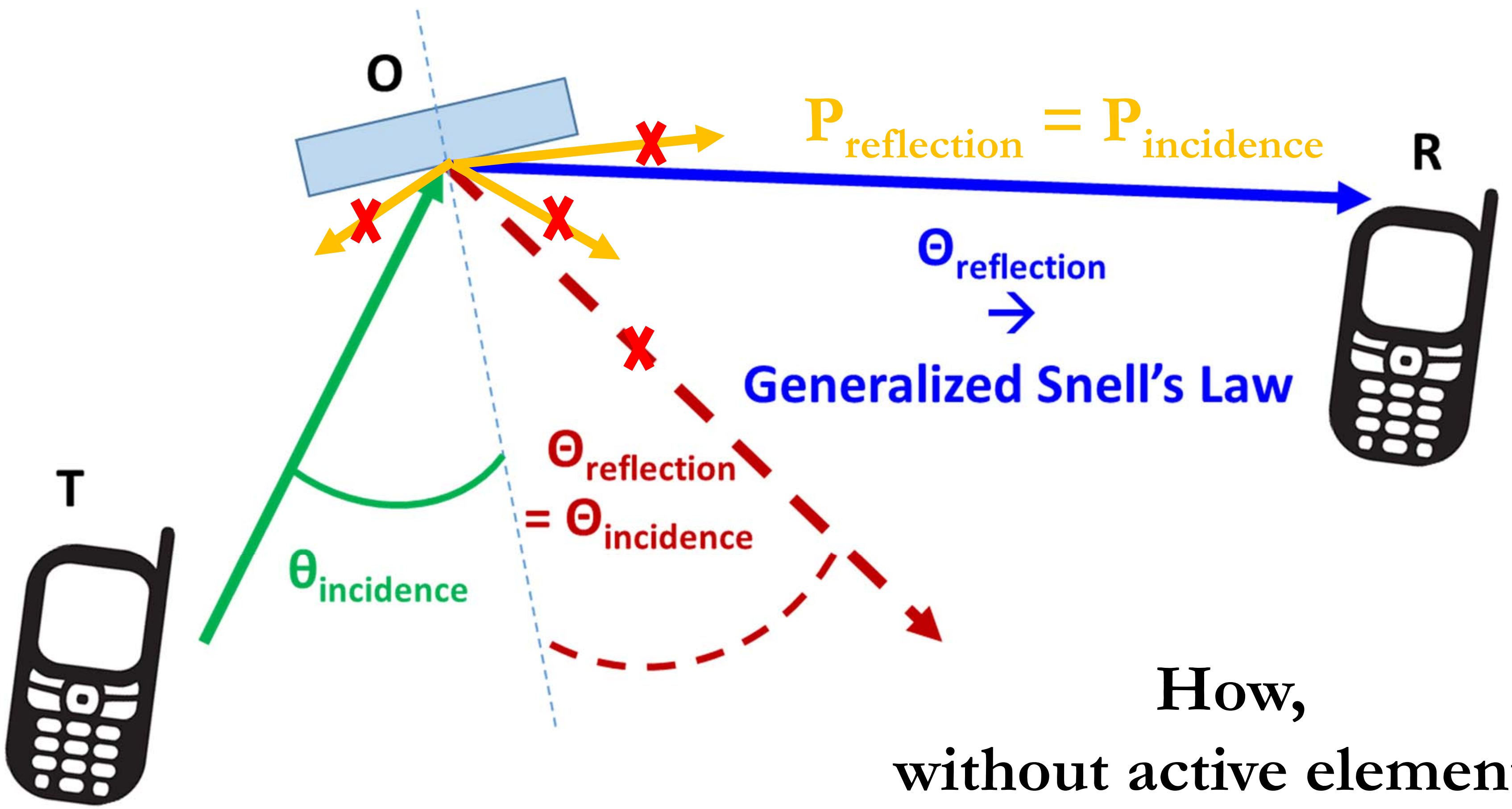

How,
without active elements?

How Can We Design Smart Radio Environments ?

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(e.g., Perfect Anomalous Reflection → non-local design)

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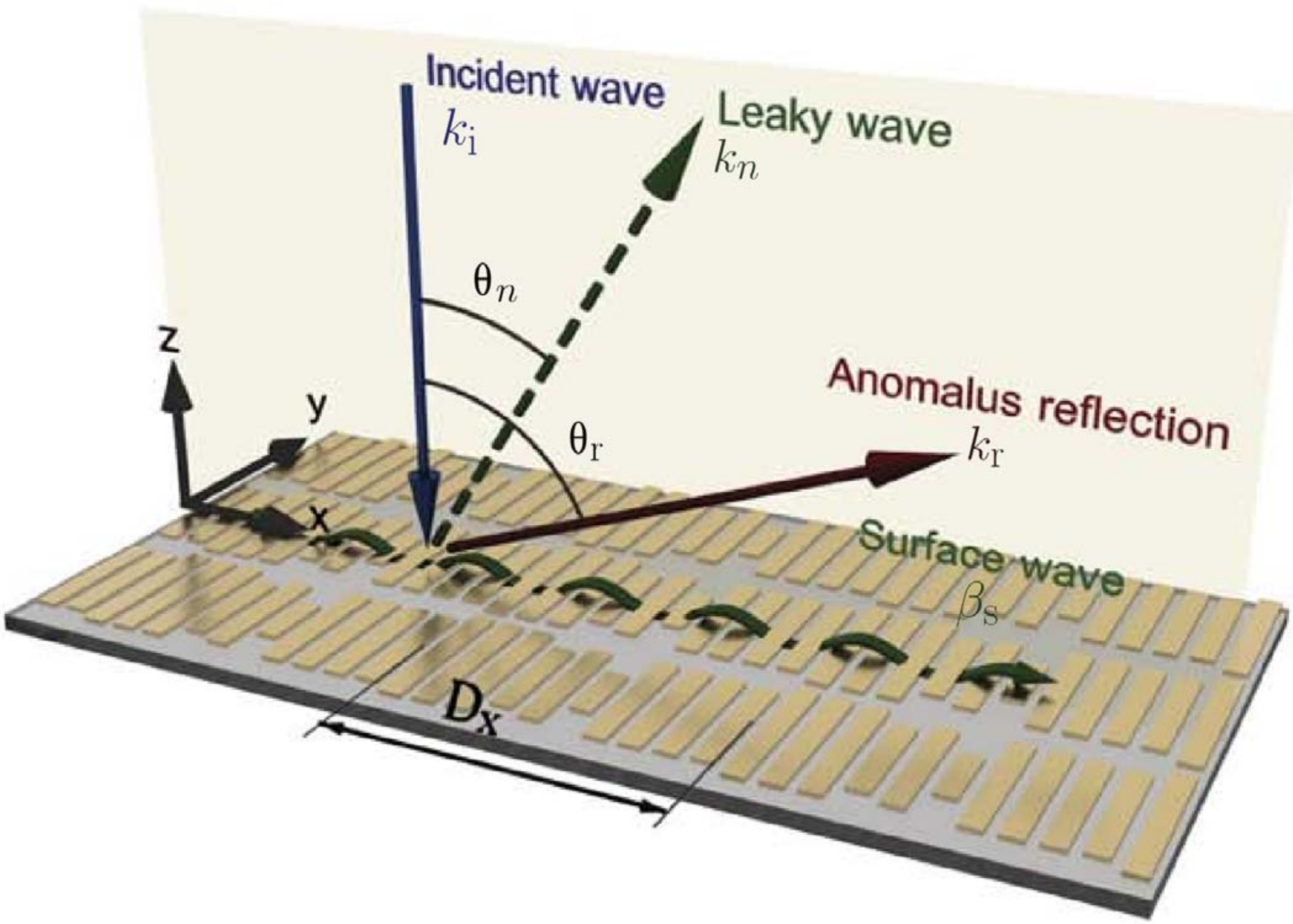

How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < $\lambda/2$

(e.g., Perfect Anomalous Reflection → why non-local design)

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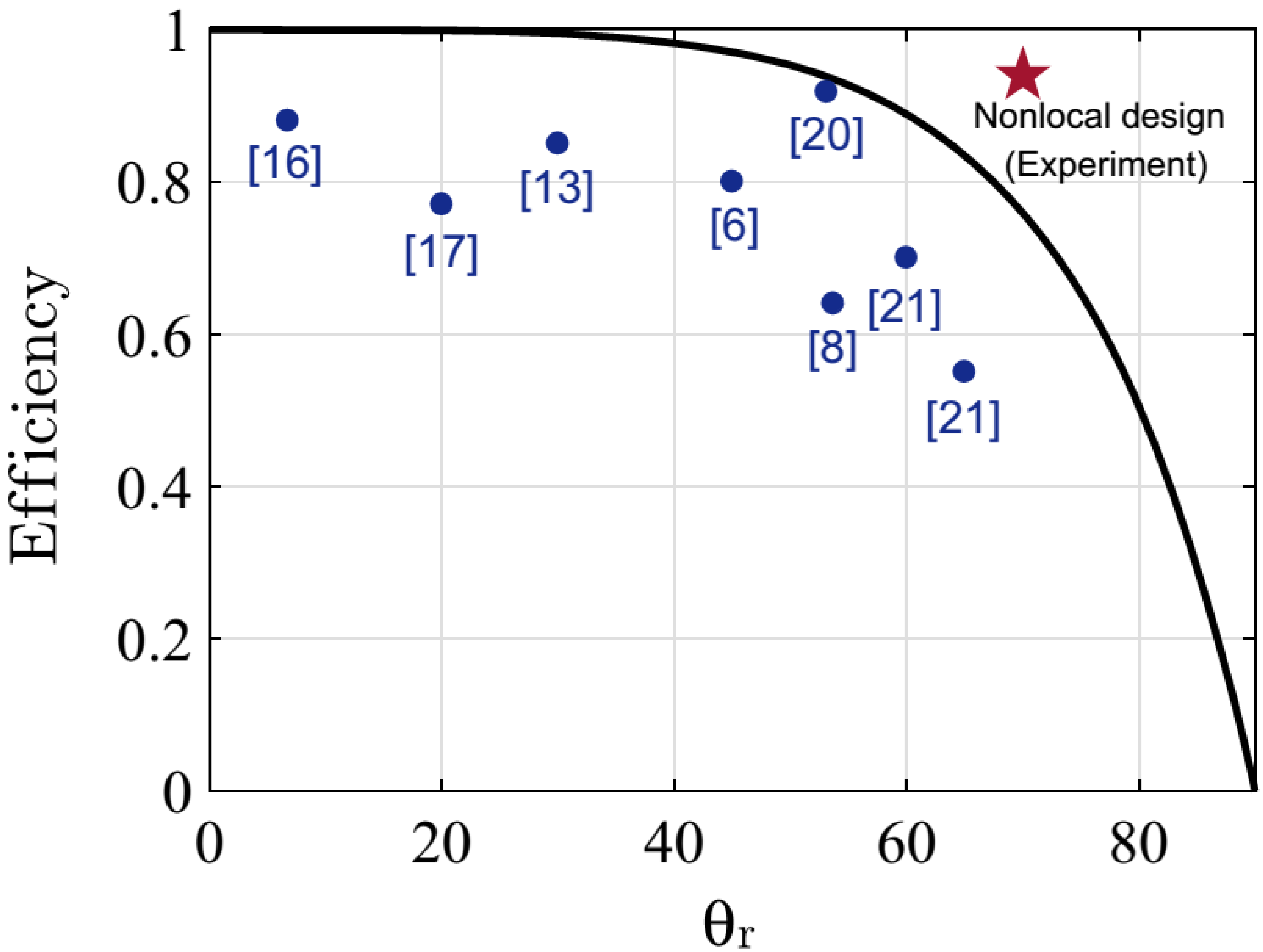

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How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < λ/2

(local design vs. non-local design)

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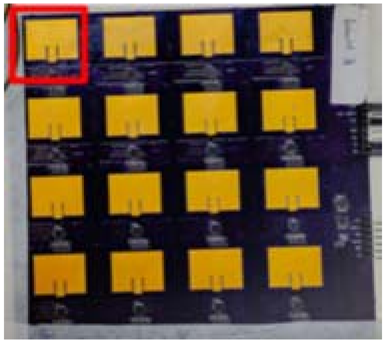

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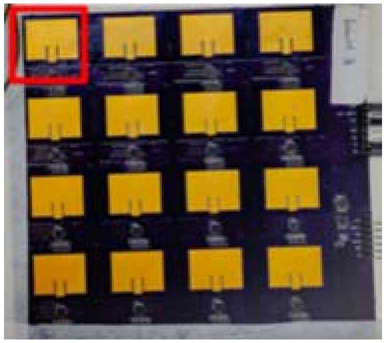

locally passive implementation

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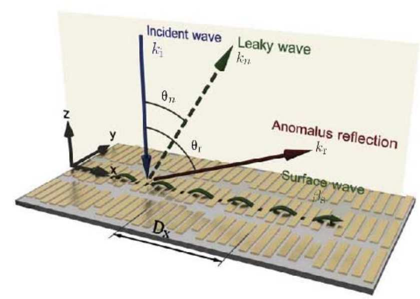

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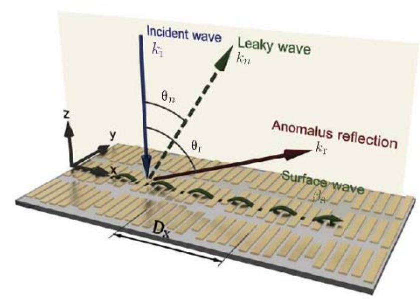

globally passive implementation

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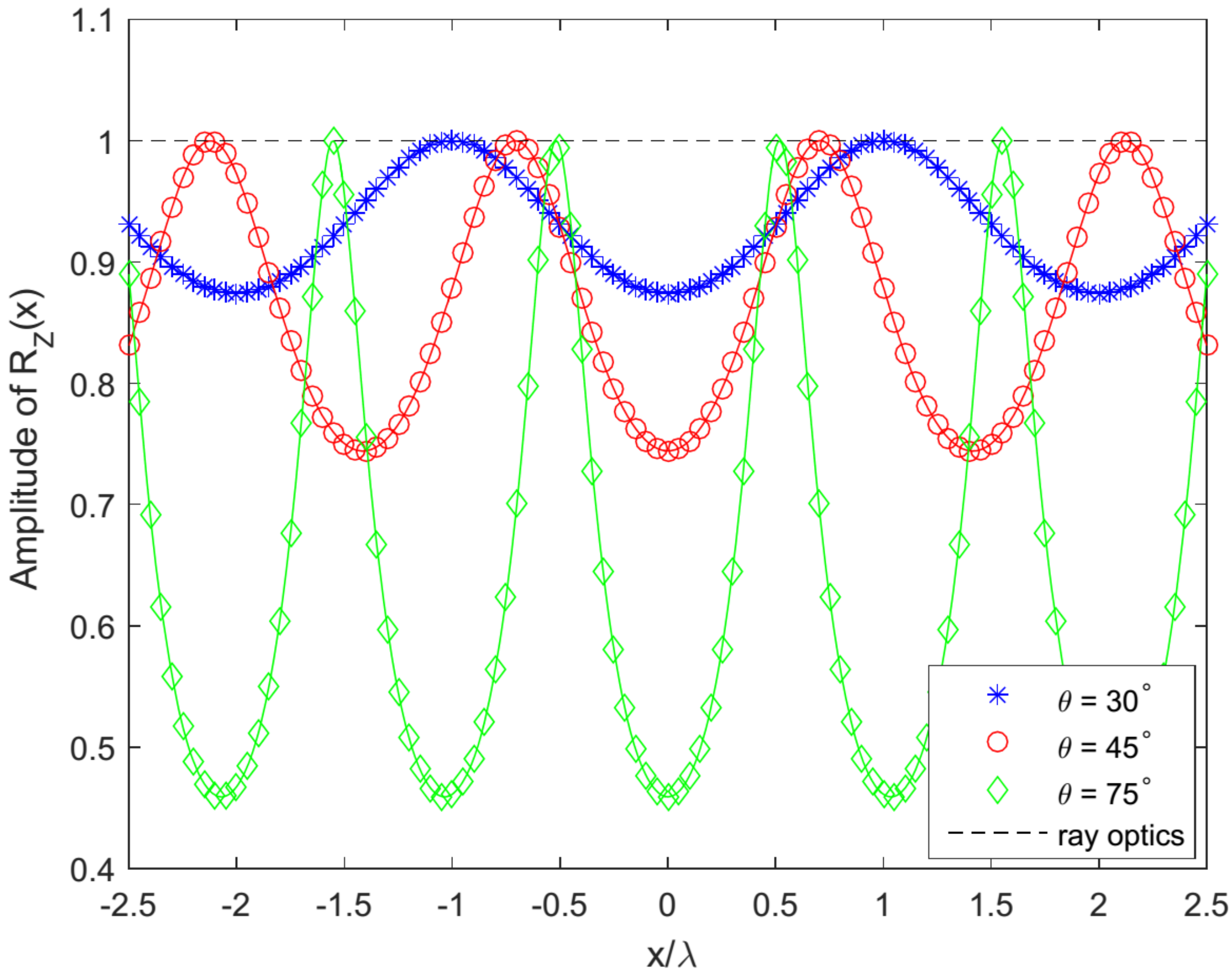

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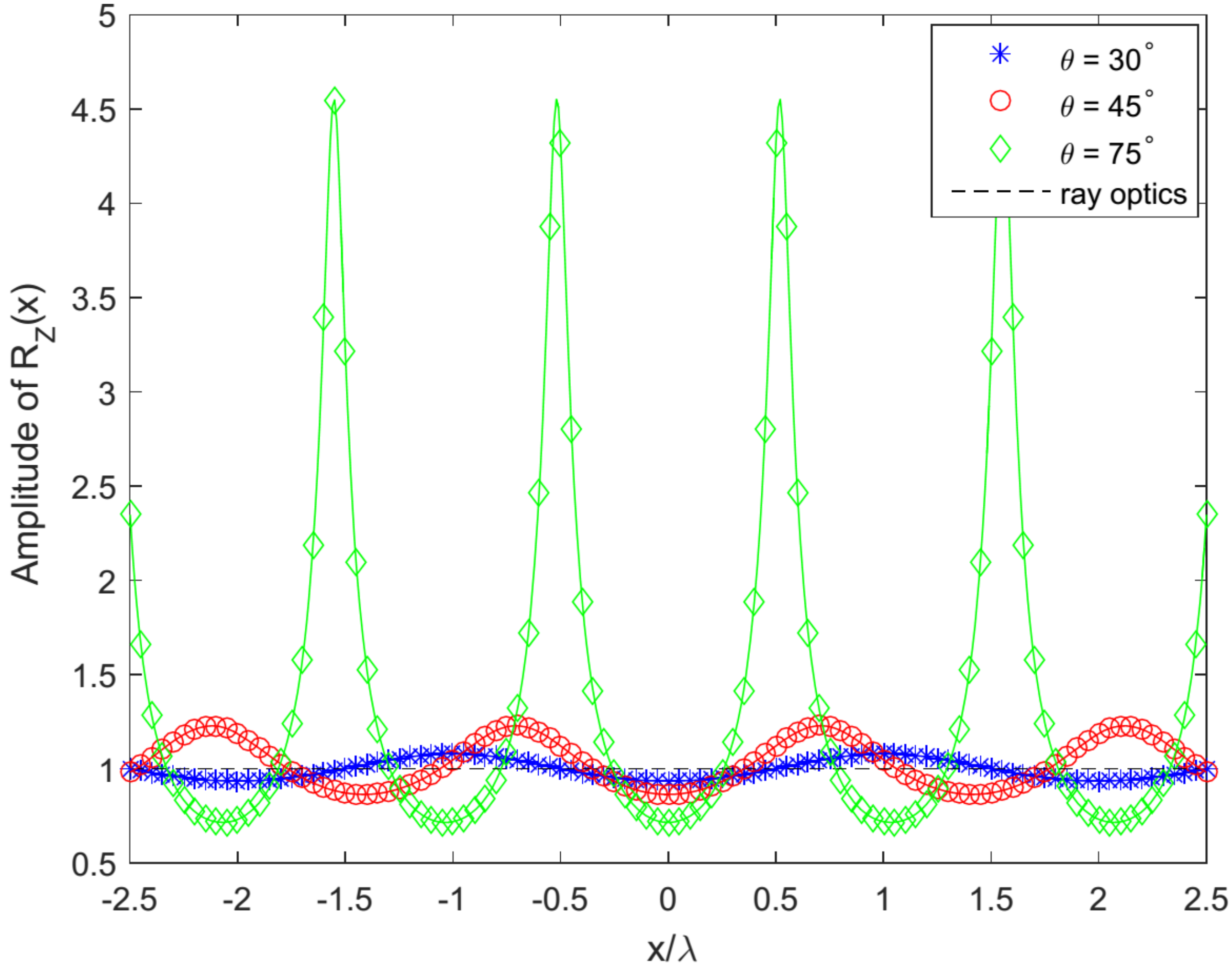
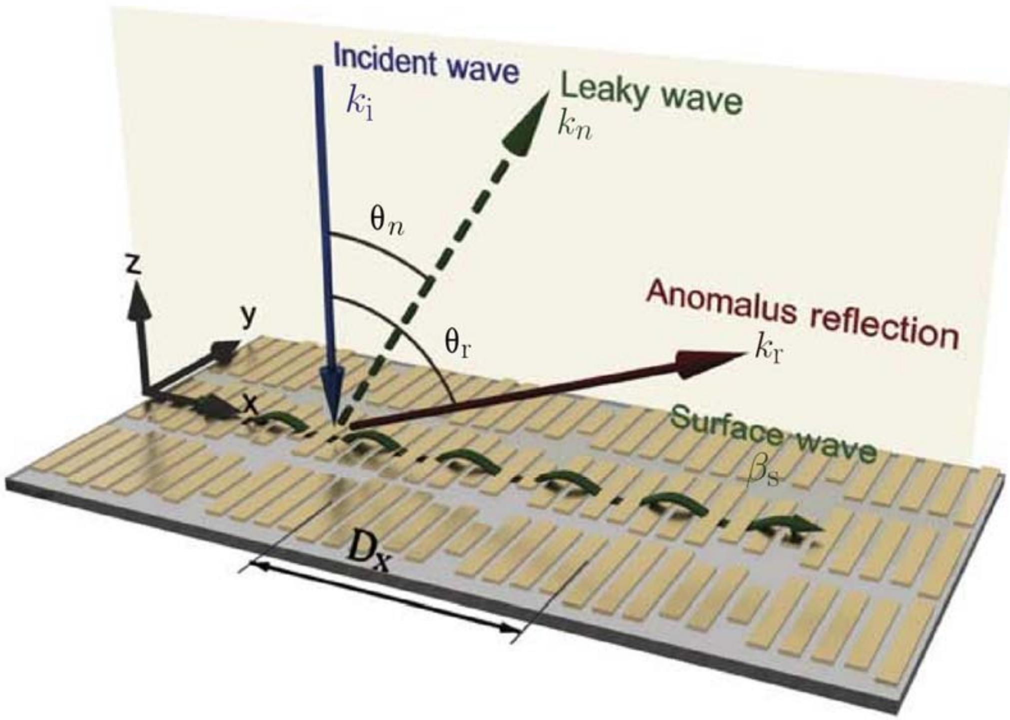


How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < λ/2
(e.g., Perfect Anomalous Reflection → non-local design)



How Can We Design Smart Radio Environments ?

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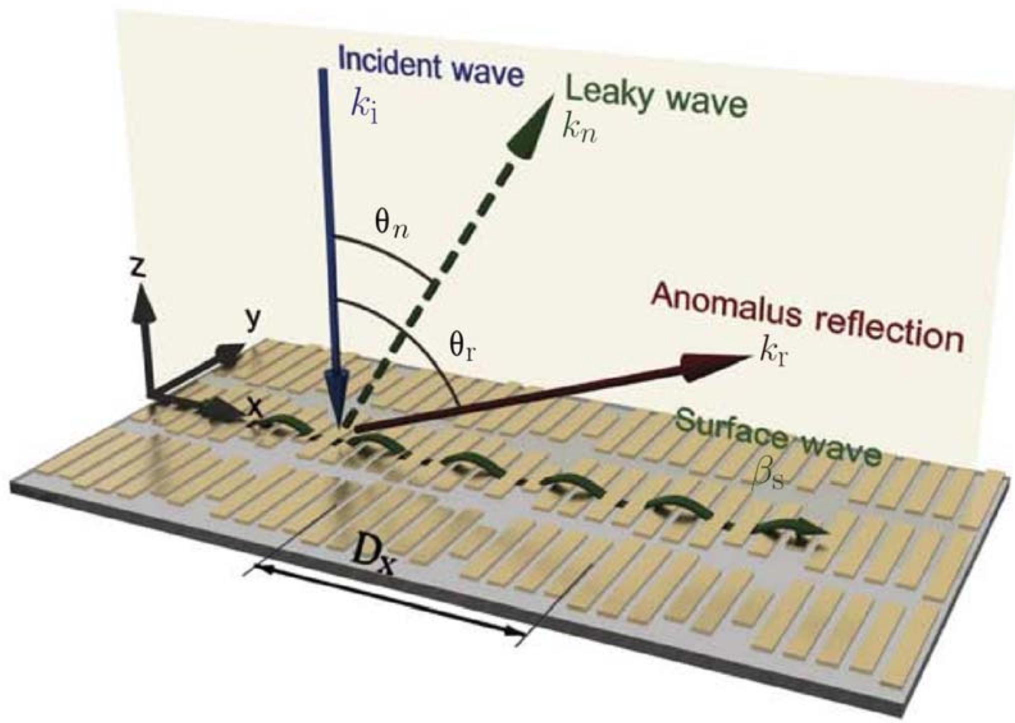

$$P^{(\text{reflected})} - P^{(\text{incident})} \geq 0 \quad \text{but} \quad \int_{\text{Surface}} \left(P^{(\text{reflected})} - P^{(\text{incident})} \right) \leq 0$$

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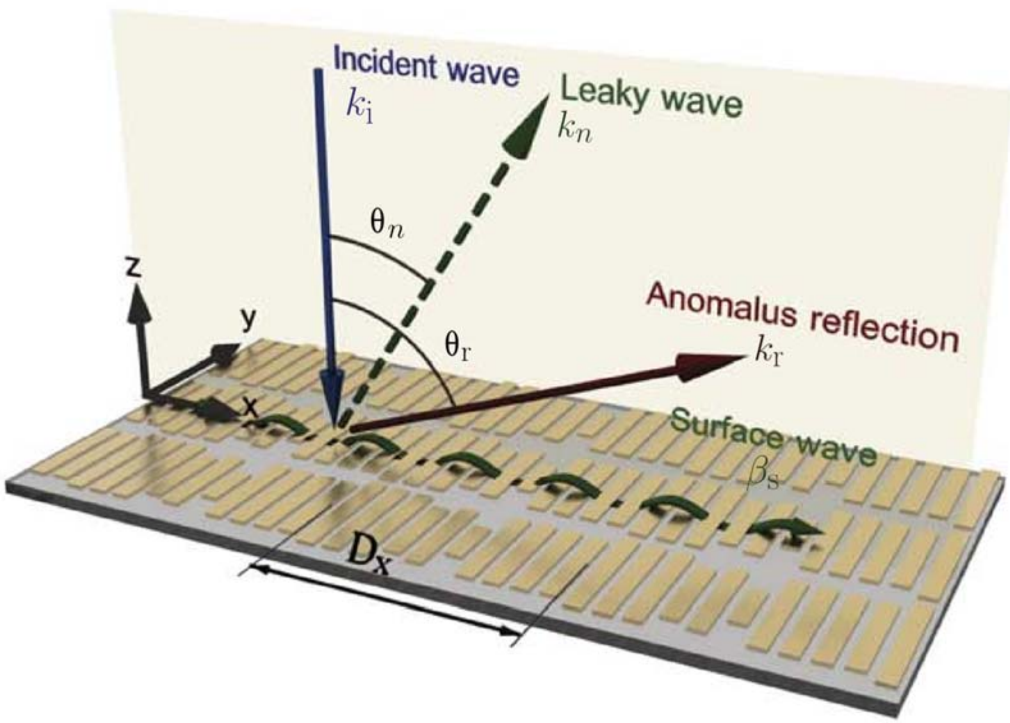

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without using active elements → surface waves

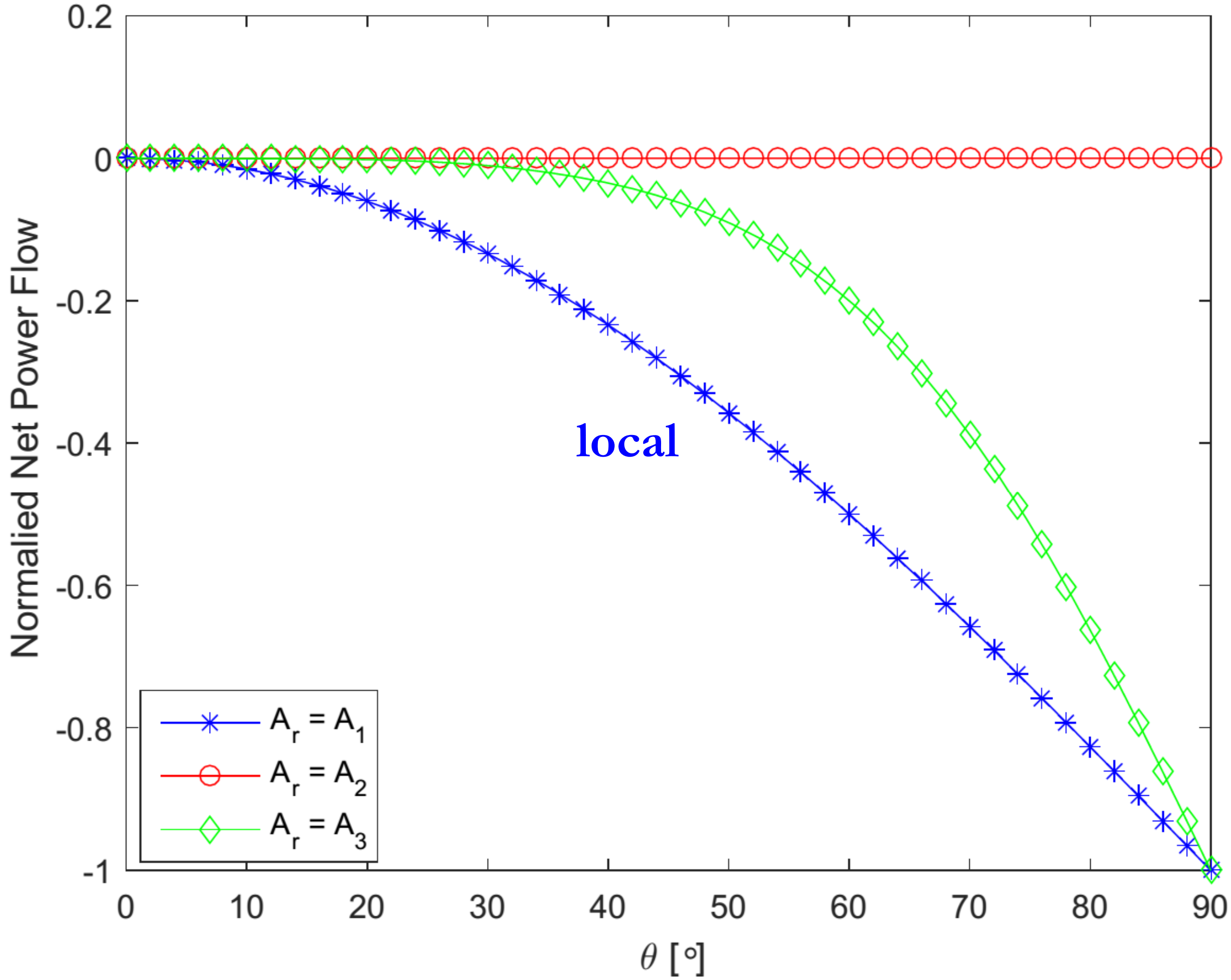
How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < λ/2

(local design vs. non-local design: Net Power Flow)

RISs: Metasurfaces Spaced < λ/2

(local design vs. non-local design: Net Power Flow)

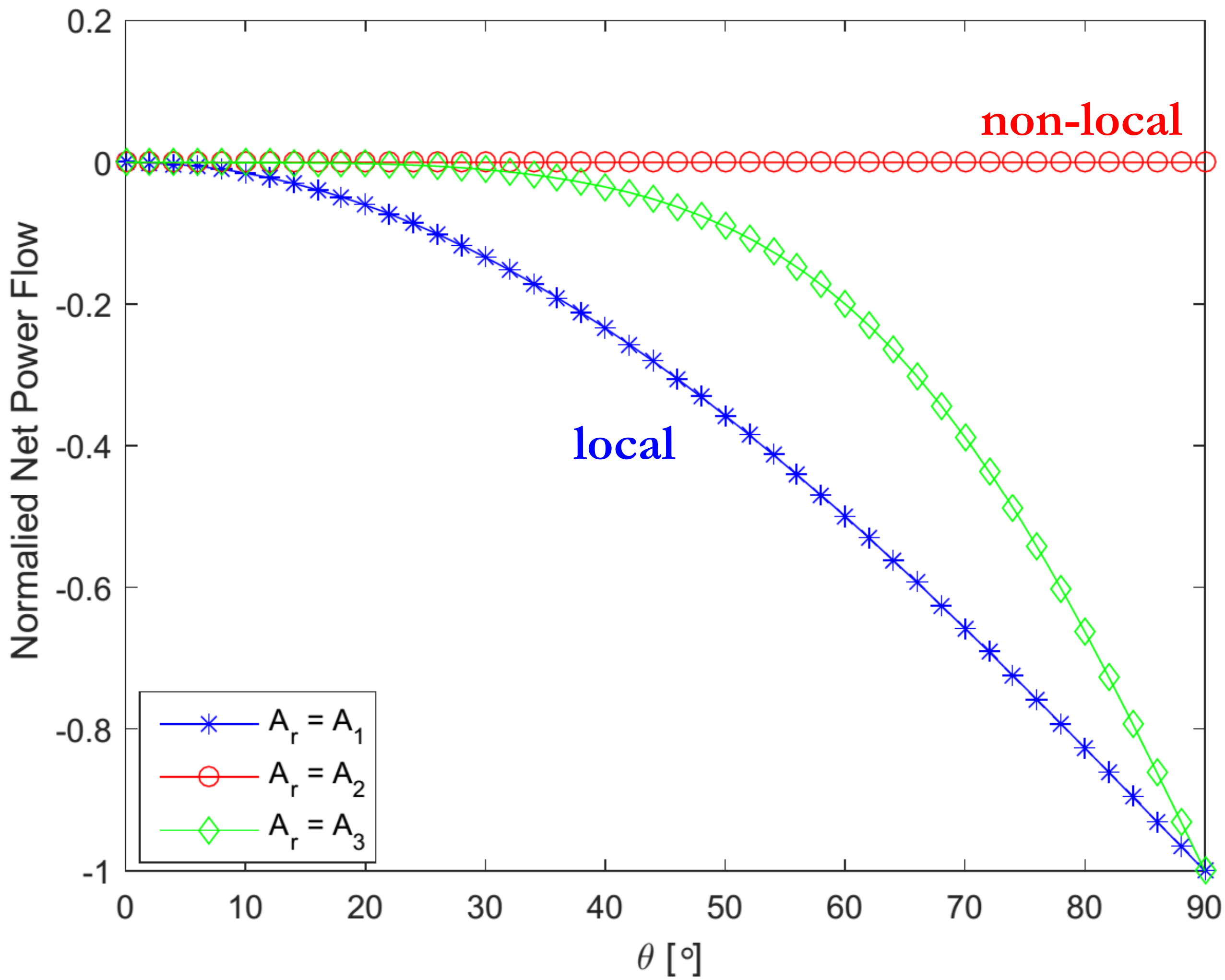


$$A\left(\theta^{(\text{incident})}, \theta^{(\text{reflected})}\right) = 1$$

How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < λ/2

(local design vs. non-local design: Net Power Flow)



$$A\left(\theta^{(\text{incident})},\theta^{(\text{reflected})}\right) = 1$$

$$A\left(\theta^{(\text{incident})},\theta^{(\text{reflected})}\right) = \sqrt{\frac{\cos\left(\theta^{(\text{incident})}\right)}{\cos\left(\theta^{(\text{reflected})}\right)}}$$

How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < λ/2

(local design vs. non-local design)

How Can We Design Smart Radio Environments ?

RISs: Metasurfaces Spaced < $\lambda/2$

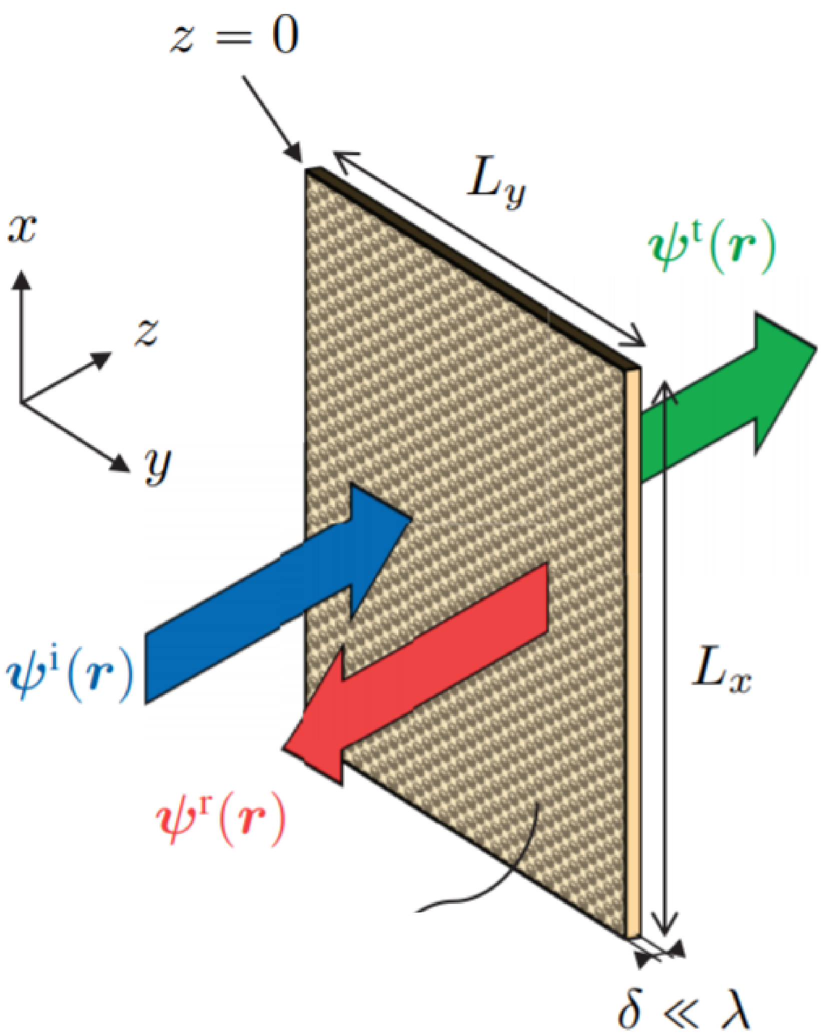
(local design vs. non-local design)

A non-local design allows one to realize

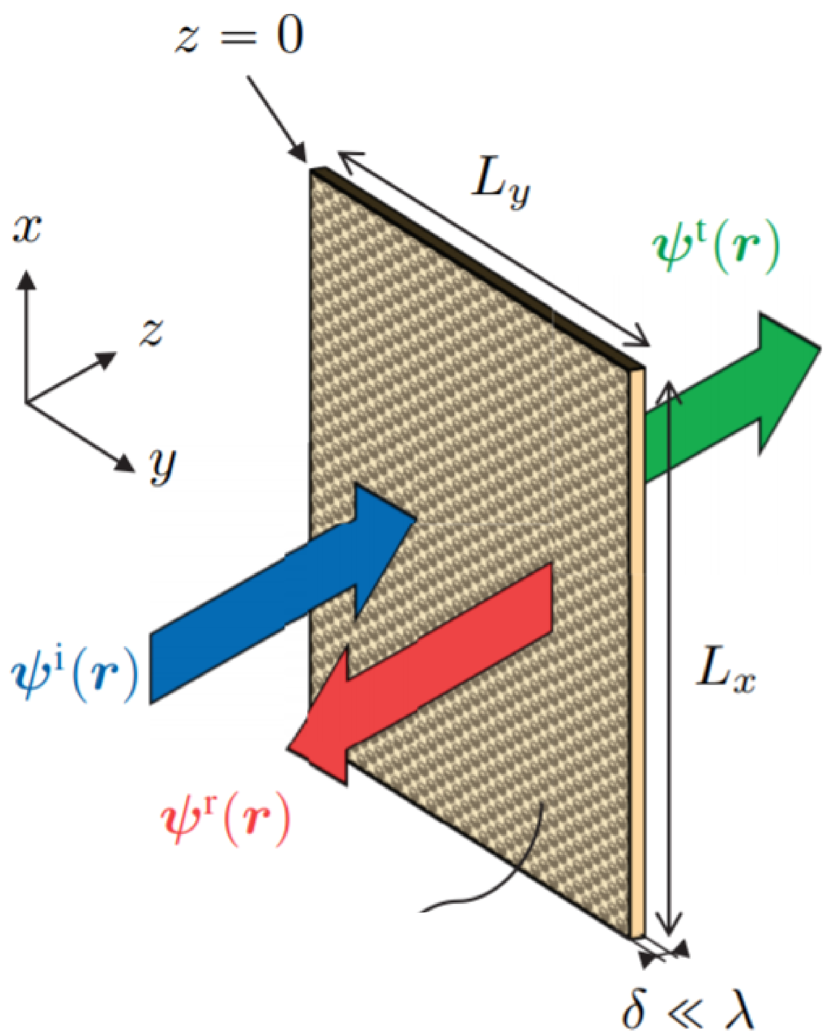
Globally Passive Structures
(with) High Power Efficiency
(for) Large Angles of Reflection

Reconfigurable Intelligent Metasurfaces

Reconfigurable Intelligent Metasurfaces

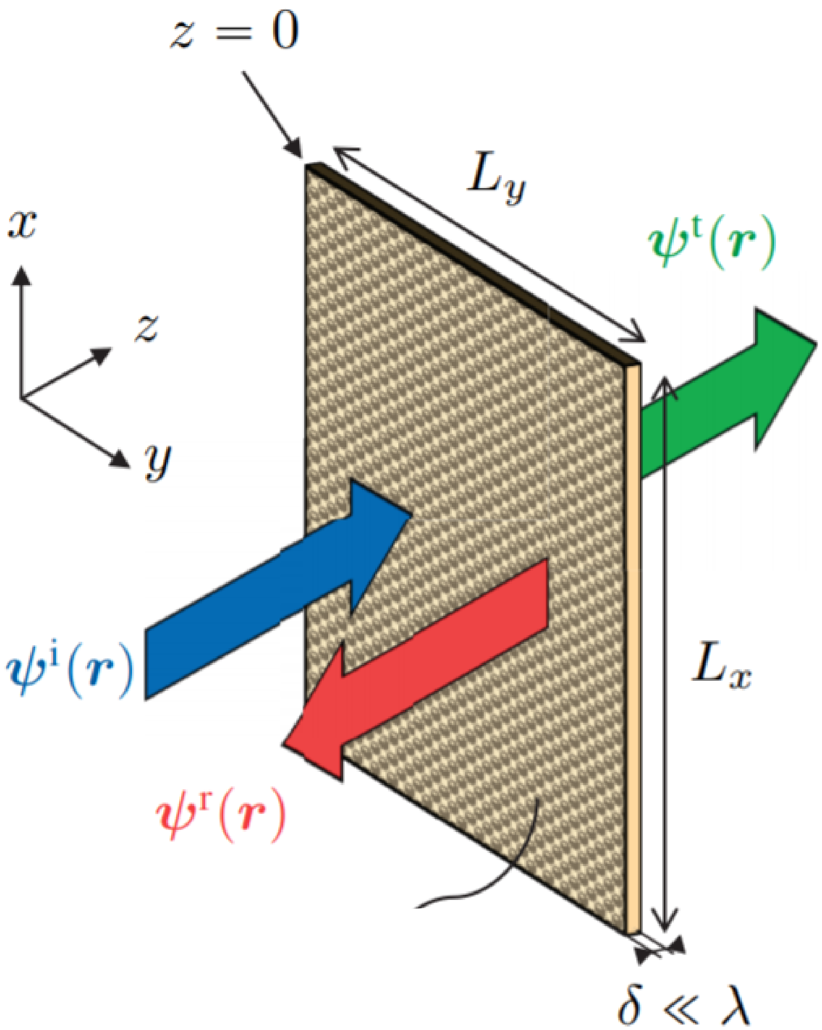


Reconfigurable Intelligent Metasurfaces



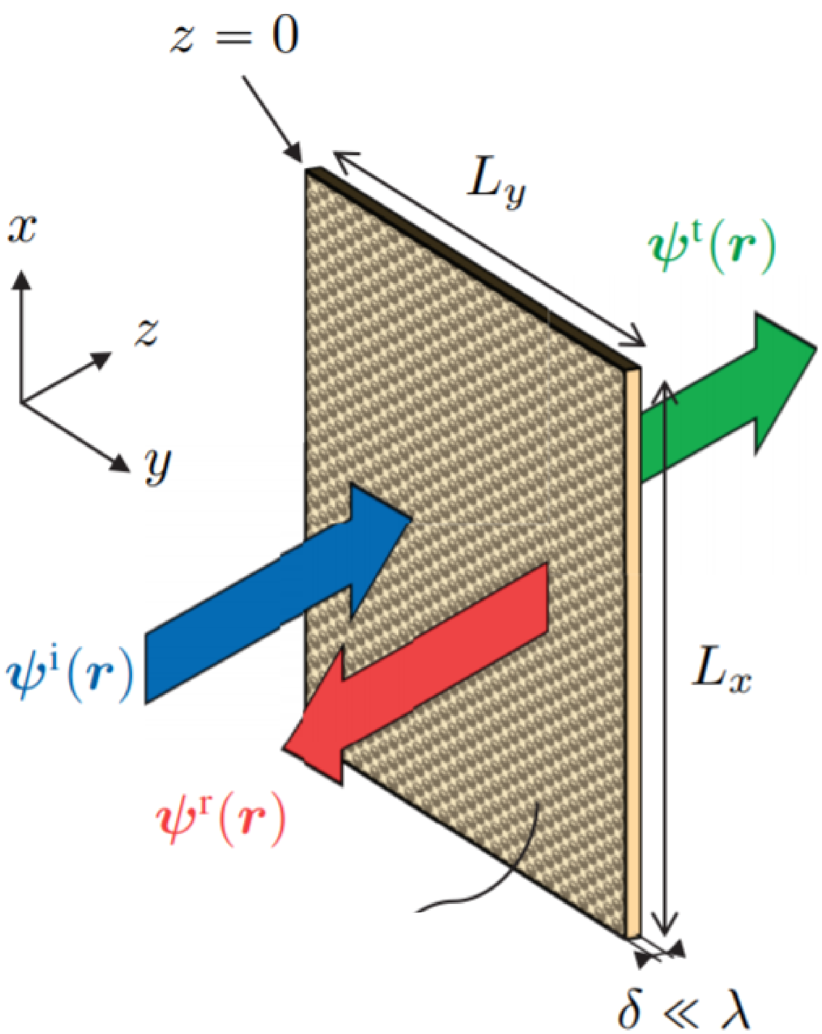
- **Main characteristics**

Reconfigurable Intelligent Metasurfaces



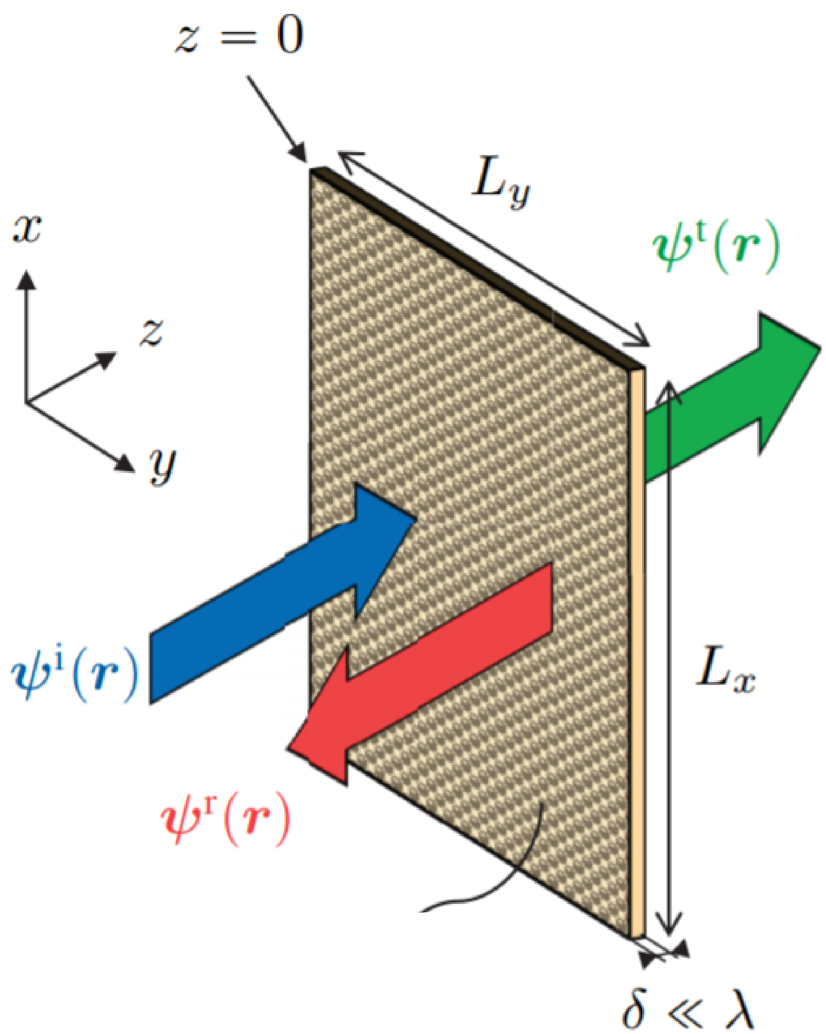
- **Main characteristics**
  - **Electrically thin:** The thickness is considerably smaller than the wavelength

Reconfigurable Intelligent Metasurfaces



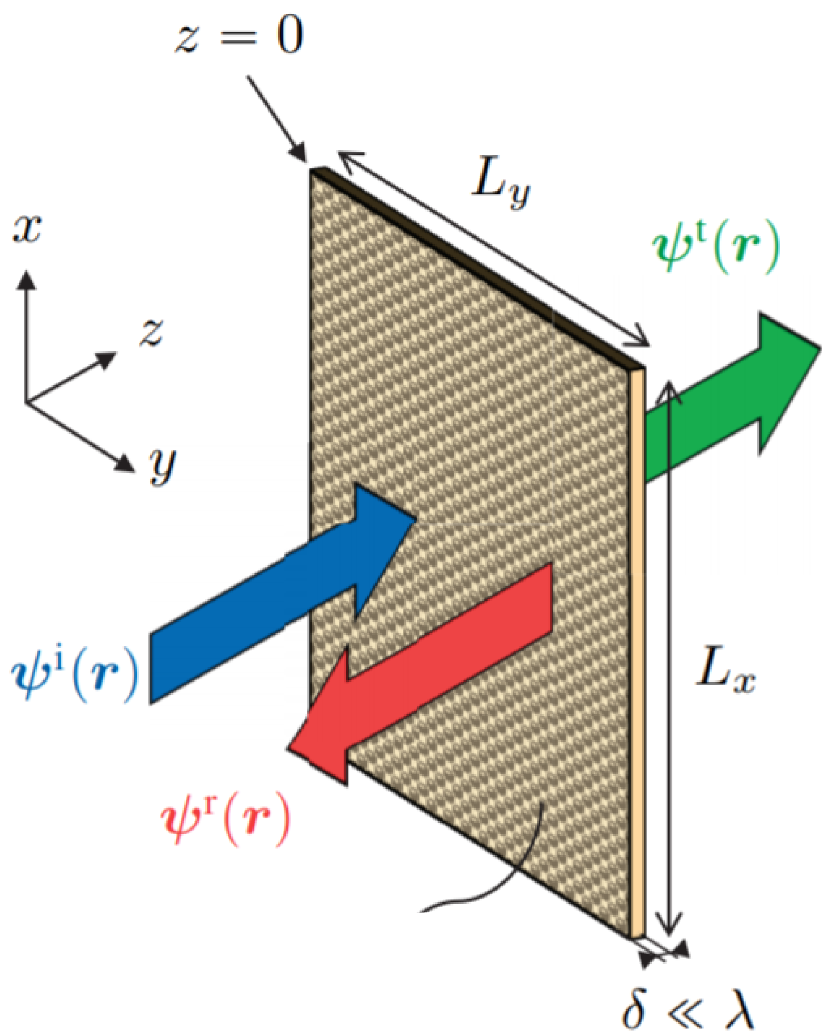
- **Main characteristics**
  - **Electrically thin:** The thickness is considerably smaller than the wavelength
  - **Electrically large:** The transverse size is relatively large as compared with the wavelength

Reconfigurable Intelligent Metasurfaces



- Main characteristics
  - Electrically thin: The thickness is considerably smaller than the wavelength
  - Electrically large: The transverse size is relatively large as compared with the wavelength
  - Homogenizable: The distance between adjacent unit cells is much smaller than the wavelength

Reconfigurable Intelligent Metasurfaces



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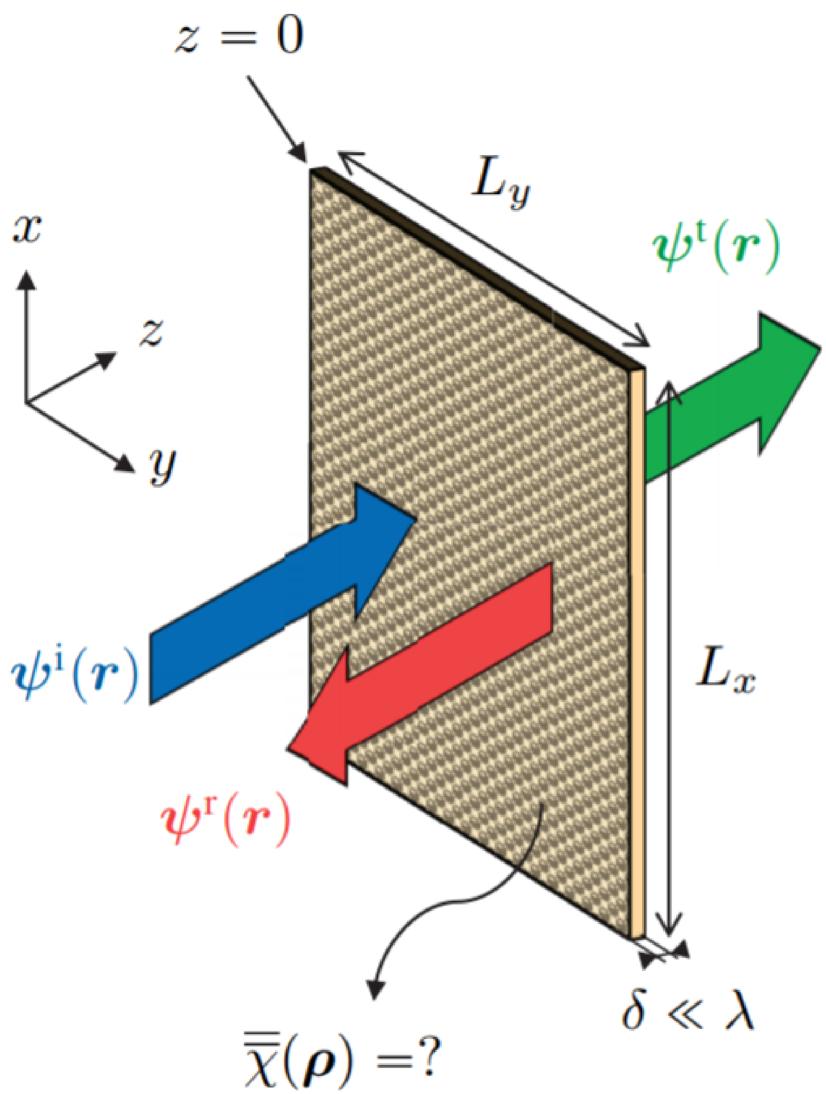
Reconfigurable Intelligent Metasurfaces



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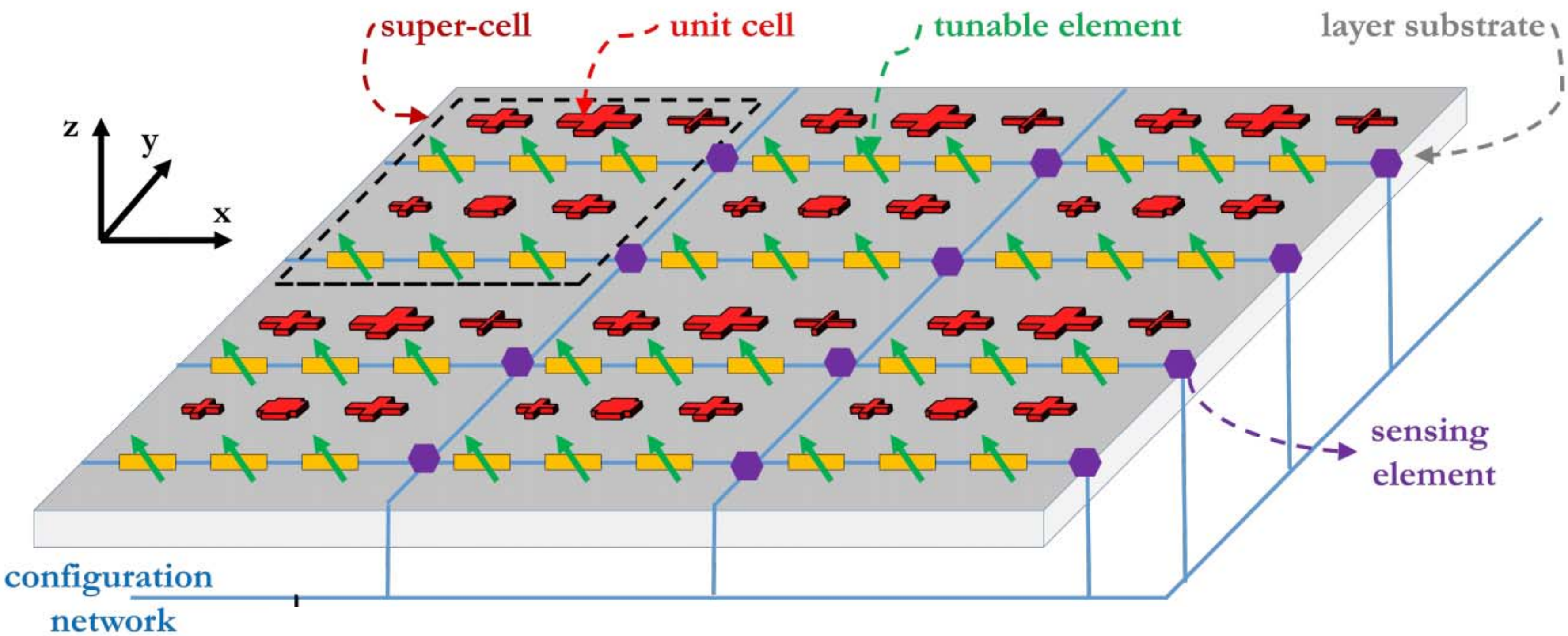
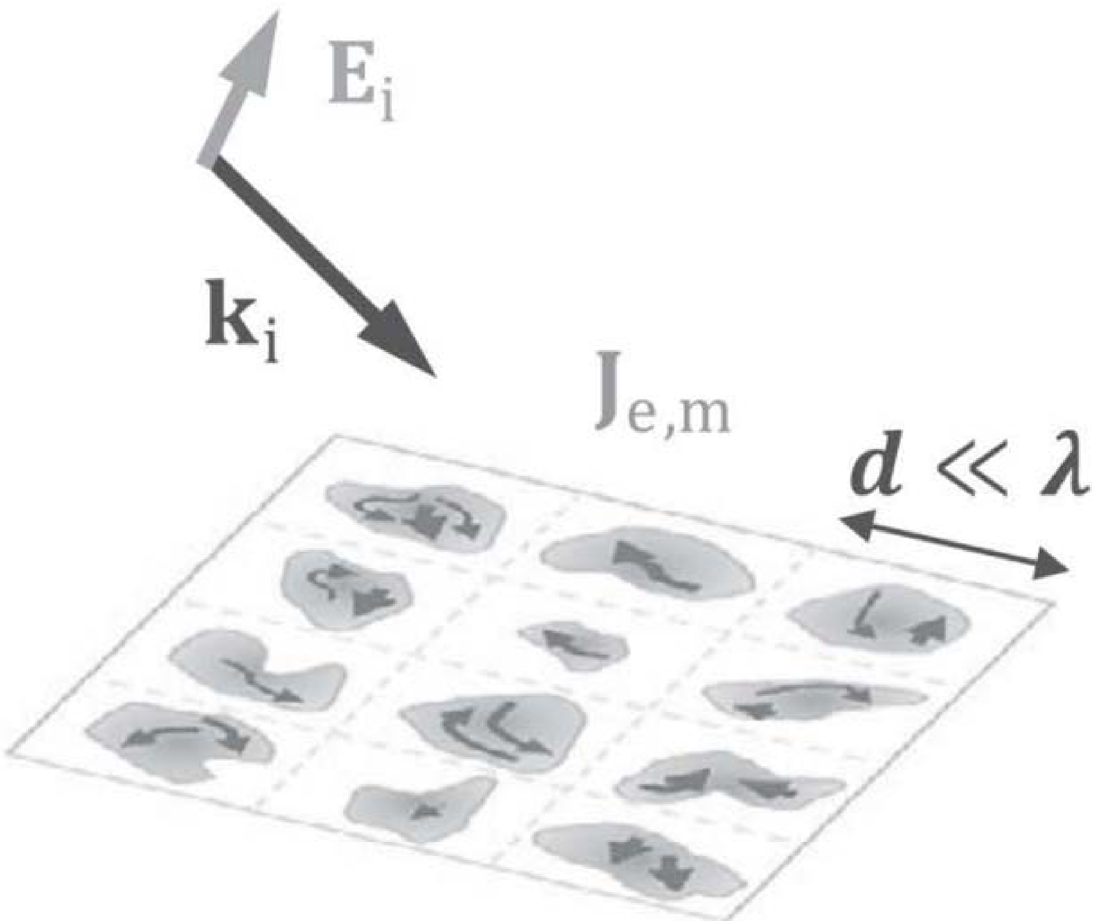
Reconfigurable Intelligent (Meta)Surfaces

Conceptual Structure



Homogenizable

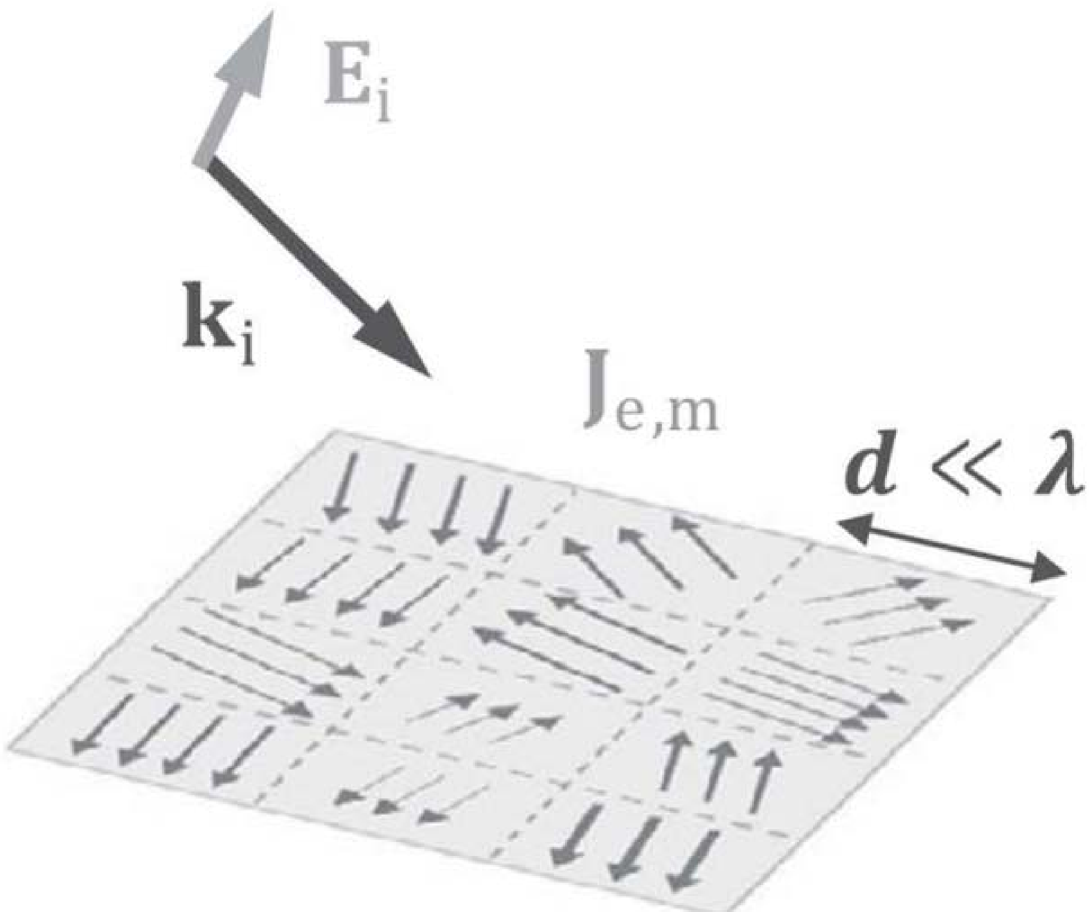
… from sub-wavelength scatterers …



Reconfigurable Intelligent Metasurfaces

Homogenizable

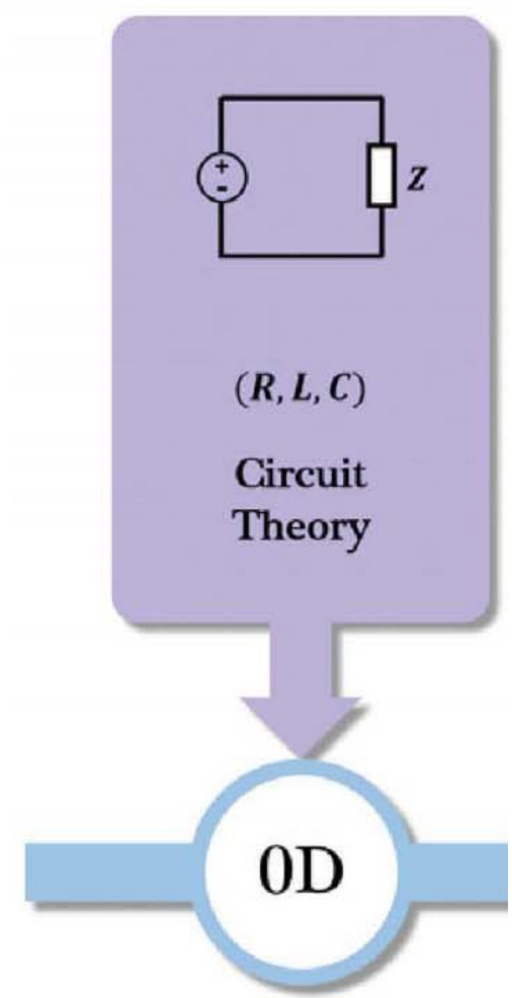
… to a continuous sheet of currents …

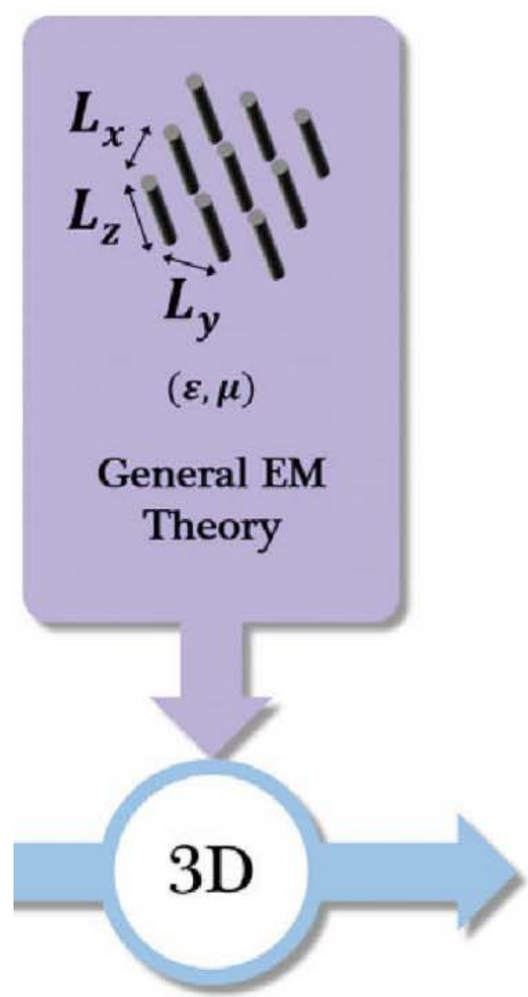


Surface Susceptibilities / Impedances

Reconfigurable Intelligent Metasurfaces: Modeling

Surface Susceptibilities / Impedances





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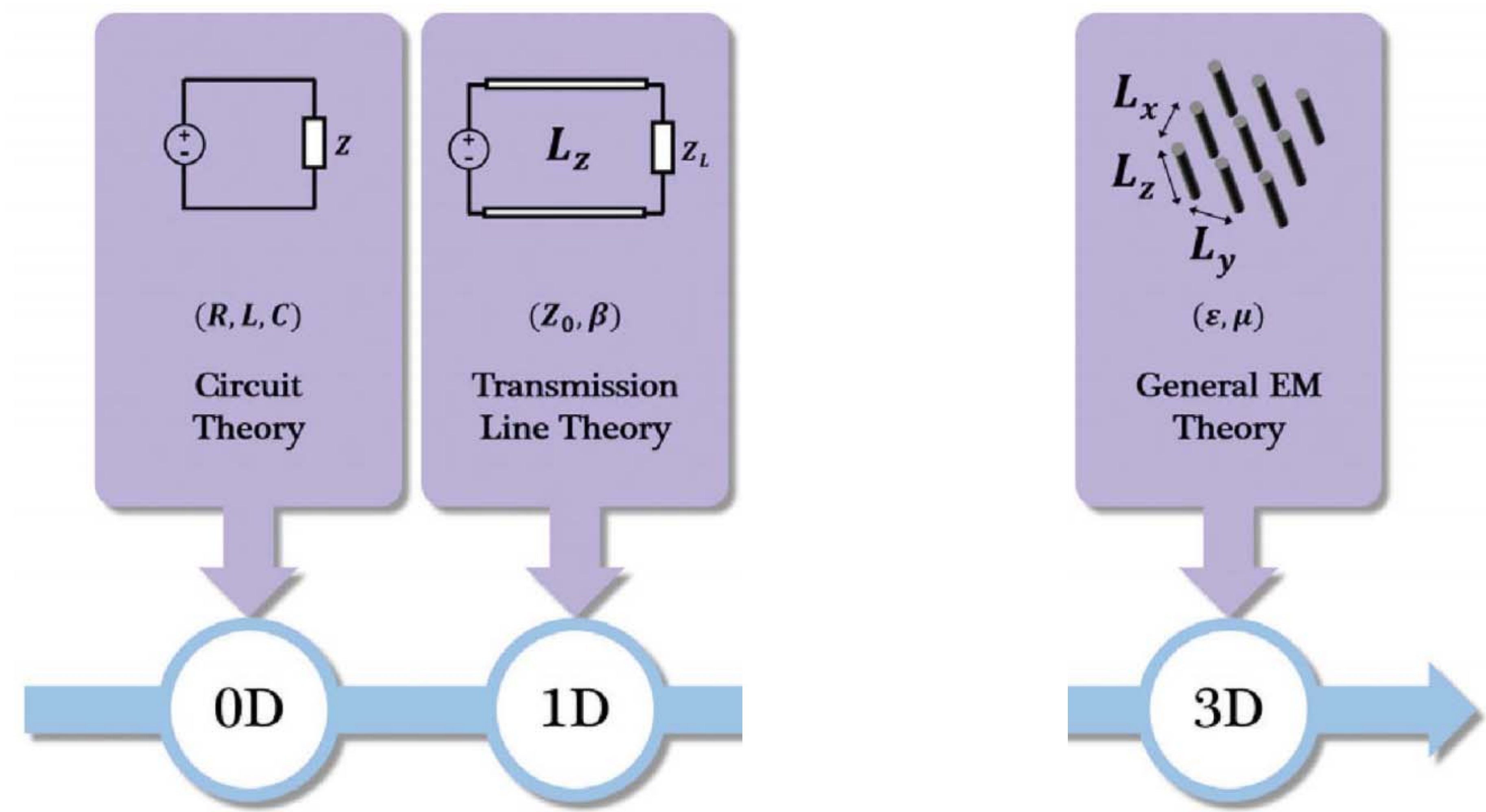
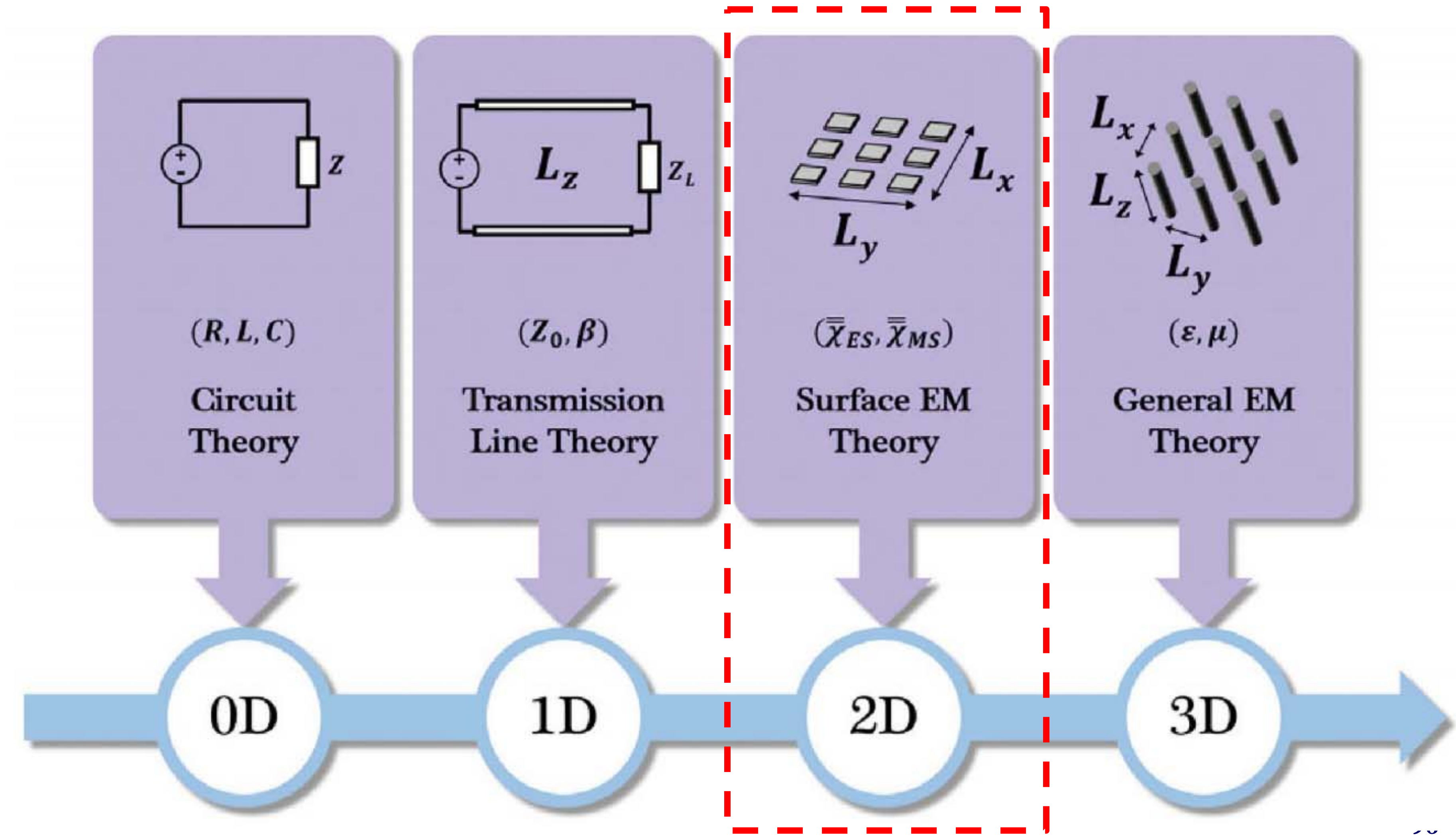


Reconfigurable Intelligent Metasurfaces: Modeling

Surface Susceptibilities / Impedances



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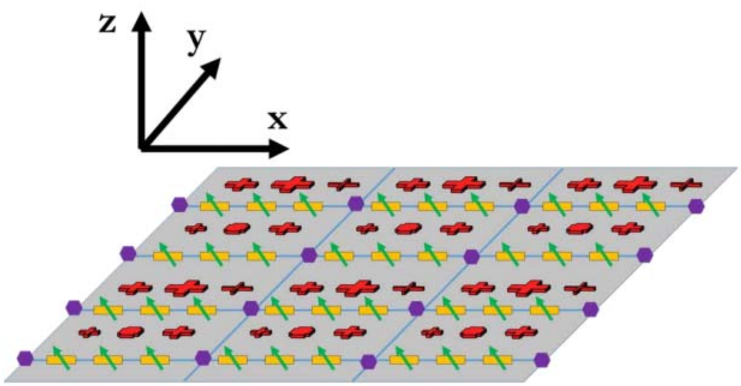
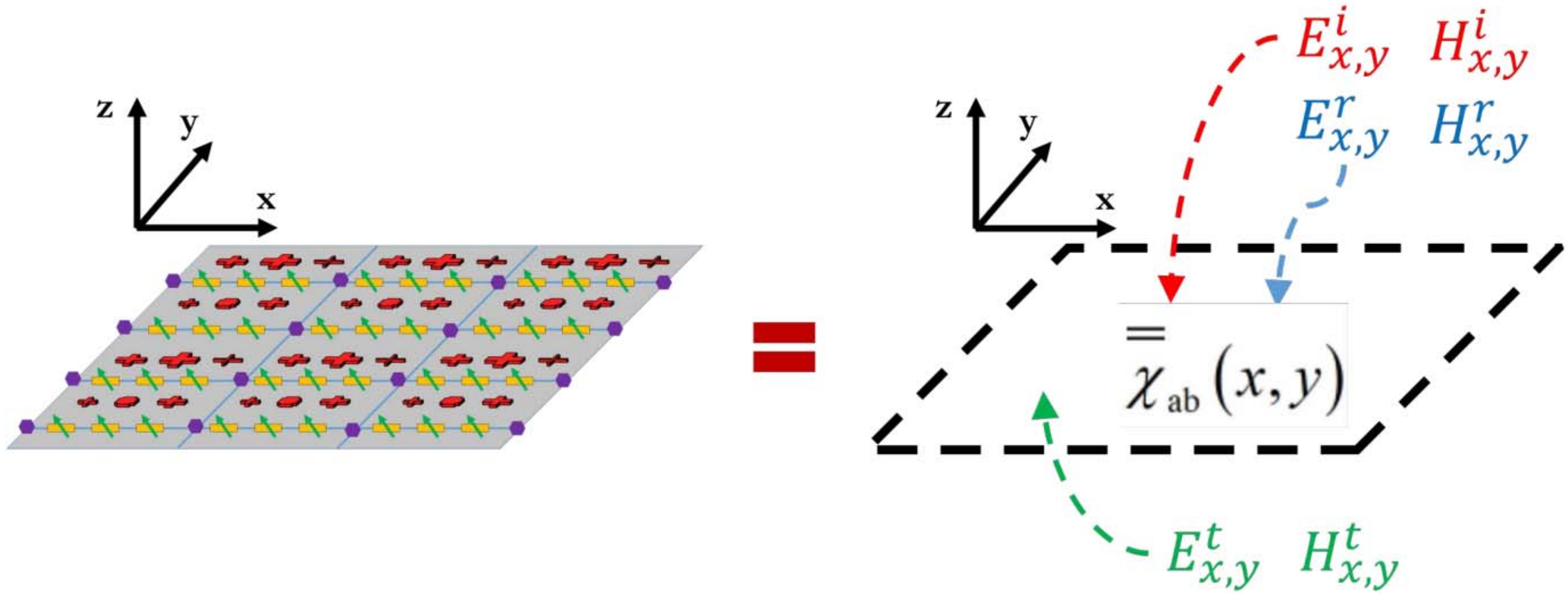
Surface Susceptibilities / Impedances



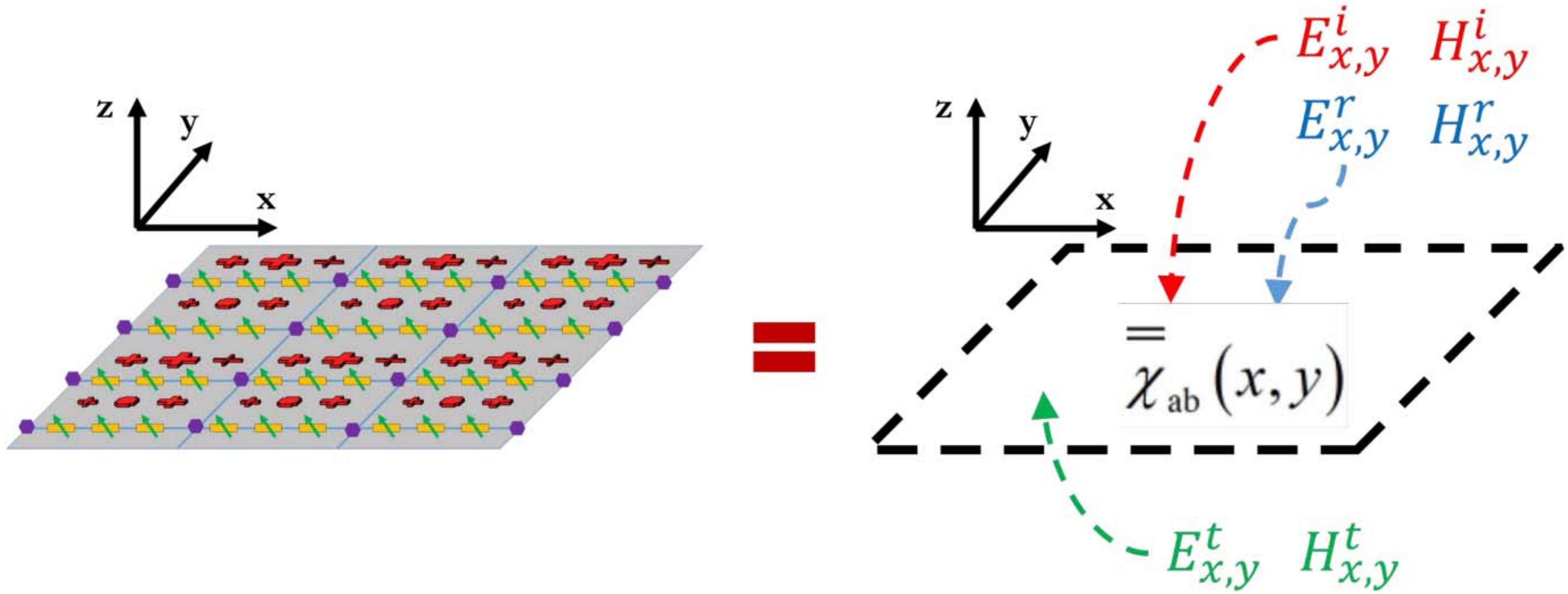
Reconfigurable Intelligent Metasurfaces: Modeling

Surface Susceptibilities / Impedances



Reconfigurable Intelligent Metasurfaces: Modeling

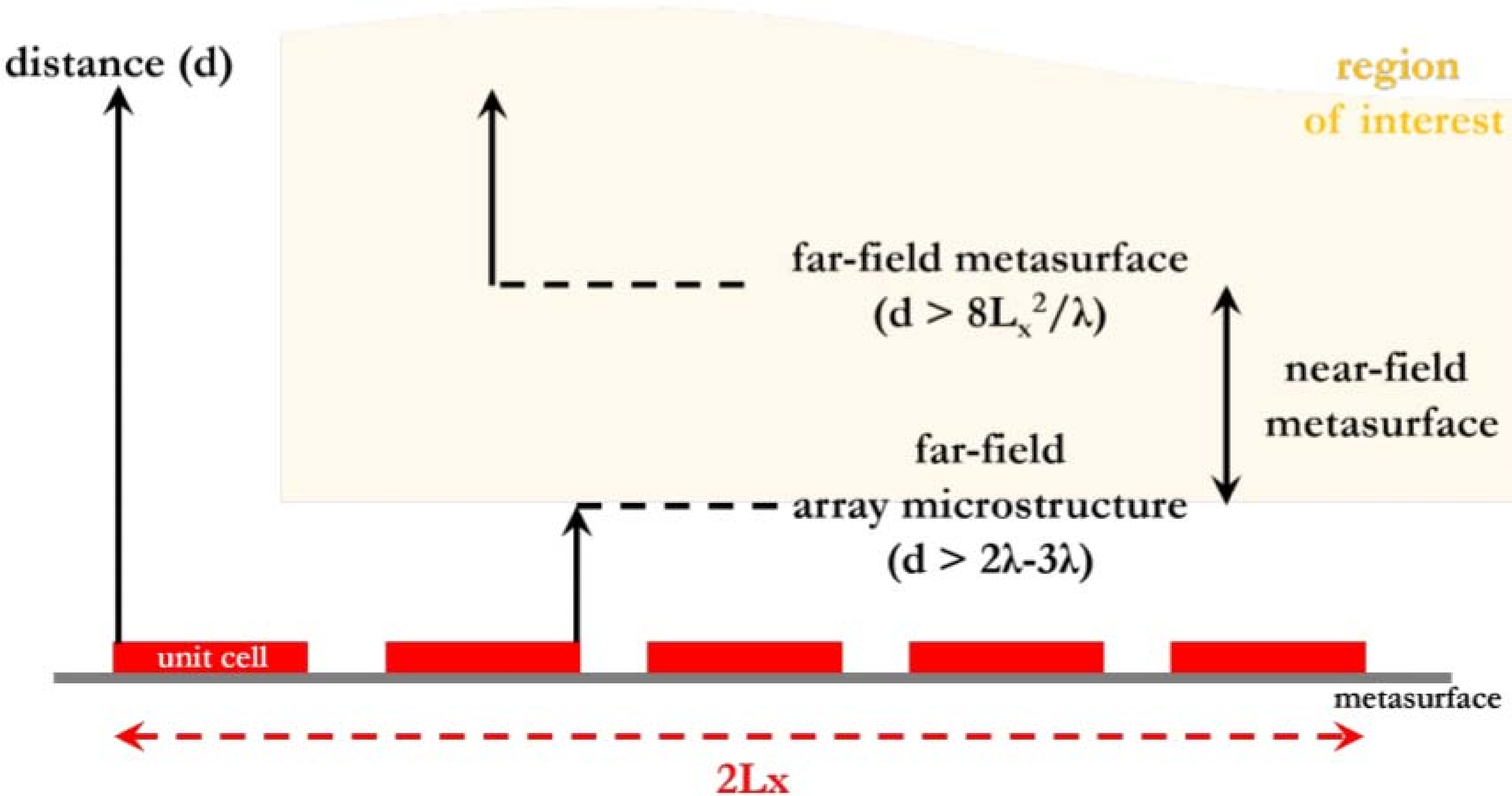
Surface Susceptibilities / Impedances



Perfect Anomalous Reflection

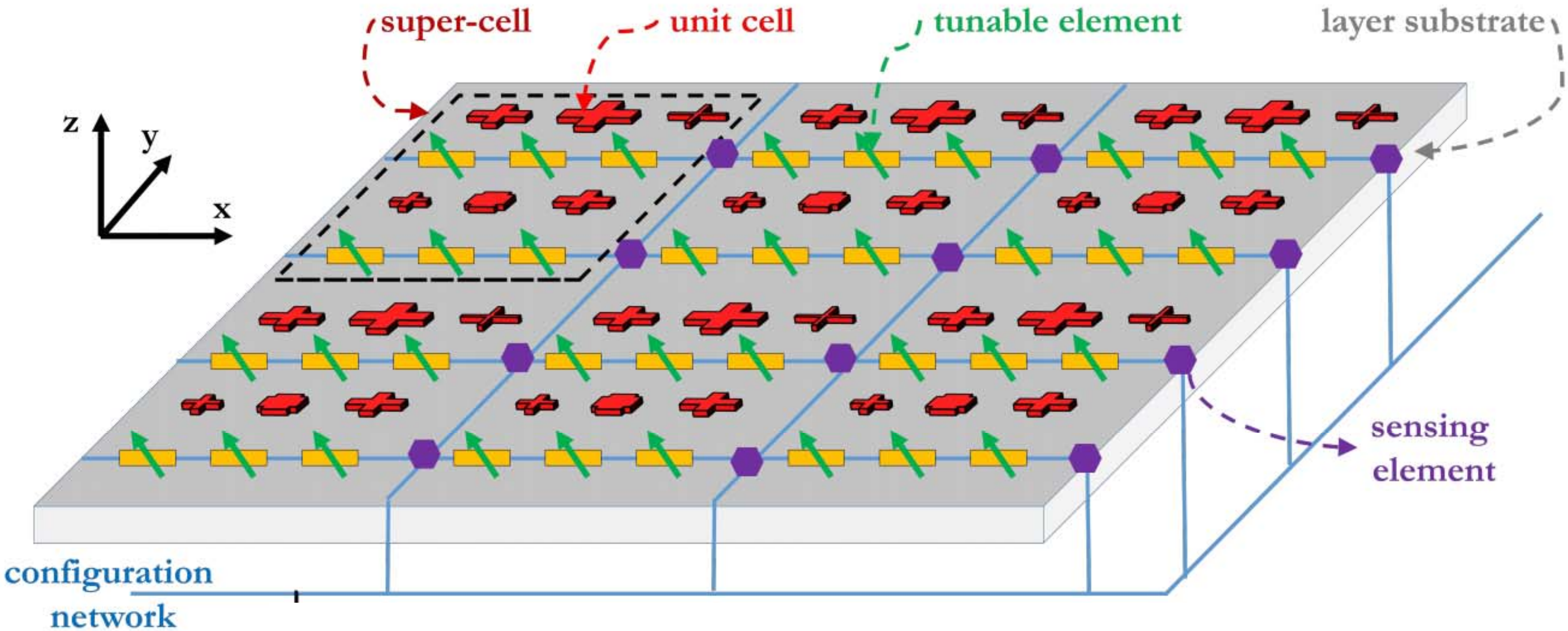
$$\chi_{ee}^{yy}(x,y) = -\frac{2}{j\omega\varepsilon}\frac{H_x^i(x,y)+H_x^r(x,y)}{E_y^i(x,y)+E_y^r(x,y)}$$

Surface Susceptibilities / Impedances: Applicability



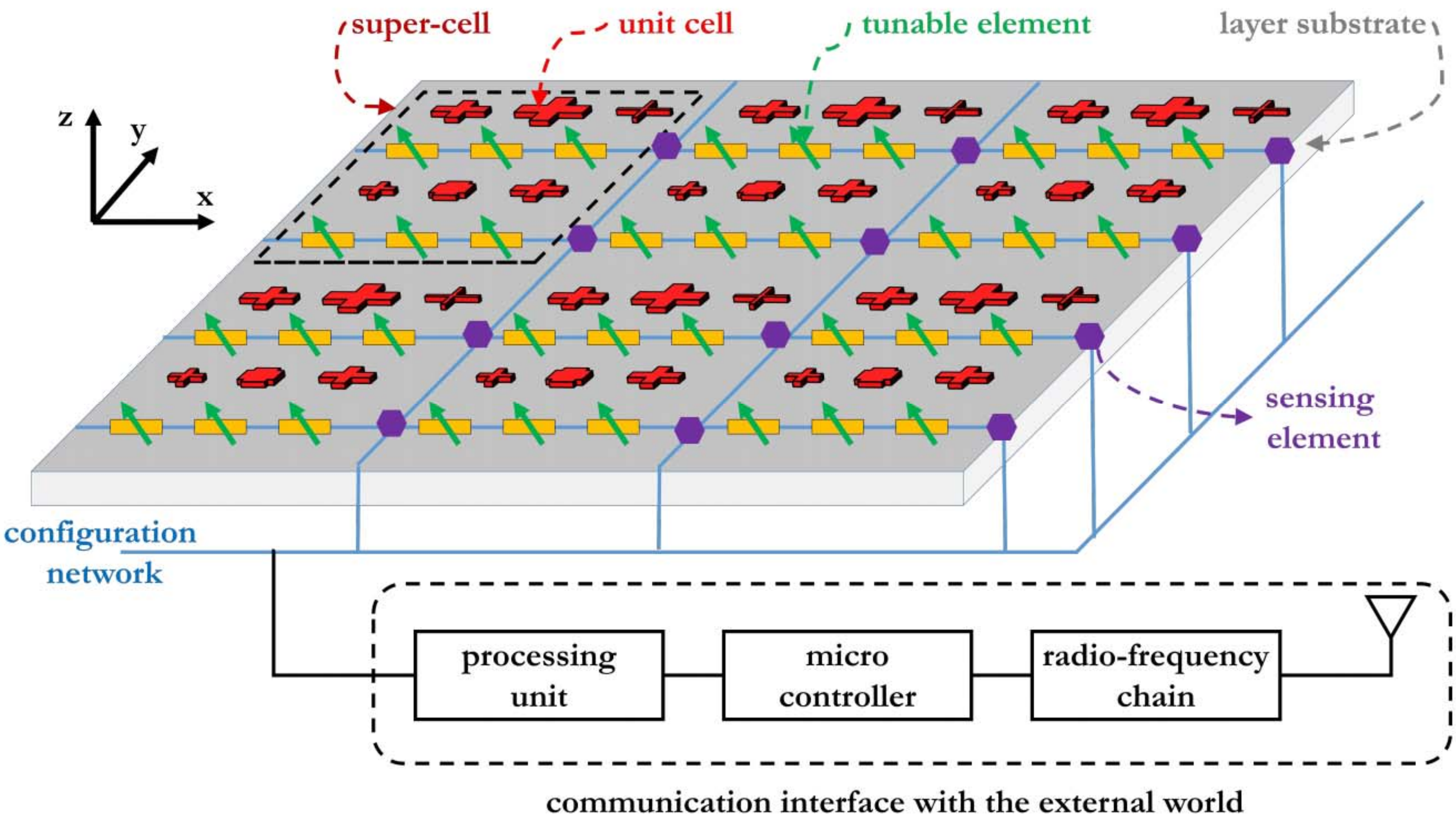
Reconfigurable Intelligent (Meta)Surfaces

Conceptual Structure



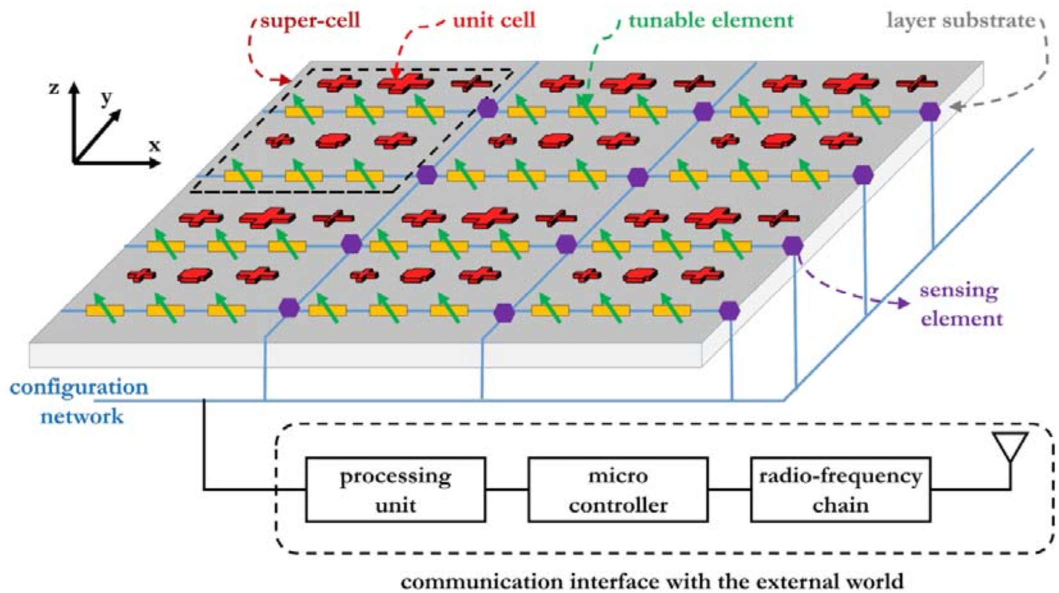
Reconfigurable Intelligent (Meta)Surfaces

Conceptual Structure and Operation

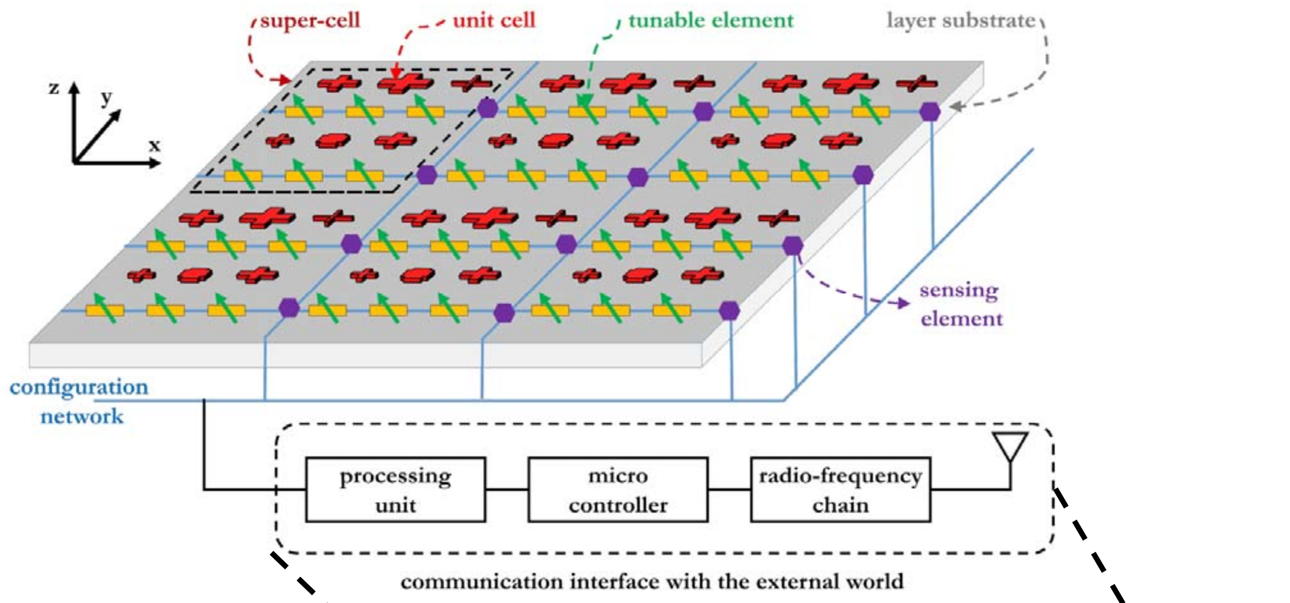


Reconfigurable Intelligent (Meta)Surfaces

Conceptual Structure and Operation

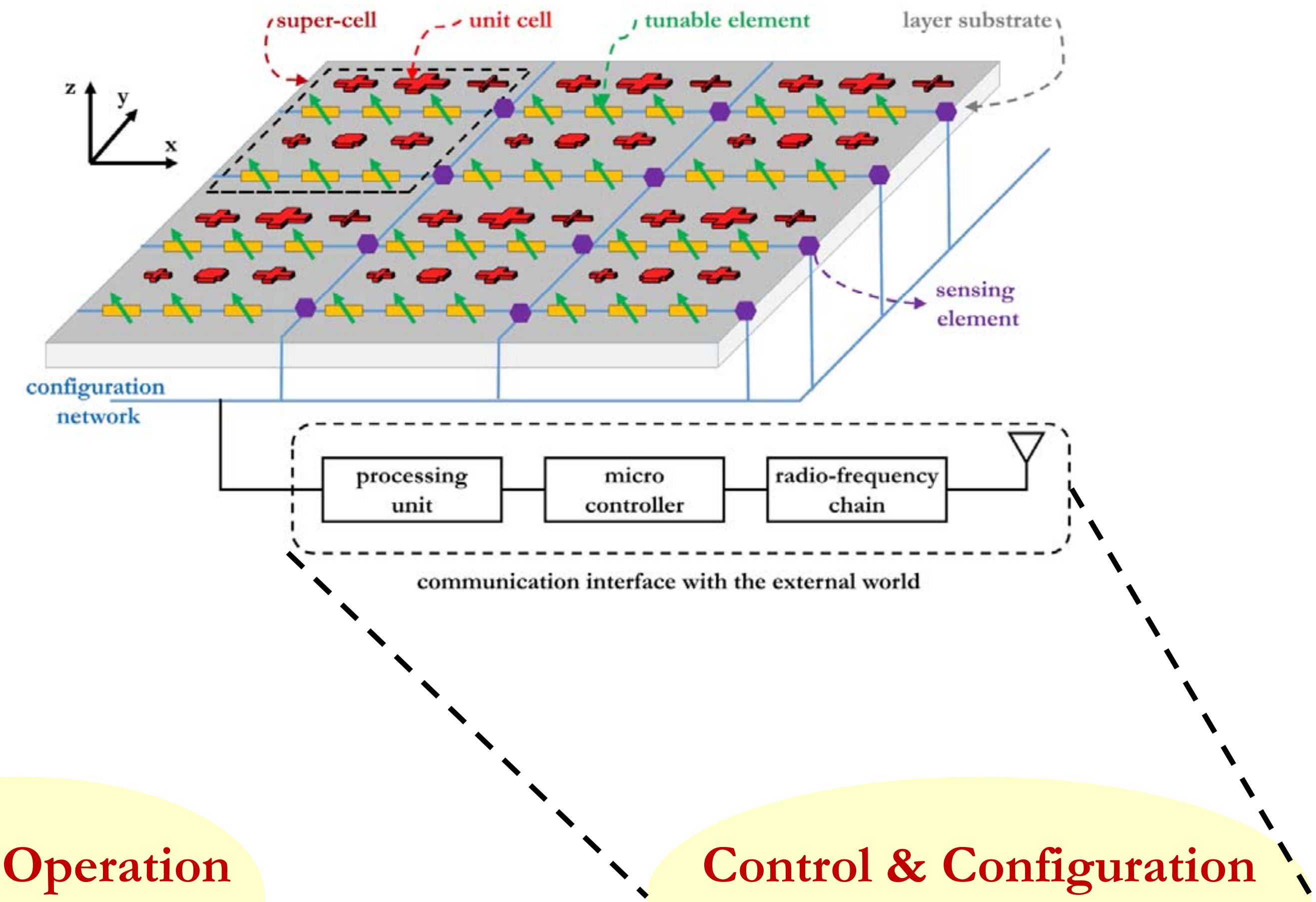


Conceptual Structure and Operation



Control & Configuration Phase

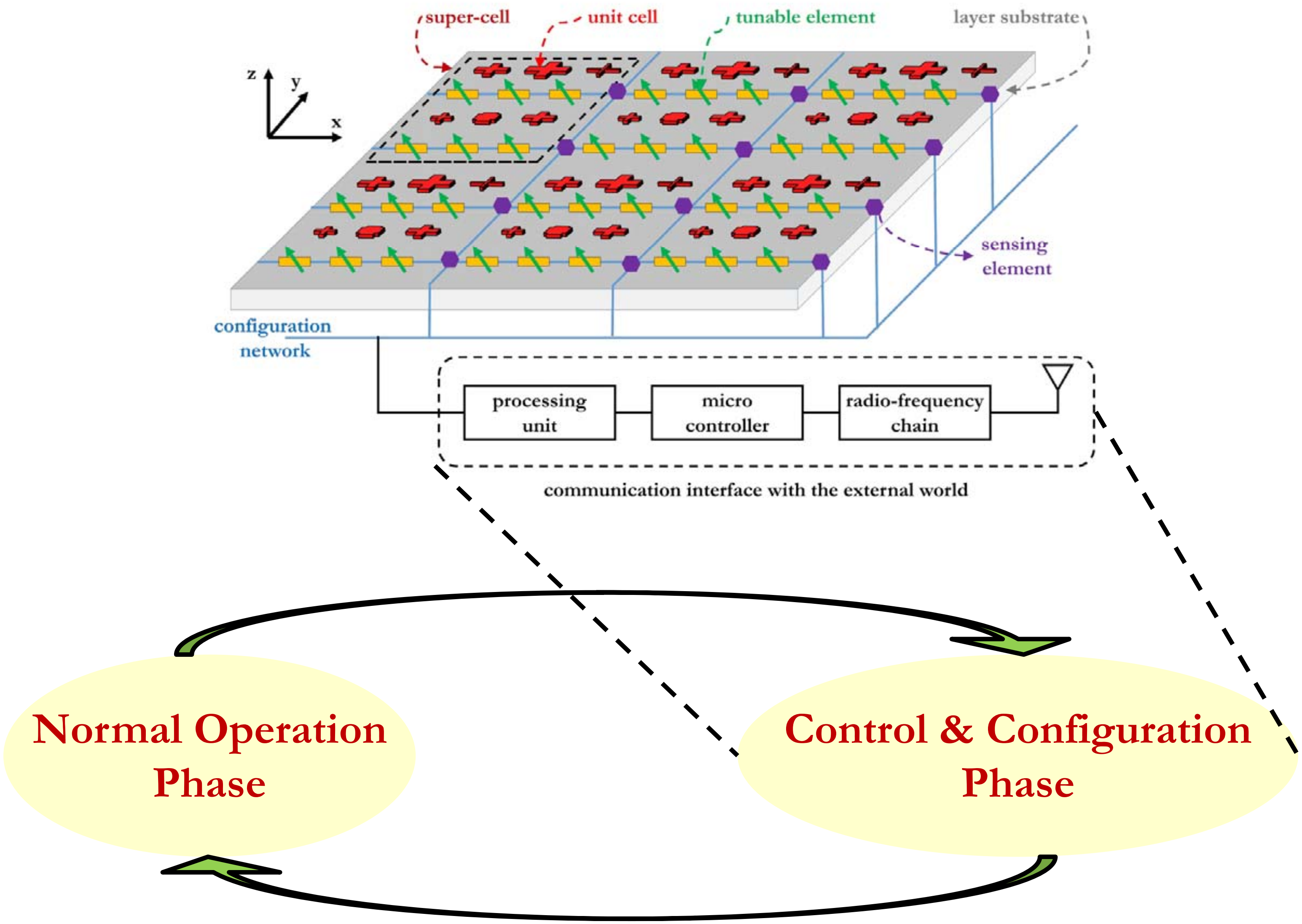
Conceptual Structure and Operation



Normal Operation Phase

Control & Configuration Phase

Conceptual Structure and Operation



Passive vs. Nearly-Passive

Passive vs. Nearly-Passive

- Non-reconfigurable surfaces may be passive

Passive vs. Nearly-Passive

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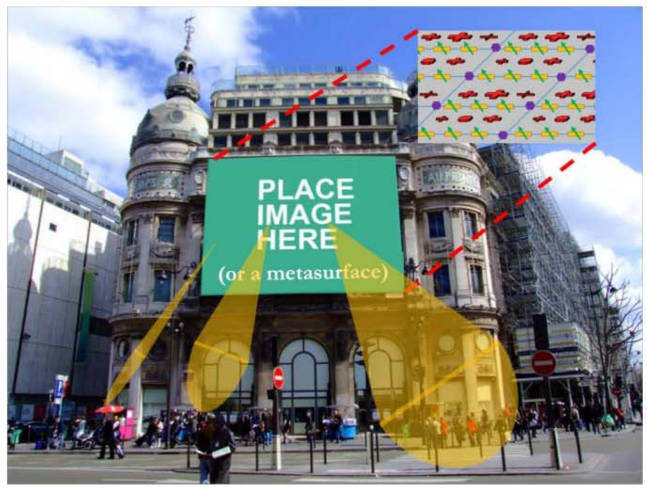
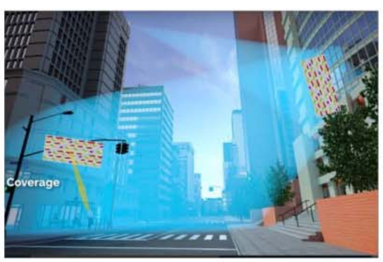
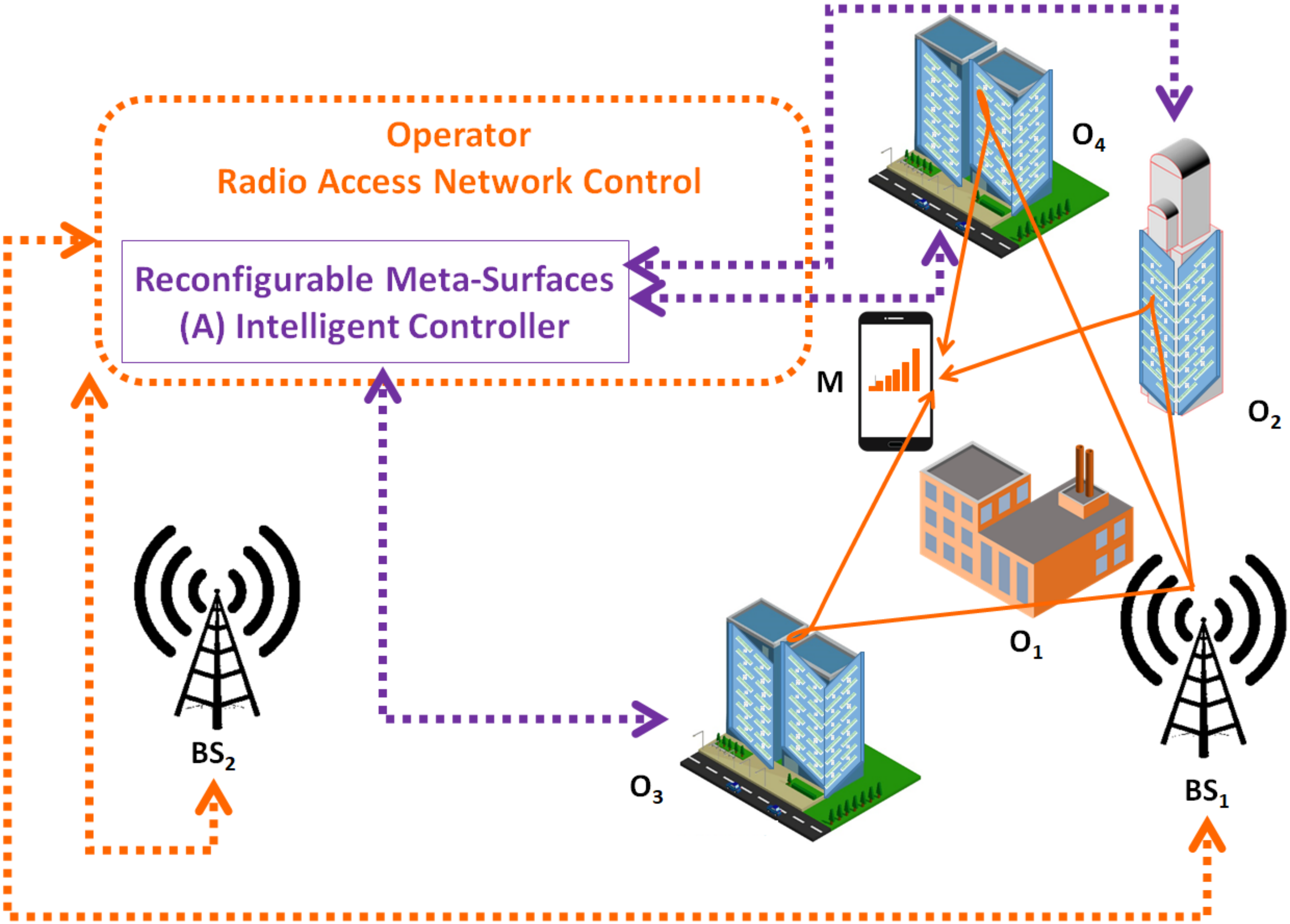
- An RIS is nearly-passive if the following three conditions are fulfilled simultaneously:
  - No power amplification is used after configuration (during the normal operation phase)
  - Minimal digital signal processing capabilities are needed only to configure the surface (during the control and programming phase)
  - Minimal power is used only to configure the surface (during the control and programming phase)

RIS-Empowered Wireless Networks: The Big Picture



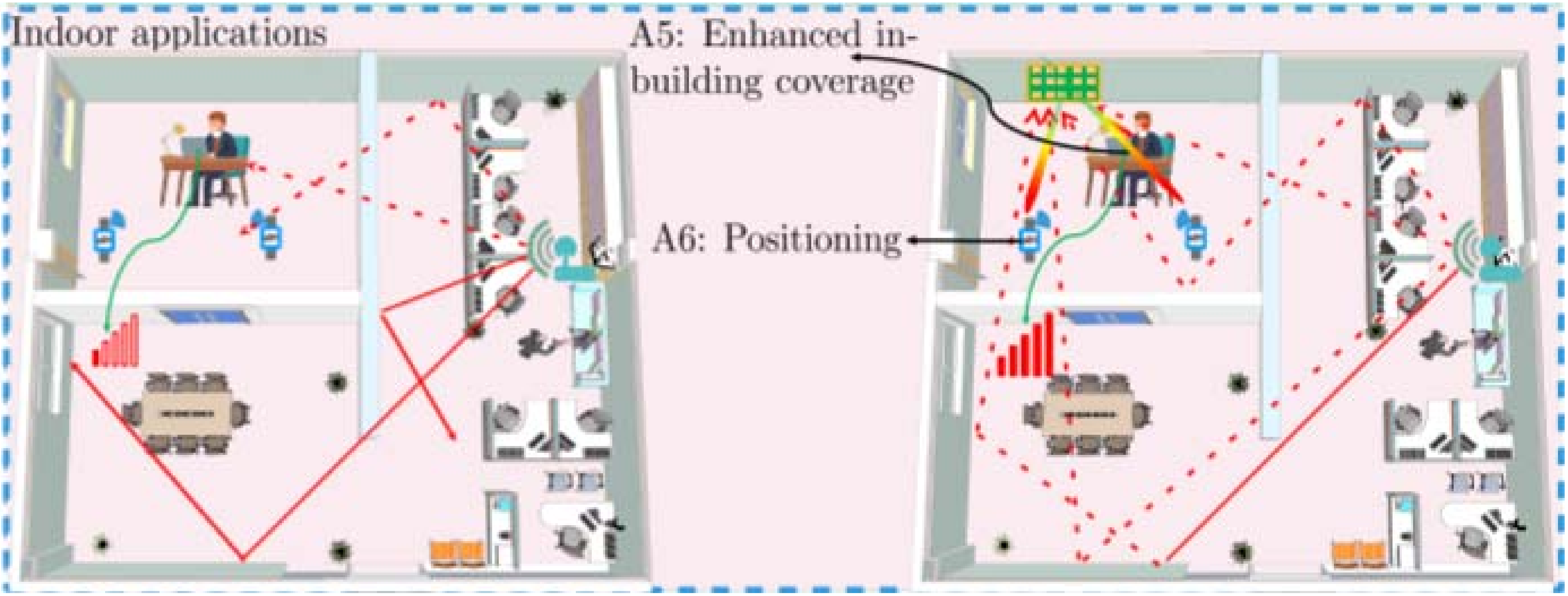


RIS-Empowered Wireless Networks: Outdoors

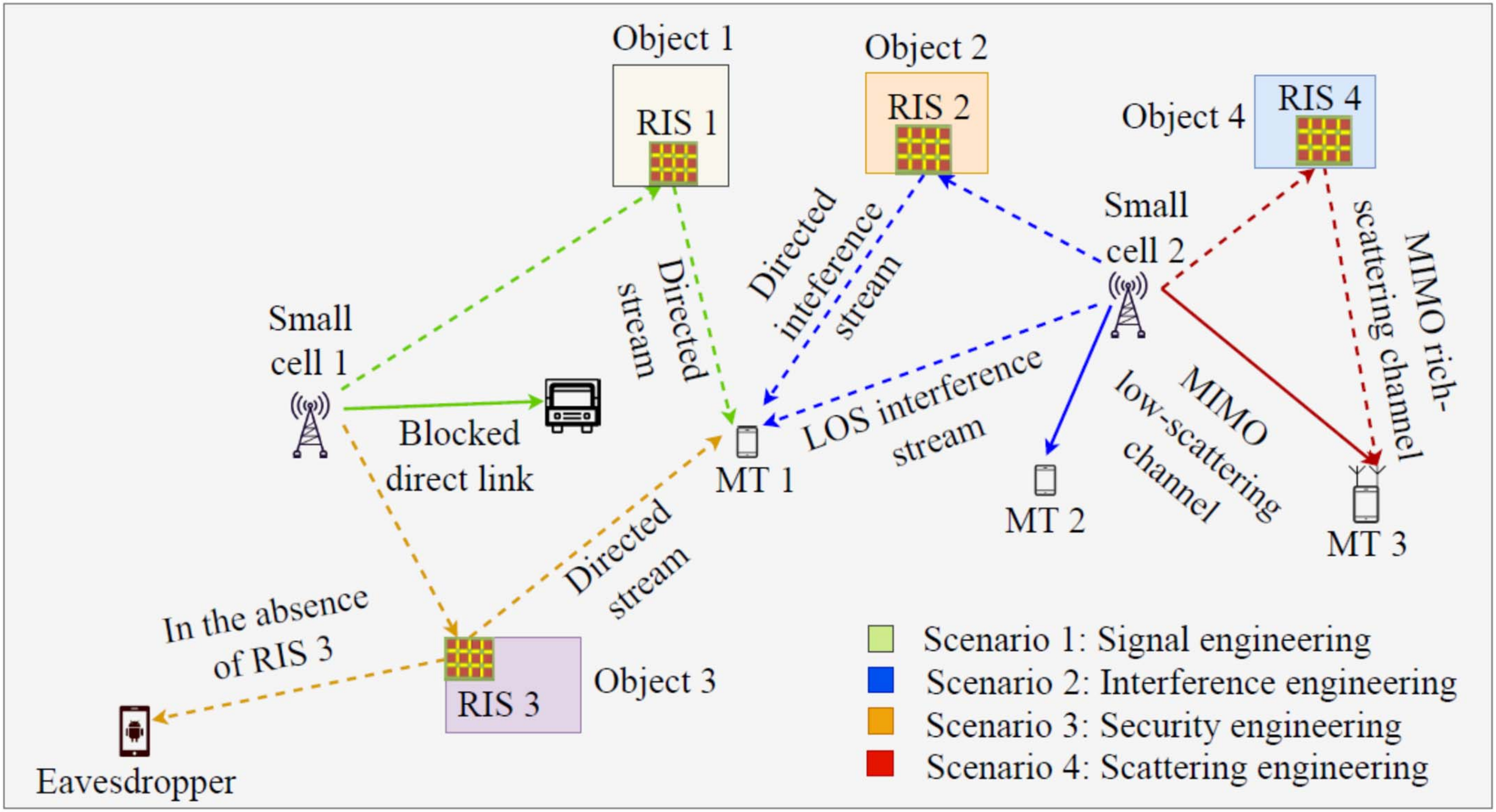


RIS-Empowered Wireless Networks: Outdoors

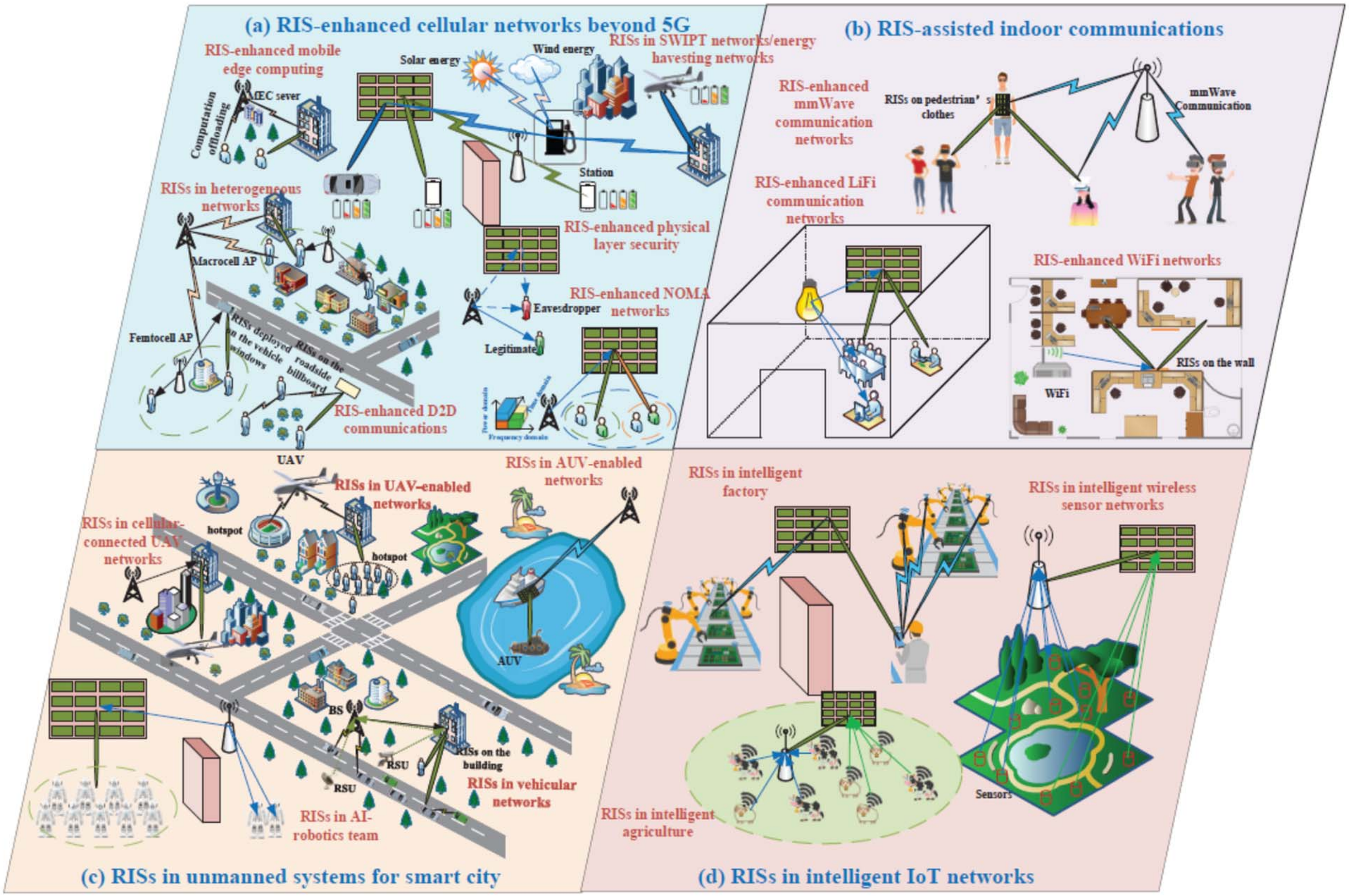
RIS-Empowered Wireless Networks: Indoors



Smart Radio Environments: RIS-Empowered Wireless



Enhancing Coverage, EE, Rate Through RISs



Y. Liu, M. Di Renzo, et al., “RISs: Principles & Opportunities”, arXiv:2007.03435

Were Are We ?

Reconfigurable Intelligent Metasurfaces

Were Are We ?

1G

Uniform Metasurface
(Homogenization of periodic)

2000-2010

2G

Non- Uniform Metasurface
(Space - variable)

2010-2020

- Extending the range of applicability
  - Ultrawideband
  - Shaped beams
  - Multibeam
  - Multifrequency

3G

Reconfigurable Metasurface
(Space-time variable)

2020-2030

- Reconfigurability by switches
- Reconfigurability by tunable material
- Topological Metasurface
- Smart metasurfaces beyond 5G

Smart space-time Metasurfaces can be the key-future technology for smart environment "beyond 5G"

Terminology: RISs & Friends

- **These structures are often referred to as:**

Terminology: RISs & Friends

- These structures are often referred to as:
  - Large intelligent surfaces (LISs)
  - Intelligent reflecting surfaces (IRSs)
  - Digitally controllable scatterers (DCSs)
  - Software-controllable surfaces
  - Reconfigurable intelligent surfaces (RISs)

Terminology: RISs & Friends

Novel Antenna Technologies

- *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.

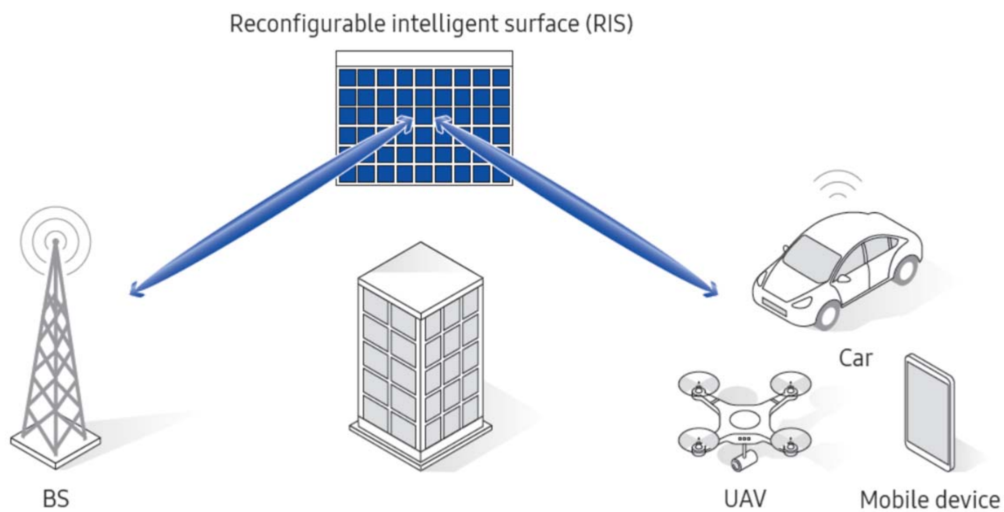
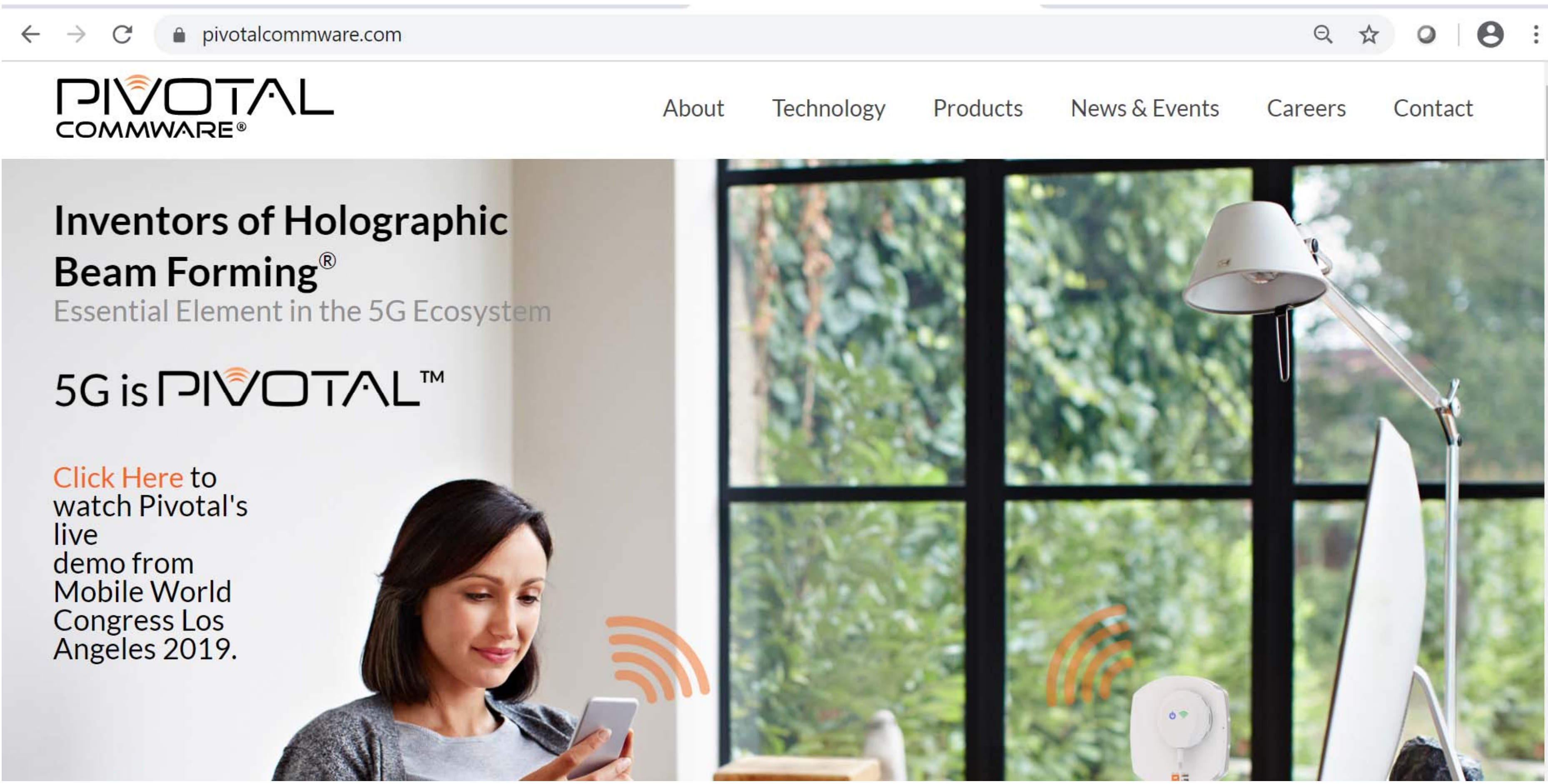


Figure 12

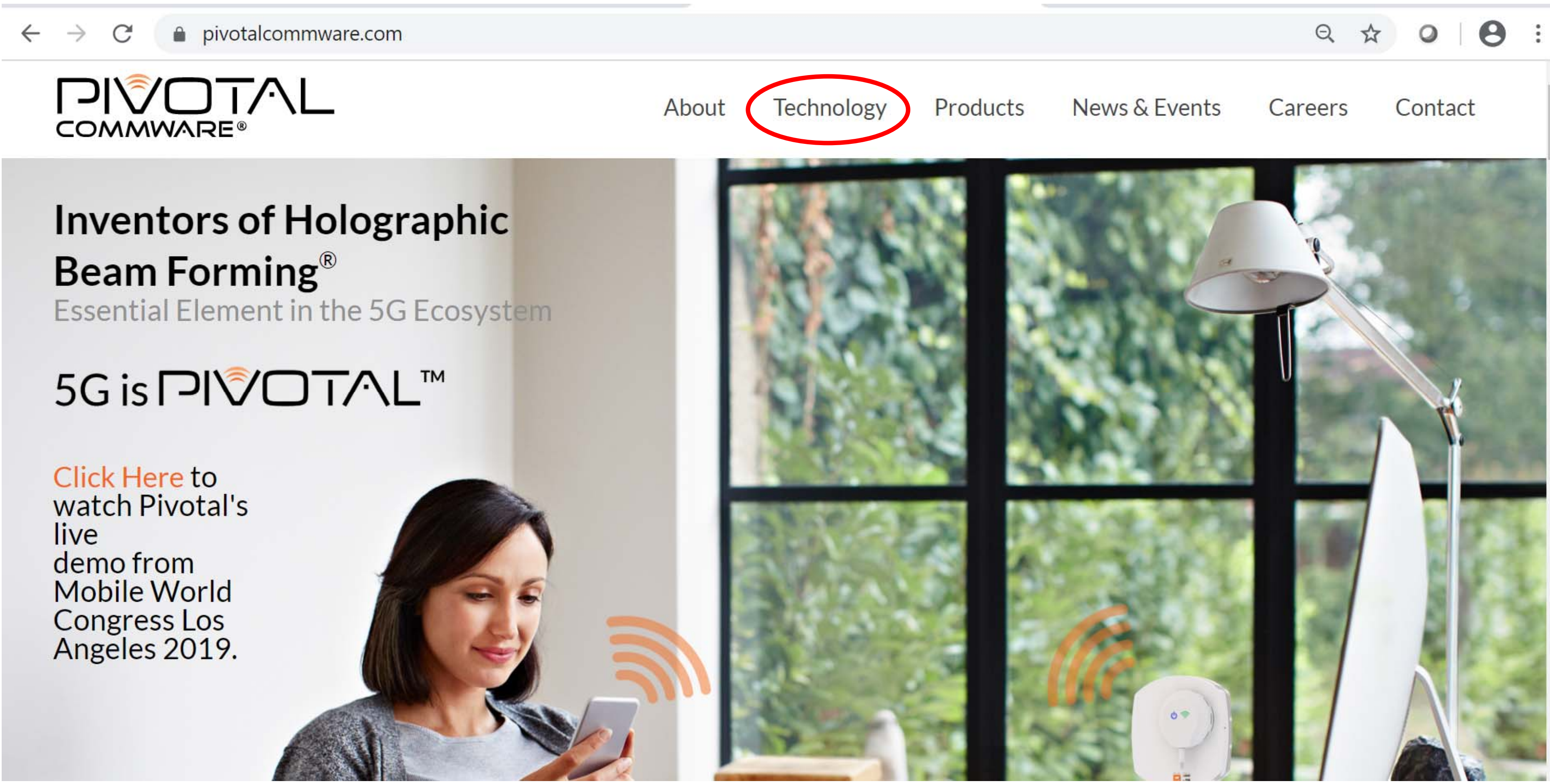
RIS-aided communication between a BS and a mobile user, where the LoS path is blocked.

Nearly-Passive RISs: Advantages and Limitations

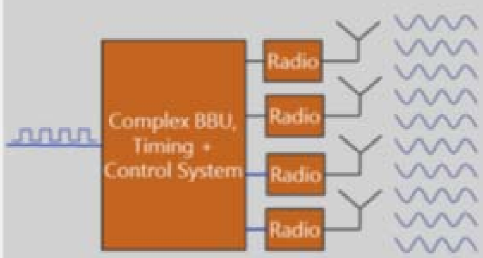
Nearly-Passive RISs: Advantages and Limitations



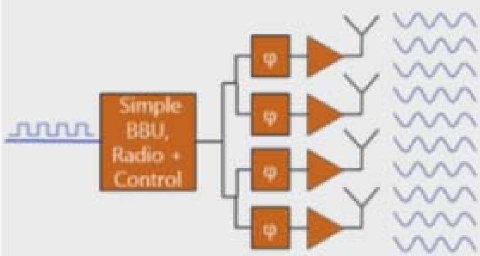
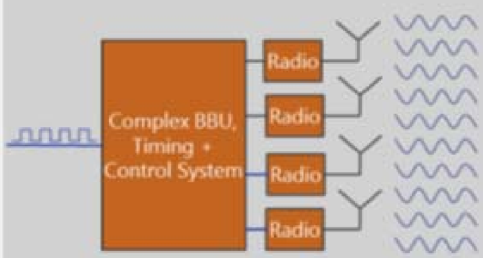
Nearly-Passive RISs: Advantages and Limitations



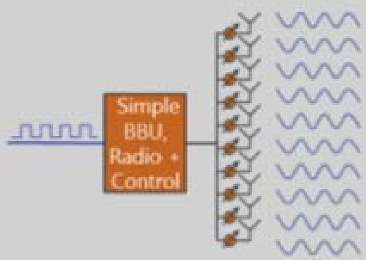
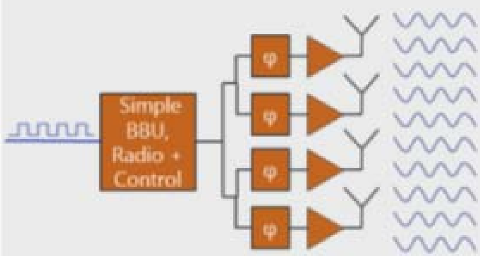
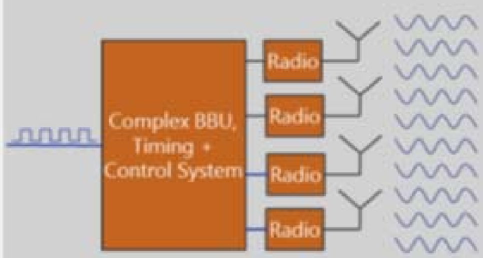
Nearly-Passive RISs: Advantages and Limitations

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

Nearly-Passive RISs: Advantages and Limitations

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

Nearly-Passive RISs: Advantages and Limitations

Architecture	Block Diagram	Cost	Size	Challenges
RIS 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

Example of Power Consumption

Nearly-Passive RISs: Advantages and Limitations

Example of Power Consumption

	Phased Array	RIS HBF	Unit
Number of Unit Cells	256	640	#
Antenna Gain	28	26	dB
Number of RF chains	256	1	#
Transmit Power per chain	6.2	2512	mW
Total RF Transmit Power	1.58	2.51	W
Power Added Efficiency	4.0%	25.0%	%
DC Draw for RF	39.6	10.0	W
HBF Controller	0	2.9	W
Total DC Power	**39.6**	**12.9**	**W**

Example of Power Consumption

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Number of Unit Cells	256	640	#

Example of Power Consumption

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Number of Unit Cells	256	640	#
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Compared with other transmission technologies, e.g., phased arrays, multi-antenna transmitters, and relays, RISs require the largest number of scattering elements, but each of them needs to be backed by the fewest and least costly components. Also, no power amplifiers are usually needed.

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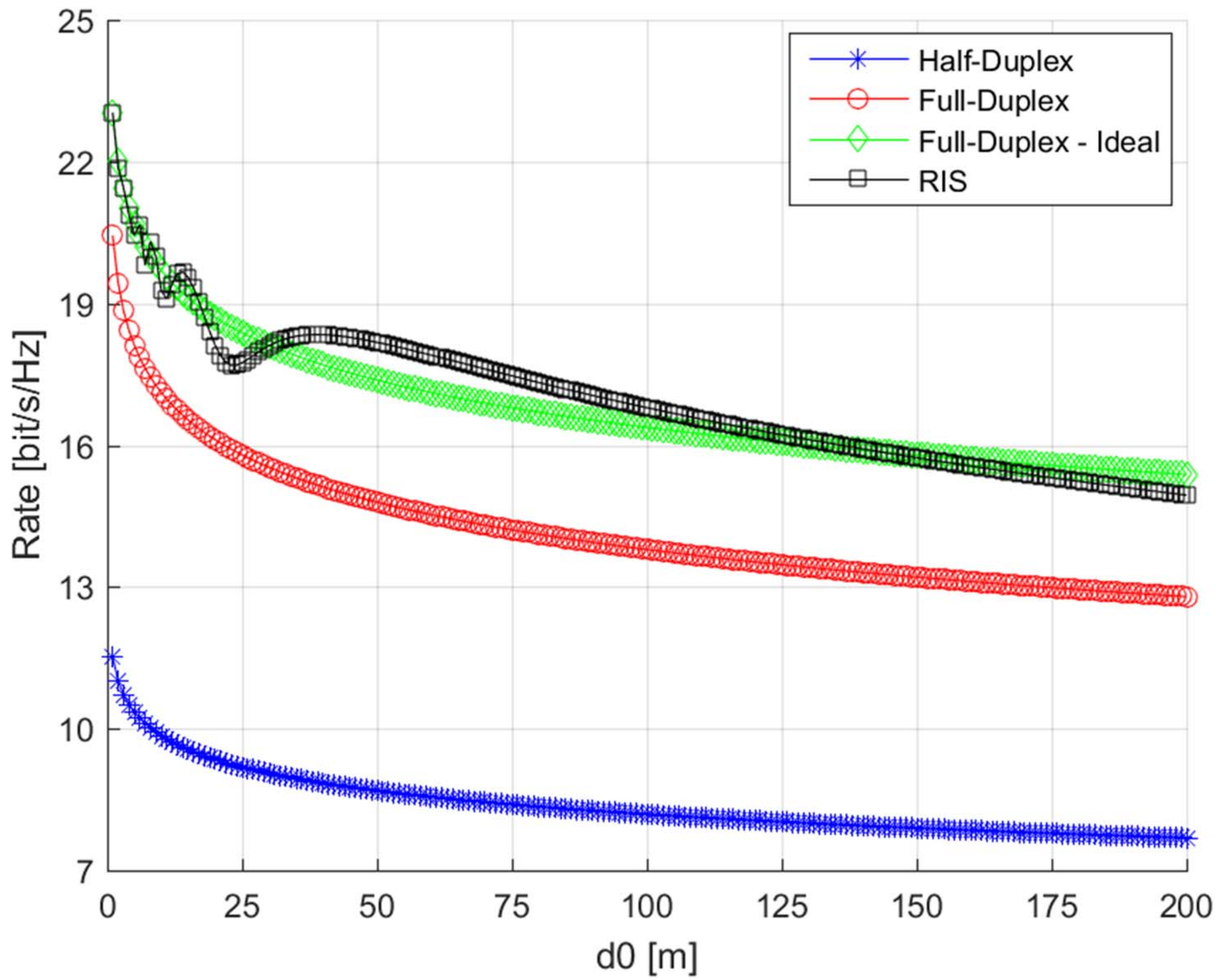
… no free lunch rule …

Example: RIS vs. Relay

Nearly-Passive RISs: Advantages and Limitations

Example: RIS (1.5m = 140λ, reflector) vs. Relay (1-antenna)



Further Information

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Reconfigurable Intelligent Surfaces vs. Relaying: Differences, Similarities, and Performance Comparison

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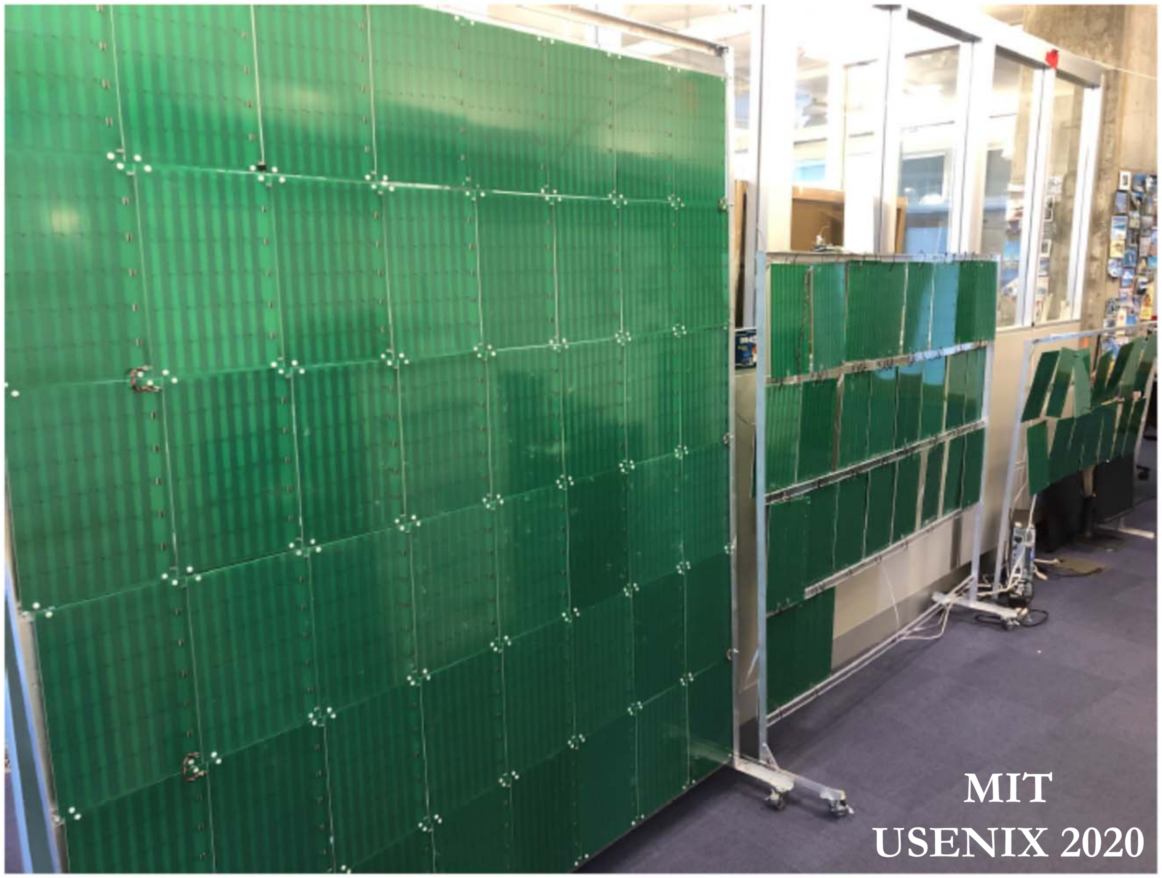
How Large/Big Can an RIS Be ?

Nearly-Passive RISs: Advantages and Limitations

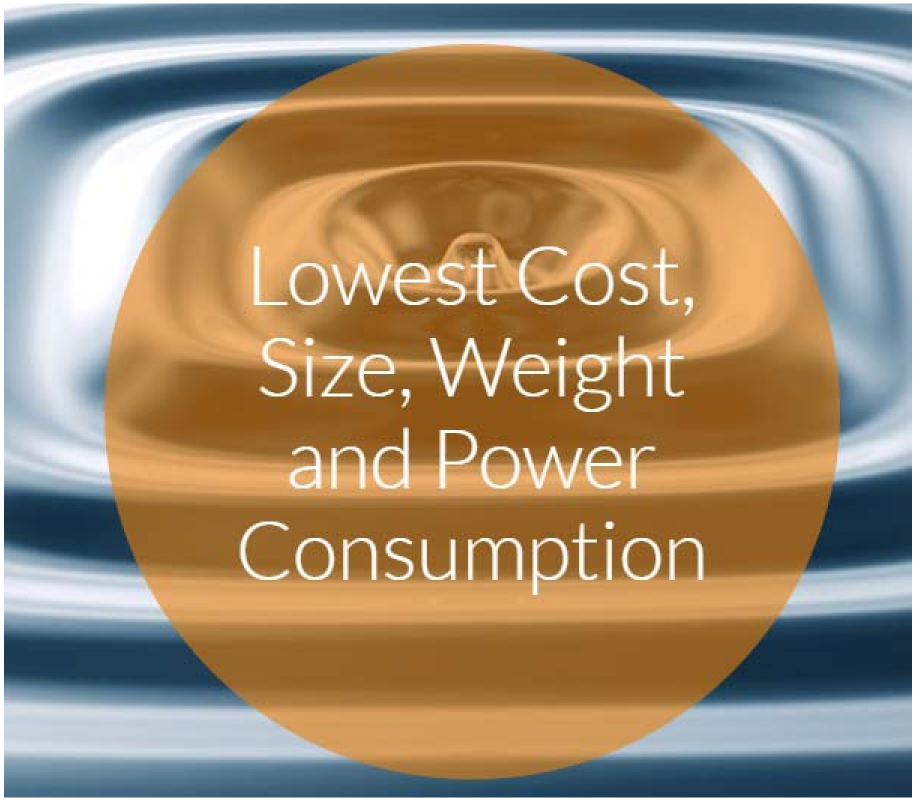
How Large/Big Can an RIS Be ?



“ Our prototype has 3,720 inexpensive antennas (at scale, each of the antenna elements is on the order of a few cents or less) on a 6 square-meter surface. We believe this configuration may be the largest number of antennas ever used to improve communication links ”

Nearly-Passive RISs: Advantages and Limitations

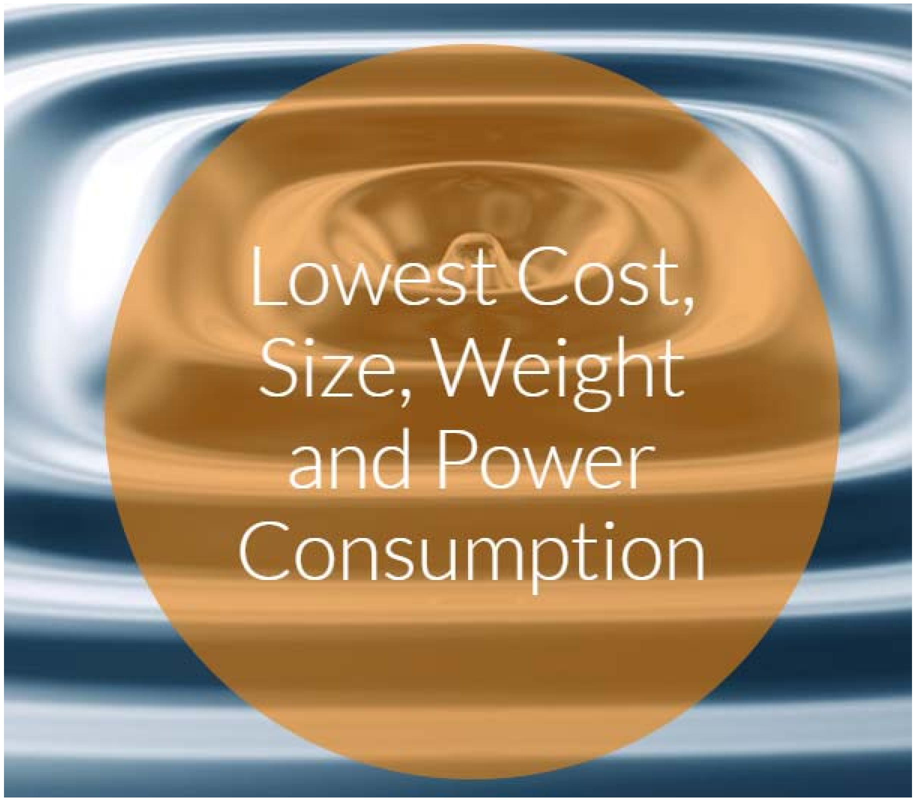
C-SWaP



For these reasons, RISs may constitute an emerging and promising software-defined architecture that can be realized at reduced cost, size, weight, and power (C-SWaP design)

Nearly-Passive RISs: Advantages and Limitations

C-SWaP



Sustainable wireless design (e.g., low EMF exposure) without generating new waves and possibly made of physically & aesthetically unobtrusive and recyclable material

Some Recent Results

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… from theory to simulations and experiments…

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- **Path-Loss – Physics-Based Foundation (SPAWC 2020 → TWC)**
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- **Joint Encoding – Capacity-Optimal Design (ISIT 2020)**
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  - **M. Di Renzo et al., Beamforming Through Reconfigurable Intelligent Surfaces in Single-User MIMO Systems: SNR Distribution and Scaling Laws in the Presence of Channel Fading and Phase Noise (arXiv:2005.07472)**
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- **… and many others on channel modeling, performance analysis, spectral & energy efficiency optimization, experiments…**

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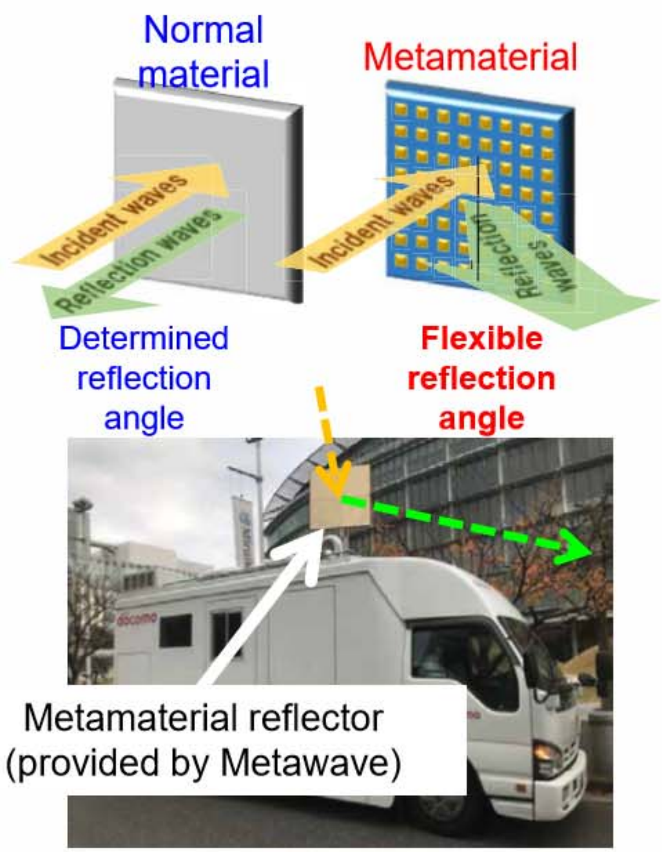
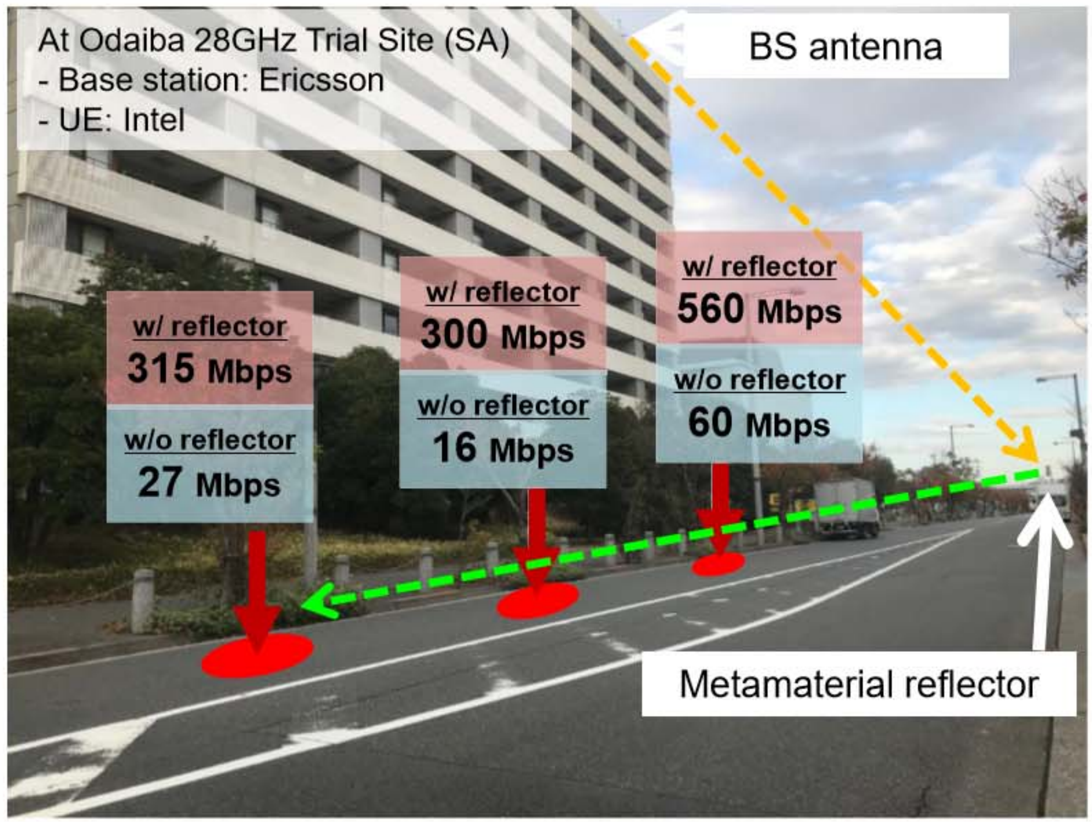
RISs for Outdoor Coverage Enhancement (mmWave)

RISs: Metasurfaces Spaced < λ/2
(DOCOMO & MetaWave, Jan. 2019)





A Transparent Dynamic RIS (reflection/refraction)

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Press Release

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

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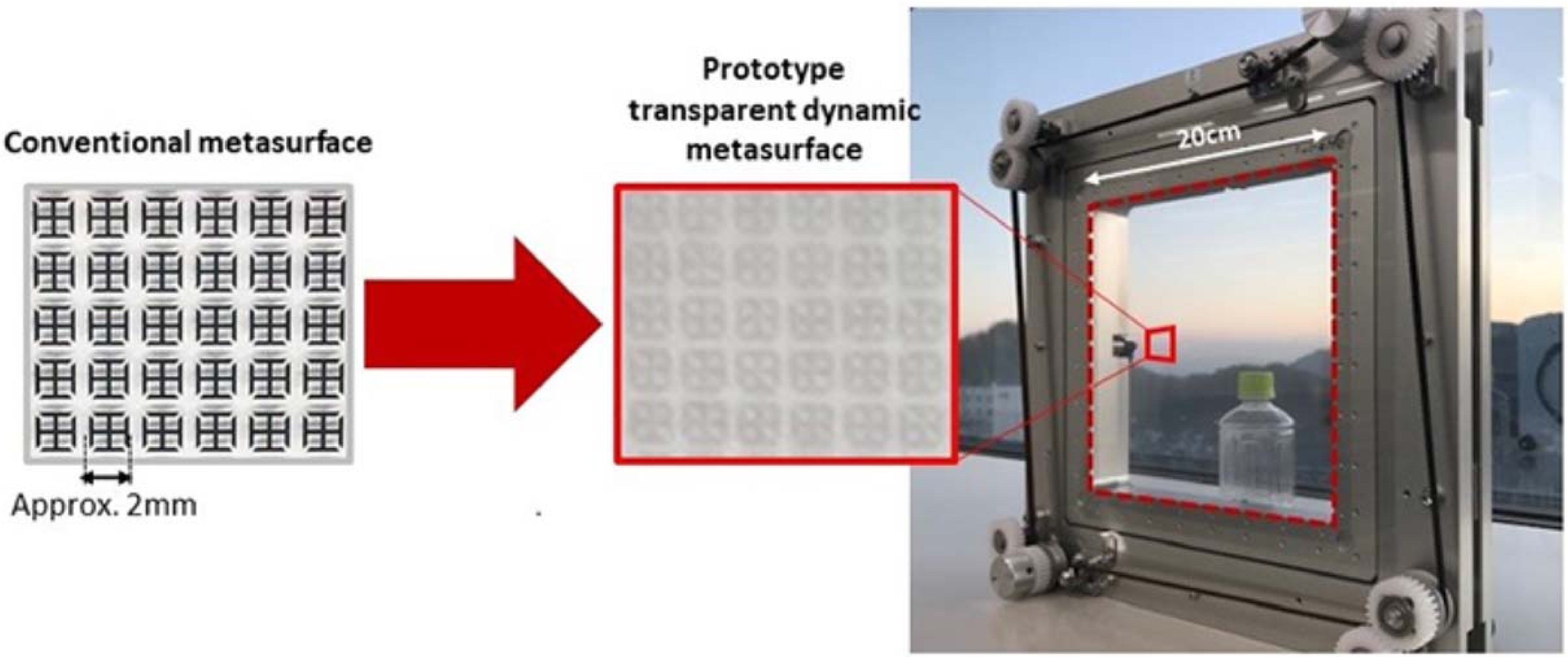
▶ 2018

A Transparent Dynamic RIS (reflection/refraction)

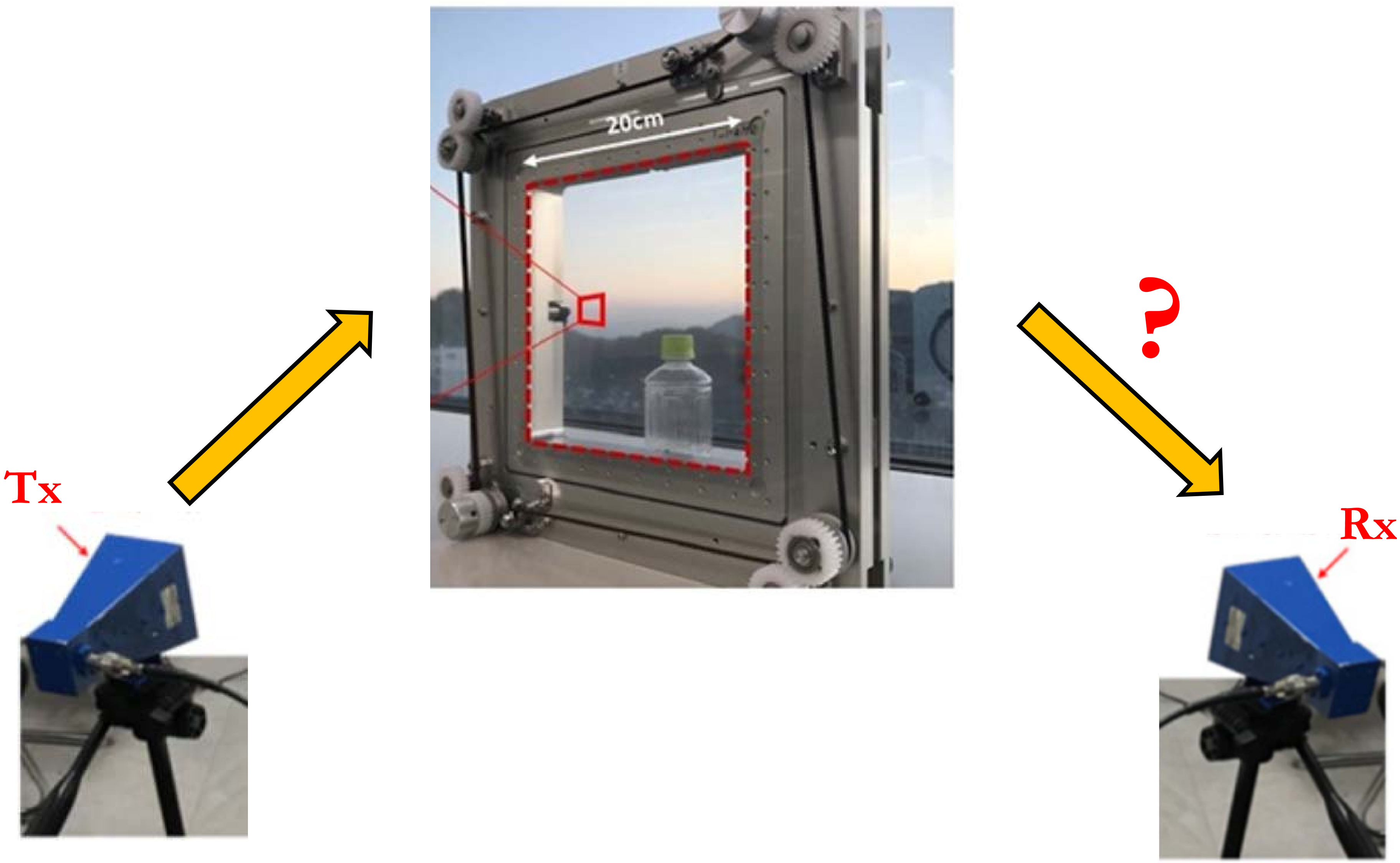
RISs: Metasurfaces Spaced < λ/2
(transparent and dynamic, Jan. 2020)



Prototype of transparent dynamic metasurface

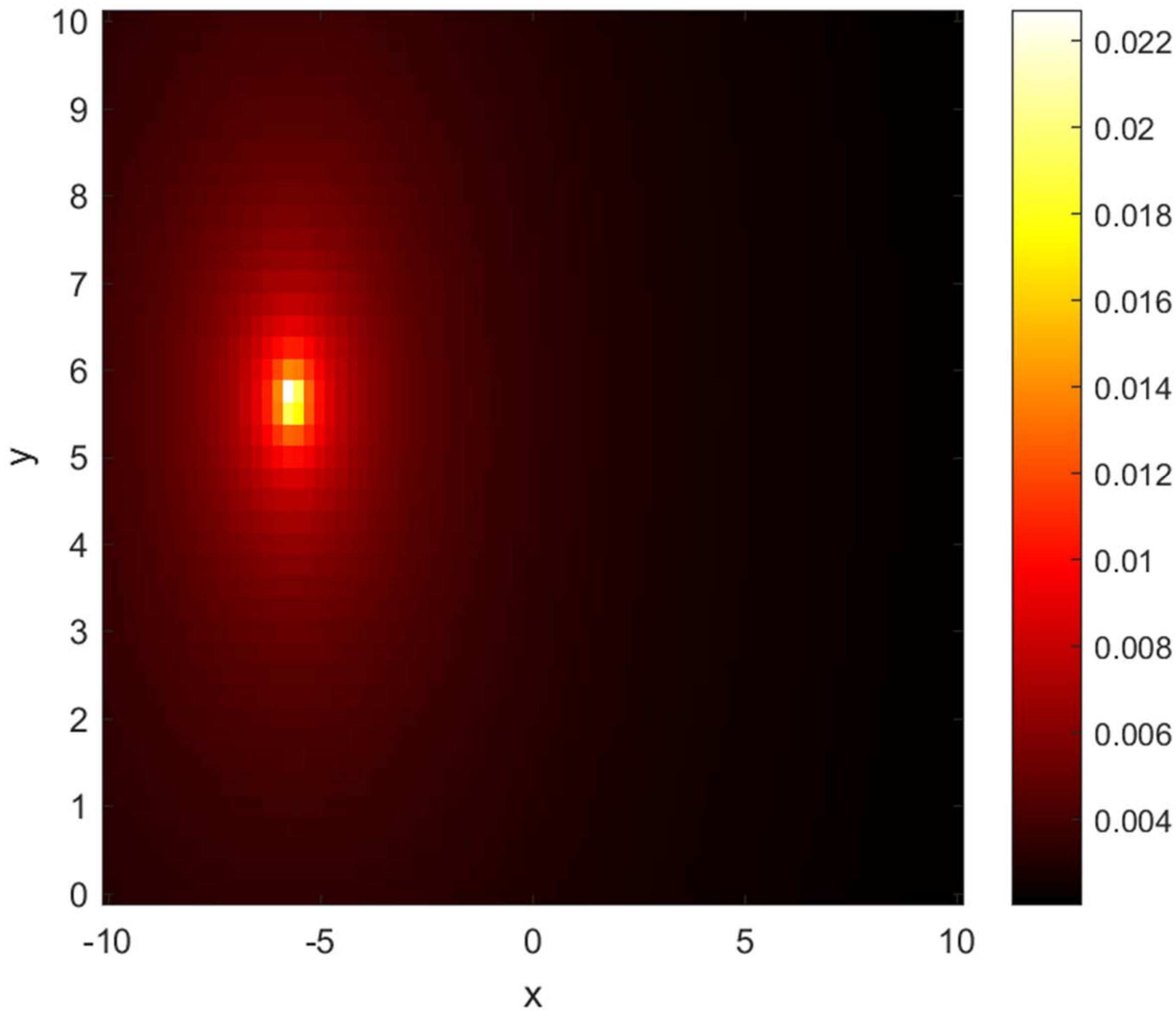
RIS-Empowered Wireless Networks: Outdoors

What is the Power Scattered by an RIS ?



System Model

System Model (2D)



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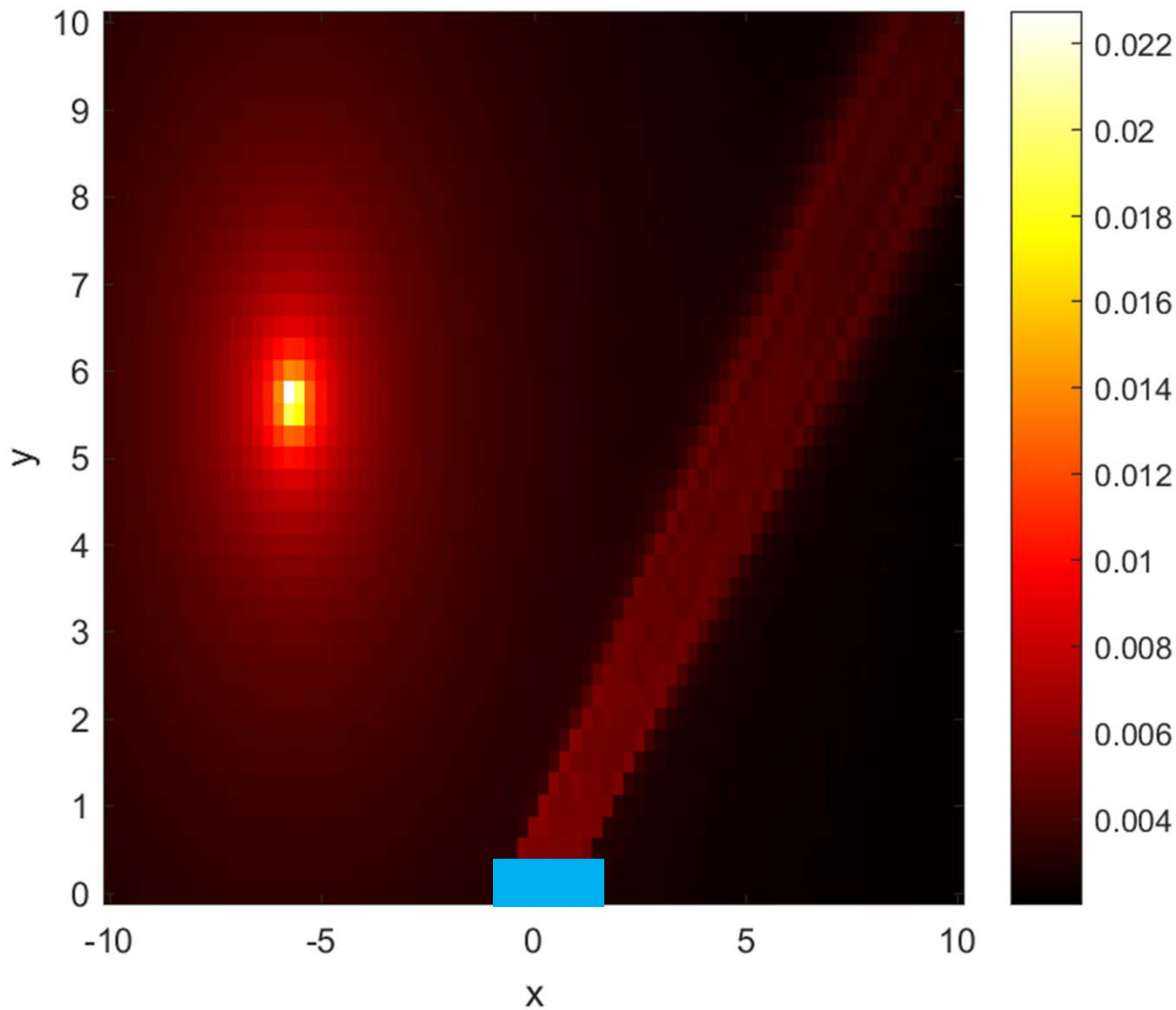
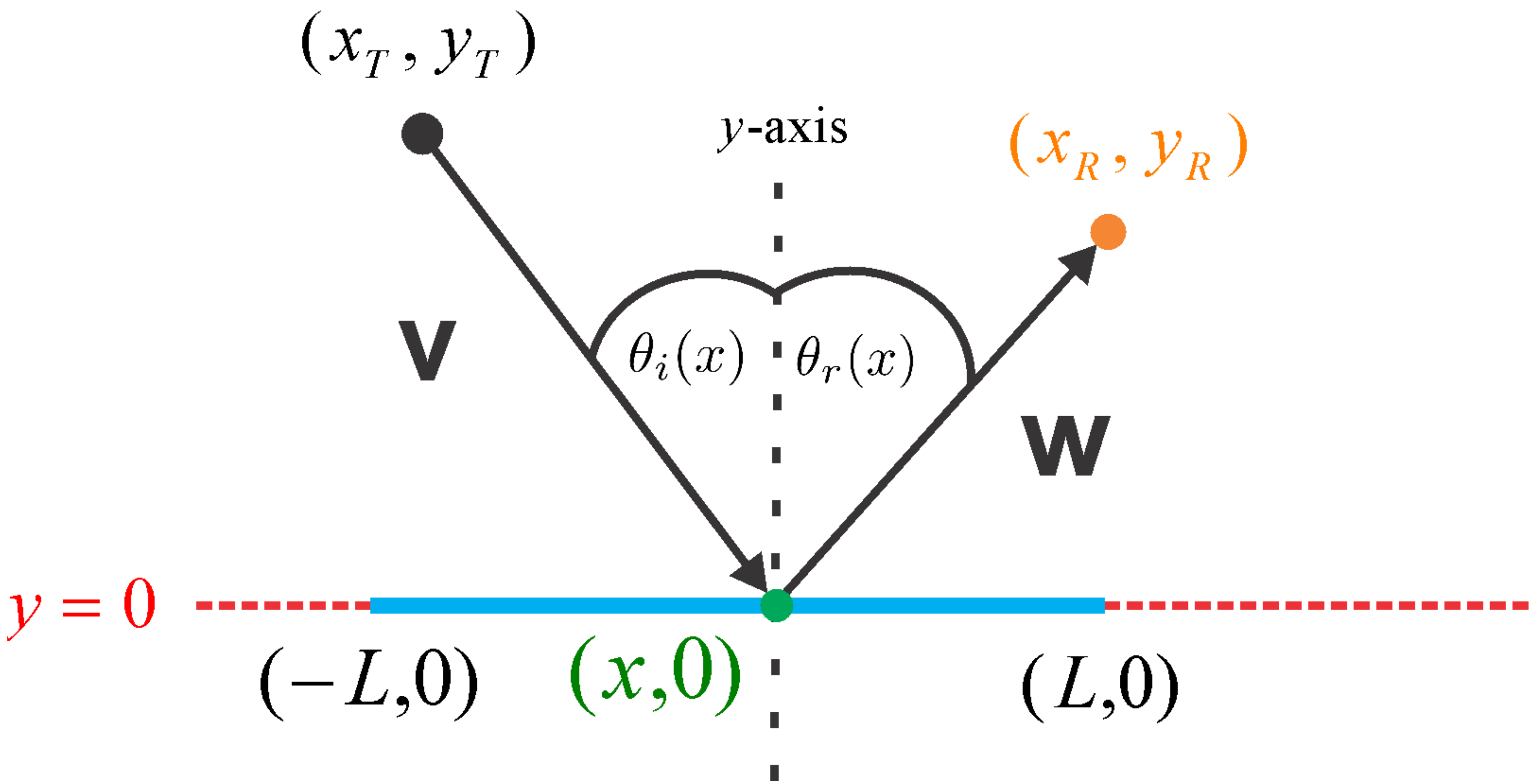


Path-Loss Modeling – Homogenized Metasurfaces

System Model (2D)



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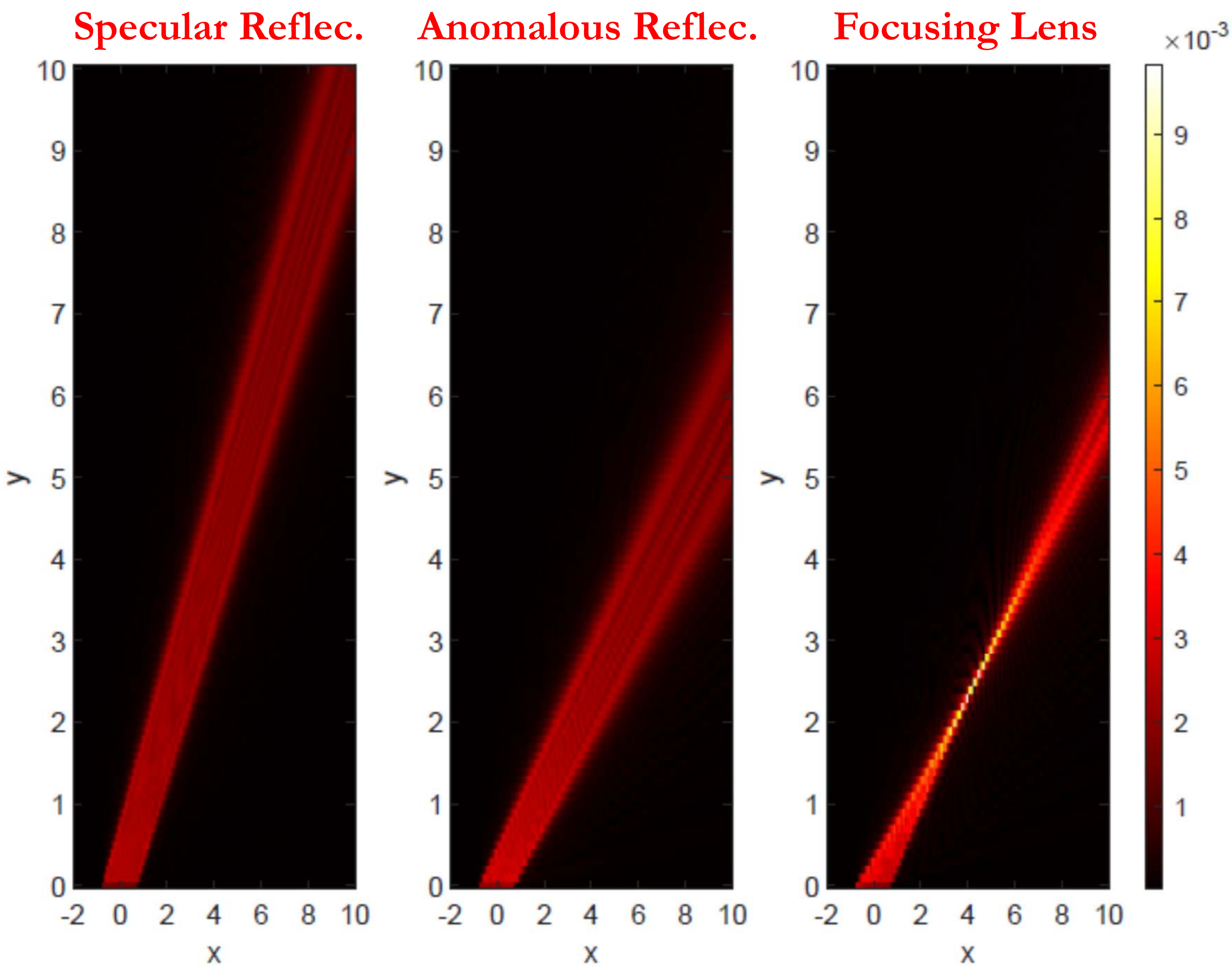
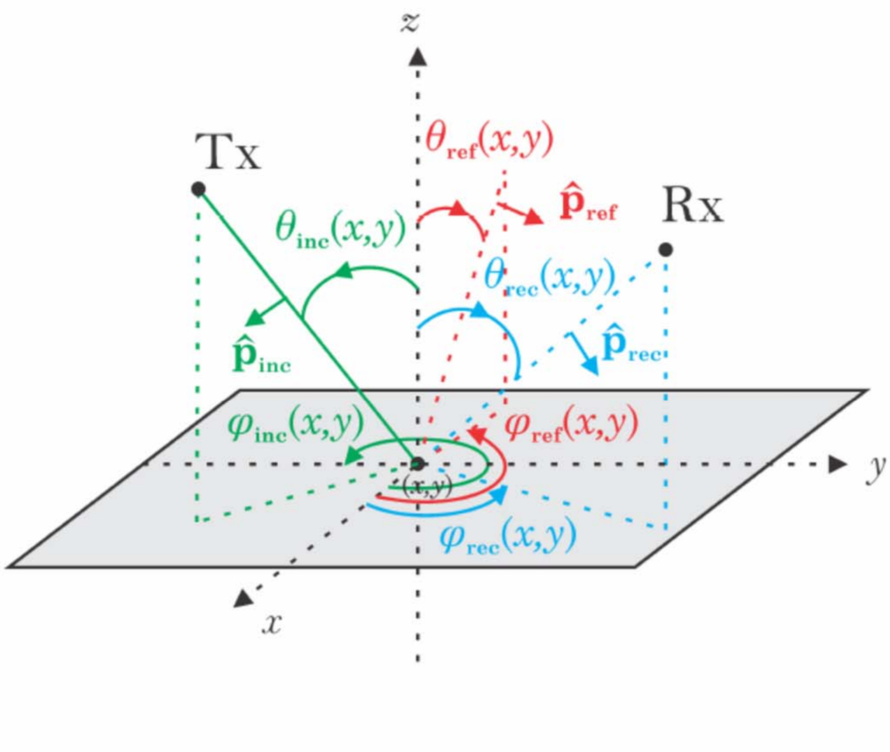
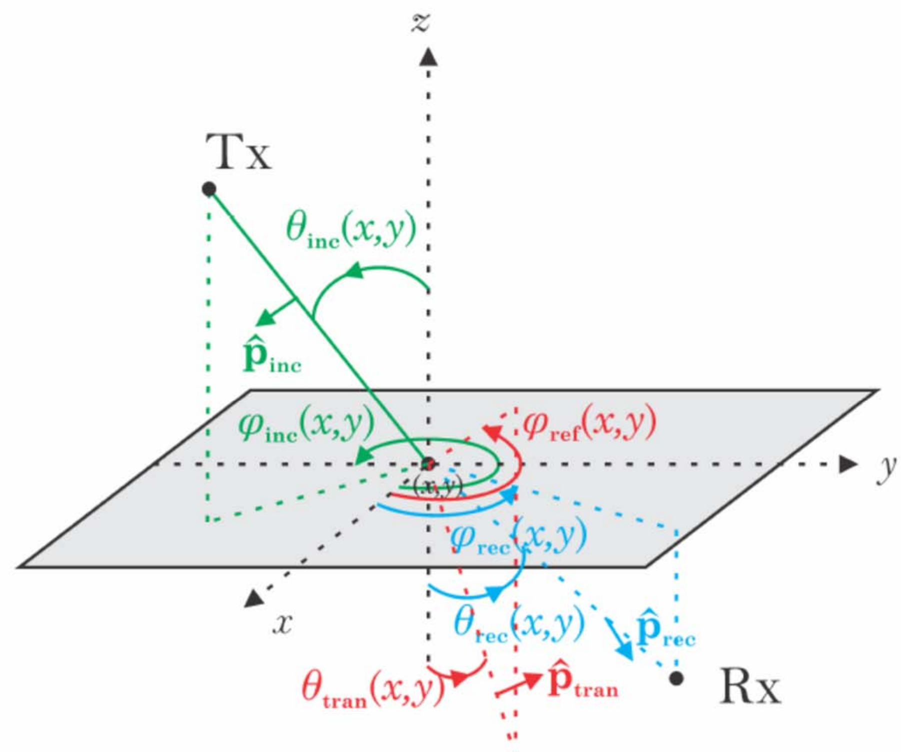


Path-Loss Modeling – Homogenized Metasurfaces

System Model (3D)

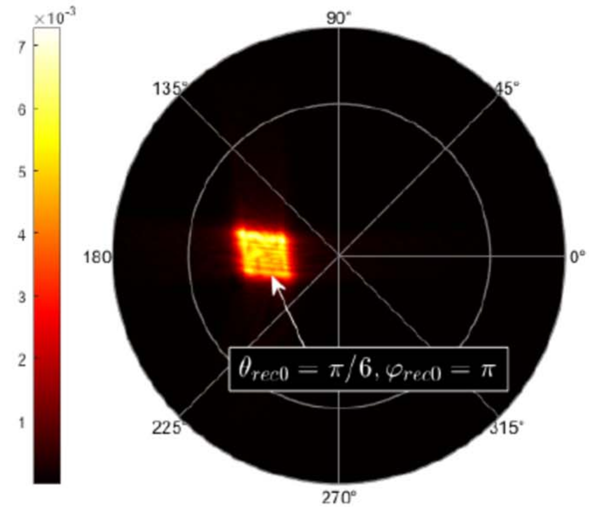


(a) Tx and Rx are on the same side of the surface.

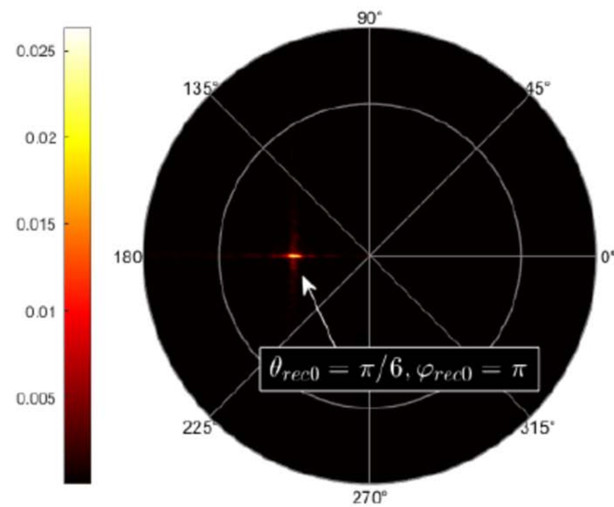


(b) Tx and Rx are on opposite sides of the surface.

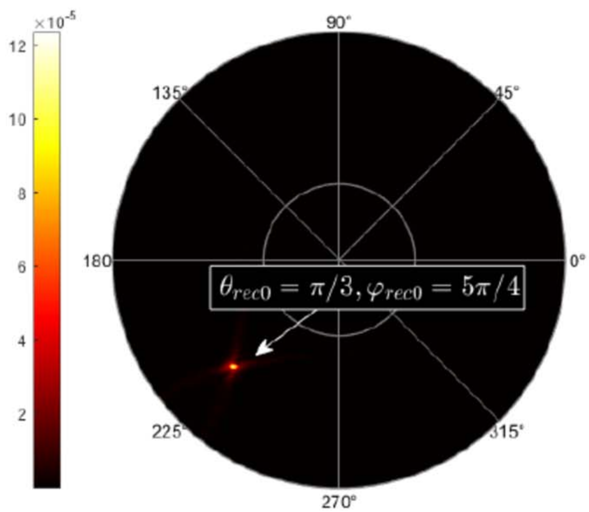
Path-Loss Modeling – Homogenized Metasurfaces



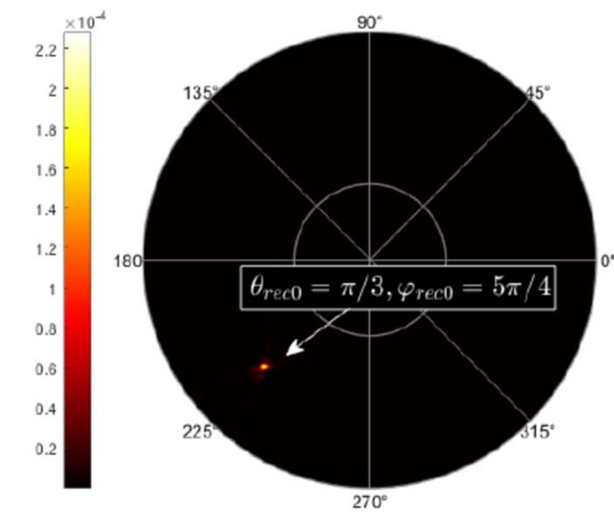
(a) Anomalous reflection, $d_{\mathrm{Tx0}} = d_{\mathrm{Rx0}} = 5$ m



(b) Focusing lens (reflection), $d_{\mathrm{Tx0}} = d_{\mathrm{Rx0}} = 5$ m



(c) Anomalous transmission, $d_{\mathrm{Tx0}} = d_{\mathrm{Rx0}} = 50$ m.



(d) Focusing lens (transmission), $d_{\mathrm{Tx0}} = d_{\mathrm{Rx0}} = 50$ m.

Path-Loss Modeling – Homogenized Metasurfaces

Main Theorem (TWC, under submission)

Proposition 1. *Let* $\hat{\mathrm{s}}_{(x,y)} = \sin\theta_{\text{inc}}(x,y)\cos\varphi_{\text{inc}}(x,y)\hat{\mathbf{x}} + \sin\theta_{\text{inc}}(x,y)\sin\varphi_{\text{inc}}(x,y)\hat{\mathbf{y}} + \cos\theta_{\text{inc}}(x,y)\hat{\mathbf{z}}$, *be the unit-norm propagation vector from* $\mathbf{r}_{\text{Tx}}$ *to* $\mathbf{s} = x\hat{\mathbf{x}} + y\hat{\mathbf{y}} \in \mathcal{S}$. *Define* $\Omega_{\text{ref}}(x,y;\hat{\mathbf{p}}_{\text{ref}},\hat{\mathbf{p}}_{\text{rec}}) = (k^2/\epsilon_0)p_{\text{dm}}\left(\tilde{\mathbf{p}}_{\text{rec}}\cdot\tilde{\mathbf{p}}_{\text{ref}} - \left(\hat{\mathrm{s}}_{(x,y)}\cdot\tilde{\mathbf{p}}_{\text{rec}}\right)\left(\hat{\mathrm{s}}_{(x,y)}\cdot\tilde{\mathbf{p}}_{\text{ref}}\right)\right)\mathcal{E}\left(\hat{\mathbf{p}}_{\text{inc}},\hat{\mathbf{p}}_{\text{ref}}\right)$. *Under the assumptions stated in Lemma 2, the electric field* $\mathbf{E}(\mathbf{r}_{\text{Rx}})$ *projected onto* $\hat{\mathbf{p}}_{\text{rec}}$ *can be formulated as follows:*

$$\mathbf{E}(\mathbf{r}_{\text{Rx}})\cdot\hat{\mathbf{p}}_{\text{rec}} \approx \hat{\mathbf{p}}_{\text{rec}}\cdot\mathbf{E}_{0,\text{inc}}\left(\mathbf{r}_{\text{Rx}};\hat{\mathbf{p}}_{\text{inc}}\right)G(\mathbf{r}_{\text{Rx}},\mathbf{r}_{\text{Tx}}) + \mathcal{I}_0\int_{-L_y}^{L_y}\int_{-L_x}^{L_x}\mathcal{I}_R(x,y)e^{-jk\mathcal{P}_R(x,y)}dxdy \tag{21}$$

where $\mathcal{I}_0 = jk/(16\pi^2)$, *and the following shorthand notation is used:*

$$\mathcal{P}_R(x,y) = d_{\text{Tx}}(x,y) + d_{\text{Rx}}(x,y) - (\phi_{\text{rec}} + \phi_{\text{ref}} + \angle\Gamma_{\text{ref}}(x,y))/k \tag{22}$$

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$$\mathbf{E}(\mathbf{r}_{\rm Rx})\cdot\hat{\mathbf{p}}_{\rm rec} \approx \boxed{\hat{\mathbf{p}}_{\rm rec}\cdot\mathbf{E}_{0,\rm inc}\left(\mathbf{r}_{\rm Rx};\hat{\mathbf{p}}_{\rm inc}\right)G(\mathbf{r}_{\rm Rx},\mathbf{r}_{\rm Tx})} + \mathcal{I}_0\int_{-L_y}^{L_y}\int_{-L_x}^{L_x}\mathcal{I}_R(x,y)e^{-jk\mathcal{P}_R(x,y)}dxdy \qquad (21)$$

where $\mathcal{I}_0 = jk/(16\pi^2)$, *and the following shorthand notation is used:*

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$$\mathcal{I}_R(x,y) = \frac{|\Gamma_{\rm ref}(x,y)|\,\Omega_{\rm ref}(x,y;\hat{\mathbf{p}}_{\rm ref},\hat{\mathbf{p}}_{\rm rec})}{d_{\rm Tx}(x,y)d_{\rm Rx}(x,y)}\left(\cos\theta_{\rm inc}(x,y) + \cos\theta_{\rm rec}(x,y)\right) \qquad (23)$$

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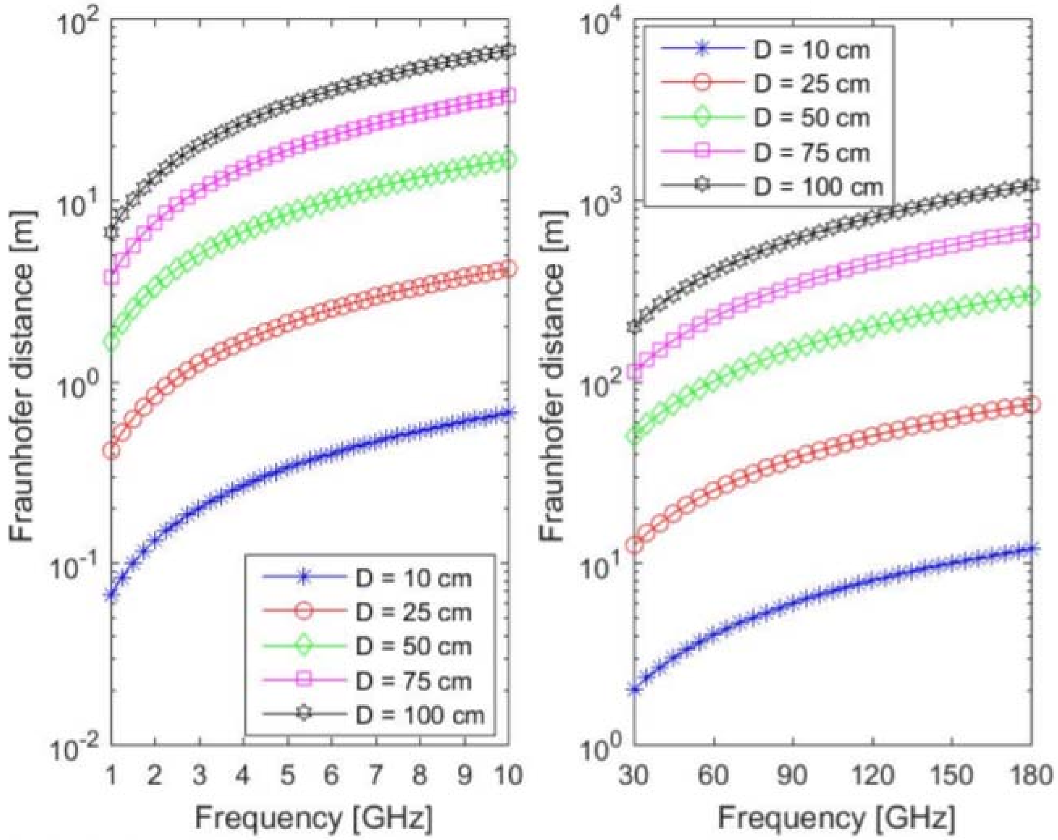
Electrically-Large (near-field) vs. Electrically-Small (far-field)

Path-Loss Modeling – Homogenized Metasurfaces

Electrically-Large (near-field) vs. Electrically-Small (far-field)

$$d_F = 4D^2/\lambda$$

Fraunhofer distance (d_F)



Path-Loss Modeling – Homogenized Metasurfaces

Electrically-Large (near-field) vs. Electrically-Small (far-field)

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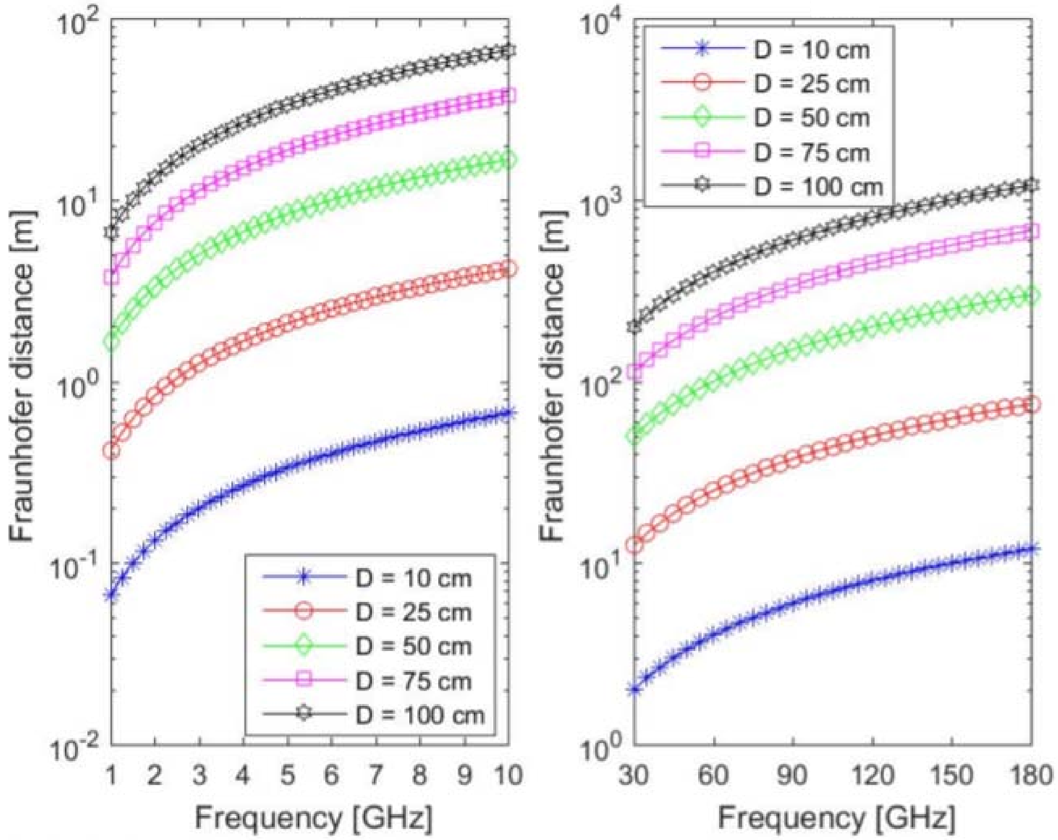


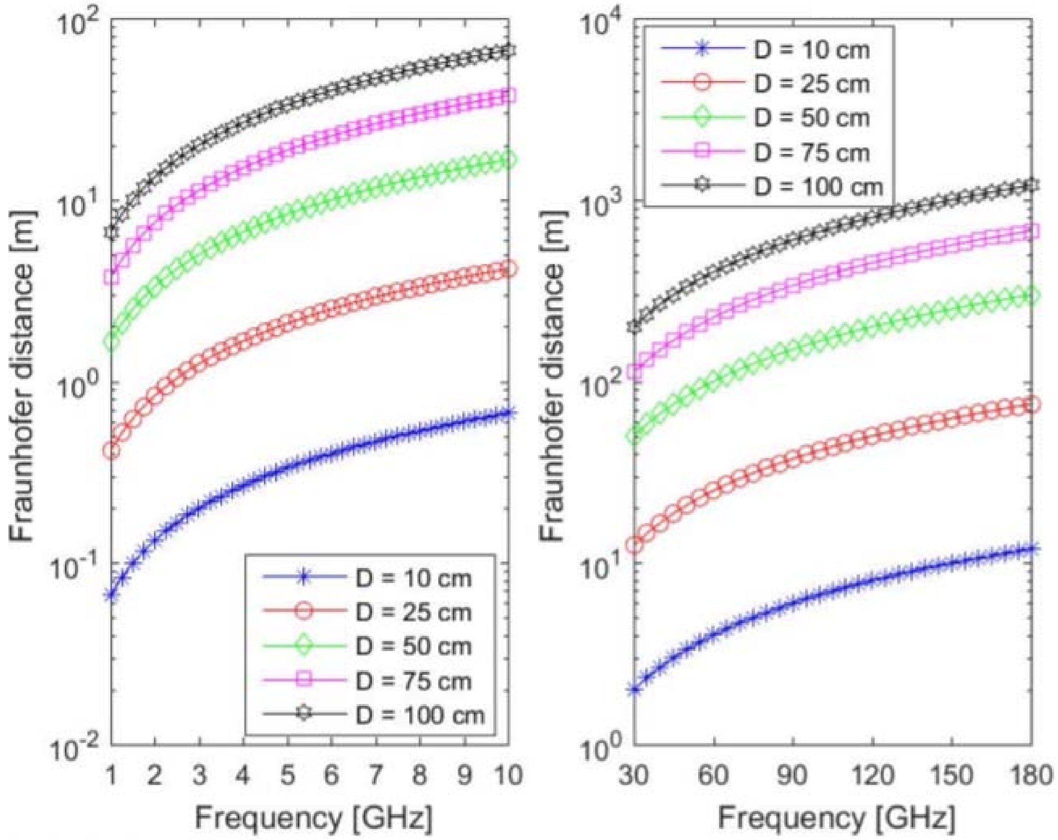
Fraunhofer distance (d_F)

- **0.1x0.1 m^2 RIS @ 6 GHz → 0.8 m**
- **1.0x1.0 m^2 RIS @ 6 GHz → 80 m**
- **6 m^2 RIS @ 6 GHz → 480 m**

Path-Loss Modeling – Homogenized Metasurfaces

Electrically-Large (near-field) vs. Electrically-Small (far-field)

$$d_F = 4D^2/\lambda$$



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- **0.1x0.1 m^2 RIS @ 6 GHz → 0.8 m**
- **1.0x1.0 m^2 RIS @ 6 GHz → 80 m**
- **6 m^2 RIS @ 6 GHz → 480 m**
- **0.1x0.1 m^2 RIS @ 60 GHz → 8 m**
- **1.0x1.0 m^2 RIS @ 60 GHz → 800 m**

Path-Loss Modeling – Anomalous Reflection

Electrically-Large vs. Electrically-Small

Electrically-Large vs. Electrically-Small

Corollary 4. *Consider* $\zeta_1' > 0$, $\zeta_2' > 0$. *Define* $K_1 = (\mathcal{R}_1\zeta_1' + \frac{1}{2}\mathcal{R}_3\zeta_2')/\sqrt{\mathcal{R}_1{\zeta_1'}^2 + \mathcal{R}_2{\zeta_2'}^2 + \mathcal{R}_3\zeta_1'\zeta_2'}$, $K_2 = (\mathcal{R}_2\zeta_2' + \frac{1}{2}\mathcal{R}_3\zeta_1')/\sqrt{\mathcal{R}_1{\zeta_1'}^2 + \mathcal{R}_2{\zeta_2'}^2 + \mathcal{R}_3\zeta_1'\zeta_2'}$. *Then,* (29) *can be approximated as follows:*

$$F_R(\mathbf{r}_{\mathrm{Rx}}) \approx \frac{|\Gamma_{\mathrm{ref}}(x_s, y_s)|\,\Omega_{\mathrm{ref}}(x_s, y_s; \hat{\mathbf{p}}_{\mathrm{ref}}, \hat{\mathbf{p}}_{\mathrm{rec}})}{8\pi(K_1 d_{\mathrm{Tx}}(x_s, y_s) + K_2 d_{\mathrm{Rx}}(x_s, y_s))} e^{-jk(d_{\mathrm{Tx}}(x_s,y_s)+d_{\mathrm{Rx}}(x_s,y_s)-(\alpha_R x_s+\beta_R y_s)-(\phi_0+\phi_{\mathrm{ref}}+\phi_{\mathrm{rec}})/k)}$$

Path-Loss Modeling – Anomalous Reflection

Electrically-Large vs. Electrically-Small

Corollary 5. *In the electrically-small regime, $F_R(\mathbf{r}_{\text{Rx}})$ can be approximated as follows:*

$$F_R(\mathbf{r}_{\text{Rx}}) \approx \frac{jk\Omega_{\text{ref}}(0,0;\hat{\mathbf{p}}_{\text{ref}},\hat{\mathbf{p}}_{\text{rec}})\left(\cos\theta_{\text{inc}0}+\cos\theta_{\text{rec}0}\right)}{16\pi^2 d_{\text{Tx}0}d_{\text{Rx}0}} e^{-jk(d_{\text{Tx}0}+d_{\text{Rx}0}-(\phi_0+\phi_{\text{ref}}+\phi_{\text{rec}})/k)} \int_{-L_y}^{L_y}\int_{-L_x}^{L_x} |\Gamma_{\text{ref}}(x,y)| e^{jk(\mathcal{D}_{\alpha_R}x+\mathcal{D}_{\beta_R}y)}dxdy \tag{31}$$

where the shorthand notation $\mathcal{D}_{\alpha_R}=\alpha_R+\mathcal{D}_x$ and $\mathcal{D}_{\beta_R}=\beta_R+\mathcal{D}_y$ is used. If $|\Gamma_{\text{ref}}(x,y)| = \Gamma_{\text{ref}} > 0$ for $(x,y)\in\mathcal{S}$, then $F_R(\mathbf{r}_{\text{Rx}})$ can be further simplified as follows:

$$F_R(\mathbf{r}_{\text{Rx}}) \approx \frac{jk\Gamma_{\text{ref}}\Omega_{\text{ref}}(0,0;\hat{\mathbf{p}}_{\text{ref}},\hat{\mathbf{p}}_{\text{rec}})L_xL_y\left(\cos\theta_{\text{inc}0}+\cos\theta_{\text{rec}0}\right)}{4\pi^2 d_{\text{Tx}0}d_{\text{Rx}0}} \operatorname{sinc}\left(kL_x\mathcal{D}_{\alpha_R}\right)\operatorname{sinc}\left(kL_y\mathcal{D}_{\beta_R}\right)e^{-jk(d_{\text{Tx}0}+d_{\text{Rx}0}-(\phi_0+\phi_{\text{ref}}+\phi_{\text{rec}})/k)} \tag{32}$$

Path-Loss Modeling – Anomalous Reflection

Electrically-Large (4) vs. Electrically-Small (5)

Corollary 4. *Consider* $\zeta_1' > 0$, $\zeta_2' > 0$. *Define* $K_1 = (\mathcal{R}_1\zeta_1' + \frac{1}{2}\mathcal{R}_3\zeta_2')/\sqrt{\mathcal{R}_1{\zeta_1'}^2 + \mathcal{R}_2{\zeta_2'}^2 + \mathcal{R}_3\zeta_1'\zeta_2'}$, $K_2 = (\mathcal{R}_2\zeta_2' + \frac{1}{2}\mathcal{R}_3\zeta_1')/\sqrt{\mathcal{R}_1{\zeta_1'}^2 + \mathcal{R}_2{\zeta_2'}^2 + \mathcal{R}_3\zeta_1'\zeta_2'}$. *Then,* (29) *can be approximated as follows:*

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Path-Loss Modeling – Anomalous Reflection

Electrically-Large (4) vs. Electrically-Small (5)

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Path-Loss Modeling – Anomalous Reflection

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$$\text{sinc}\,(kL_x\mathcal{D}_{\alpha_R})\,\text{sinc}\,(kL_y\mathcal{D}_{\beta_R})\, e^{-jk(d_{\text{Tx0}}+d_{\text{Rx0}}-(\phi_0+\phi_{\text{ref}}+\phi_{\text{rec}})/k)} \quad (32)$$

Path-Loss Modeling – Anomalous Reflection

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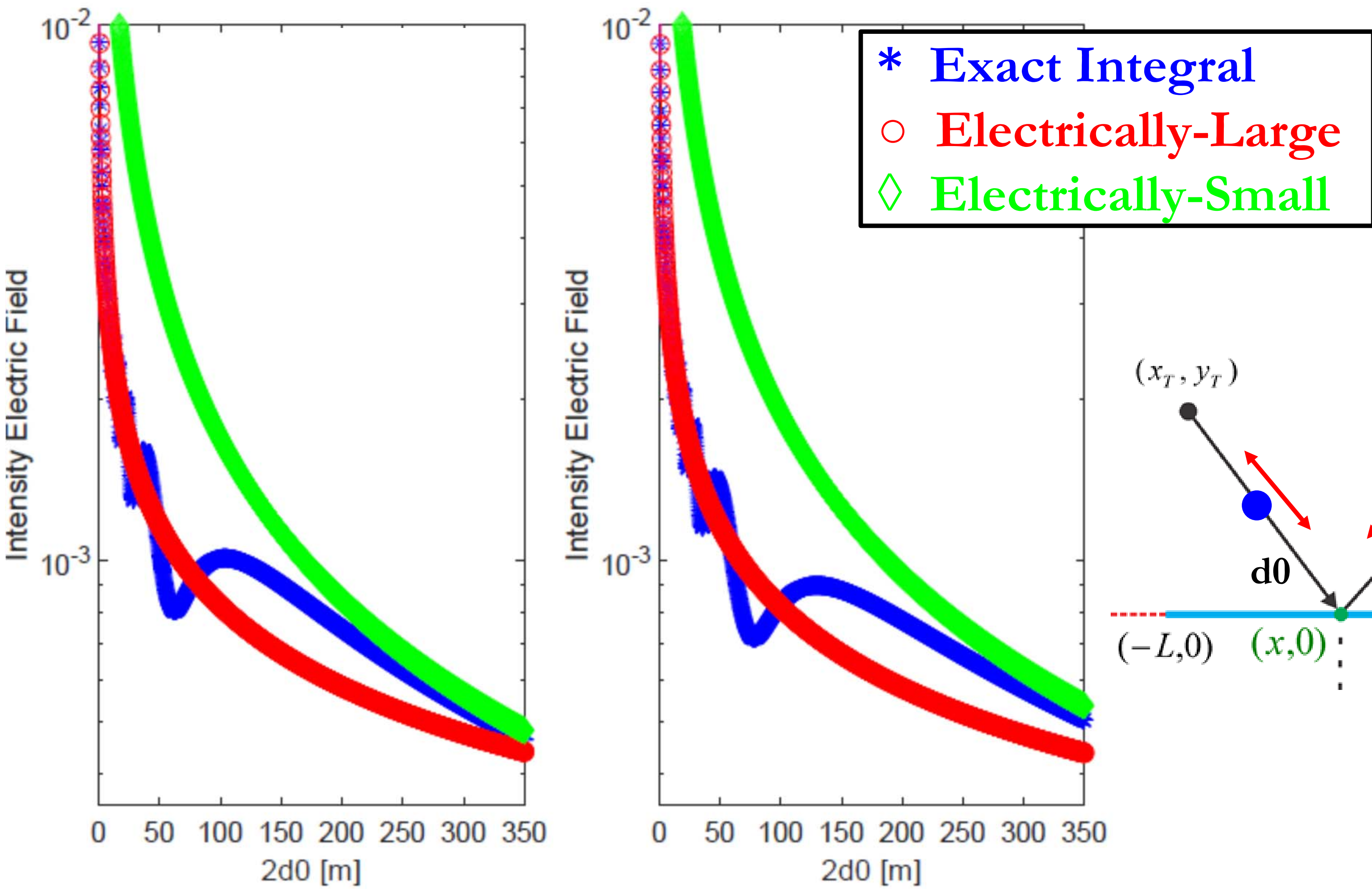
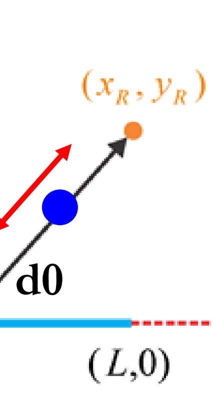
Path-Loss Modeling – Anomalous Reflection

1.5 m RIS @ 28 GHz





On the Path-Loss of Reconfigurable Intelligent Surfaces

F. H. Danufane, M. Di Renzo, *Fellow, IEEE*, J. de Rosny, and S. Tretyakov, *Fellow, IEEE*

Abstract

In this paper, we introduce a physics-based analytical characterization of the free-space path-loss of a wireless link in the presence of a reconfigurable intelligent surface. The obtained path-loss model can be applied to two-dimensional homogenized metasurfaces, which are made of sub-wavelength scattering elements and that operate either in reflection or transmission mode. The path-loss is formulated in terms of a computable integral that depends on the transmission distances, the polarization of the radio waves, the size of the surface, and the desired surface transformation. Closed-form expressions are obtained in two asymptotic regimes that are representative of far-field and near-field transmissions. Based on the proposed approach, the impact of several design parameters and operating regimes is unveiled.

… in submission …

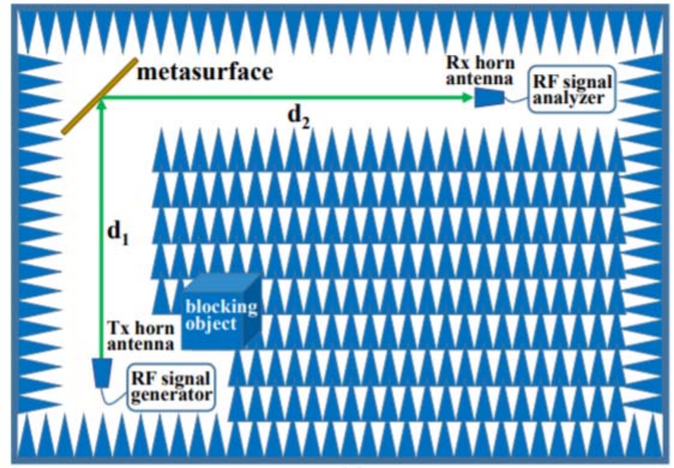
Experimental Validation (joint with Southeast Univ.)

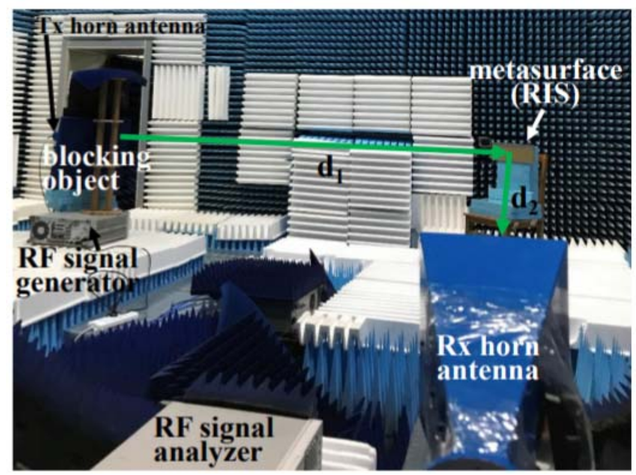
Wireless Communications with Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement

Wankai Tang, Ming Zheng Chen, Xiangyu Chen, Jun Yan Dai, Yu Han, Marco Di Renzo, Yong Zeng, Shi Jin, Qiang Cheng, and Tie Jun Cui

Abstract

Reconfigurable intelligent surfaces (RISs) comprised of tunable unit cells have recently drawn significant attentions due to their superior capability in manipulating electromagnetic waves. In particular, RIS-assisted wireless communications have the great potential to achieve significant performance improvement and coverage enhancement in a cost-effective and energy-efficient manner, by properly programming the reflection coefficients of the unit cells of RISs. In this paper, the free-space path loss models of RIS-assisted wireless communications are developed for different scenarios by studying the physics and electromagnetic nature of RISs. The proposed models, which are first validated through extensive simulation results, reveal the relationships between the free-space path loss of RIS-assisted wireless communications and the distances from the transmitter/receiver to the RIS, the size of the RIS, the near-field/far-field effects of the RIS, and the radiation patterns of antennas and unit cells. In addition, three fabricated RISs (metasurfaces) are utilized to further corroborate theoretical findings through experimental measurements conducted in a microwave anechoic chamber. The measurement results match well with the modeling results, thus validating the proposed free-space path loss models for RIS, which may pave the way for further theoretical studies and practical applications in this field.





arXiv:1911.05326

Some Recent Results

… from theory to simulations and experiments…

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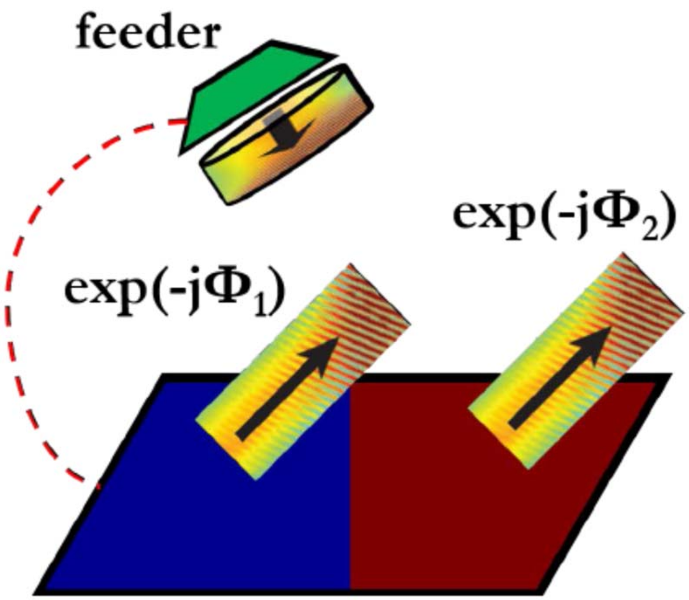
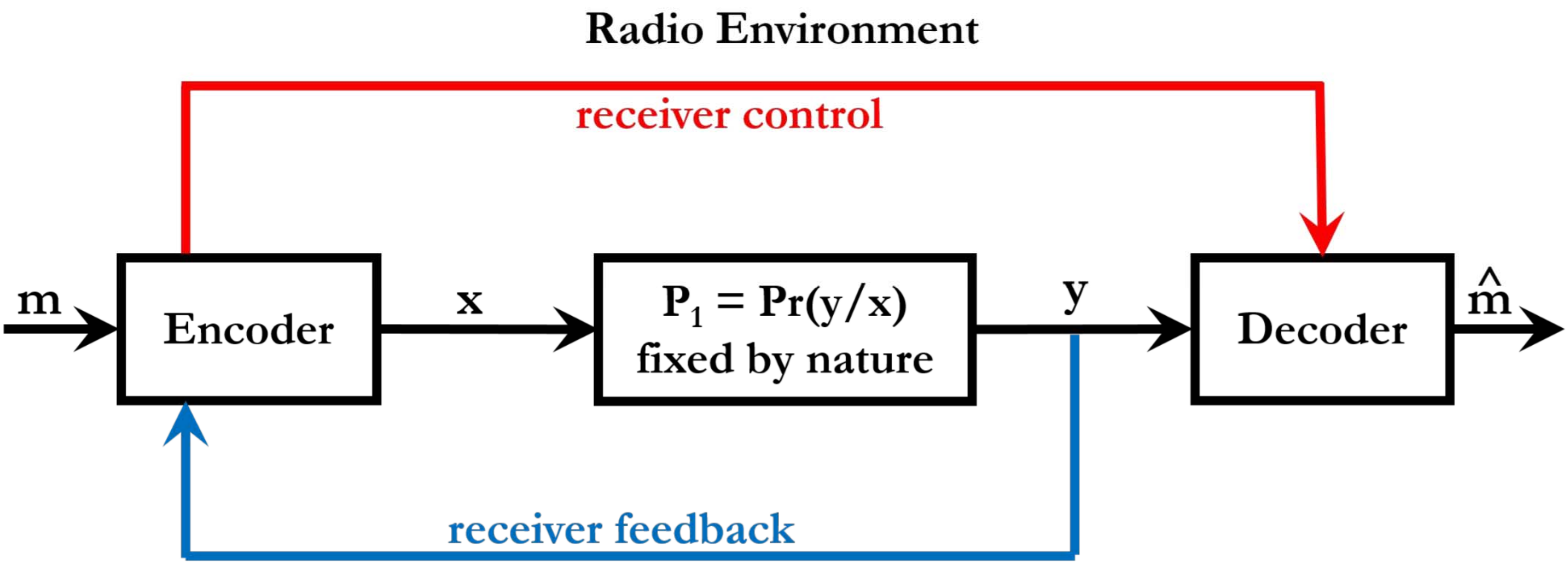
- **… and many others on channel modeling, performance analysis, spectral & energy efficiency optimization, experiments…**

Rethinking Communication-Theoretic Models

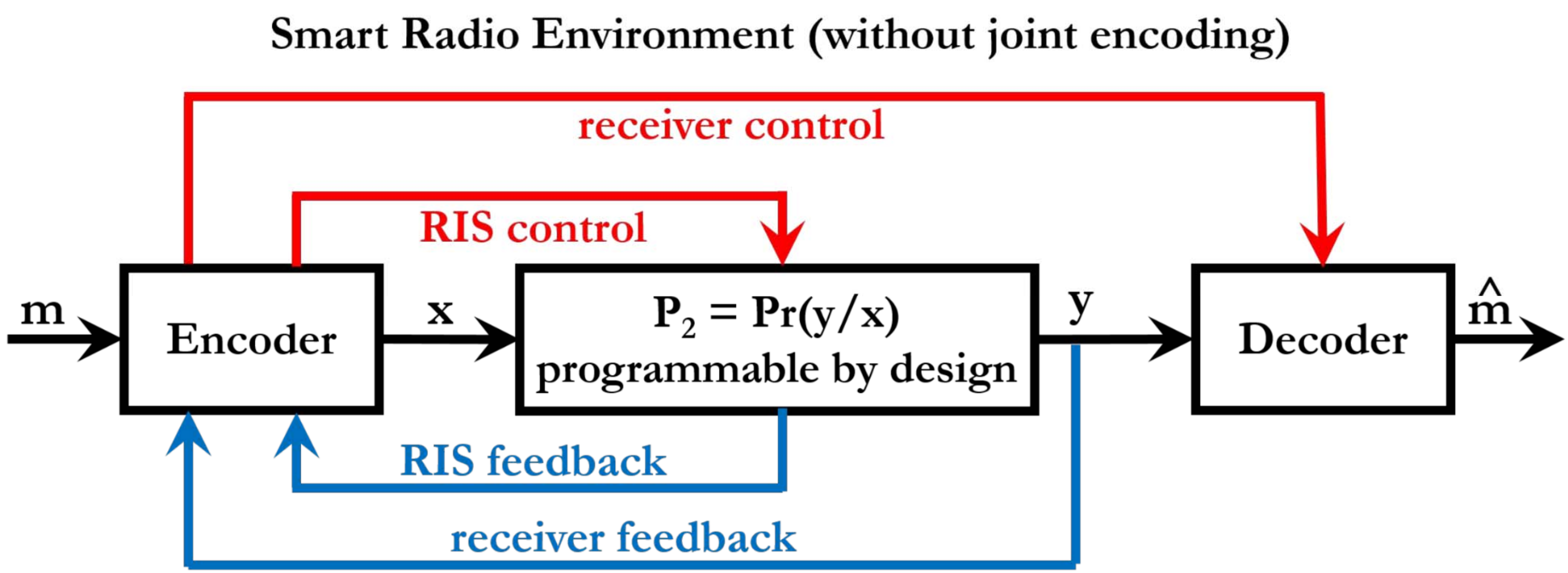


Joint Encoding &
Single-RF Transmitter

Rethinking Communication-Theoretic Models

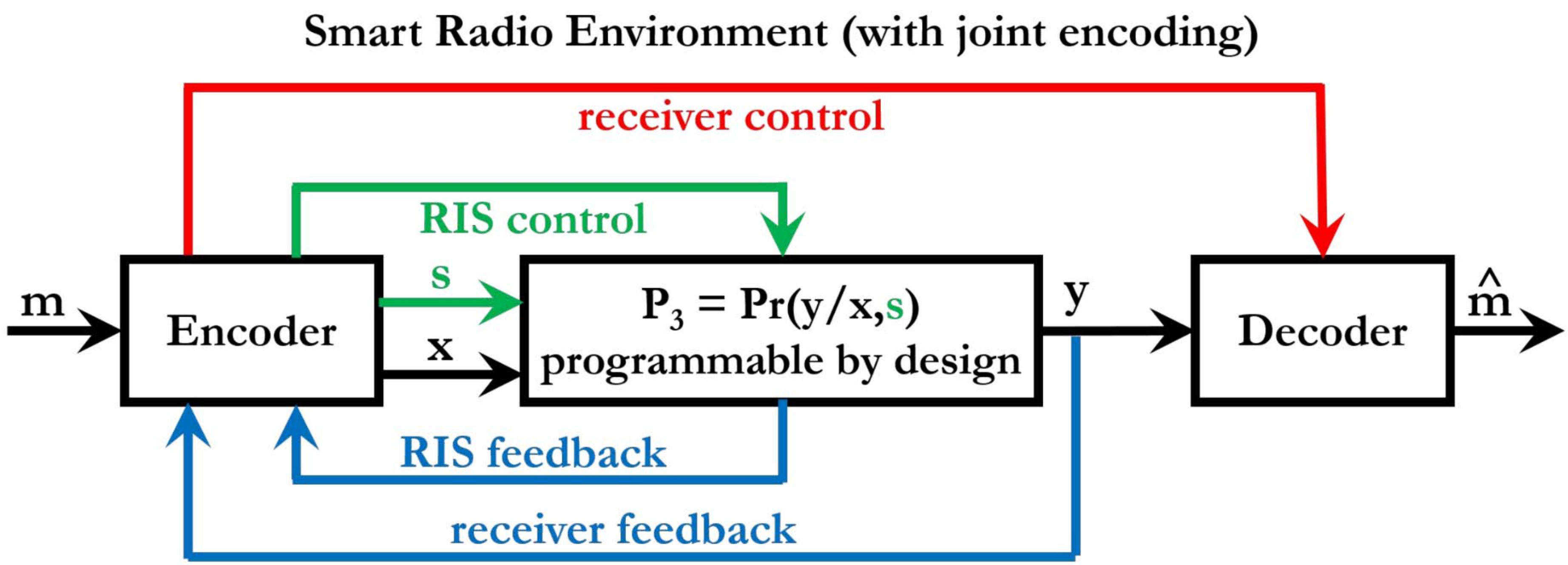


Rethinking Communication-Theoretic Models



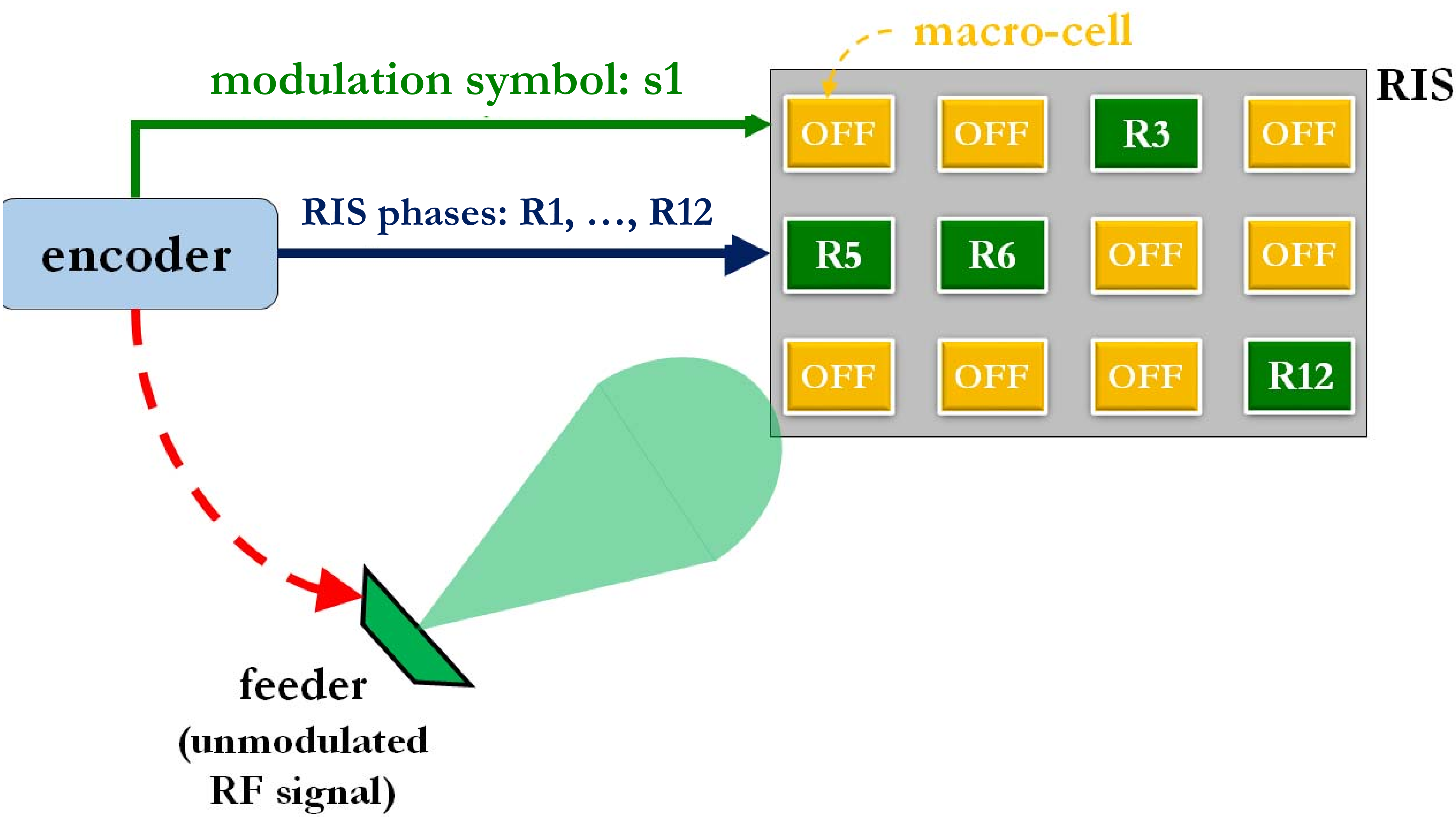
Joint Encoding for RISs

Rethinking Communication-Theoretic Models



Joint Encoding for RISs (index-based modulation)

Rethinking Communication-Theoretic Models



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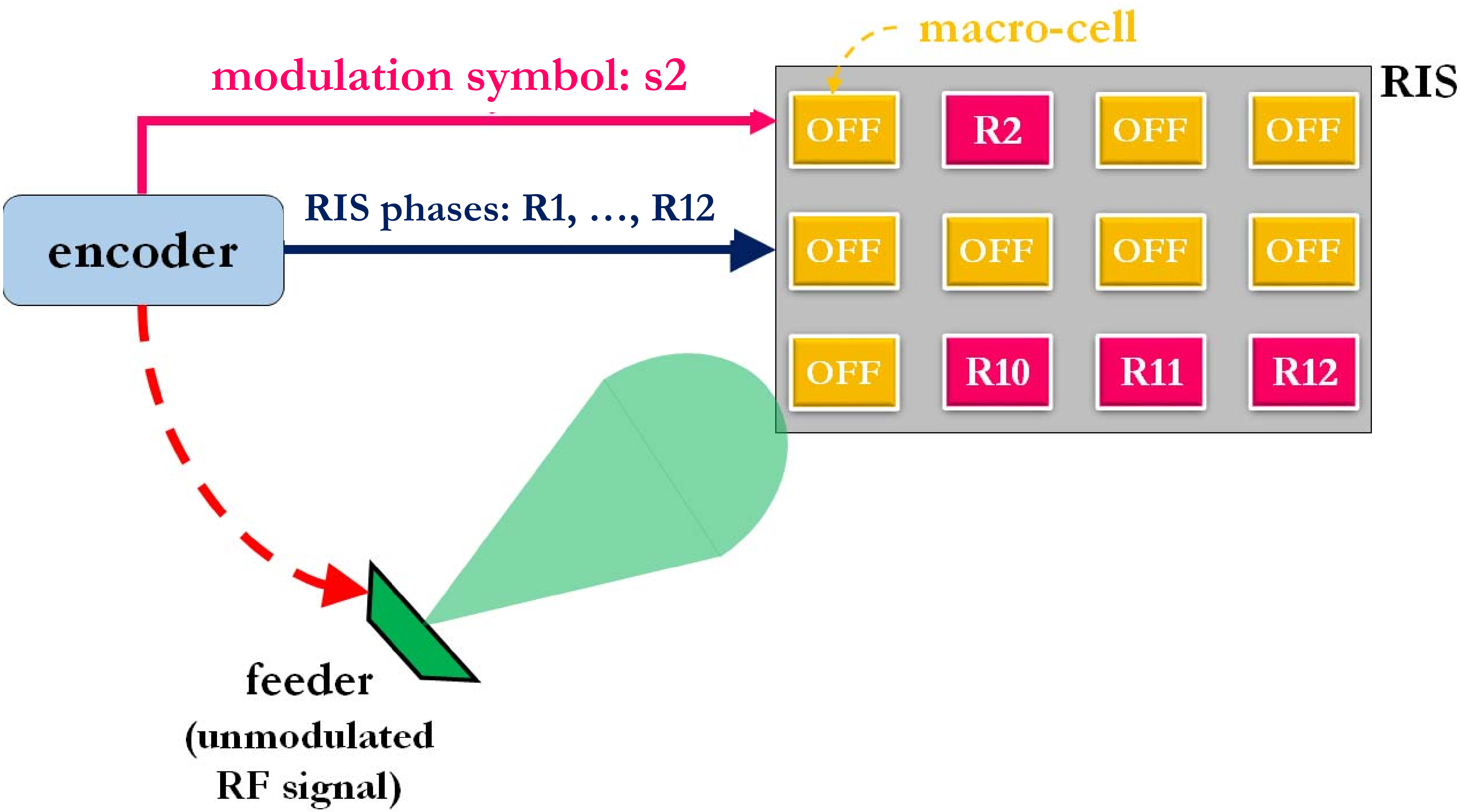
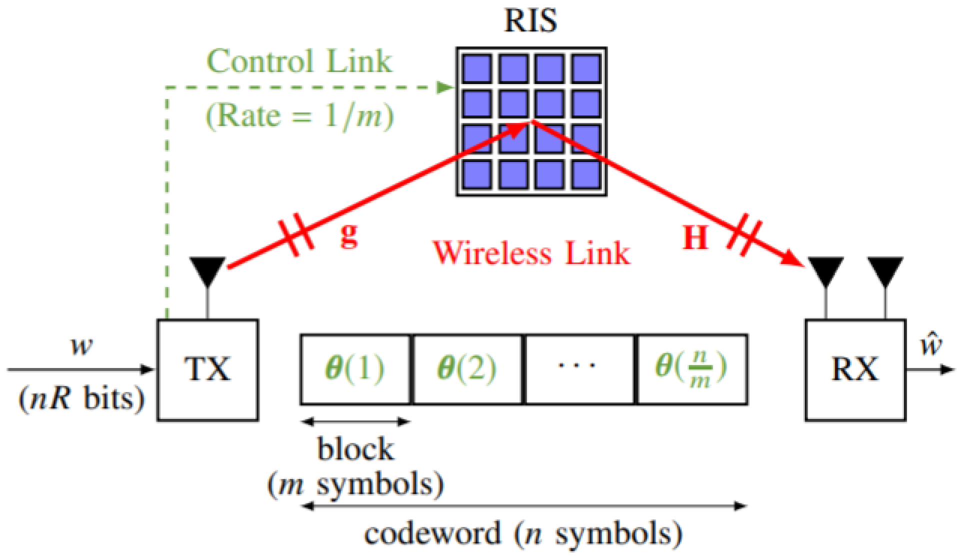


Joint Encoding for RISs (capacity achieving)



Proposition 1: The capacity of the channel (1) is given as

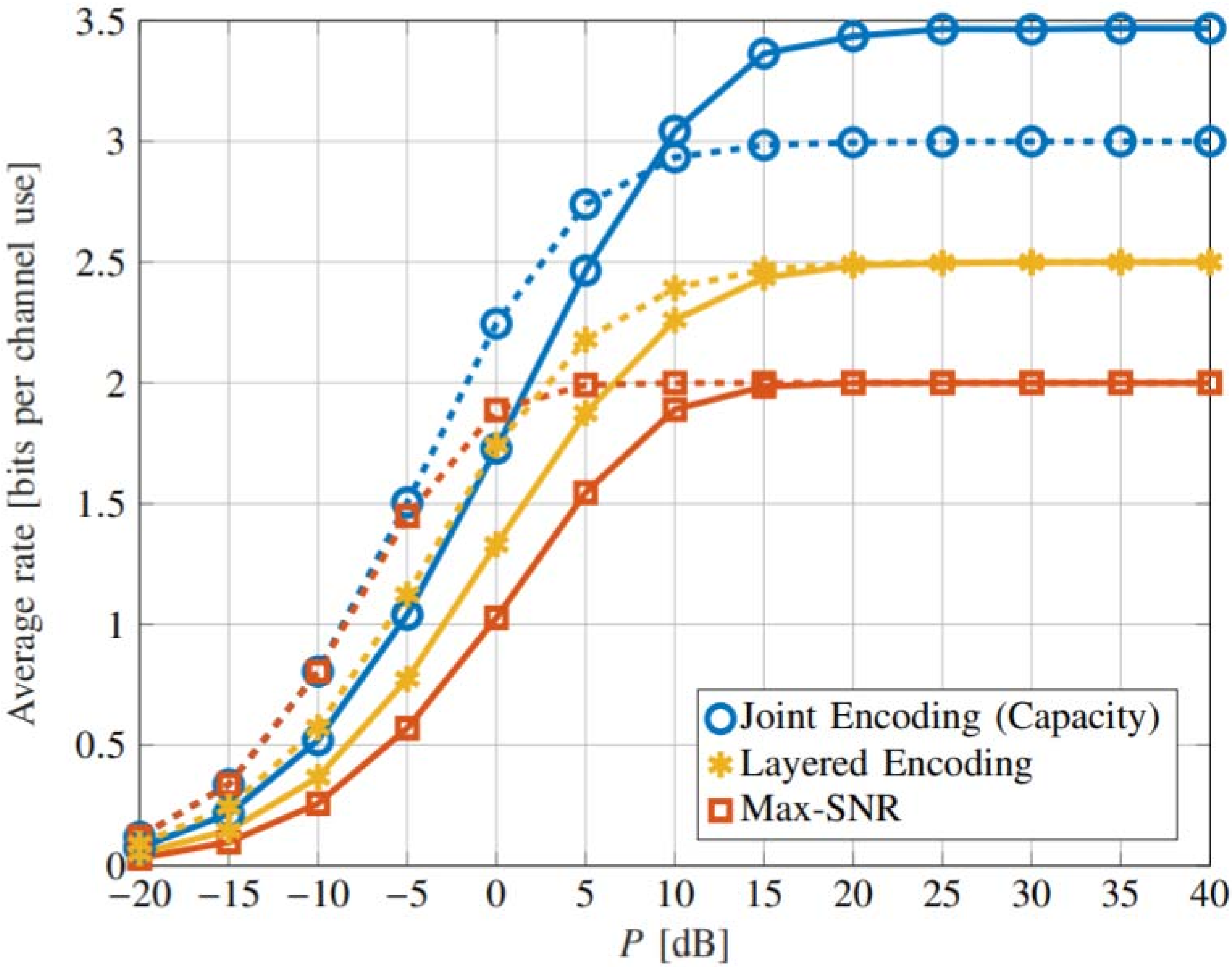
$$C(\mathbf{g}, \mathbf{H}) = -N \log_2(e) - \frac{1}{m} \min_{\substack{p(\mathbf{x},\boldsymbol{\theta}): \\ \mathbb{E}[|x_i|^2] \le P, \\ \mathbf{x} \in \mathcal{B}^m,\ \boldsymbol{\theta} \in \mathcal{A}^K}} \sum_{\mathbf{x} \in \mathcal{B}^m} \sum_{\boldsymbol{\theta} \in \mathcal{A}^K} p(\mathbf{x}, \boldsymbol{\theta}) \mathbb{E}\left[f_c(\mathbf{x}, \boldsymbol{\theta}, \mathbf{Z}) \right], \tag{5}$$

where we have defined function

$$f_c(\mathbf{x}, \boldsymbol{\theta}, \mathbf{Z}) \triangleq \log_2 \left(\sum_{\mathbf{x}' \in \mathcal{B}^m} \sum_{\boldsymbol{\theta}' \in \mathcal{A}^K} p(\mathbf{x}', \boldsymbol{\theta}') \exp\left(- \|\mathbf{Z} + \mathbf{H}(\mathbf{S}\mathbf{g}\mathbf{x} - \mathbf{S}'\mathbf{g}\mathbf{x}')\|_F^2 \right) \right) \tag{6}$$

with matrices $\mathbf{S} = \text{diag}(\exp(j\theta_1), \ldots, \exp(j\theta_K))$ and $\mathbf{S}' = \text{diag}(\exp(j\theta_1'), \ldots, \exp(j\theta_K'))$, and the expectation in (5) being taken with respect to a matrix $\mathbf{Z}$ whose elements are i.i.d. as $\mathcal{CN}(0, 1)$.

Joint Encoding for RISs (capacity achieving)



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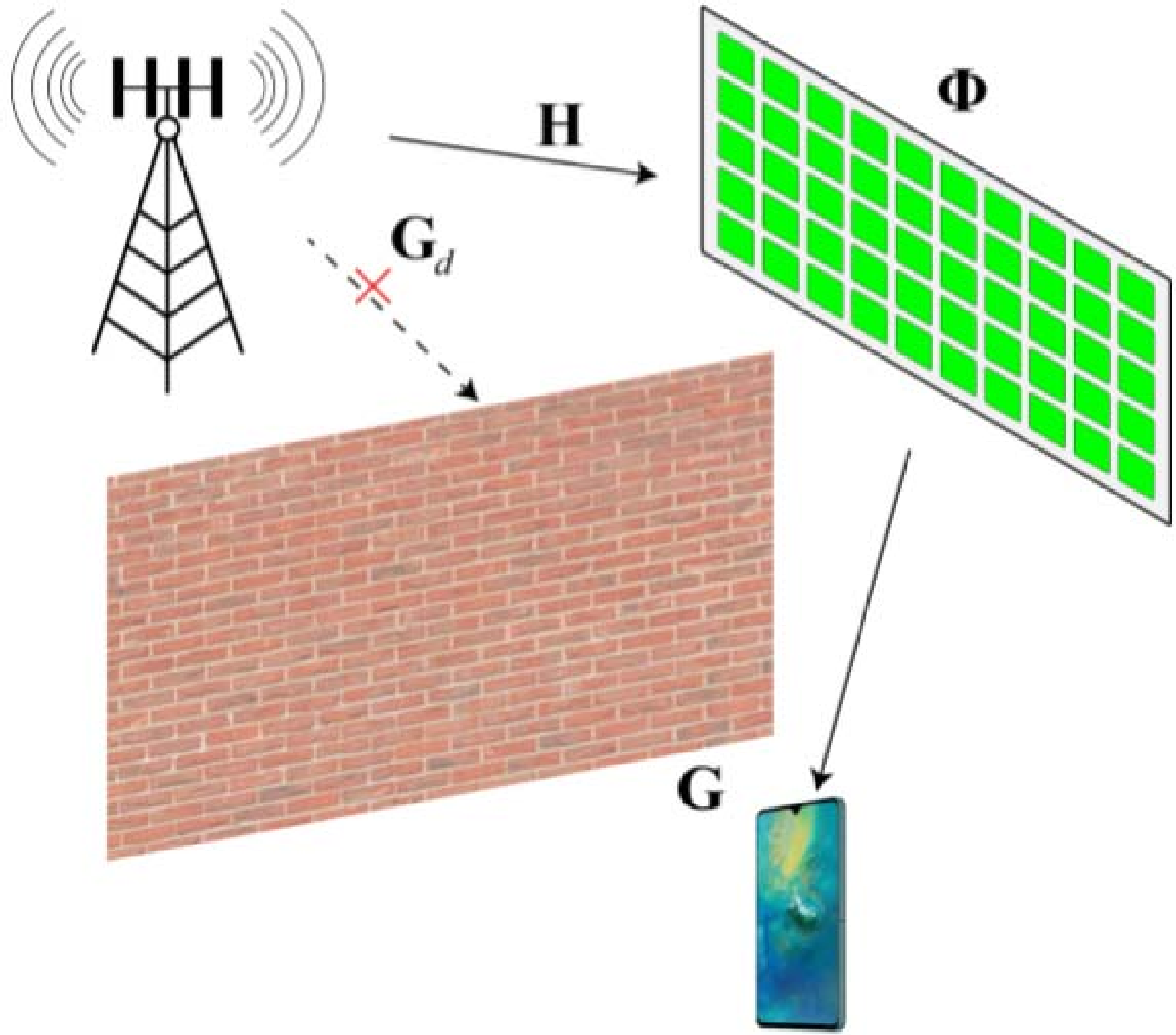
RIS-Aided Transmission: MIMO System Model



… Amount of Fading (RMT) ~ 1/N …

Proposition 3: Define $\mathrm{D} = \{\mathrm{RR}, \mathrm{LR}\}$, and assume $s_1 = 0$ and $N \gg 1$. Let $\mathrm{AF}_{\mathrm{SNR_D}} = \mathbb{V}\{\mathrm{SNR_D}\} \big/ (\mathbb{E}\{\mathrm{SNR_D}\})^2$ be the AF of $\mathrm{SNR_D}$. As a function of N, while keeping the other system parameters fixed, the following scaling laws hold true:

$$\begin{aligned}
&\mathbb{E}\{\mathrm{SNR_D}\} \overset{N \gg 1}{\propto} o_{e0} N^1 \mathbf{1}(c_1 = 0) + o_{e1} N^2 \mathbf{1}(c_1 \neq 0) \\
&\mathbb{V}\{\mathrm{SNR_D}\} \overset{N \gg 1}{\propto} o_{v0} N^2 \mathbf{1}(c_1 = 0) + o_{v1} N^3 \mathbf{1}(c_1 \neq 0) \qquad (20) \\
&\mathrm{AF}_{\mathrm{SNR_D}} \overset{N \gg 1}{\propto} \frac{o_{v0}}{o_{e0}^2} N^0 \mathbf{1}(c_1 = 0) + \frac{o_{v1}}{o_{e1}^2} N^{-1} \mathbf{1}(c_1 \neq 0)
\end{aligned}$$

where o_{e0}, o_{e1}, o_{v0}, and o_{v1} are defined in Table III.

Impact of Phase Noise on Inexpensive Antennas

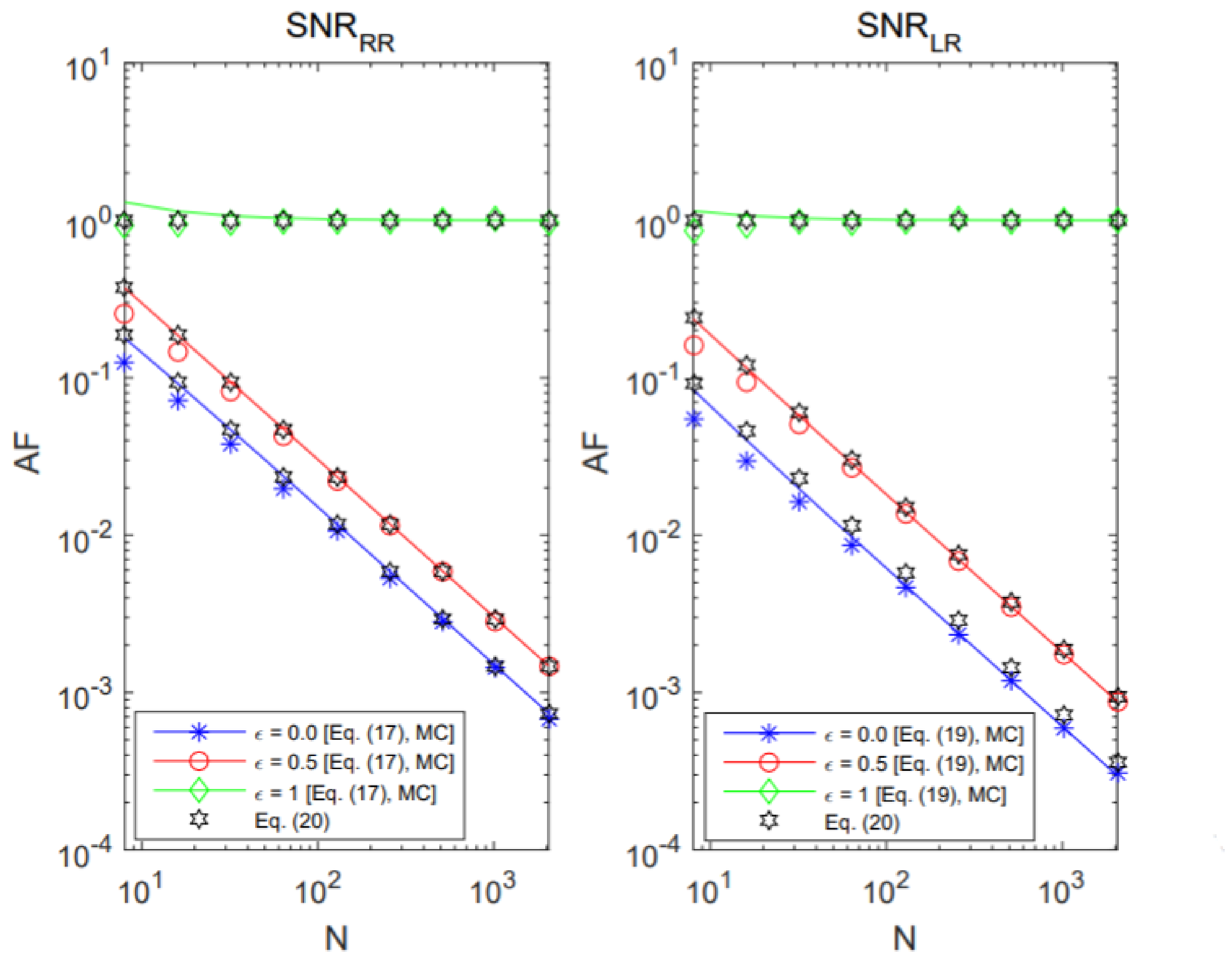


Fig. 1: AF ($\gamma_0 = 1$, $N_T = N_R = 4$, $\delta_n \sim \mathcal{U}(-\varepsilon\pi, \varepsilon\pi)$).

Impact of Phase Noise on Inexpensive Antennas

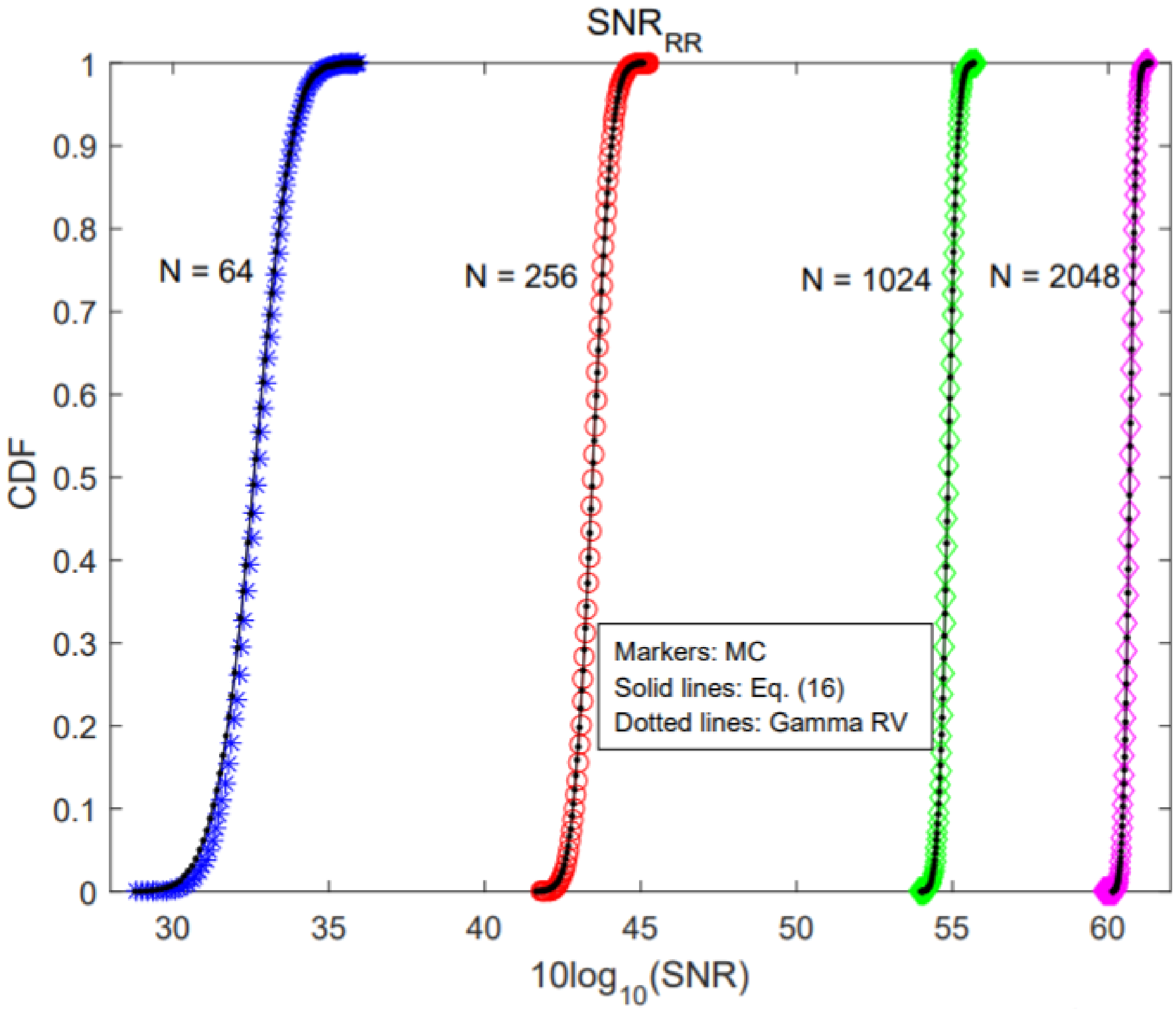


Fig. 2: CDF ($\gamma_0 = 1$, $N_T = N_R = 4$, $\delta_n \sim \mathcal{U}(-\varepsilon\pi, \varepsilon\pi)$).

Some Recent Results

… from theory to simulations and experiments…

- **Path-Loss – Physics-Based Foundation (SPAWC 2020 → TWC)**
  - **M. Di Renzo et al., Analytical Modeling of the Path-Loss for Reconfigurable Intelligent Surfaces - Anomalous Mirror or Scatterer? (arXiv:2001.10862)**
- **Joint Encoding – Capacity-Optimal Design (ISIT 2020)**
  - **M. Di Renzo et al., Beyond max-SNR: Joint Encoding for Reconfigurable Intelligent Surfaces (arXiv:1911.09443)**
- **SNR Distribution – Improving Signal Reliability (WCL 2020)**
  - **M. Di Renzo et al., Beamforming Through Reconfigurable Intelligent Surfaces in Single-User MIMO Systems: SNR Distribution and Scaling Laws in the Presence of Channel Fading and Phase Noise (arXiv:2005.07472)**
- **Overhead-Aware Design – SE & EE (TWC 2020)**
  - **M. Di Renzo et al., Overhead-Aware Design of Reconfigurable Intelligent Surfaces in Smart Radio Environments (arXiv:2003.02538)**

- **… and many others on channel modeling, performance analysis, spectral & energy efficiency optimization, experiments…**

Active/Passive Beamforming, Power, Bandwidth

Overhead-Aware Optimization of RISs

Active/Passive Beamforming, Power, Bandwidth

Denoting by T the total duration of the time slot comprising channel estimation, feedback, and data communication, the system achievable rate can be expressed as

$$R(p, B, p_F, B_F, \boldsymbol{\Phi}, \boldsymbol{q}, \boldsymbol{w}) = \left(1 - \frac{T_E + T_F}{T}\right) B \log\left(1 + \frac{p|\boldsymbol{w}^H \boldsymbol{G} \boldsymbol{\Phi} \boldsymbol{H} \boldsymbol{q}|^2}{B N_0}\right) , \tag{1}$$

while the system energy efficiency is written as

$$\text{EE}(p, B, p_F, B_F, \boldsymbol{\Phi}, \boldsymbol{q}, \boldsymbol{w}) = \frac{R(p, B, p_F, B_F, \boldsymbol{\Phi}, \boldsymbol{q}, \boldsymbol{w})}{P_{tot}(p, B, p_F, B_F)}, \tag{2}$$

wherein P_{tot} denotes the total power consumption in the whole timeframe T, which is equal to

$$P_{tot}(p, B, p_F, B_F) = P_E + \frac{1}{T}\left[(T - T_E - T_F)\mu p + \mu_F p_F T_F + T P_c\right] , \tag{3}$$

Overhead-Aware Optimization of RISs

Active/Passive Beamforming, Power, Bandwidth

Denoting by T the total duration of the time slot comprising channel estimation, feedback, and data communication, the system achievable rate can be expressed as

$$R(p,B,p_F,B_F,\boldsymbol{\Phi},\boldsymbol{q},\boldsymbol{w}) = \left(1-\frac{T_E+T_F}{T}\right)B\log\left(1+\frac{p|\boldsymbol{w}^H\boldsymbol{G}\boldsymbol{\Phi}\boldsymbol{H}\boldsymbol{q}|^2}{BN_0}\right), \tag{1}$$

while the system energy efficiency is written as

$$\mathrm{EE}(p,B,p_F,B_F,\boldsymbol{\Phi},\boldsymbol{q},\boldsymbol{w}) = \frac{R(p,B,p_F,B_F,\boldsymbol{\Phi},\boldsymbol{q},\boldsymbol{w})}{P_{tot}(p,B,p_F,B_F)}, \tag{2}$$

wherein P_{tot} denotes the total power consumption in the whole timeframe T, which is equal to

$$P_{tot}(p,B,p_F,B_F) = P_E + \frac{1}{T}\left[(T-T_E-T_F)\mu p + \mu_F p_F T_F + TP_c\right], \tag{3}$$

Joint Active and Passive Beamforming Optimization

$$\max_{\boldsymbol{\Phi},\boldsymbol{q},\boldsymbol{w}} \quad |\boldsymbol{w}^H \boldsymbol{G}\boldsymbol{\Phi}\boldsymbol{H}\boldsymbol{q}|^2$$

$$\text{s.t. } \|\boldsymbol{q}\| = \|\boldsymbol{w}\| = 1 \, , 0 \leqslant \phi_n \leqslant 2\pi \; , \; \forall \, n = 1, \ldots, N \; .$$

Proposition 1: For any p, B, p_F, B_F, defining

$$\bar{j}(i) = \text{argmax}_j \mu_{j,H}^2 \left(\sum_{n=1}^{N} \left| \boldsymbol{v}_{i,G}^{(n)} \right| \left| \boldsymbol{u}_{j,H}^{(n)} \right| \right)^2, \forall i = 1, \ldots, r_G, \; \bar{i} = \text{argmax}_i \; \mu_{i,G}^2 \mu_{\bar{j}(i),H}^2 \left(\sum_{n=1}^{N} \left| \boldsymbol{v}_{i,G}^{(n)} \right| \left| \boldsymbol{u}_{\bar{j}(i),H}^{(n)} \right| \right)^2 \tag{8}$$

the global maximizer of the upper-bound in (6) is obtained by setting the beamforming vector as $\boldsymbol{q} = \boldsymbol{v}_{\bar{j}(\bar{i}),H}$, the receive filter as $\boldsymbol{w} = \boldsymbol{u}_{\bar{i},G}$, and the RIS phase shifts are $\phi_n = -\angle \left\{ \boldsymbol{v}_{\bar{i},G}^{*(n)} \boldsymbol{u}_{\bar{j}(\bar{i}),H}^{(n)} \right\}$, with $^{(*)}$ denoting complex conjugate.

Joint Spectral/Energy Efficiency Optimization

$$\max_{p,p_F,B} \left\{R(p,p_F,B,\mathbf{\Phi}^{\text{opt}},\boldsymbol{q}^{\text{opt}},\boldsymbol{w}^{\text{opt}}),\text{EE}(p,p_F,B,\mathbf{\Phi}^{\text{opt}},\boldsymbol{q}^{\text{opt}},\boldsymbol{w}^{\text{opt}})\right\}$$

$$\text{s.t. } p + p_F \leqslant P_{max}$$

$$0 \leqslant B \leqslant B_{max}\ , p \geqslant 0\ ,\ p_F \geqslant 0$$

$$\frac{d}{(B_{max}-B)\log\left(1+\frac{p_F|h_F|^2}{(B_{max}-B)N_0}\right)} \leqslant \beta\ ,$$

Algorithm 3 Rate-EE Maximization

Set $M > 0$ and compute $\Delta = \frac{B_{max}\log\left(1+\frac{P_{max}|h_F|^2}{B_{max}N_0}\right)-\frac{d}{\beta}}{M}$

for $m = 1, \ldots, M$ **do**

$\tilde{y}_m = \frac{d}{\beta} + (m-1)\Delta$;

Solve (39) by bisection over t and compute

$$F_m = \min\left\{\alpha\big(R(p^*,p_F^*,B^*,\mathbf{\Phi}^{\text{opt}},\boldsymbol{q}^{\text{opt}},\boldsymbol{w}^{\text{opt}},)-R_{\text{opt}}\big),(1-\alpha)\big(\text{EE}(p^*,p_F^*,B^*,\mathbf{\Phi}^{\text{opt}},\boldsymbol{q}^{\text{opt}},\boldsymbol{w}^{\text{opt}})-\text{EE}_{\text{opt}}\big)\right\} \quad (40)$$

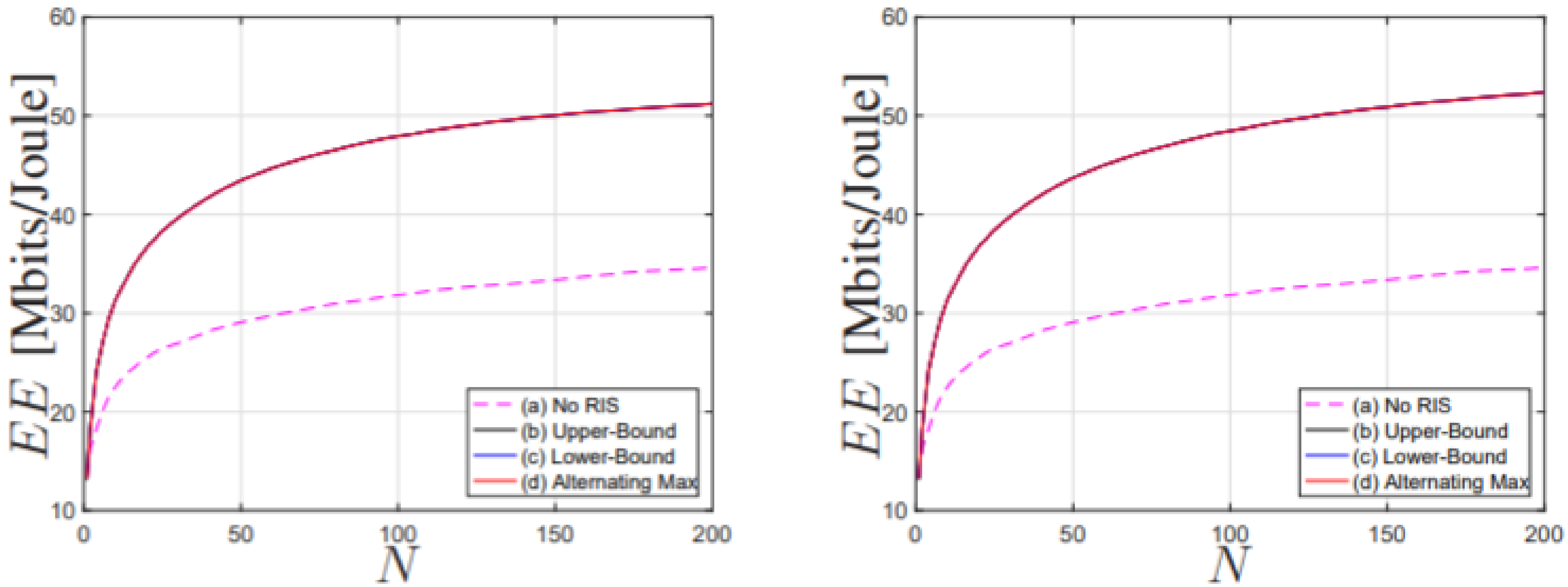
end for

Compute $m^* = \text{argmax } F_m$;

Output $p^*_{m*}, p^*_{m*,F}, B^*_{m*}, B^*_{m*,F} = B_{max} - B^*_{m*}$;

Overhead-Aware Optimization of RISs

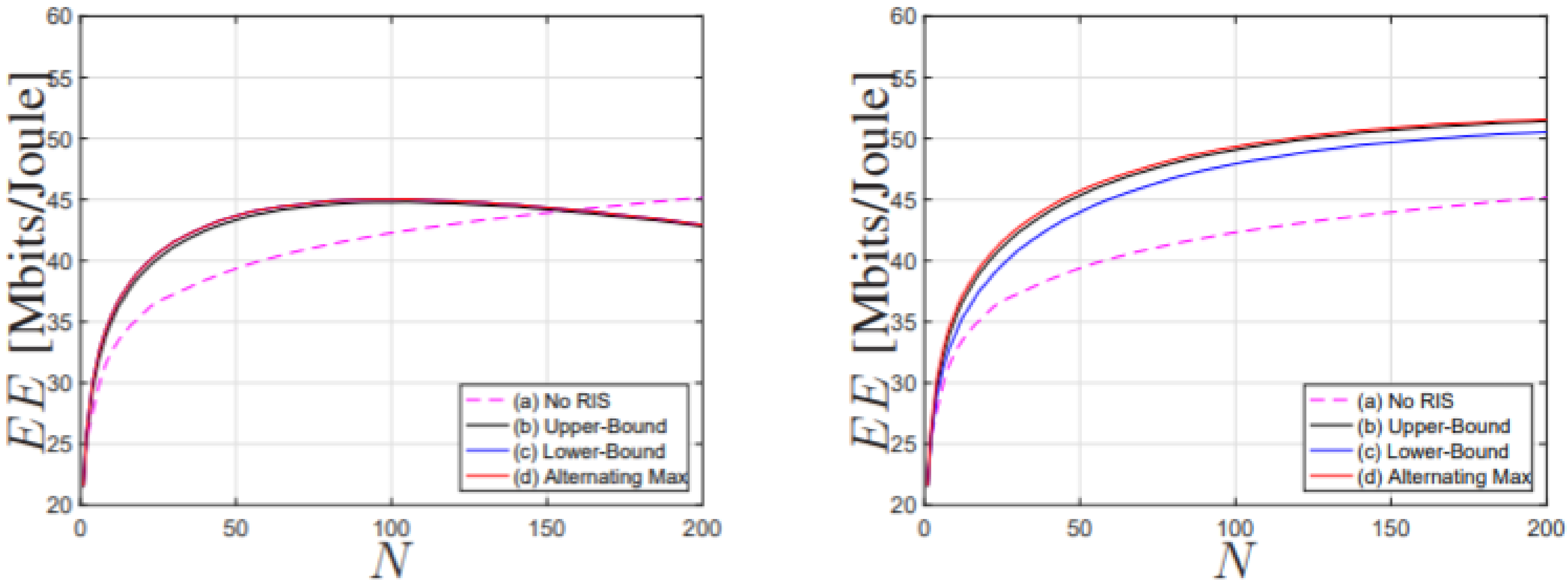
EE – $N_r = 1$ and $N_t = 1$



(a) EE for $T_0 = 0.8\,\mu s$, $P_0 = 2.5\,\text{mW}$ (b) EE for $T_0 = 0.15\,\mu s$, $P_0 = 0.5\,\text{mW}$

Fig. 4: Achieved EE in [Mbit/Joule] as a function of N for $N_T = N_R = 1$.

EE – N_r = 1 and N_t = 8

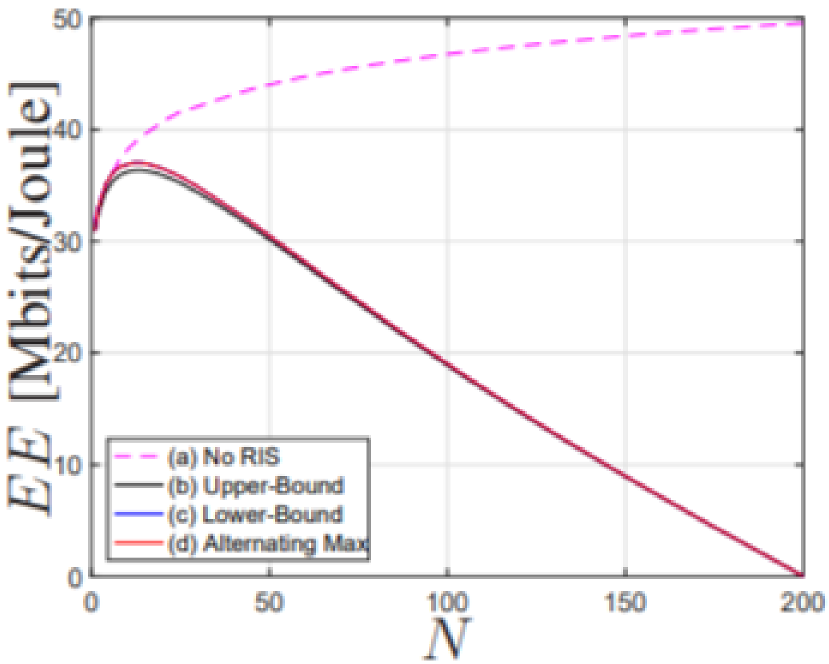


(a) EE for $T_0 = 0.8\,\mu s$, $P_0 = 2.5\,\text{mW}$ (b) EE for $T_0 = 0.15\,\mu s$, $P_0 = 0.5\,\text{mW}$

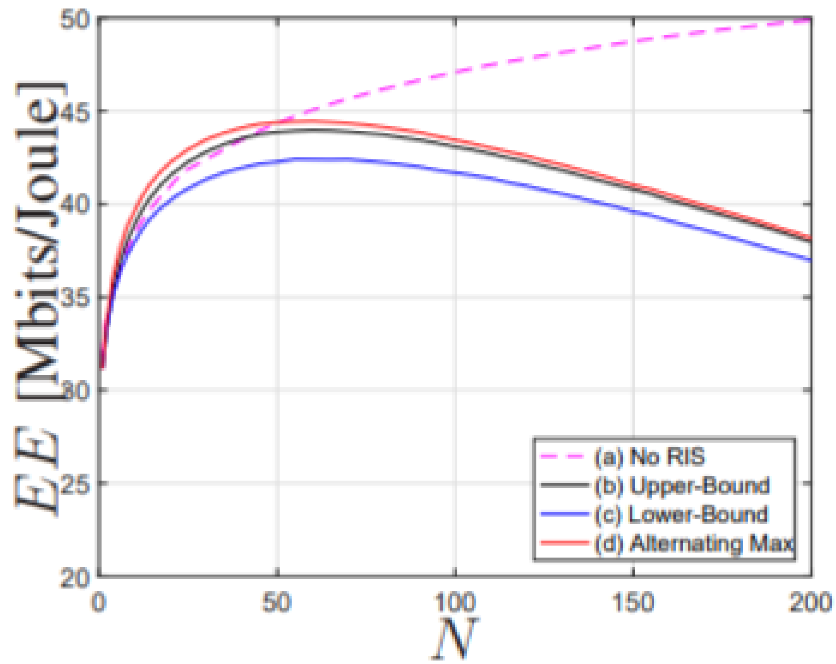
Fig. 5: Achieved EE in [Mbit/Joule] as a function of N for $N_T = 1$, $N_R = 8$.

Overhead-Aware Optimization of RISs

EE – N_r = 8 and N_t = 8



(a) EE for $T_0 = 0.8\,\mu s$, $P_0 = 2.5\,\mathrm{mW}$



(b) EE for $T_0 = 0.15\,\mu s$, $P_0 = 0.5\,\mathrm{mW}$

Fig. 6: Achieved EE in [Mbit/Joule] as a function of N for $N_T = 8$, $N_R = 8$.

Programming the Environment: Towards Wireless 2.0

Di Renzo *et al. EURASIP Journal on Wireless Communications and Networking* (2019) 2019:129
https://doi.org/10.1186/s13638-019-1438-9

EURASIP Journal on Wireless Communications and Networking

REVIEW **Open Access**

Smart radio environments empowered by reconfigurable AI meta-surfaces: an idea whose time has come

Marco Di Renzo[1*], Merouane Debbah[2], Dinh-Thuy Phan-Huy[3], Alessio Zappone[4], Mohamed-Slim Alouini[5], Chau Yuen[6], Vincenzo Sciancalepore[7], George C. Alexandropoulos[8], Jakob Hoydis[9], Haris Gacanin[10], Julien de Rosny, Ahcene Bounceur[12], Geoffroy Lerosey[13] and Mathias Fink[11]

Abstract

Future wireless networks are expected to constitute a distributed intelligent wireless communications, sensing, and computing platform, which will have the challenging requirement of interconnecting the physical and digital worlds in a seamless and sustainable manner. Currently, two main factors prevent wireless network operators from building such networks: (1) the lack of control of the wireless environment, whose impact on the radio waves cannot be customized, and (2) the current operation of wireless radios, which consume a lot of power because new signals are generated whenever data has to be transmitted. In this paper, we challenge the usual "more data needs more power and emission of radio waves" status quo, and motivate that future wireless networks necessitate a smart radio environment: a transformative wireless concept, where the environmental objects are coated with artificial thin films of electromagnetic and reconfigurable material (that are referred to as reconfigurable intelligent meta-surfaces), which are capable of sensing the environment and of applying customized transformations to the radio waves. Smart radio environments have the potential to provide future wireless networks with uninterrupted wireless connectivity,

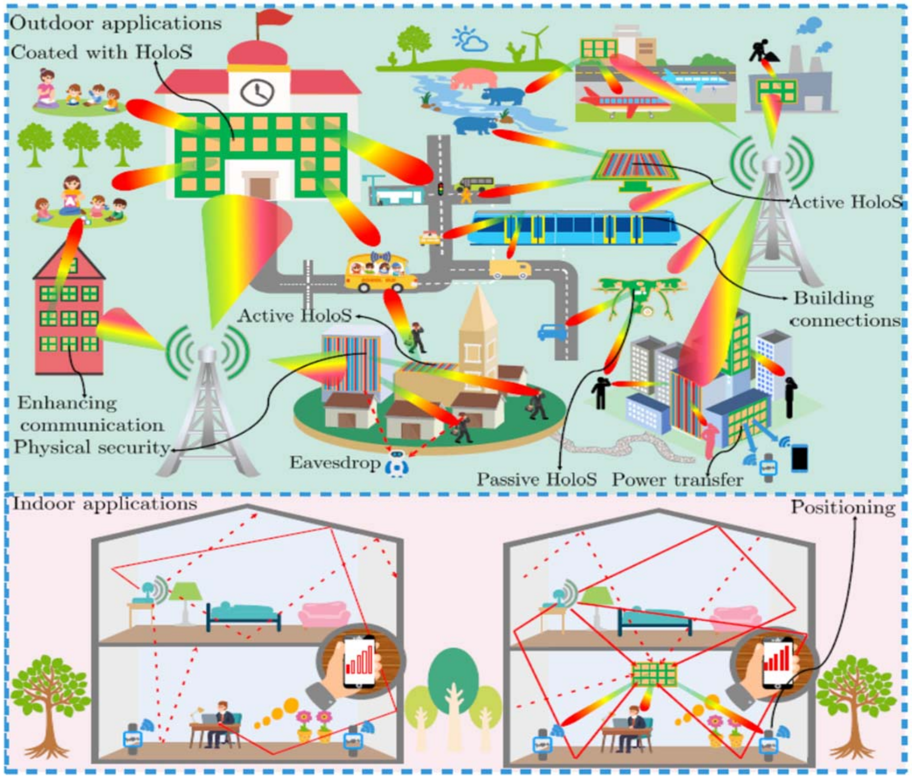
Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How it Works, State of Research, and Road Ahead

Marco Di Renzo, *Fellow, IEEE*, Alessio Zappone, *Senior Member, IEEE*, Merouane Debbah, *Fellow, IEEE*, Mohamed-Slim Alouini, *Fellow, IEEE*, Chau Yuen, *Senior Member, IEEE*, Julien de Rosny, and Sergei Tretyakov, *Fellow, IEEE*

arXiv:2004.09352 (76 pages)

***Abstract*—What is a reconfigurable intelligent surface? What is a smart radio environment? What is a metasurface? How do metasurfaces work and how to model them? How to reconcile the mathematical theories of communication and electromagnetism? What are the most suitable uses and applications of reconfigurable intelligent surfaces in wireless networks? What are the most promising smart radio environments for wireless applications? What is the current state of research? What are the most important and challenging research issues to tackle?**

These are a few of the many questions that we investigate in this short opus, which has the threefold objective of introducing the emerging research field of smart radio environments empowered by reconfigurable intelligent surfaces, putting forth the need of reconciling and reuniting C. E. Shannon's mathematical theory of communication with G. Green's and J. C. Maxwell's mathematical theories of electromagnetism, and reporting pragmatic guidelines and recipes for employing appropriate physics-based models of metasurfaces in wireless communications.



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- H2020 ARIADNE (6 million Euro, Nov. 2019)
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  - University of Piraeus Research Center, Greece
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❑ H2020 MetaWireless (4 million Euro, Nov. 2020)

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The Road Ahead

- EM-based circuital models
- Path-loss and channel modeling
- Fundamental performance limits
- Robust optimization and resource allocation
- Constrained system design and optimization
- EM-based communications: “Layer-0” networking
- Large-scale networks: Deployment, analysis, optimization
- Ray tracing and system-level simulators
- Beyond far-field communications
- Beyond communications
- Advantages and limitations

The Road Ahead

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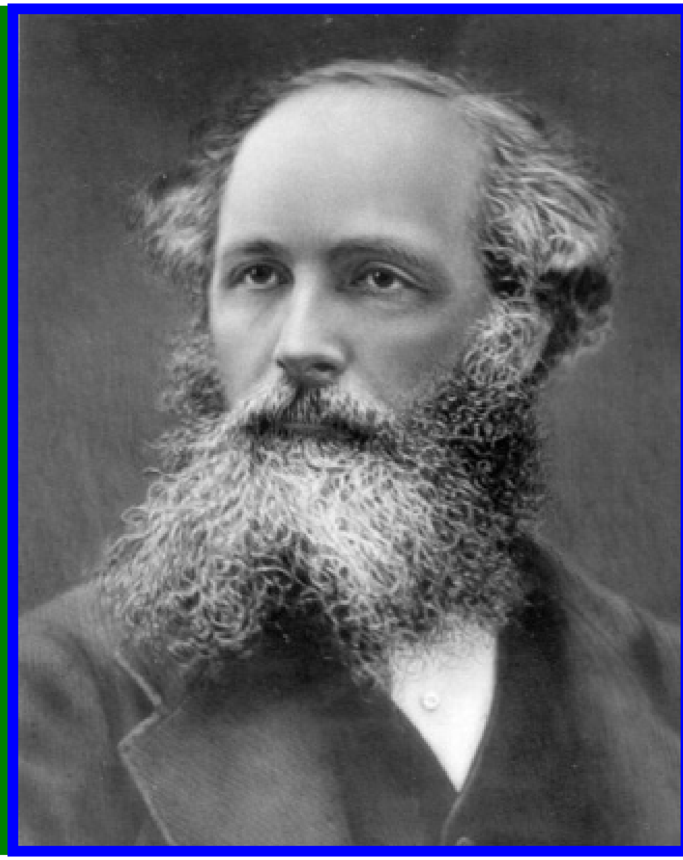
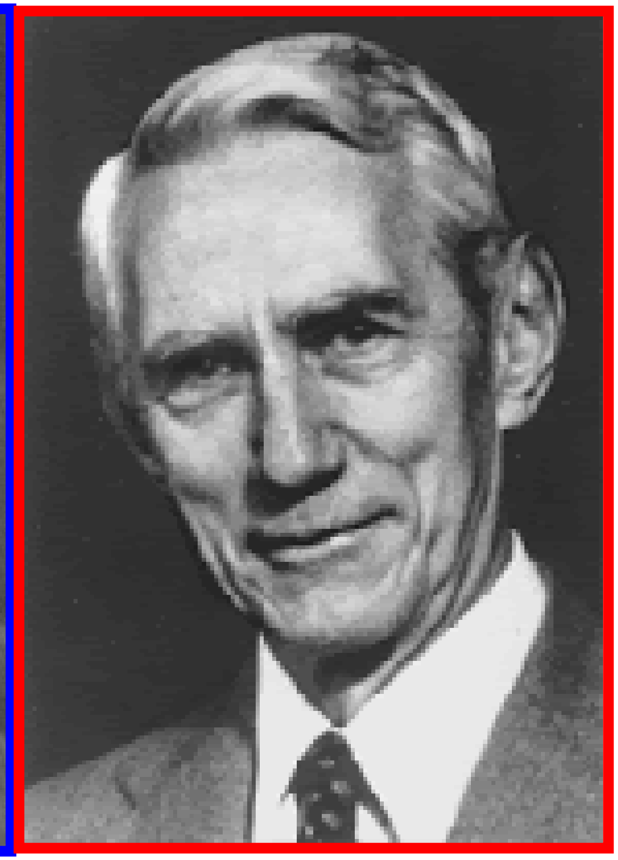
… do RISs bring any (substantial) gains as compared with other well-established technologies in wireless networks ?

The Road Ahead: Reconciling COMM, SP, IT, EM, …





G. Green, "An Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism", 1828.

J. C. Maxwell, "A Dynamical Theory of the Electromagnetic Field", 1865.

C. E. Shannon, "A (The) Mathematical Theory of Communication", 1948.

RIS @ IEEE-COMSOC

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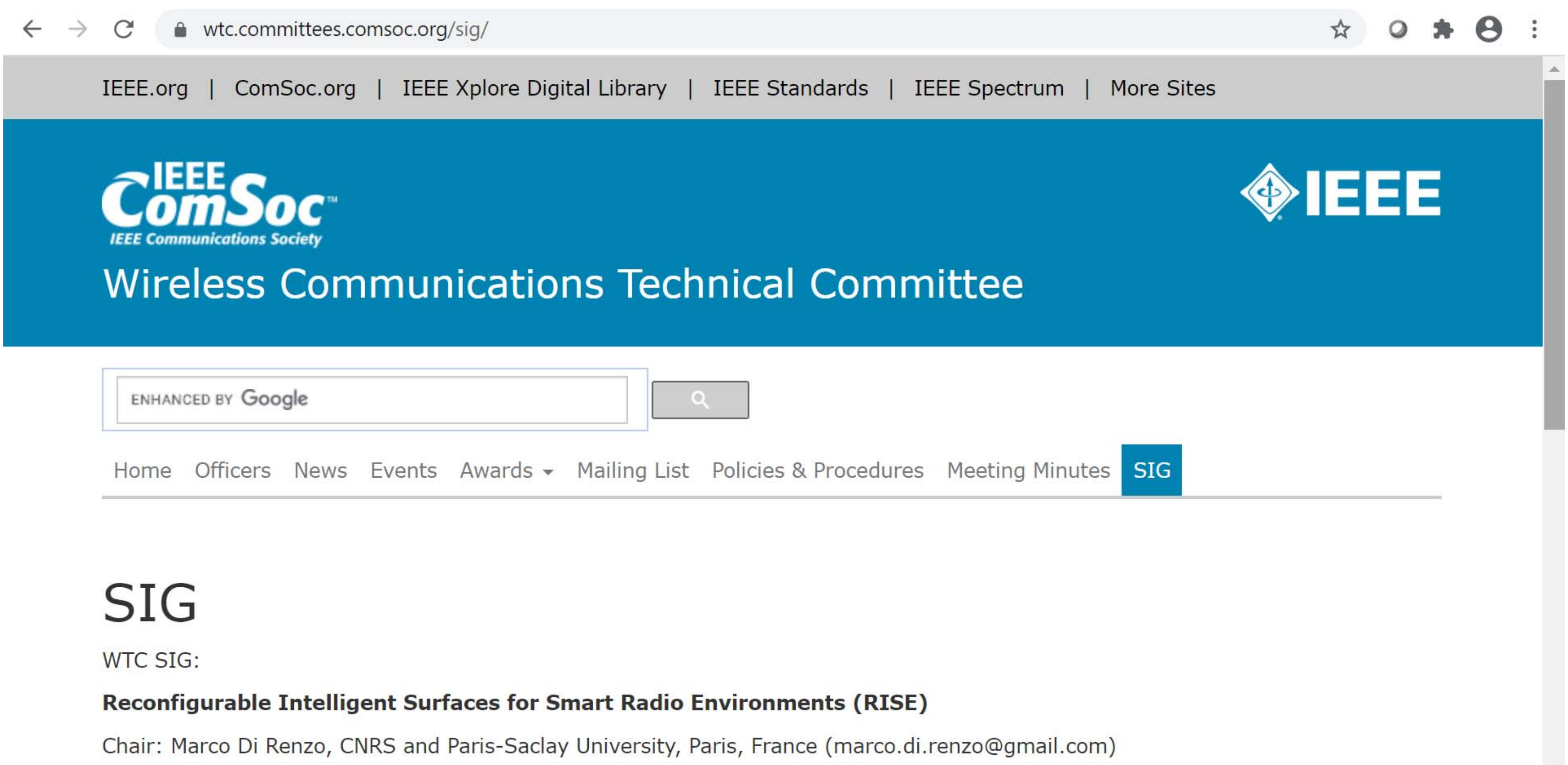

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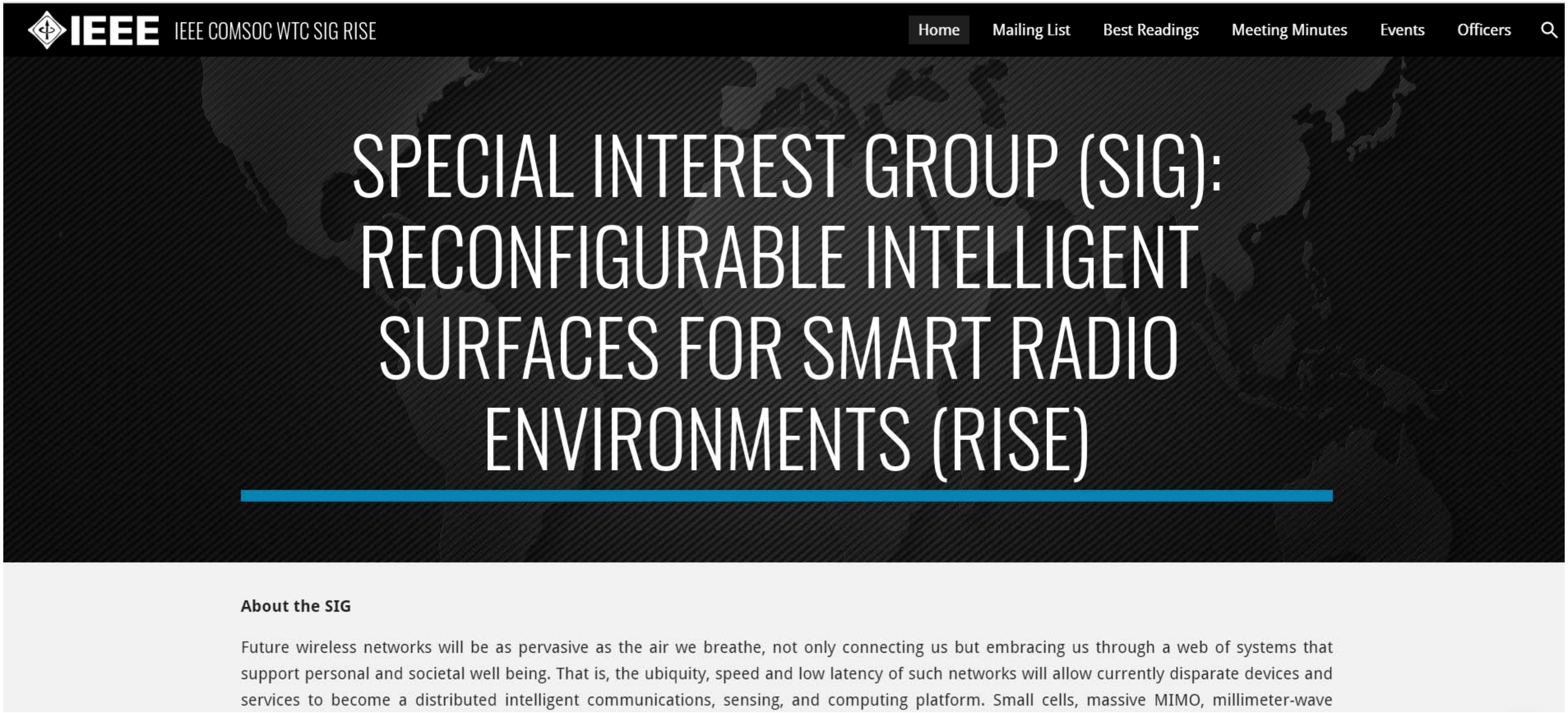
https://sites.google.com/view/ieee-comsoc-wtc-sig-rise



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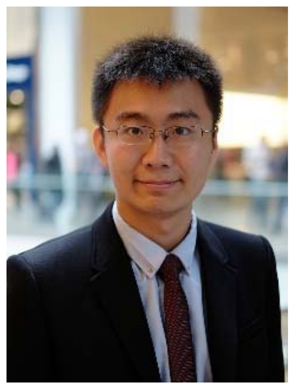

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Best Readings "RIS" @ COMSOC (submitted)

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Title (proposed): REconFigurabLE Intelligent Surfaces for Signal Processing and CommunicatIONS (REFLECTIONS)

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Wireless Networks Empowered by Reconfigurable Intelligent Surfaces

Publication Date	Manuscript Submission Deadline
Third Quarter 2020	15 December 2019

Open Special Issues

Reconfigurable Intelligent Surface-Based Communications for 6G Wireless Networks, IEEE Open Journal of the Communications Society, First Quarter 2021.
https://www.comsoc.org/publications/journals/ieee-ojcoms/cfp/reconfigurable-intelligent-surface-based-communications-6g
Manuscript Submission Deadline: 1 September 2020

Intelligent Surfaces for Smart Wireless Communications, IEEE Transactions on Cognitive Communications and Networking, Second Quarter 2021.
https://www.comsoc.org/publications/journals/ieee-tccn/cfp/intelligent-surfaces-smart-wireless-communications
Manuscript Submission Deadline: 1 September 2020

Wireless Communications with Reconfigurable Intelligent Surfaces, China Communications, Feature Topic, Vol.18, No.2, 2021.
Manuscript Submission Deadline: 15 August 2020

RIS @ IEEE-COMSOC

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Workshop paper submission deadline: **August 1, 2020**

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- **ICT-ARIADNE (H2020, 5G-PPP, grant 871464)**
- **November 1st, 2019 – October 31st, 2022**

  A collaborative research project on RISs & AI

H2020-2018-2020, ICT

ARIADNE

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Editor-in-Chief, IEEE Communications Letters

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