ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Localization and communication in Smart Radio Environments

PhD discussion

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Outline

- Introduction
- Enabling technologies for SREs
- Localization and communication algorithms for SREs
    - Metaprism aided localization
    - Self Conjugation Metasurface aided communication
- Conclusions

RESTART

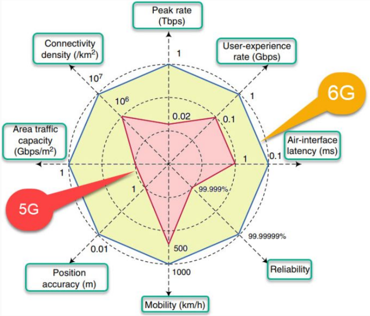
TIMES

6G SHINE

ATTRACT

Introduction

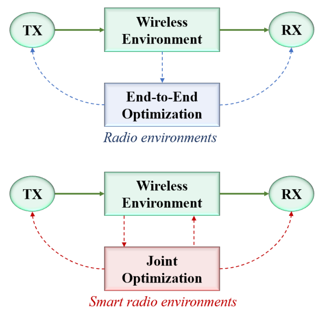
Introduction



To enable wireless networks to deliver ultra-high data rates and to support a diverse array of services, such as sensing, localization, low-latency, and ultra-reliable communications, a revolutionary concept gained attraction in the last few years: the **Smart Radio Environment (SRE)**.

F. Tariq et all, "A Speculative Study on 6G," in IEEE Wireless Communications, vol. 27, no. 4, pp. 118-125, August 2020

Introduction



SRE shifts the perception of the wireless environment from a passive, uncontrollable entity to an *active*, programmable component. The SRE exploits the inputs received from the wireless environment and optimizes its signals.

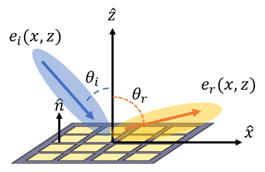
Renzo, Marco Di, et al. "Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come." EURASIP Journal on Wireless Communications and Networking 2019.1.

Enabling technologies for SREs

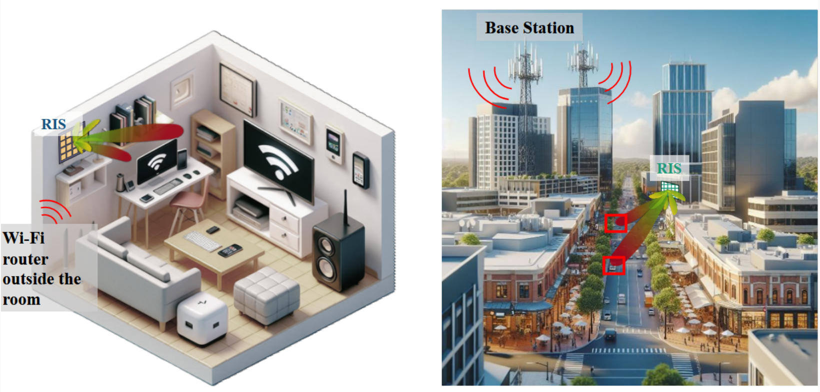
Reconfigurable intelligent surface

Central to the SRE concept is the *Reconfigurable Intelligent Surface* (RIS), which turns the wireless environment into a controllable variable.

RISs are programmable metasurfaces that can shape incoming electromagnetic waves to achieve desired effects.
By balancing absorption and gain, they enable smarter and more efficient wireless communication, paving the way for next-generation networks.



Reconfigurable intelligent surface



RIS employed in indoor and outdoor environments

Ph.D. Research Summary – Smart Radio Environments

Main Activities:

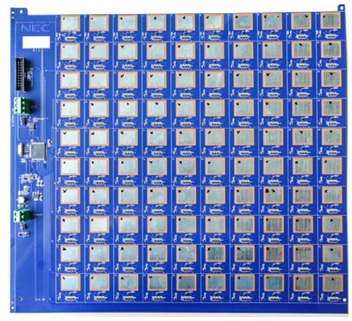
- Study of **Reconfigurable Intelligent Surfaces (RISs)** and **metasurfaces** for environment-aware communications.
- **Metaprism:** investigated as a **passive alternative to RIS**, mitigating their limitations in reconfigurability, CSI estimation, and power consumption.
- **SCM (Self-Conjugating Metasurface):** explored as a **low-complexity backscattering communication** enabling **multi-antenna links** without active beamforming and ability to **include data** in backscatter mode.
- **Experimental campaigns:** THz mapping and personal radar validation, UWB localization tests, and RIS measurements (3.47 GHz / 5.3 GHz) in collaboration with Aalborg University.

Projects Involved:

- **PRIMELOC (ATTRACT):** Personal radar for infrastructure-less localization.
- **RESTART (PNRR):** Smart electromagnetic nodes for Smart Radio Environments.
- **6G-SHINE (EU):** Short-range extreme communication for in-X subnetworks.
- **TIMES (EU):** THz mesh networks and smart sensing with metasurfaces.

Outcome: Bridging simulation and experimental validation toward **intelligent, low-power, and reconfigurable wireless environments.**

RIS vs Metasurface



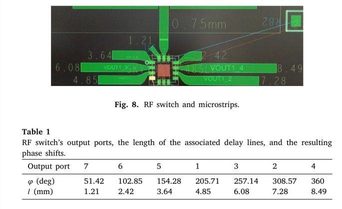


Fig. 8. RF switch and microstrips.

Table 1
RF switch's output ports, the length of the associated delay lines, and the resulting phase shifts.

Output port	7	6	5	1	3	2	4
φ (deg)	51.42	102.85	154.28	205.71	257.14	308.57	360
l (mm)	1.21	2.42	3.64	4.85	6.08	7.28	8.49

[1]

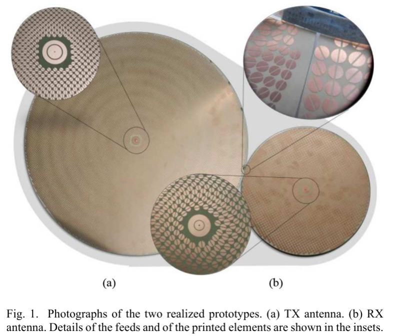


Fig. 1. Photographs of the two realized prototypes. (a) TX antenna. (b) RX antenna. Details of the feeds and of the printed elements are shown in the insets.

[2]

[1] M. Rossanese et al., "Design and validation of scalable reconfigurable intelligent surfaces," Computer Networks, vol. 241,2024.
[2] M. Faenzi et al., "Realization and Measurement of Broadside Beam Modulated Metasurface Antennas," in IEEE Antennas and Wireless Propagation Letters, 2016.

Frequency-selective surfaces (Metaprism)

RIS Disadvantages:

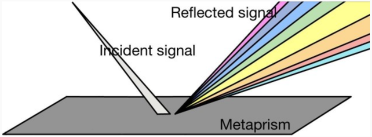
- Real-time reconfiguration requires a control channel → signaling overhead, cost, and complexity.
- CSI estimation is challenging → may need extra hardware or dedicated protocols.

Alternative 1: Frequency-Selective Surfaces (Metaprism)
Alternative 2: Self-Conjugating Metasurface (SCM). SCMs are metasurfaces that *retro-direct* incoming signals and can embed data in the reflected wave.

Localization and communication algorithms for SREs

NLOS Localization with Metaprism

The metaprism is a passive, non-reconfigurable metasurface. The reflection angle depends on signal frequency. By designing cell impedance, the metasurface can exhibit a frequency-dependent reflection across the bandwidth W.



In the next-generation wireless systems: *Integrated Sensing and Communication (ISAC)*. Indoor/obstacle-rich scenarios make target localization difficult; RISs are one solution, but RISs have limitations (reconfigurability, CSI, power) → metaprism as passive alternative.

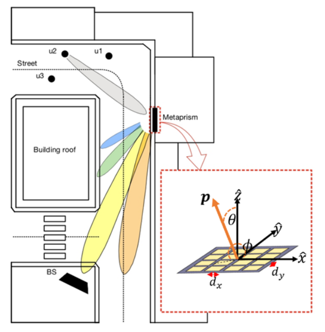


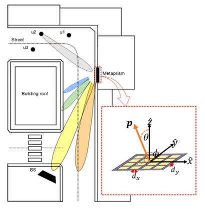
Figure 1: Example scenario for ISAC

Metaprism Design – Frequency-Dependent Reflection

- Each metaprism cell has frequency-dependent reflection:

$$r_{nm}(f) = e^{j\Psi_{nm}(f)}, \quad \Psi_{nm}(f) = \alpha_{nm}(f - f_r)$$

- **Design criteria:**
  - **Beamsteering (far-field):** linear phase gradient $\alpha_{nm} = a_0 x_n + b_0 y_m \rightarrow$ directs reflections predictably.
  - **Random design (near-field):** $\alpha_{nm} \sim \mathcal{UD}(0, 10^{-6}) \rightarrow$ unique frequency signature for each user position.
- The **array factor** determines the reflected signal direction for each OFDM subcarrier, enabling localization.

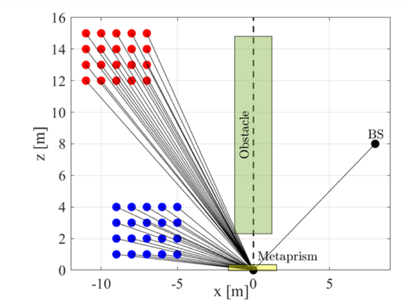


Signal Model and Localization

- Received signal at BS (per subcarrier):

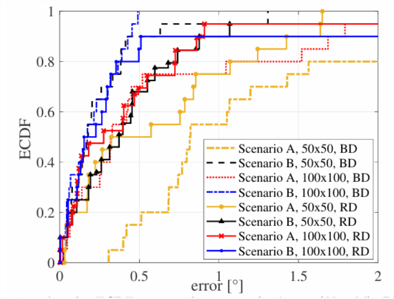
$$y_k = s_k(\mathbf{p}_u) + v_k + n_k, \quad \widehat{\mathbf{p}}_u = \arg\max_{\mathbf{p}_u} \sum_k \mathrm{Re}(y_k s_k^*(\mathbf{p}_u))$$

- Exploits frequency-dependent signature of metaprism (*fingerprinting localization*).
- Near-field vs far-field handled by random vs beamsteering α_{nm} design.

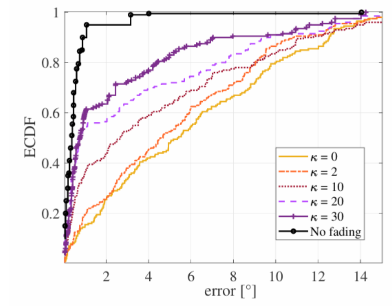


Parameter	Value
f_0	28 GHz
P_T	20 dBm
$G_{\mathrm{BS}} = G_{\mathrm{UE}}$	6 dB
W	198 MHz
K	3300
$\mathbf{p}_{\mathrm{BS}}$	$(8, 0, 8)$ m
F_{noise}	3 dB
$N \times M$	50×50 $(26.7 \times 26.7\mathrm{cm}^2)$ to 100×100 $(53.5 \times 53.5\mathrm{cm}^2)$

Numerical Results



Angular ECDF vs metasurface size ($N \times M$). BD=beamsteering, RD=random. No fading.

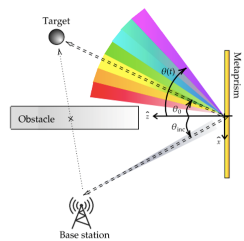


Angular ECDF vs Rice factor κ (scenario B).

M. Lotti, G. Calesini, D. Dardari, ”NLOS Localization Exploiting Frequency-selective Metasurfaces,” IEEE ICC Workshops, 2024.

NLOS localization using metaprism - FMCW

Goal: estimate the target position (angle and distance) using an FMCW signal reflected by a metaprism. The **BS acts as a radar**, transmitting a FMCW. The **metaprism** is in LOS with both the BS and the target. No particular assumption is made on the BS antenna (can be single-element or array).



Suppose the transmitted signal impinges on the metaprism with an incident angle $\Theta_{\mathrm{inc}} = (\theta_{\mathrm{inc}}, 0)$ in the x–z plane ($\phi = 0^\circ$). Then the **frequency-dependent reflection angle**:

$$\theta(f) = \arcsin\left(-\sin(\theta_{\mathrm{inc}}) - \frac{a_0\lambda}{2\pi}(f - f_0)\right). \qquad (1)$$

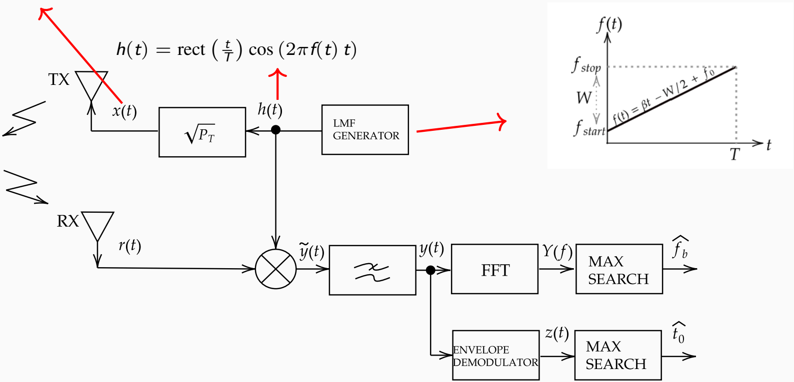
When illuminated by an FMCW signal, the reflection angle becomes **time-dependent** during the chirp duration T:

$$\theta(t) = \arcsin\left(-\sin(\theta_{\mathrm{inc}}) - \frac{a_0\lambda}{2\pi}\,(\beta t - W/2)\right). \qquad (2)$$

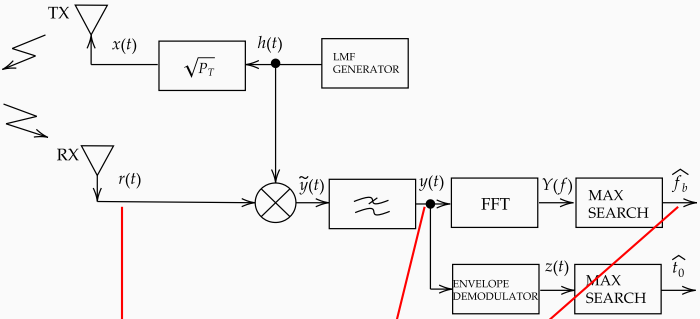
NLOS localization using metaprism: receiver structure

$$x(t) = \sqrt{2\mathrm{P}_T}\, h(t)$$

$$h(t) = \mathrm{rect}\left(\frac{t}{T}\right) \cos\left(2\pi f(t)\, t\right)$$



NLOS localization using metaprism: receiver structure



$r(t) = \sqrt{2p(t)}\cos\big(2\pi f(t-\tau)(t-\tau) + \phi_r\big) + n(t)$

with $\tau = \frac{2r_0}{c}$,

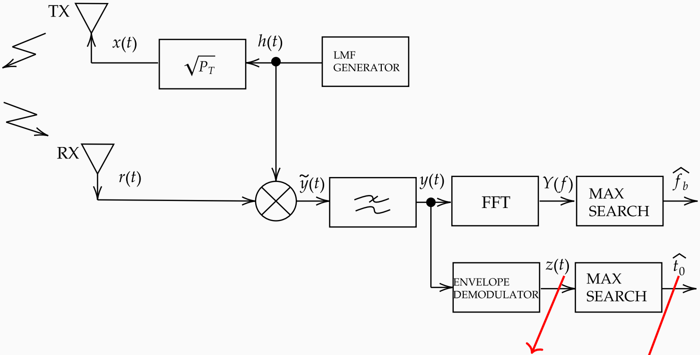
$n(t)$ AWGN noise, ϕ_r carrier phase.

$$y(t) = s(t - t_0)\cos(2\pi f_b t + \phi_Y) + w(t)$$

$$\phi_Y = 2\pi f_0 \tau - \pi W \tau - 2\pi\beta\tau^2$$

$$f_b = 2\beta\tau = \frac{4r_0\beta}{c}$$

NLOS localization using metaprism: receiver structure



$$z(t) \simeq s(t - t_0) + v(t)$$

$$\theta(t) = \arcsin\left(-\sin(\theta_{\text{inc}}) - \frac{a_0\lambda}{2\pi}\left(\beta t - W/2\right)\right)$$

NLOS localization using metaprism: Theoretical performance of θ_0 estimation

Since θ_0 is obtained through the estimation of the intermediate parameter t_0, we first compute the CRLB on the estimation error variance of t_0:

$$\mathrm{CRLB}_{t_0} = \frac{N_0}{2(2\pi)^2 B_{\mathrm{eff}}^2 E_s} = \frac{1}{8\pi^2\,\mathrm{SNR}\,B_{\mathrm{eff}}^2}\,, \tag{3}$$

where

$$B_{\mathrm{eff}}^2 = \frac{\int f^2 |S(f)|^2 df}{\int |S(f)|^2 df}, \qquad \mathrm{SNR} = \frac{E_s}{N_0} = \frac{1}{N_0}\int_T p(t)\,dt.$$

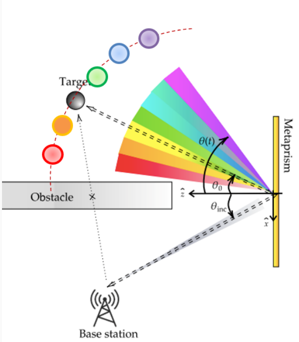
The CRLB of θ_0 follows from $\mathrm{CRLB}_{\theta_0} = \mathrm{CRLB}_{t_0}\left(\frac{\partial\theta(t)}{\partial t}\right)^2$, where the derivative is evaluated at $t = t_0$, given by

$$t_0 = \frac{W}{2\beta} - [\sin(\theta_0) + \sin(\theta_{\mathrm{inc}})]\,\frac{2\pi}{a_0\lambda\beta}\,. \tag{4}$$

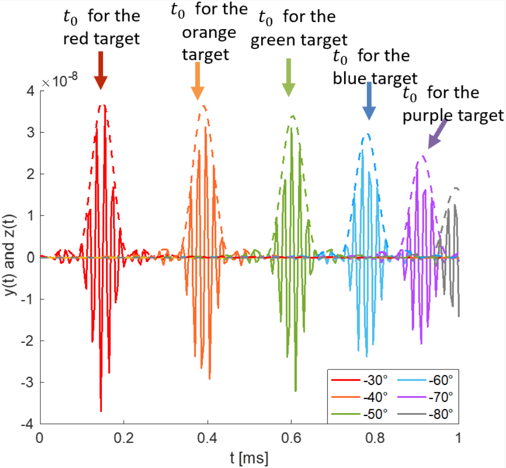
By substitution and simplification, we obtain:

$$\boxed{\mathrm{CRLB}_{\theta_0} = \frac{K^2}{8\pi^2\,\mathrm{SNR}\,B_{\mathrm{eff}}^2\cos^2(\theta_0)}}, \quad \text{with } K = \frac{a_0\lambda\beta}{2\pi}\,. \tag{5}$$

NLOS localization using metaprism: Numerical results



Parameter	Symbol	Value
Carrier frequency	f_0	77 GHz
BS antenna gain	G_T	5 dB
Bandwidth	W	4 GHz
Chirp time	T	1 ms
Target radius	r	0.05 m
Receiver's noise figure	F_{noise}	3 dB
Test angles	θ_{test}	-(0:3:90)°
Parameter for F	q	0.57


t_0 for the red target

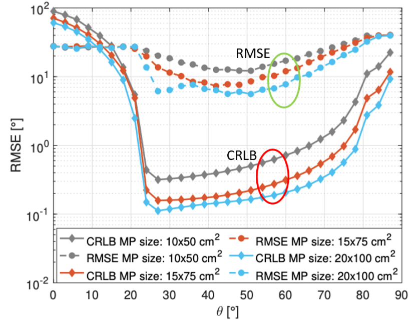
t_0 for the orange target

t_0 for the green target

t_0 for the blue target

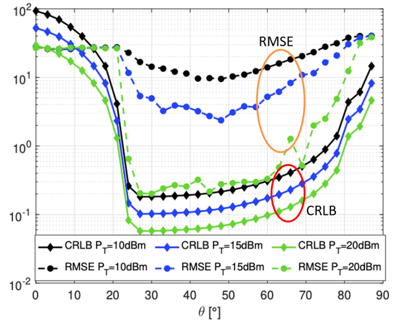
t_0 for the purple target

NLOS localization using metaprism: Numerical results



RMSE varying the metaprism size,

$P_{\mathrm{T}} = 15$ dBm



RMSE varying the P_{T},

metaprism size: $20 \times 50\,\mathrm{cm}^2$

Lotti Marina, and Davide Dardari. "Metaprism-aided NLOS target localization." 2023 31st EUSIPCO, IEEE.

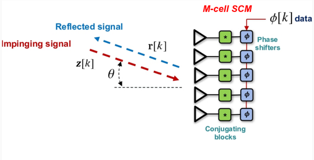
SCM: establishing MIMO communications automatically

Why SCM?

- **mmWave/THz** systems rely on (massive) MIMO to mitigate path loss and support dense users.
- Devices must be **low-complexity, low-power**, and react to **fast channel variations**.
- < 100 *microsec* **latency** required for beam alignment and access.
- Conventional methods need long training or complex feedback.

Signal Model: $\mathbf{r}[k] = g\, e^{j\phi[k]}\, \mathbf{z}^*[k], \quad \mathbf{z}[k] = A[k][1, e^{j\theta_1}, \ldots, e^{j\theta_{M-1}}]^T + \boldsymbol{\eta}[k],$

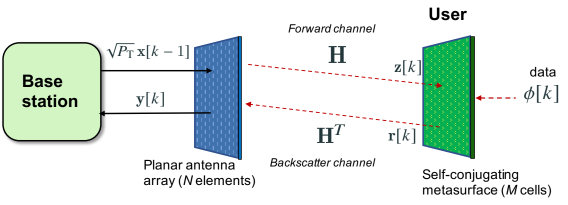
where $\phi[k]$ encodes transmitted information and $\boldsymbol{\eta}[k]$ is AWGN.



The SCM concept: three pillars

1. **Retrodirective antenna (UE):** reflects incoming waves toward their origin.
2. **EM-level modulation:** UE encodes data by phase-modulating the reflected signal.
3. **Smart BS algorithm:** jointly demodulating the received data and deriving the optimal precoding vector.

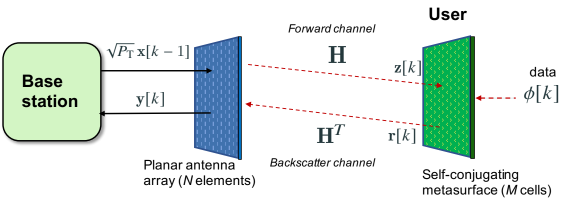
SCM: establishing MIMO communications automatically



Assumptions:

- Narrow-band channel with bandwidth B. Symbol time T=1/W
- Full-duplex BS (or separated antennas)
- No complexity limitation on the BS
- Synchronization at the symbol level

SCM: establishing MIMO communications automatically

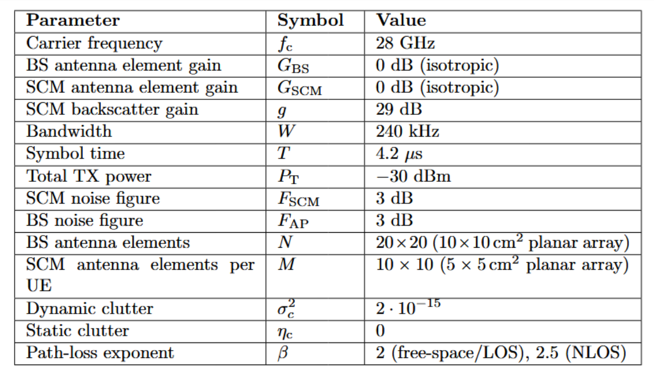


Algorithm: Modified Power Method (or Von Mises Iteration) for joint communication and beamforming between the single-UE and the BS

```
Initialization: generate a guess unitary norm precoding vector $\mathbf{x}[0]$ ;
for $k = 1, \ldots, K$ do
    transmit: $\sqrt{P_T}\,\mathbf{x}[k-1]$ ;                               // signal transmitted by the BS
    $\mathbf{z}[k] = \sqrt{P_T}\,\mathbf{H}\,\mathbf{x}[k-1] + \boldsymbol{\eta}[k]$ ;          // signal received by the UE
    $\mathbf{r}[k] = g e^{\jmath\phi[k]} \mathbf{z}^*[k]$ ;                           // signal retrodirected by the UE
    receive: $\mathbf{y}[k] = e^{\jmath\phi[k]}\,\mathbf{A}^*\,\mathbf{x}^*[k-1] + \mathbf{n}^*[k]$ ;   // signal received by the BS
    $\mathbf{x}[k] = \mathbf{y}^*[k] / \|\mathbf{y}[k]\|$ ;                              // precoding vector update
    $u[k] = \mathbf{x}^\dagger[k-1]\,\mathbf{x}[k]$ ;                                  // decision variable
    $\widehat{\phi}[k] = \text{detection}\,(-\arg\{u[k]\})$ ;                          // data detection
end
```

where $\mathbf{A} = \sqrt{P_T}\, g\, \mathbf{H}^\dagger \mathbf{H} \in \mathbb{C}^{N \times N}$ is the (modified) round-trip channel, and $\mathbf{n}^*[k]$ is the total noise.

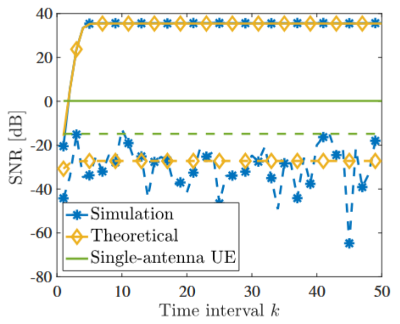
SCM: numerical result

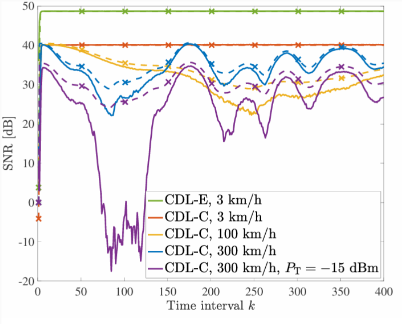


Parameter	**Symbol**	**Value**
Carrier frequency	f_c	28 GHz
BS antenna element gain	G_{BS}	0 dB (isotropic)
SCM antenna element gain	G_{SCM}	0 dB (isotropic)
SCM backscatter gain	g	29 dB
Bandwidth	W	240 kHz
Symbol time	T	4.2 μs
Total TX power	P_{T}	-30 dBm
SCM noise figure	F_{SCM}	3 dB
BS noise figure	F_{AP}	3 dB
BS antenna elements	N	20×20 ($10\times10\,\mathrm{cm}^2$ planar array)
SCM antenna elements per UE	M	10×10 ($5\times5\,\mathrm{cm}^2$ planar array)
Dynamic clutter	σ_c^2	$2\cdot10^{-15}$
Static clutter	η_c	0
Path-loss exponent	β	2 (free-space/LOS), 2.5 (NLOS)

Simulation parameters

SCM: numerical result



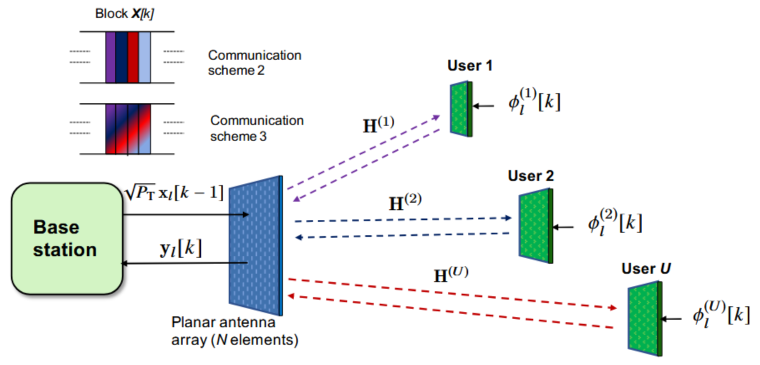


Free space propagation. Dynamic clutter. Continuous lines $P_T = -30$ dBm; dashed lines $P_T = -45$ dBm.

Transients of the SNR for the single-user scenario. Dynamic clutter. LOS/NLOS 3GPP channel models. Continuous lines refer to simulation results; dashed lines with markers refer to theoretical curves. $P_T = -10$ dBm.

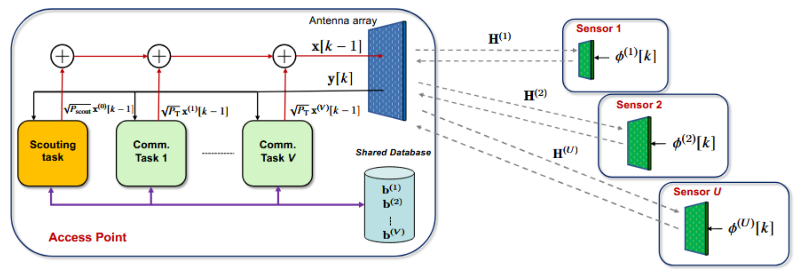
Dardari D., Lotti M., Decarli N., Pasolini G. Establishing MIMO communications automatically using self-conjugating metasurfaces. ICC May 2023.

SCM: Multi-user Communication



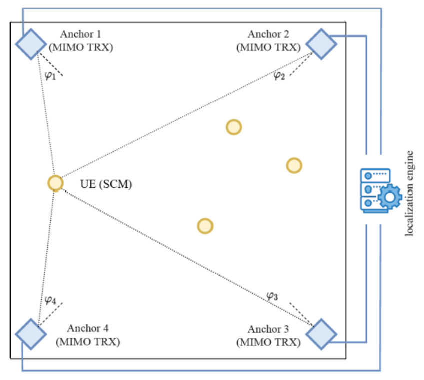
Dardari D., Lotti M., Decarli N., Pasolini G. Establishing multi-user MIMO communications automatically using retrodirective arrays. IEEE Open Journal of the Communications Society, 4, 1396-1416.

SCM: Grant-Free Random Access scheme

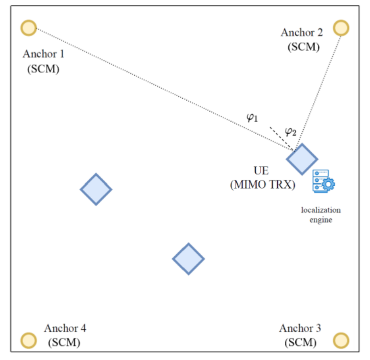


Dardari D., Lotti M., Decarli N., Pasolini G. Grant-Free Random Access With Backscattering Self-Conjugating Metasurfaces. 2024, IEEE Transactions on Cognitive Communications and Networking.

SCM: Localization scheme



Localization of SCMs-equipped mobile UEs (yellow circles) by using array-equipped anchors (blue squares). Anchors are also labelled a MIMO transceivers (TRX).



Navigation of array-equipped mobile UEs (blue squares) through the interaction with SCMs (yellow circles) used as anchor nodes. UEs are also labeled MIMO transceivers (TRX).

Lotti, M., Decarli, N., Pasolini, G., and Dardari, D. (2025). Real-time Localization Based on MIMO Backscattering from Retro-Directive Antenna Arrays. IEEE Transactions on Vehicular Technology.

Conclusions

Conclusions

Smart Radio Environments:

- Relies on enabling technologies such as **Reconfigurable Intelligent Surfaces**.
- **RISs** can re-radiate incident signals at angles *beyond Snell's law*, following a generalized reflection principle.
- When the surface is **non-reconfigurable** yet still controls the reflection angle, it is referred to as a **metasurface**.
- These passive structures require no active components while maintaining advanced reflection control capabilities.

In this work:

- Two types of metasurfaces were investigated:
  - *Metaprism* → a frequency-selective metasurface;
  - *Self-Conjugated Metasurface (SCM)* → exploits retroreflectivity.
- Both demonstrated **communication and localization performance** comparable to active RISs.

Metasurfaces pave the way toward low-complexity, energy-efficient Smart Radio Environments.

Pubblication List

[1]. **M. Lotti**, G. Pasolini, A. Guerra, F. Guidi, M. Caillet, R. D'Errico, D. Dardari, "Radio simultaneous localization and mapping in the terahertz band", *WSA 2021; 25th International ITG Workshop on Smart Antennas, Sophia-Antipolis, Nov. 2021*.

[2]. **M. Lotti**, G. Pasolini, A. Guerra, F. Guidi, M. Caillet, R. D'Errico, D. Dardari, "Radio SLAM for 6G systems at THz frequencies: Design and experimental validation", *IEEE Journal of Selected Topics in Signal Processing, vol. 17, no. 4, pp. 834-849, July 2023*.

[3]. **M. Lotti**, D. Dardari, "Metaprism-aided NLOS Target Localization" *31st European Signal Processing Conference (EUSIPCO), Helsinki, Finland, Sep. 2023, pp. 895-899*.

[4]. D. Dardari, **M. Lotti**, N. Decarli, G. Pasolini, "Establishing MIMO communications automatically using self-conjugating metasurfaces", *IEEE International Conference on Communications (ICC), Rome, Italy, Jun. 2023, pp. 1286-1292*. ***(Best Paper Award in SAC-Reconfigurable Intelligent Surfaces and Smart Environments)***

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[6]. D. Dardari, **M. Lotti**, N. Decarli, G. Pasolini, "Establishing multi-user MIMO communications automatically using retrodirective arrays", *IEEE Open Journal of the Communications Society, vol. 4, pp. 1396-1416, Jun. 2023*.

[7]. D. Dardari, **M. Lotti**, N. Decarli, G. Pasolini, "Grant-Free Random Access With Backscattering Self-Conjugating Metasurfaces", *IEEE Transactions on Cognitive Communications and Networking, vol. 10, no. 5, pp. 1620-1634, Oct. 2024*.

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Thank you for your attention!

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