access protocols for wireless systems with reconfigurable intelligent surfaces

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thanks

part of my team:

- Fabio Saggese
- Victor Croisfelt Rodrigues
- Radoslaw Kotaba
- Israel Leyva-Mayorga
- Kun Chen Hu
- Robin J. Williams

THE VELUX FOUNDATIONS

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RISE-6G

outline

- 6G and basics of Reconfigurable Intelligent Surfaces (RIS)
- models for RIS access protocols
- random access protocol for RIS
- beyond the current RIS concept

RIS disclaimer

- not taking sides in the (religious) pro- and contra-RIS fights
- this work:

outline

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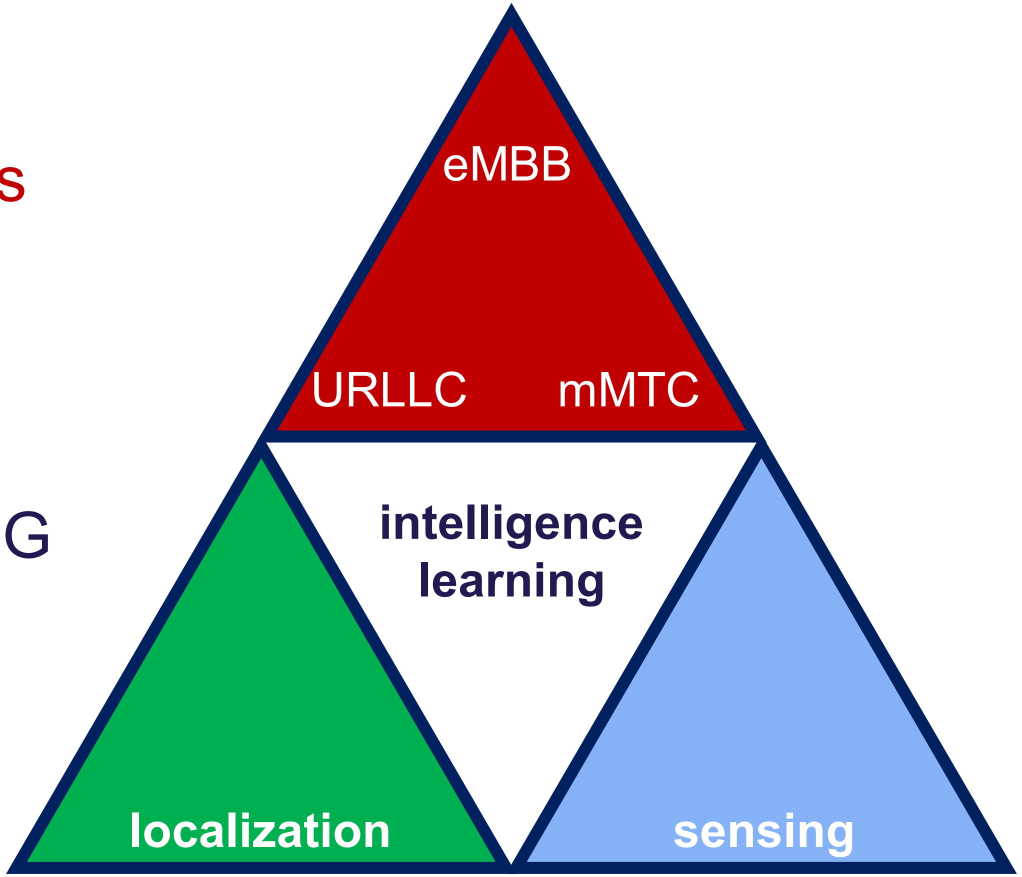
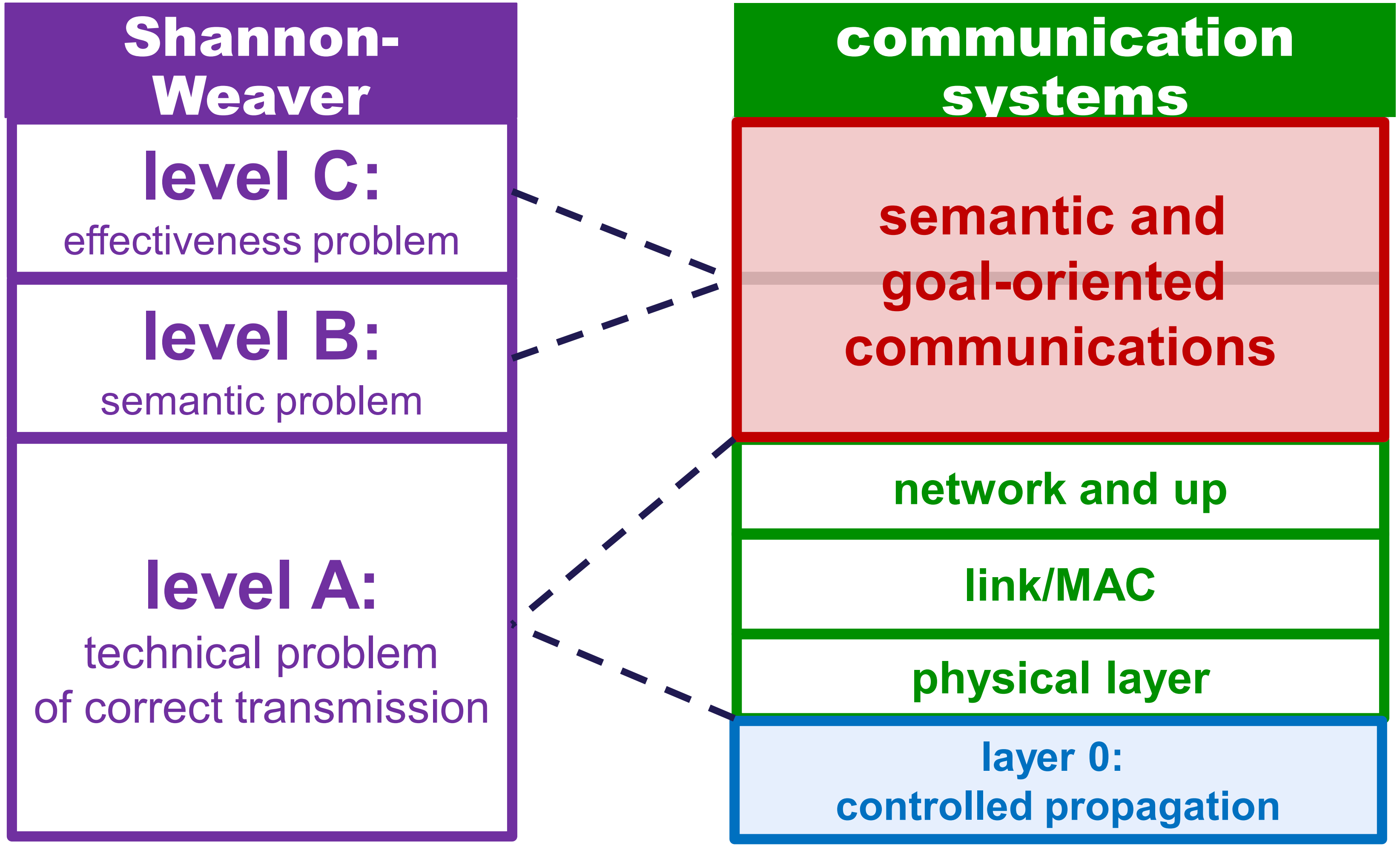
6G: more than communications

the 5G triangle was about communications

this triangle is about to be augmented in 6G



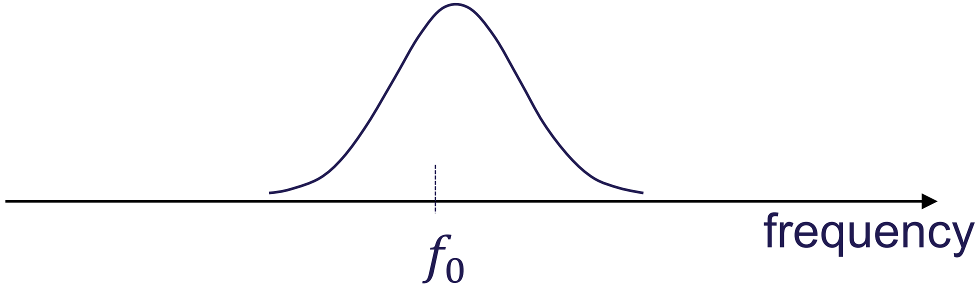
augmenting the design space for communications



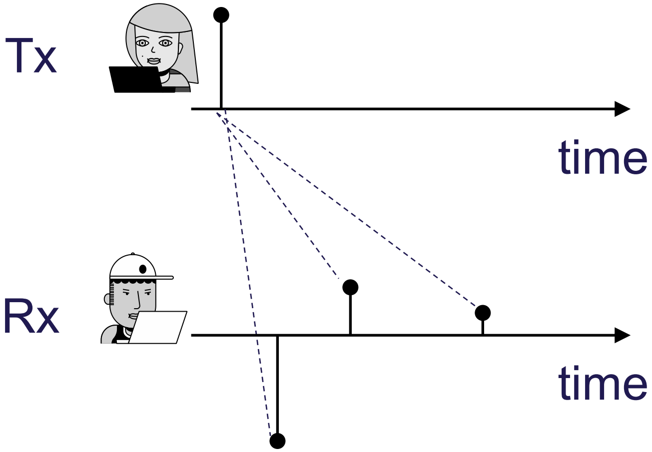
Renzo, M.D., Debbah, M., Phan-Huy, D.T., Zappone, A., Alouini, M.S., Yuen, C., Sciancalepore, V., Alexandropoulos, G.C., Hoydis, J., Gacanin, H. and Rosny, J.D., 2019. Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come. EURASIP Journal on Wireless Communications and Networking, 2019(1), pp.1-20.

wireless propagation environment so far

- **linearity**
  in a static environment,
  frequency spectrum is
  determined by the transmitter

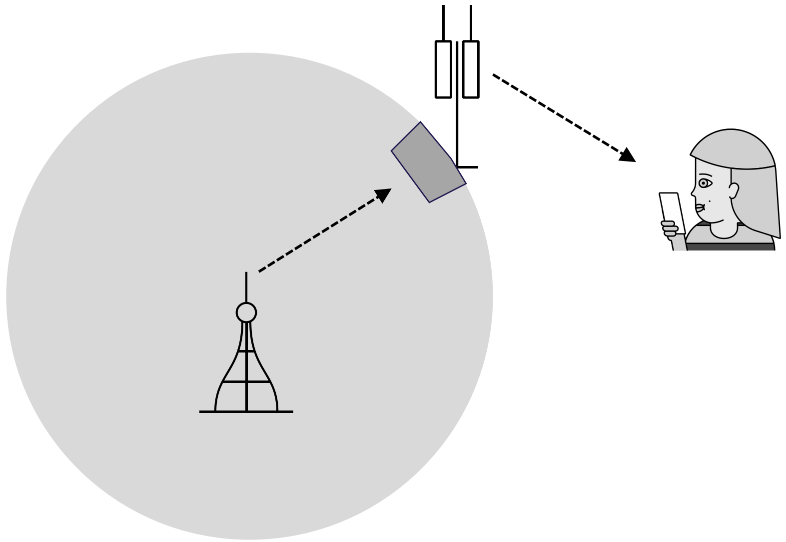


- **reciprocity**
  at a given frequency the channel is invariant
  if Tx/Rx roles are swapped



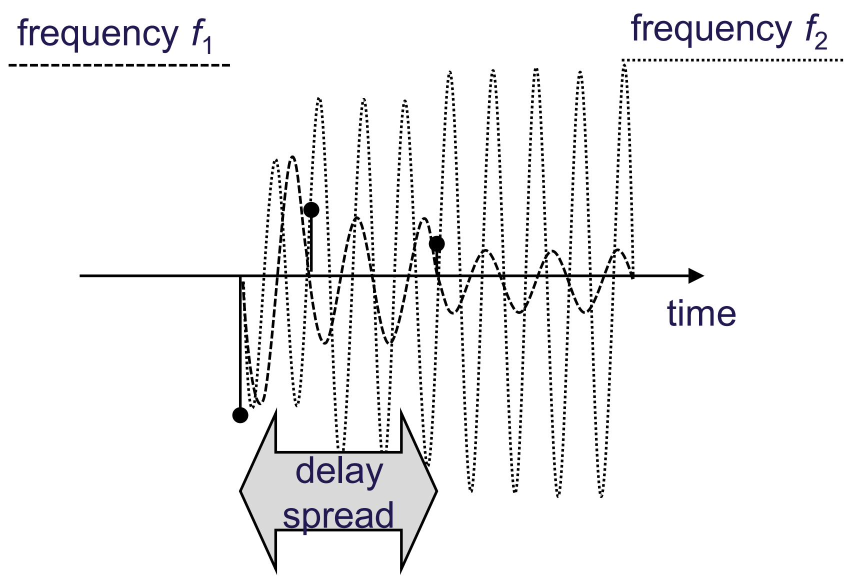
wireless propagation environment so far

- passive
  signal power decays with distance,
  relays can partially repair this loss



- lack of real-time control
  the wireless channel is an
  uncontrollable, external factor

how to send in a traditional propagation environment

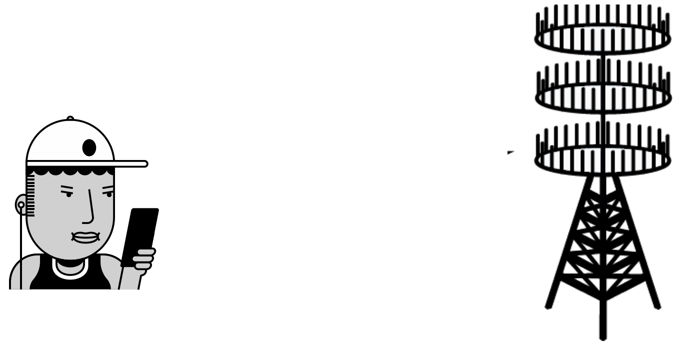


OFDM

- take advantage of uncontrollable superposition of paths

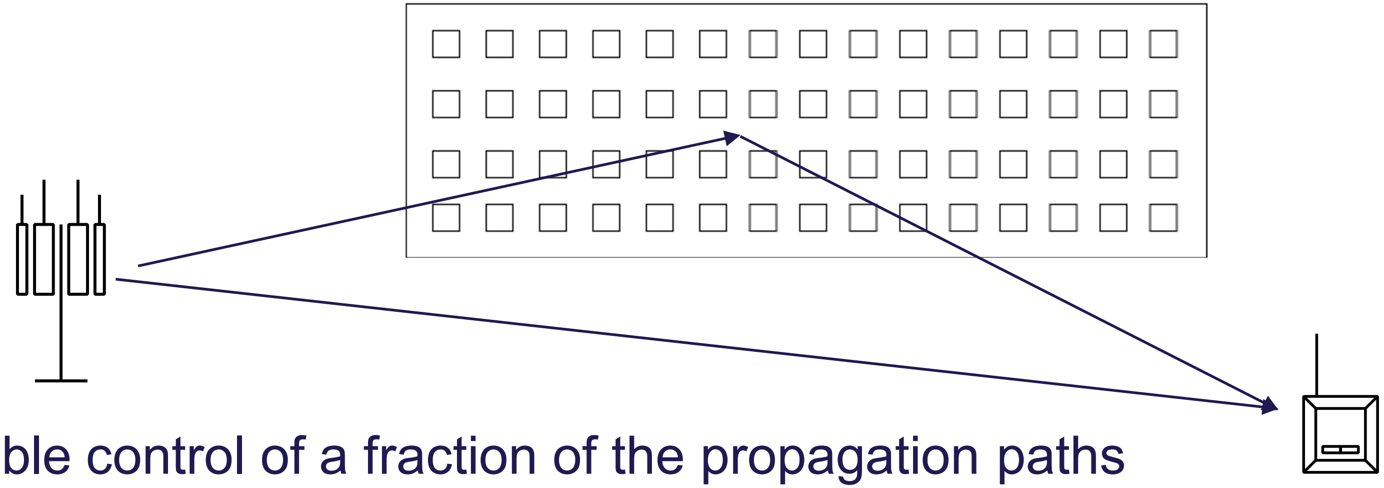
massive MIMO

- take advantage of reciprocity to estimate channel



P. Popovski. Wireless Connectivity: An Intuitive and Fundamental Guide. John Wiley & Sons, 2020.

reconfigurable intelligent surface (RIS)



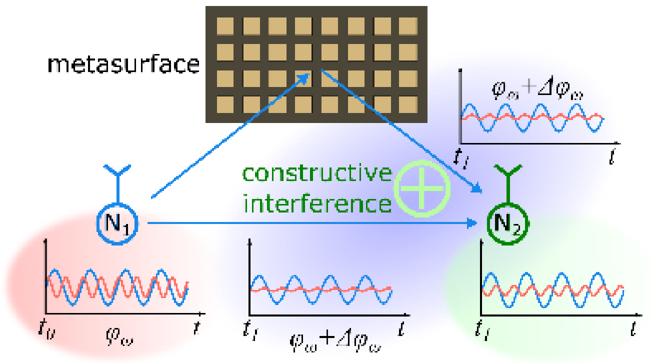
- programmable control of a fraction of the propagation paths
- generally, the objective in communication is to cause constructive interference where desirable
- the objective in localization is to provide additional spatial references
- the objective in sensing is to provide controlled diversity of the sensing inputs

E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti and E. de Carvalho, "Reconfigurable Intelligent Surfaces: A signal processing perspective with wireless applications," IEEE Signal Processing Magazine, vol. 39, no. 2, pp. 135-158, March 2022

RIS basics

RIS promises

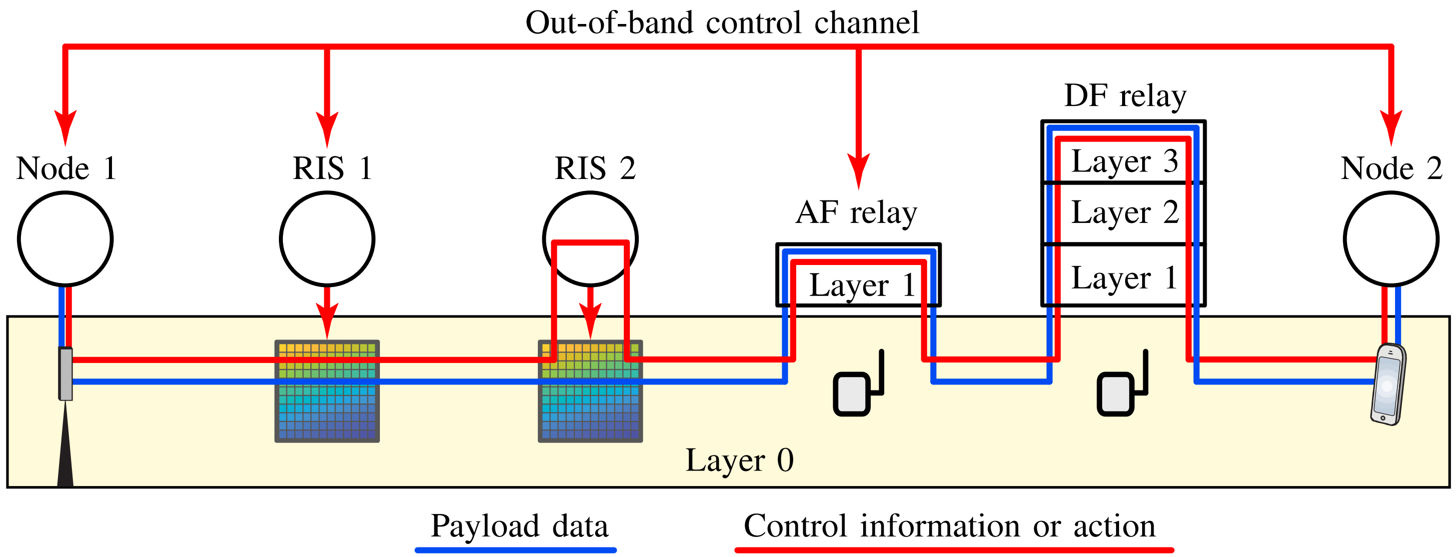
- low-cost implementation
- low power consumption
- boosted coverage
- improved sensing and positioning



large number of works on:
rate analysis, beamforming, resource optimization, channel estimation, …

less discussed question:
how to materialize the RIS promises by
taking into account the impact of the control channel

RIS versus relay



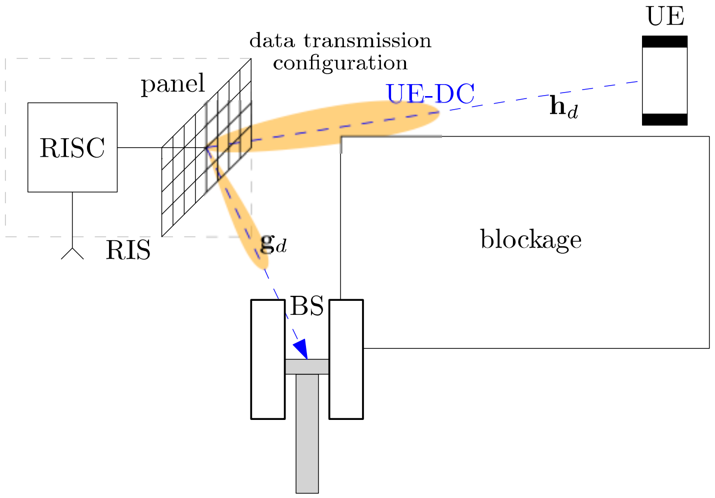
- in-band control channel: affected by RIS operation
- out-of-band control channel: not affected by RIS operation

data and control flows

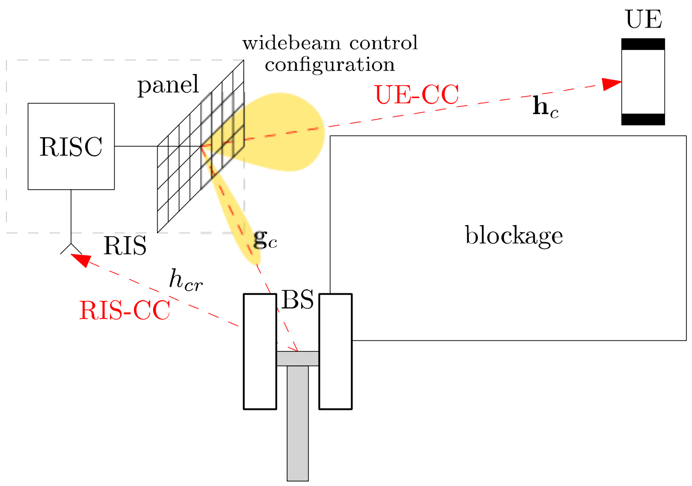
- **data flow:** UE transmits the payload towards the BS through the RIS
- **control flow:** the BS needs to inform the RIS controller (RISC) and the UE to perform the correct action

uplink scenario

single-antenna BS
a single-antenna UE
a fully-reflective RIS
BS-UE path is blocked.



data flow



control flow

F. Saggese, V. Croisfelt, R. Kotaba, K. Stylianopoulos, G. C. Alexandropoulos, P. Popovski, “On the Impact of Control Signaling in RIS-Empowered Wireless Communications”, arXiv:2303.16797, October 2023

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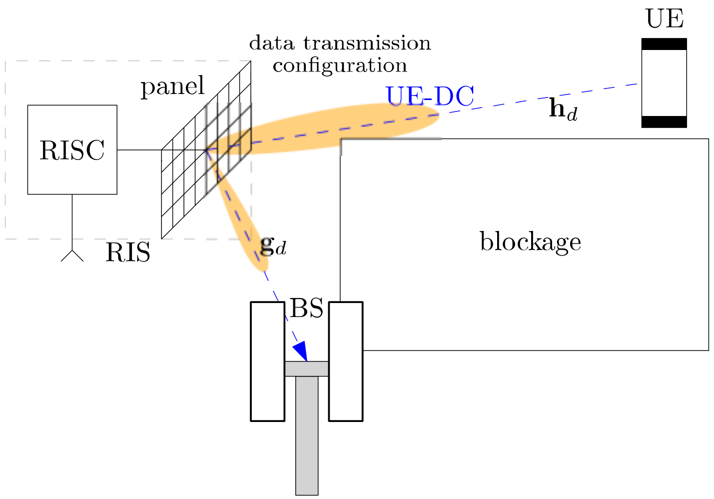

data flow

the RIS loads a configuration able to let UE communicate to the BS at the SNR of

$$\gamma = \frac{\rho}{\sigma^2}\left|\boldsymbol{\phi}^{\mathsf{T}}(\mathbf{h}_d \odot \mathbf{g}_d)\right|^2 = \frac{\rho}{\sigma^2}\left|\boldsymbol{\phi}^{\mathsf{T}}\mathbf{z}_d\right|^2$$

F. Saggese, V. Croisfelt, R. Kotaba, K. Stylianopoulos, G. C. Alexandropoulos, P. Popovski, “On the Impact of Control Signaling in RIS-Empowered Wireless Communications”, arXiv:2303.16797, October 2023

data and control flows

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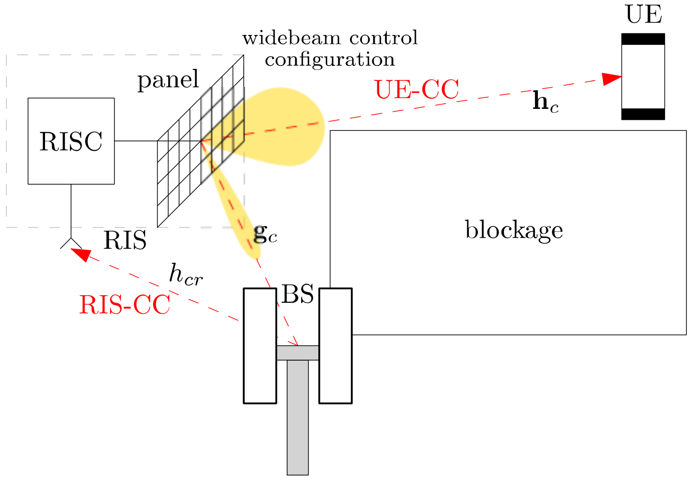
the BS informs:

- the UE to prepare payload and send it over the UE-CC
- the RISC to load the right configuration over the RIS-CC



control flow

F. Saggese, V. Croisfelt, R. Kotaba, K. Stylianopoulos, G. C. Alexandropoulos, P. Popovski, “On the Impact of Control Signaling in RIS-Empowered Wireless Communications”, arXiv:2303.16797, October 2023

control channel types

RIS-CC:

- in-band (IB-CC): the physical resources employed by the data are employed by the RIS-CC and are affected by the RIS configuration.
- out-of-band (OB-CC): the physical resources are non-interfering, e.g. a cabled connection between the decision maker and the RISC.

UE-CC:

- channel that is in-band (IB-CC) sharing the resources with data

$$h_{cu} = \boldsymbol{\phi}_{\text{ctrl}}^{\mathsf{T}}(\mathbf{h}_c \odot \mathbf{g}_c) = \boldsymbol{\phi}_{\text{ctrl}}^{\mathsf{T}}\mathbf{z}_c,$$

as a default, the RISC loads a wideband ctrl configuration to ensure the control messages to reach the UE.

$$\Gamma_u = \frac{\rho_b}{\sigma_u^2}|h_{cu}|^2$$

F. Saggese, V. Croisfelt, R. Kotaba, K. Stylianopoulos, G. C. Alexandropoulos, P. Popovski, "On the Impact of Control Signaling in RIS-Empowered Wireless Communications", arXiv:2303.16797, October 2023

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two transmission paradigms

myriad of possible RIS protocols

- how can we capture the basic insights
  without going through many diffferent protocol designs?

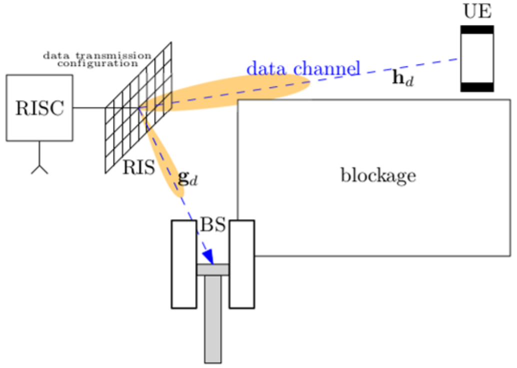
back to wireless basics: the stochastic variability of wireless propagation leads to two principal transmission modes

- **multiplexing**: learn the instantaneous propagation conditions
  and adapt the transmission rate
- **in RIS:** estimate the conditions
  and create a channel to which rate is adapted
- **diversity**: fix the rate and hope that the channel will support it
- **in RIS:** fix a rate and hope that
  some of the RIS configurations will support it.

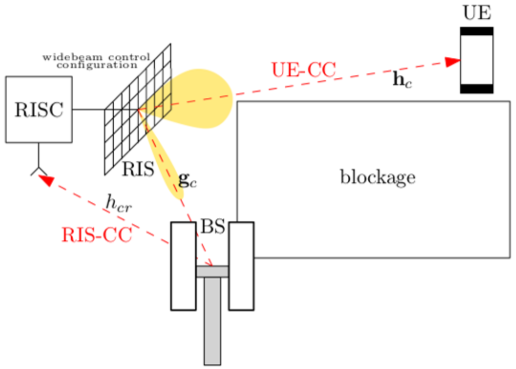
generalized protocol structure for RIS

four general phases

- **initialization:** BS inform the RISC and the scheduled UE about the start of the new round of transmissions
- **algorithmic:** encompasses the processes and computations to optimize data transmission. objective: determine the appropriate configuration for the RIS, and/or transmission parameters.
- **setup:** the appropriate transmission parameters are communicated to the RISC and UE
- **payload:** the actual data transmissions take place



(a) Data flow.

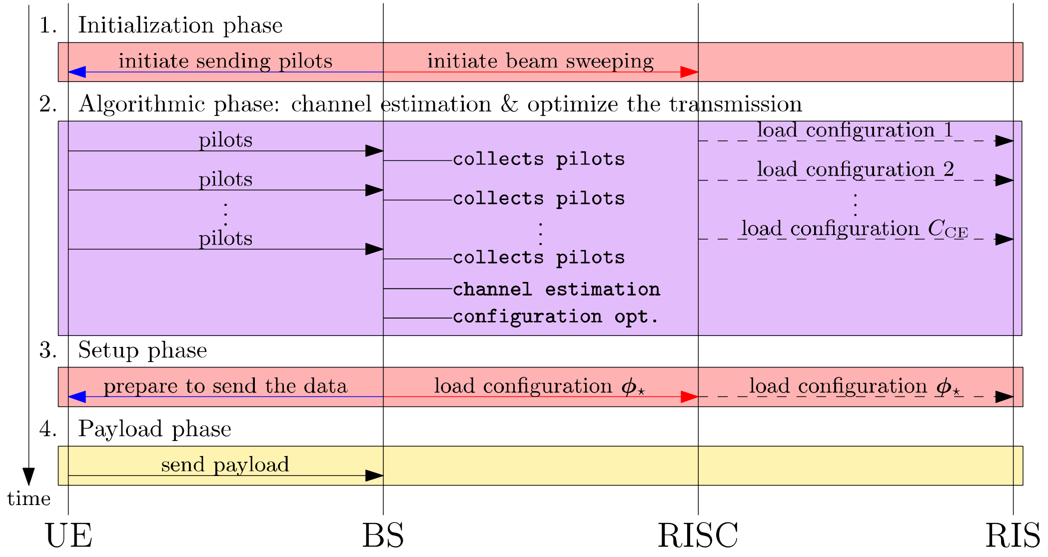


(b) Control flow.

everything must be done in a coherence block!

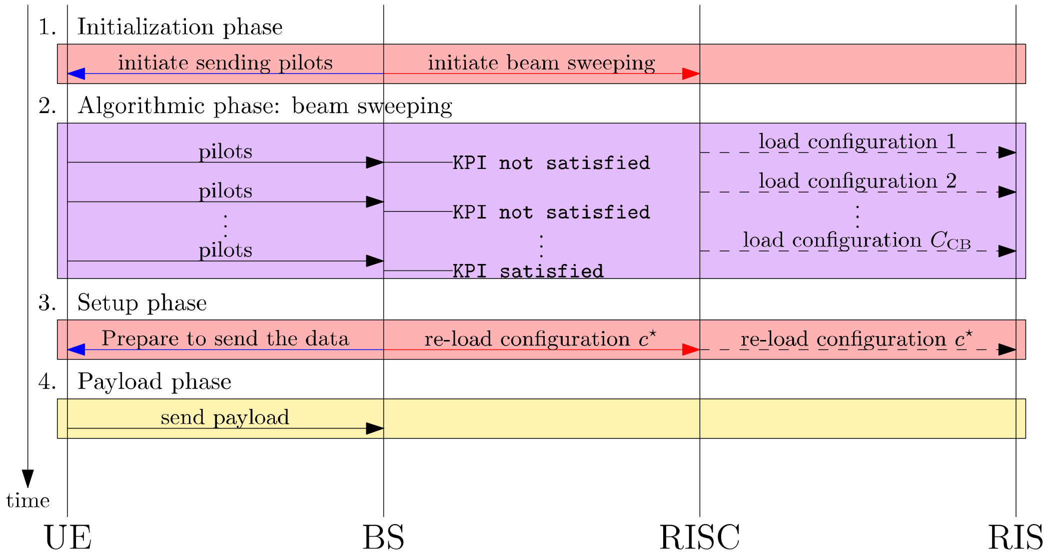
two protocol models

optimization based on channel estimation (OPT-CE)



multiplexing

codebook-based beam sweeping (CB-BSW)



diversity

optimization based on channel estimation (OPT-CE)

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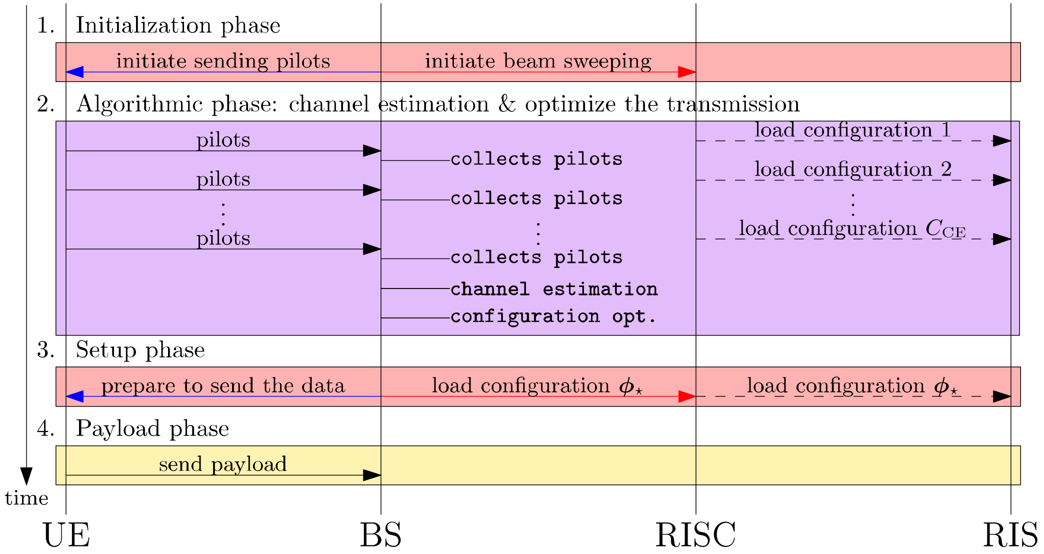


multiplexing

- estimate the channel $\hat{\mathbf{z}}_d$
- obtain the optimal configuration $\phi_\star$
- estimated SNR is

$$\hat{\gamma}_{CE} = \frac{\rho}{\sigma^2}|\phi_\star^\mathsf{T}\hat{\mathbf{z}}_d|^2$$

- set the transmission SE to

$$\eta_{CE} = \log_2(1+\hat{\gamma}_{CE})$$

codebook-based beam sweeping (CB-BSW)

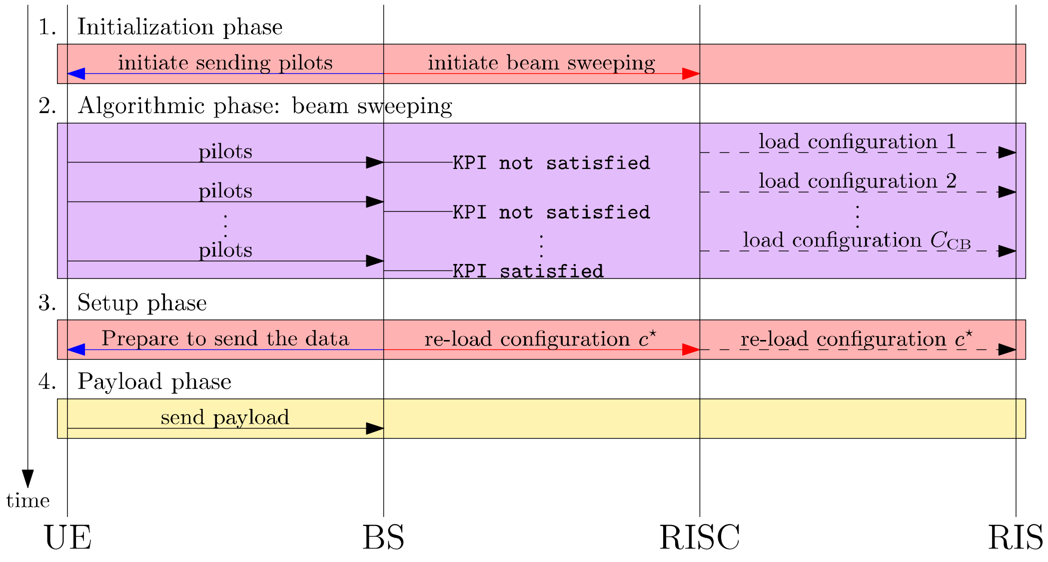
- set the target SNR (KPI) γ_0
- the transmission SE is

$$\eta_{\mathrm{CB}} = \log_2(1+\gamma_0)$$

- find the configuration for the KPI

$$c^\star = \underset{c \in \mathcal{C}_{\mathrm{CB}}}{\arg\max} \{\hat{\gamma}_c \,|\, \hat{\gamma}_c \geq \gamma_0\}$$

codebook-based beam sweeping (CB-BSW)



diversity

comparison metric

- spectral efficiency of data transmission cannot be considered as a fair term of comparison, as the schemes have a different protocol structure
- instead, we look at the net throughput
  by considering the time during which payload is sent:

$$R(\tau_{\text{pay}}, \eta) = \begin{cases} \frac{\tau_{\text{pay}}}{\tau} B_d \, \eta, & \text{with prob. } 1 - p_{\text{ae}}, \\ 0, & \text{with prob. } p_{\text{ae}}, \end{cases}$$

$$\tau_{pay} = \tau - \tau_{ini} - \tau_{alg} - \tau_{set}$$

setup phase duration

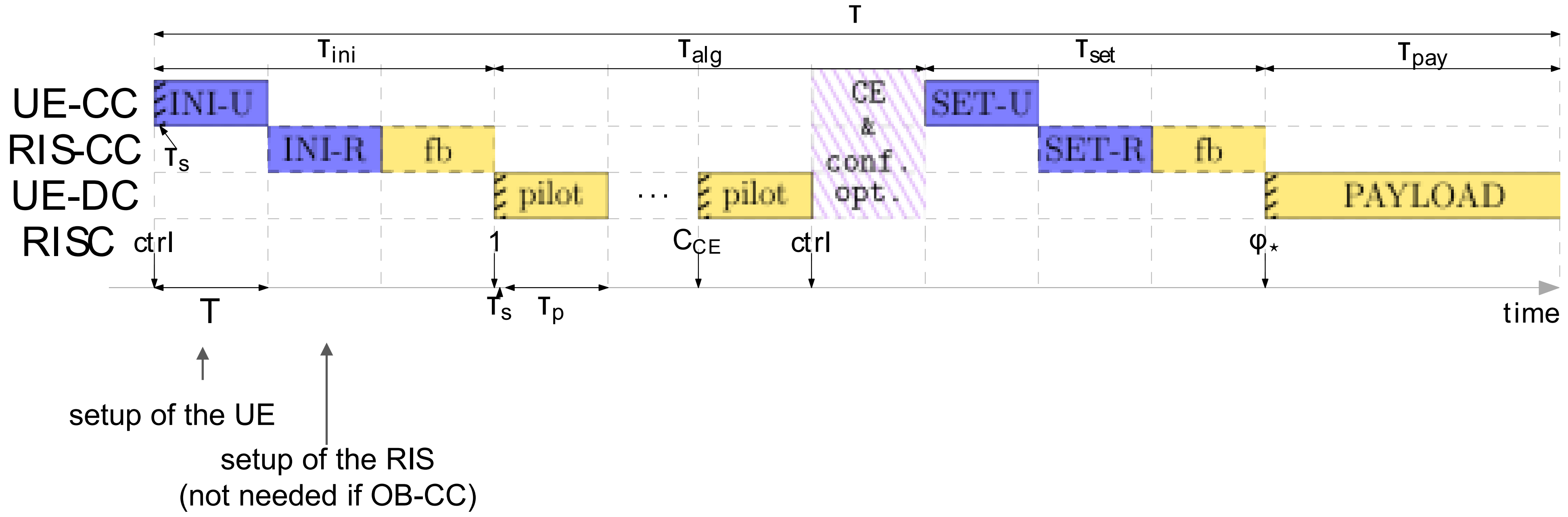
frame duration

algorithmic phase duration

initialization phase duration

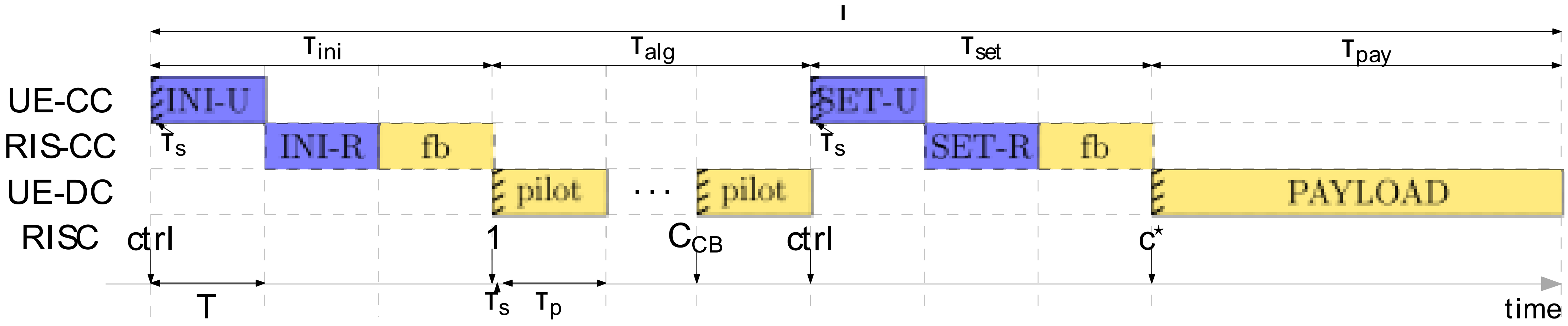
the actual times depend on the protocol structure

frame structure for multiplexing OPT-CE

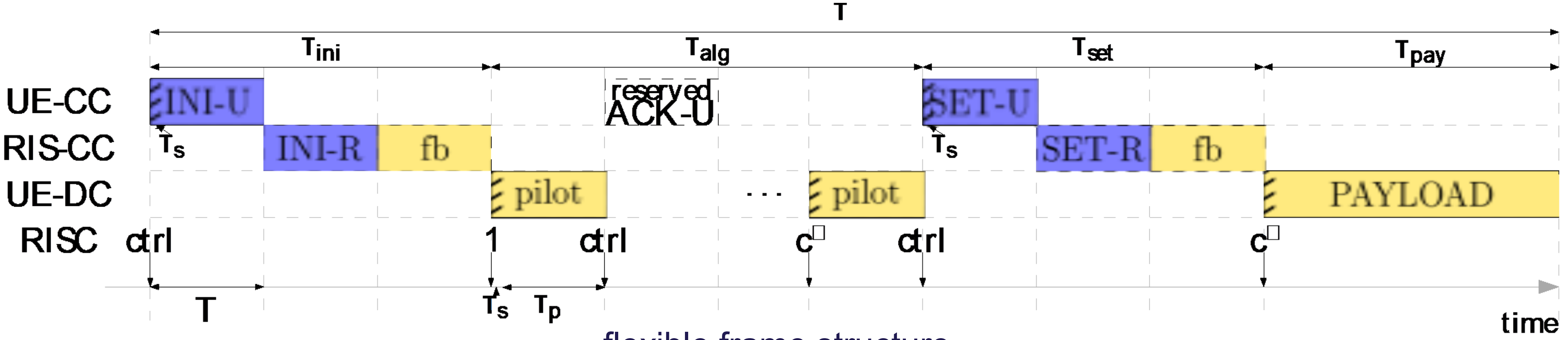


T is the time length of a TTI

frame structure for outage CB-BSW (fixed)

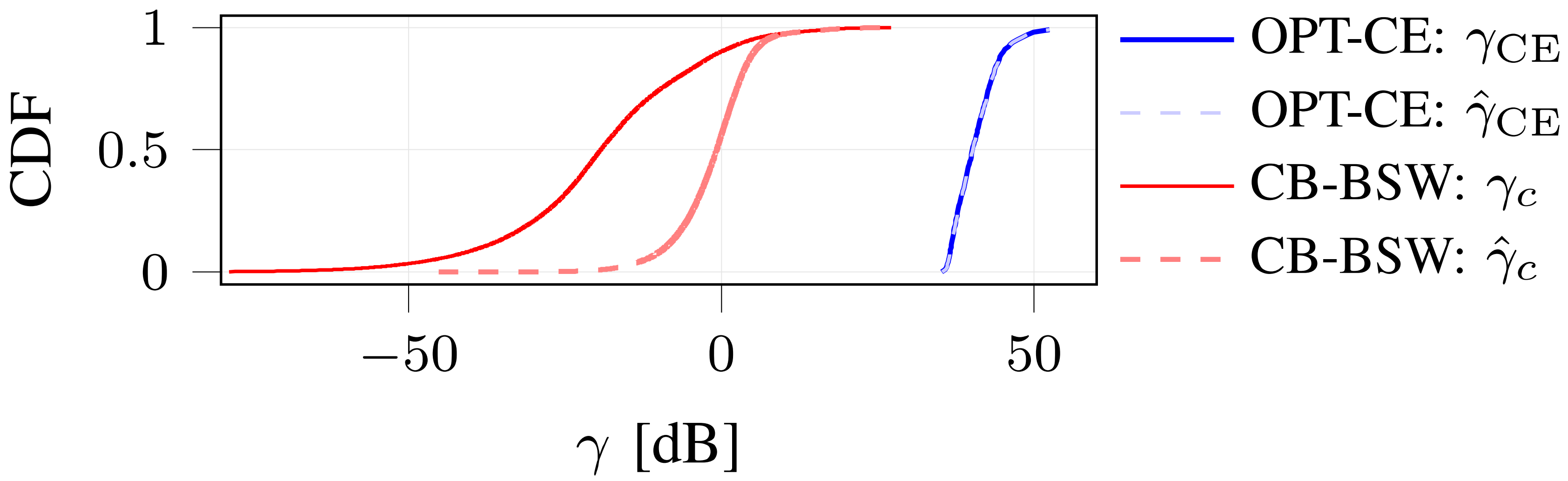


fixed frame structure



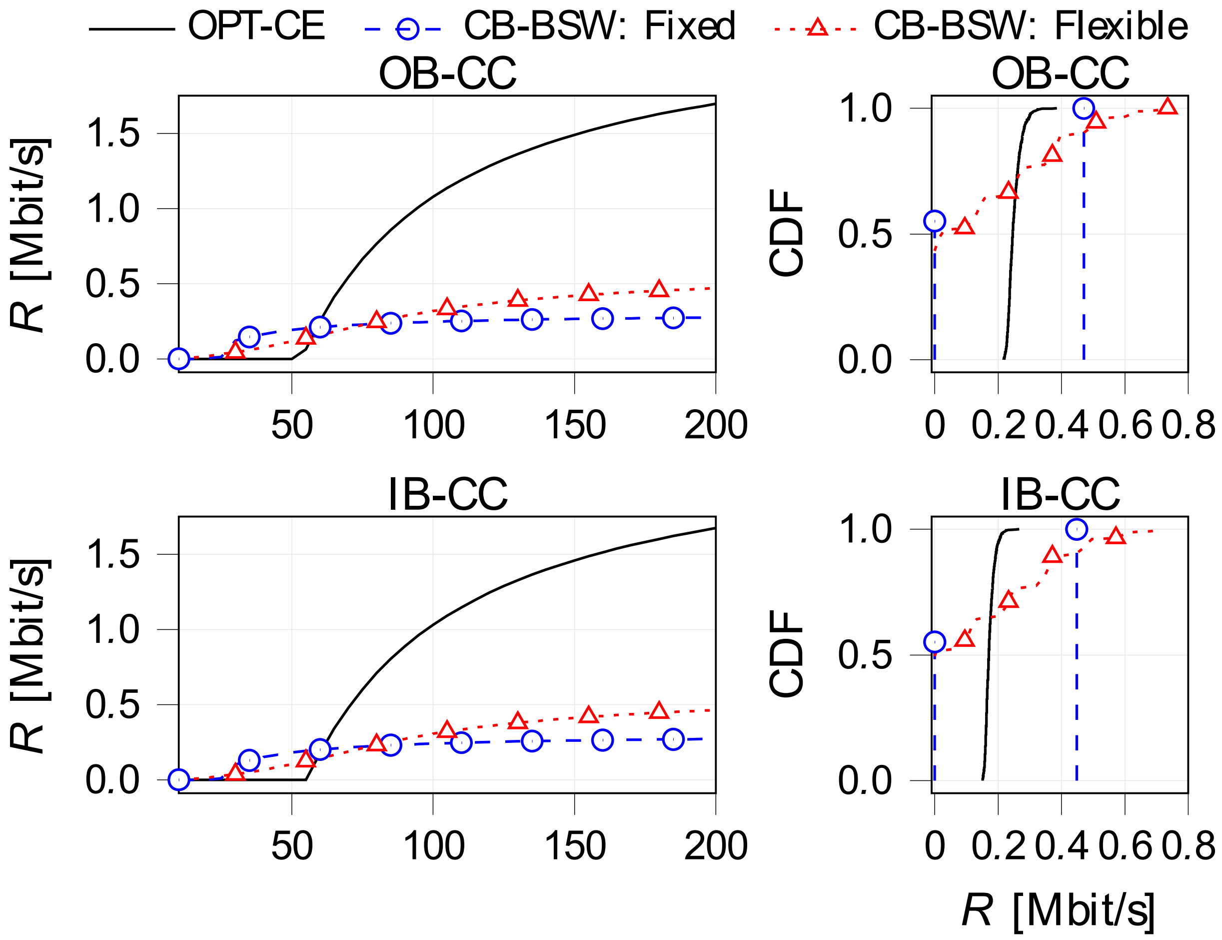
flexible frame structure

numerical illustration



CDF of the actual and estimated SNR

numerical illustration: goodput



(a) R vs ⌧ OB-CC.   (b) CDF of R, ⌧= 60 ms.

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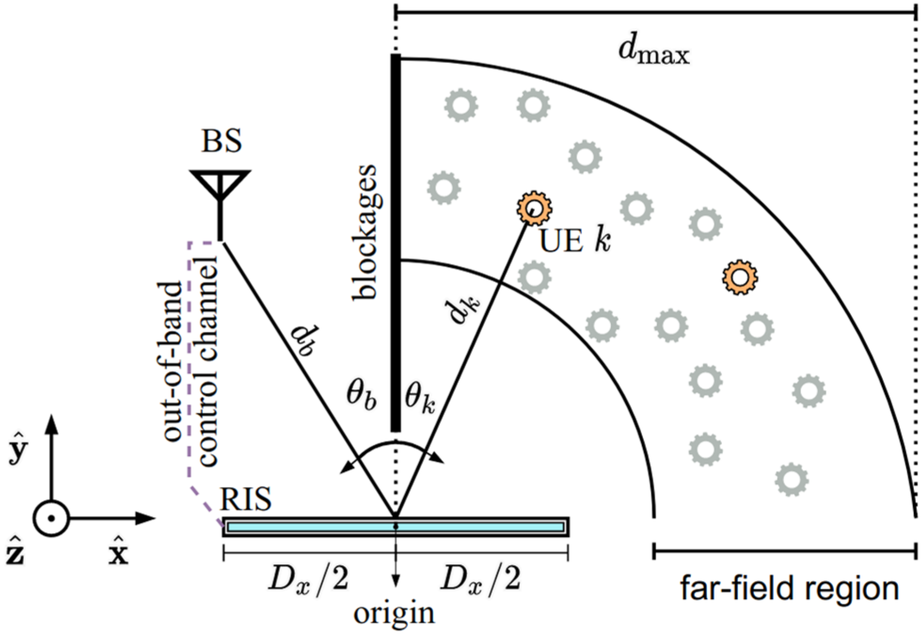
beam sweeping protocol for multiple users

grant-free access



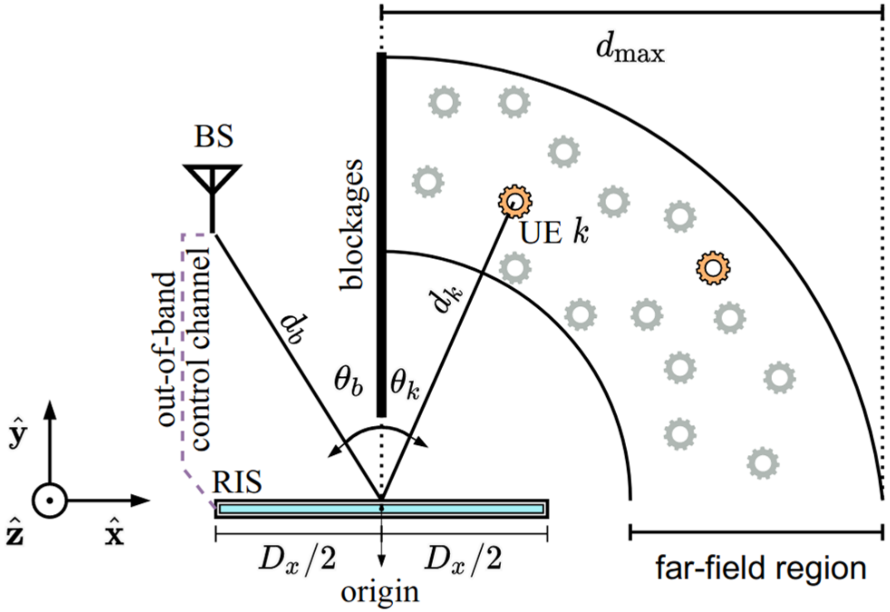
- multiple uncoordinated UEs
- no explicit channel estimation
- no explicit phase optimization

A **codebook-based sweeping procedure** can solve the problem

V. Croisfelt, F. Saggese, I. Leyva-Mayorga, R. Kotaba, G. Gradoni and P. Popovski, "Random Access Protocol with Channel Oracle Enabled by a Reconfigurable Intelligent Surface," in IEEE Transactions on Wireless Communications, doi: 10.1109/TWC.2023.3268765.

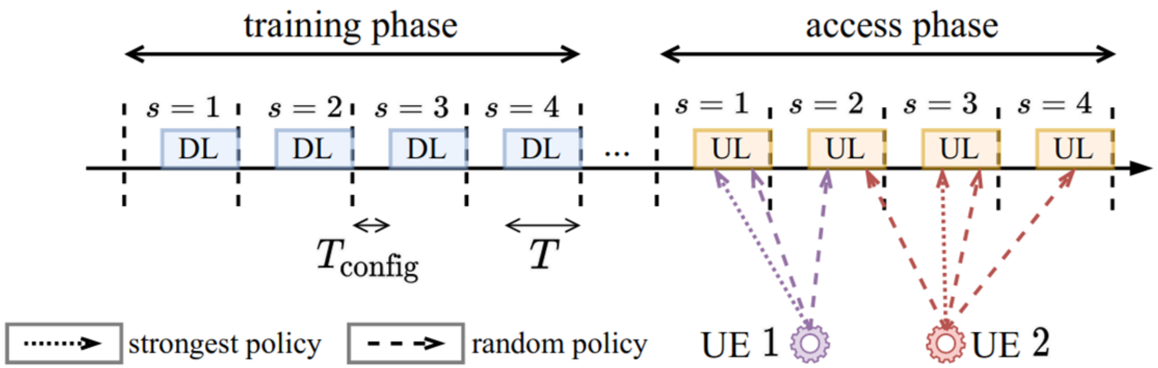
beam sweeping protocol for multiple users

sweeping: the RIS periodically loads configuration from a pre-determine codebook

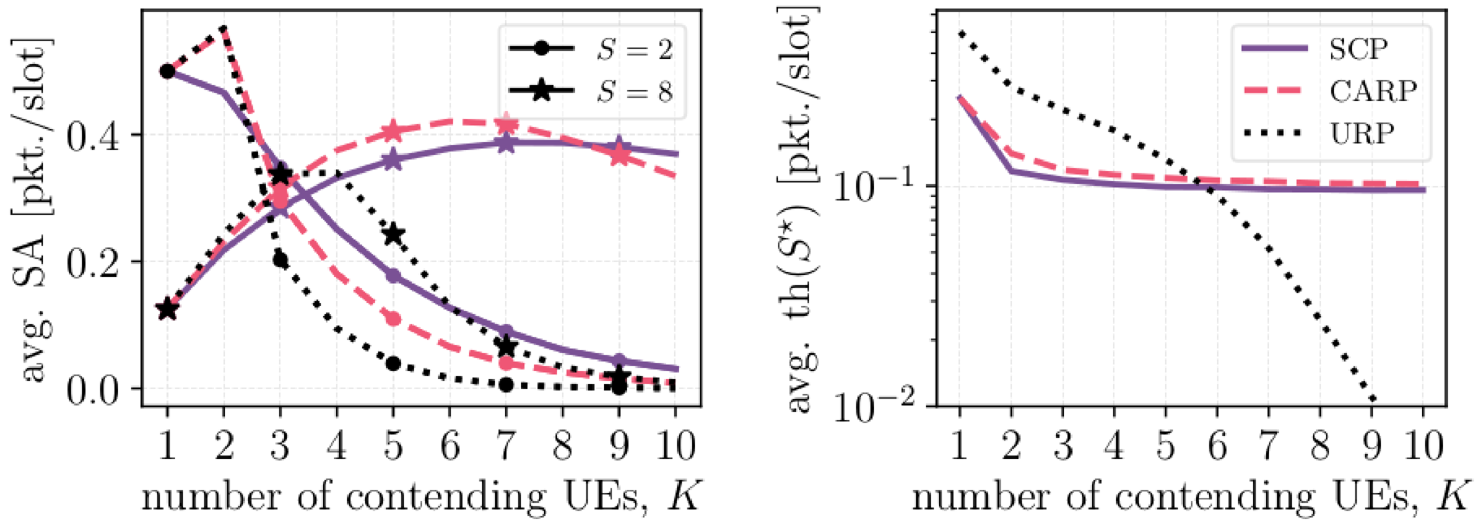


Downlink training phase: RIS sweeps; UEs measure their channel qualities with respect to the different configurations.

Uplink access phase: RIS sweeps; UEs try to access the network based on access policies.



numerical illustration

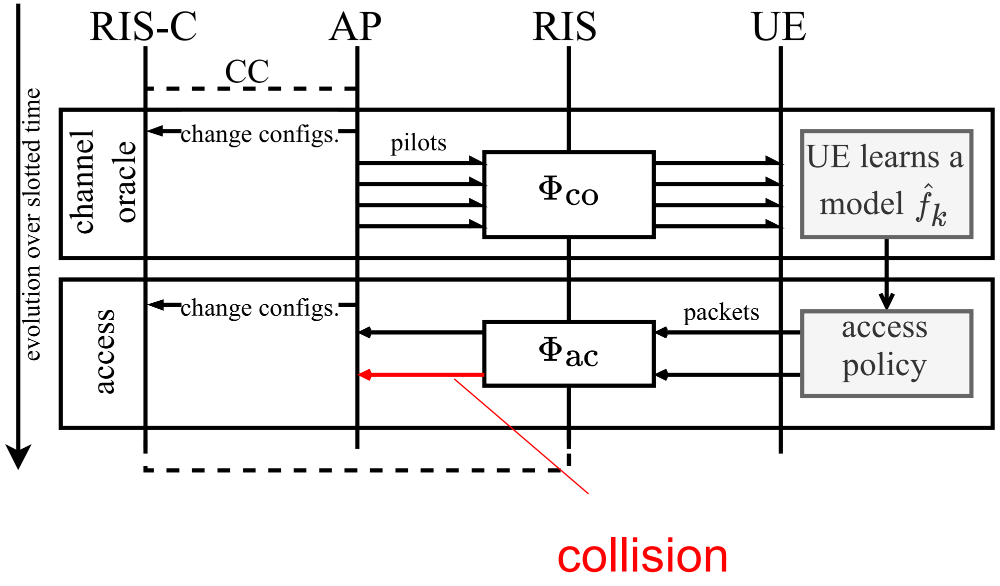


(a) Avg. successful access attempts. (b) Optimal avg. throughput w.r.t. S.

performance trade-off: RIS-based policies improve access at the cost of relying on a training phase

can we spend less time on the training phase?

introducing the oracle

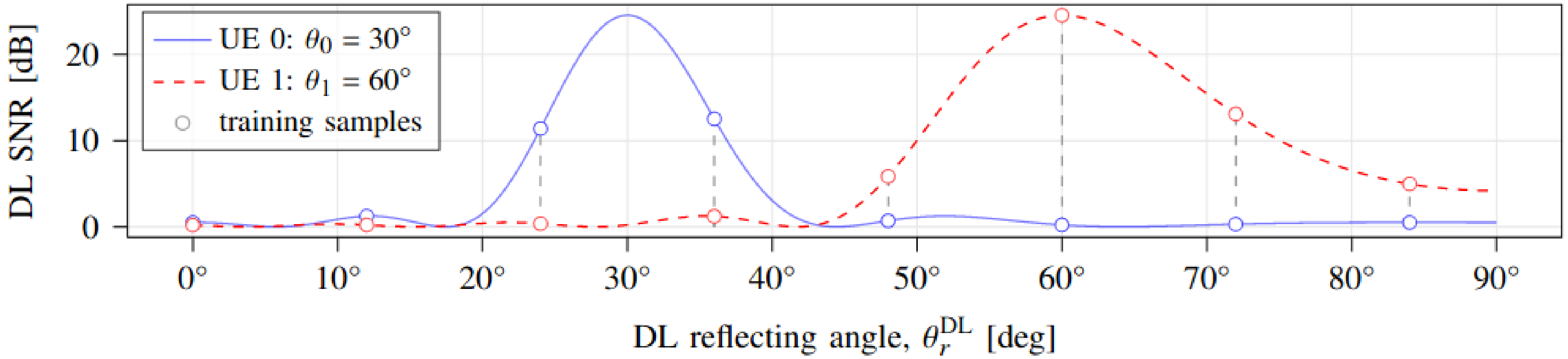


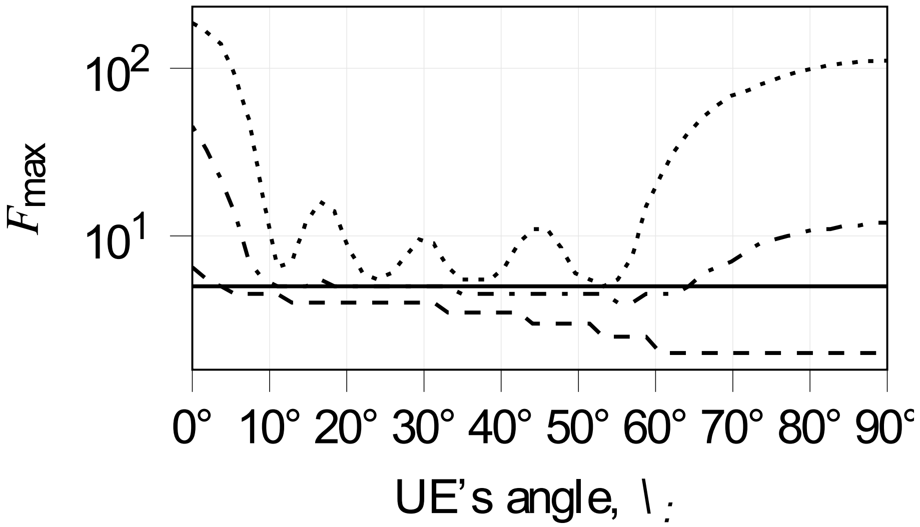
the oracle predicts the access codebook from the training one!

V. Croisfelt, F. Saggese, I. Leyva-Mayorga, R. Kotaba, G. Gradoni and P. Popovski, "Random Access Protocol with Channel Oracle Enabled by a Reconfigurable Intelligent Surface," in IEEE Transactions on Wireless Communications, doi: 10.1109/TWC.2023.3268765.

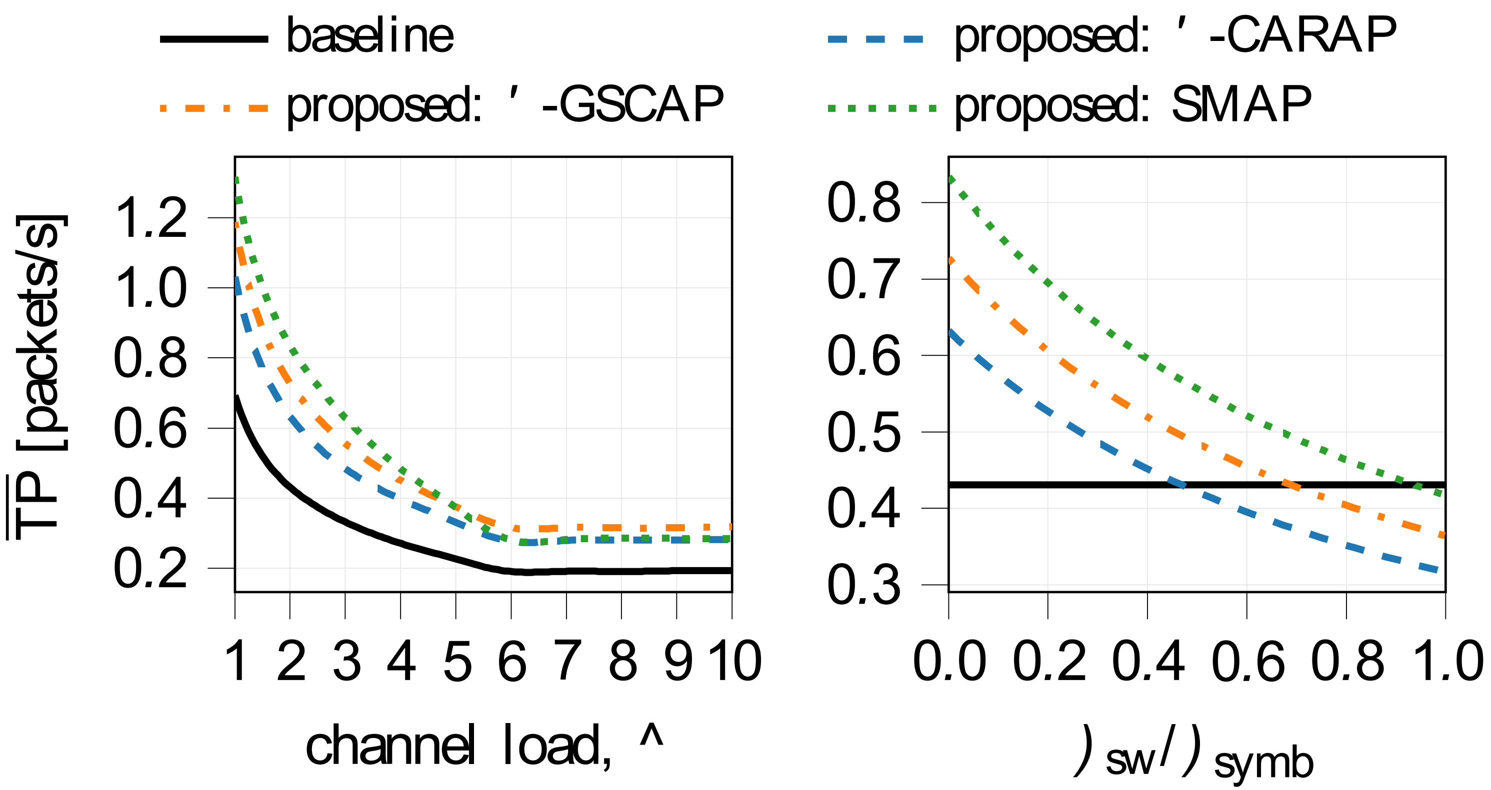
why is oracle possible

Shannon-Nyquist in a spatial domain





numerical illustration



(a) Varying channel load with no switching time) sw = 0.

(b) Varying switching time with fixed channel load, ^ = 2.

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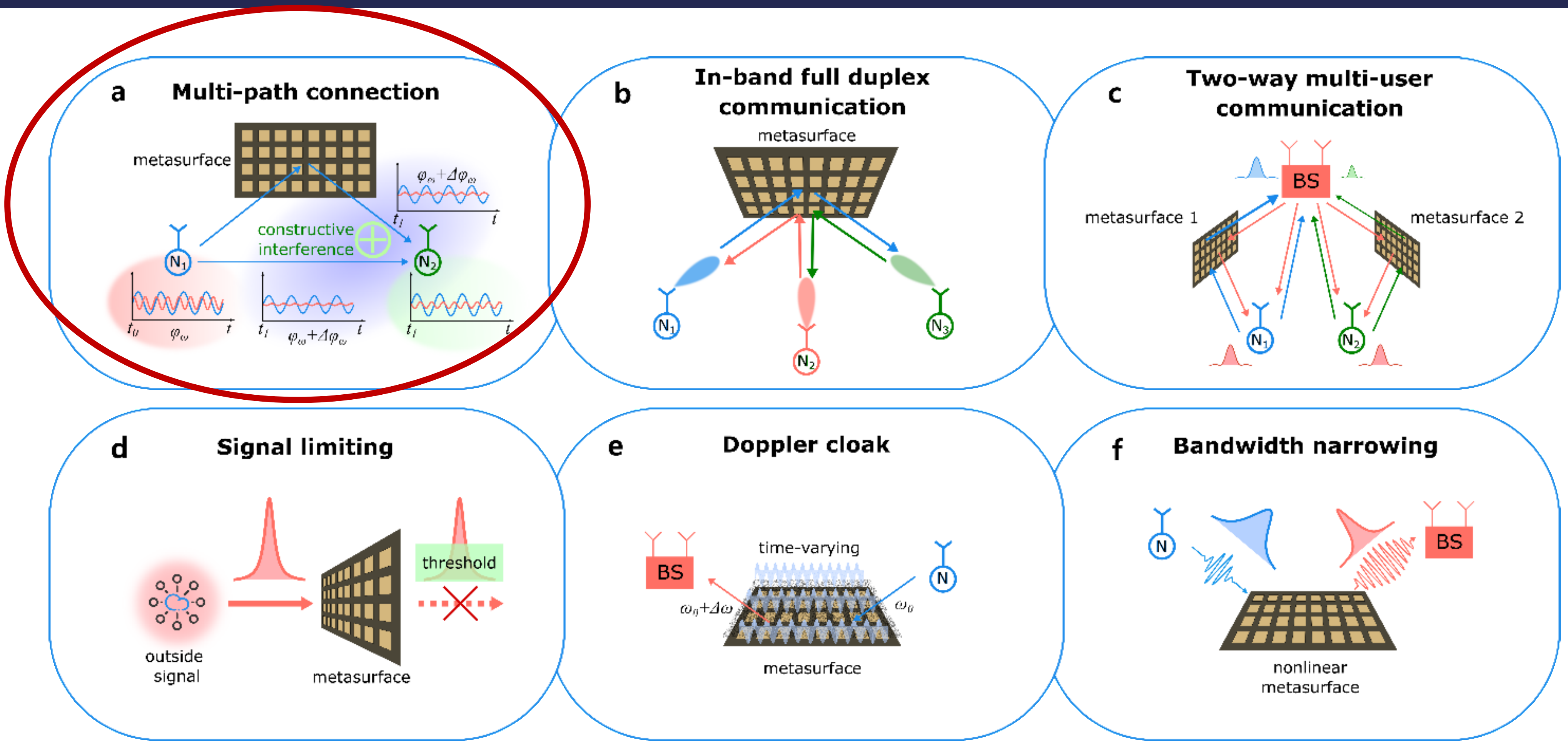
possibilities with new electromagnetic materials

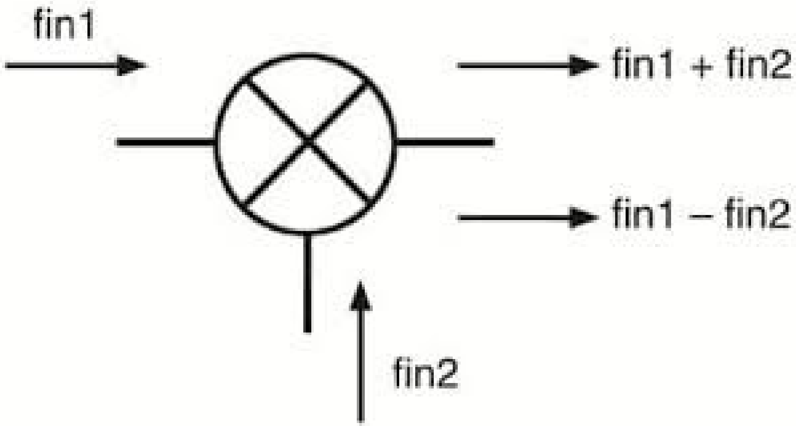
RIS



Ra'di, Younes, Nikita Nefedkin, Petar Popovski, and Andrea Alù. "Metasurfaces for next-generation wireless communication systems." National Science Review (2023)

frequency mixer

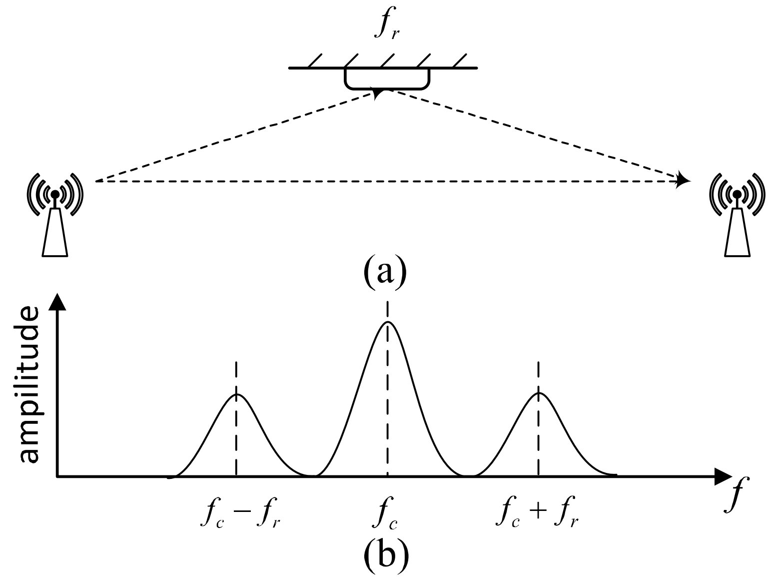
Edwin Howard Armstrong

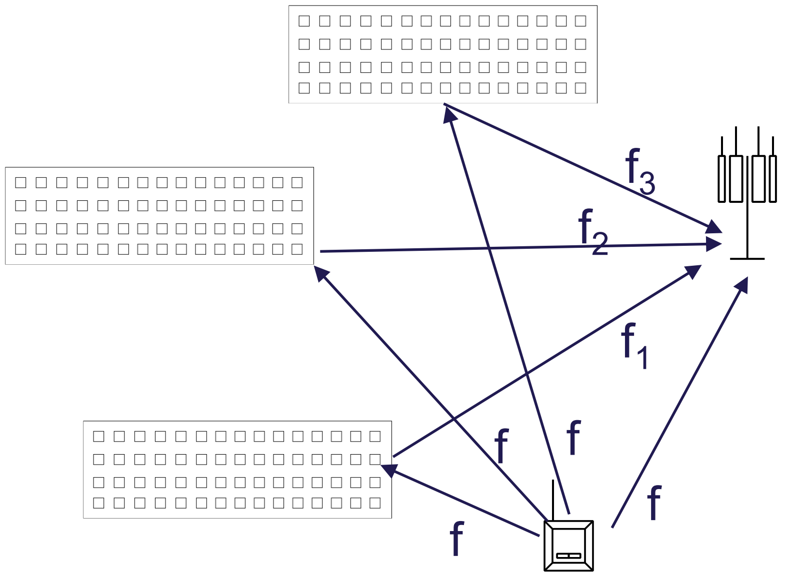


what if the mixer is part of the radio environment?

a primer on nonlinear wireless environment

- each RIS changes the reflection coefficients sinusoidally, according to some frequency



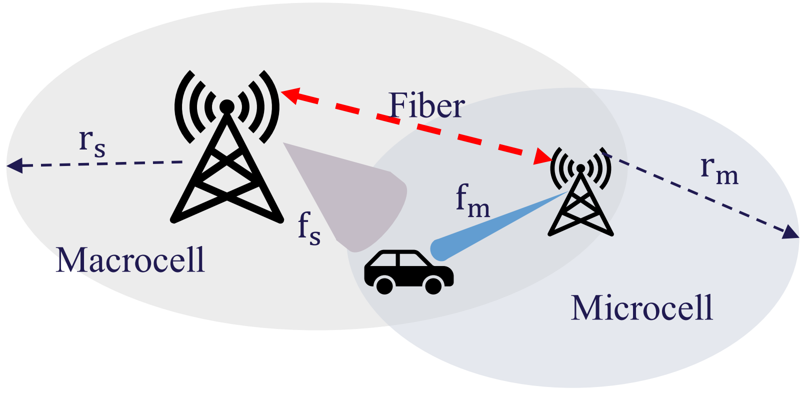


J. Yuan, E. de Carvalho, R. Williams, E. Björnson, and P. Popovski, , "Frequency-Mixing Intelligent Reflecting Surfaces for Nonlinear Wireless Propagation," in IEEE Wireless Communications Letters, accepted, 2021.

FS-RIS assisted mmWave Cellular Links

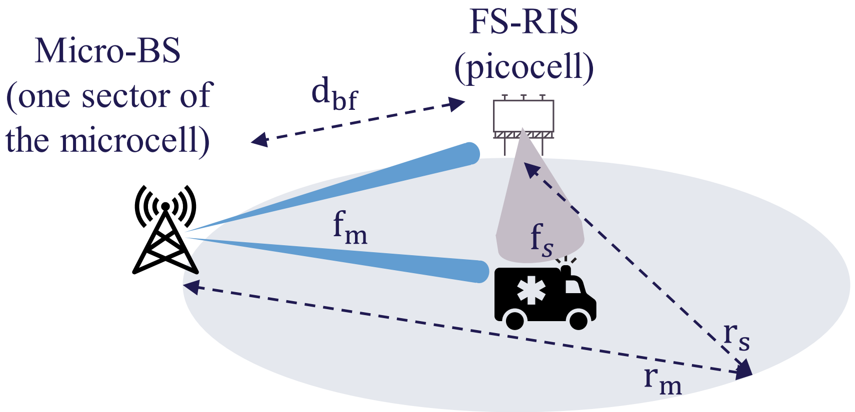
coordinated Multi-Point (CoMP)

- multiple BSs with different freqs.
- f_m mmWave and f_s sub-6 GHz



proposed FS-RIS scenario

- RIS is changing the freq (beam width)
- standalone mmWave network



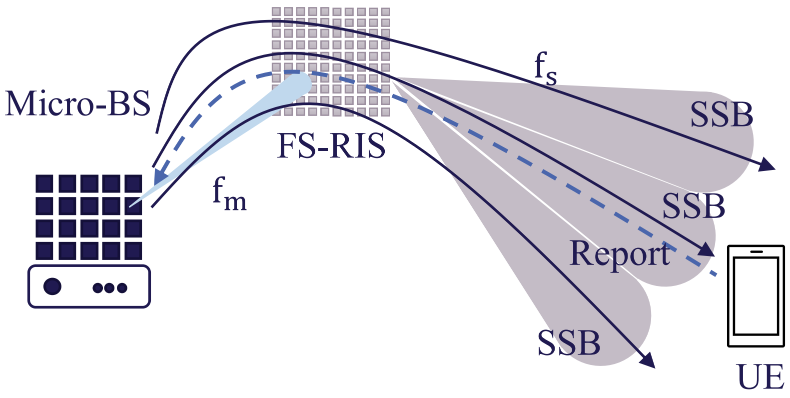
FS-RIS Beam Management Procedure

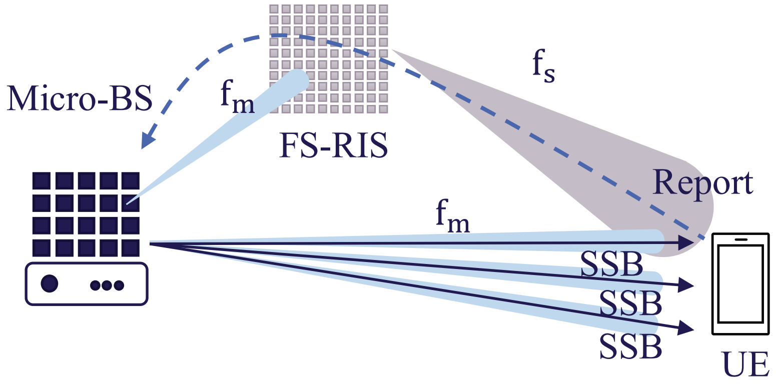
Coarse beam search:

- Lower frequencies are used to rapidly seek the UE.
- The wide beams can be used for tracking fast targets (drones).

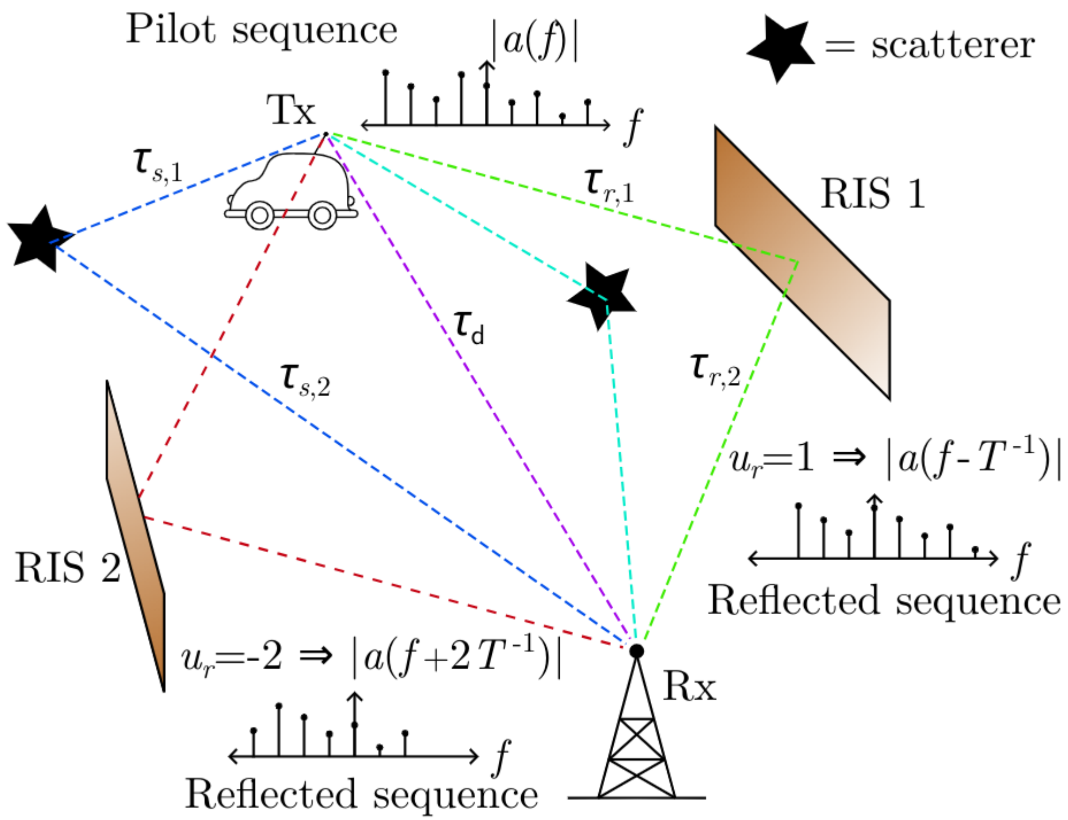
Beam refinement:

- A higher carrier frequency is used to refine the position of the UE
- The beam report can be sent back to the BS via previous established link (delay reduction).
- Provide higher data-rate links
- Provide extremely accurate localization





single OFDM frame RIS channel estimation

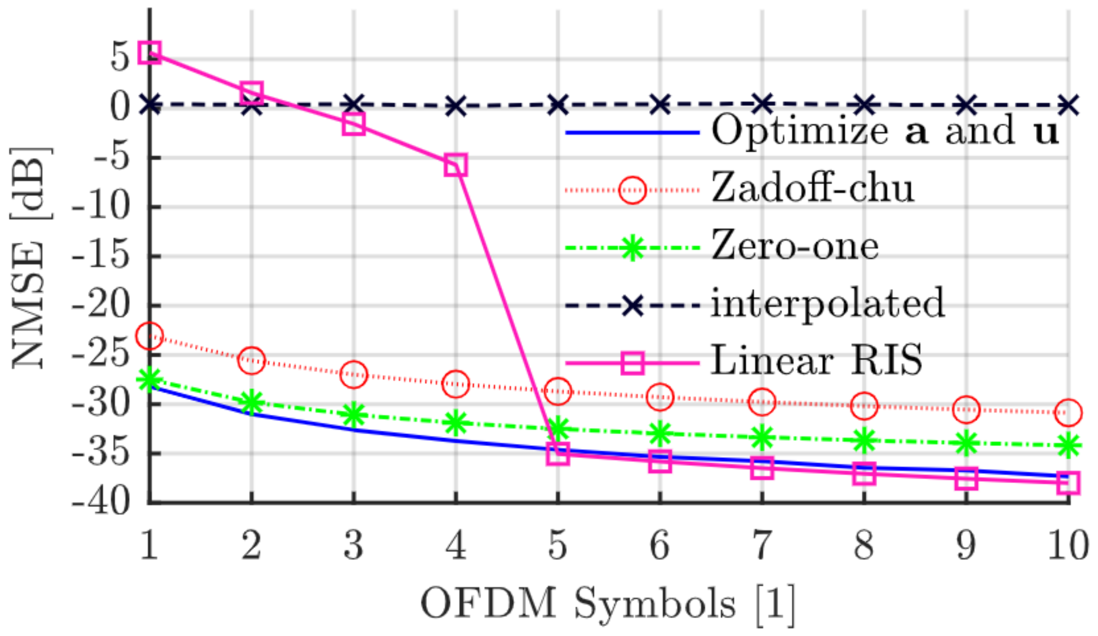


u_r is the frequency shift induced by the r'th RIS expressed in number of subcarriers.

T^{-1} is the subcarrier spacing

- conventional approach requires coding channel information in time using orthogonal pilots
- utilizing frequency shifting, multiple channels estimated simultaneously.
  - coding can be built on top to increase accuracy over time
- channels either independent RISs as illustrated, or paths through sub-arrays of one larger RIS.

single OFDM frame RIS channel estimation



- estimation of line-of-sight and 4 RIS channels
- metric is the sum of MSE of the channels individually normalized by the respective channel powers.
  - estimation error relative to channel power.
- conventional approach (Linear RIS) requires coding over 5 OFDM symbols
- shifting approach obtains good estimate after a single symbol.
  - performance can be further improved by coding over time.

conclusion and outlook

- reconfigurable intelligent surface (RIS) is a step towards controlling the propagation environment
- we have presented the basic models for access protocols tailored to RIS
  - a specific random access protocol that uses the oracle principle
- materials with new electromagnetic properties significantly expand the possibilities for controlling the propagation environment