“Tutorial Presentation: Ambient Sensing through Reconfigurable Intelligent Surfaces”

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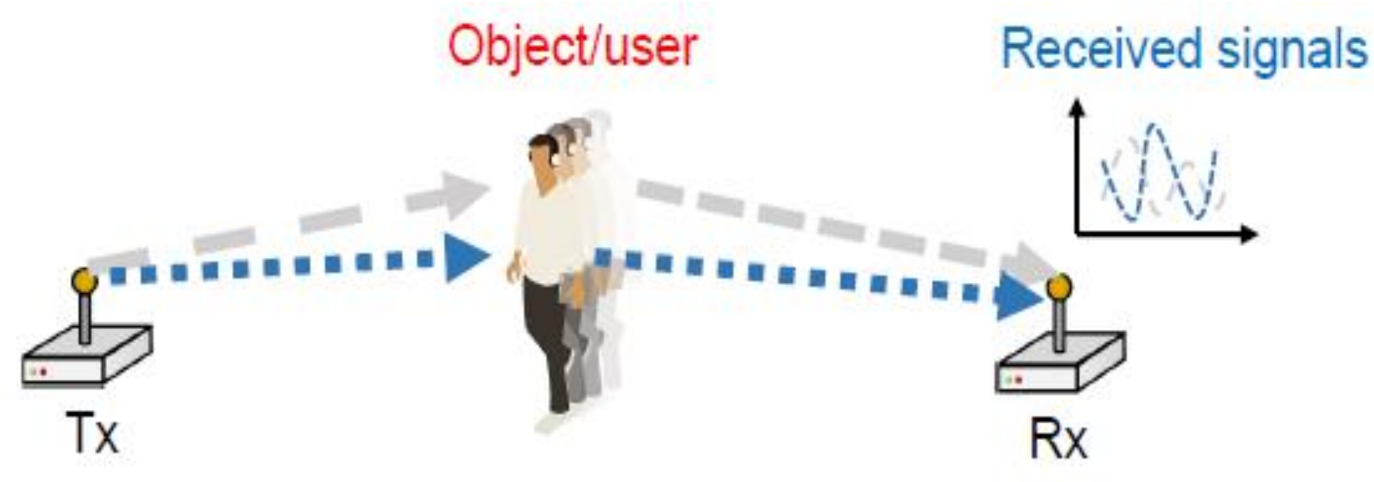
Working principle of wireless sensing

• **RF sensing** is the process of **detecting** and **tracking** targets, such as vehicles, obstacles, humans, and so on, and **estimating** their relative range, velocity, size, shape, orientation, and material properties **by extracting information from wireless signals.**



✓ The existence of objects within the sensing area will cause significant signal attenuation, i.e., α (the path loss exponent) will be different, which leads to the variation of RSS measurements, as follows (d:Distance between Tx and Rx, n_{RSS} :Noise for the RSS measurement):

$$P(d) = P_T - 10\alpha \log d + n_{RSS}$$

Typical applications of wireless sensing

- **Radar sensing,** where the radar radiates electromagnetic waves to hit the target and the reflected echo signals are received to estimate the target's physical information such as distance, velocity, azimuth, height, etc.
- **Wireless localization,** where wireless device sends signal to one or more BSs to estimate its location.
- **Simultaneous localization and mapping (SLAM),** which extends wireless localization by simultaneously estimating the location of the wireless device as well as scatterers/obstacles in its surrounding environment for constructing a map of the unknown environment.
- **RF imaging**, which generates/reconstructs high-resolution image of environment objects by exploiting RF signals that bounce off the objects and are resolved in different dimensions such as time, space, and frequency.
- **Human-activity recognition,** which detects or recognizes human activities (e.g., gesture, sleep, and breathing) by leveraging the amplitude/phase variations in wireless signals.
- **Spectrum sensing**, which aims to obtain awareness about the spectrum usage and detect the existence of primary (high-priority) users to enable the communications of secondary (low-priority) users.

Limiting factors of existing wireless sensing systems

- **Non-availability of line-of-sight (LOS) link**: Wireless sensing performance can be significantly deteriorated in unfavorable propagation environment with severe signal blockages. In such a case (e.g. radar sensing or human activity recognition), only the signal that propagates over the LoS links is useful for sensing, while the signals from other non-LoS (NLoS) links cause interferences that lead to **degradation of the sensing accuracy.**

- **Lack of multipath propagation:** Some sensing applications, such as wireless localization, rely on the multipath propagation in the environment.

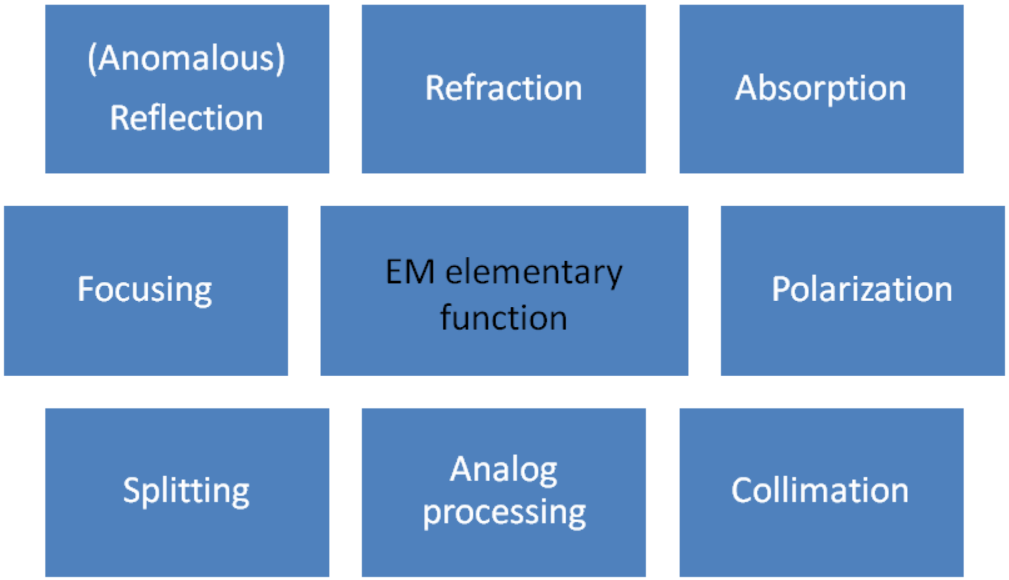
- **Limited sensing range due to high path loss:** Due to the increased path loss of wireless signals over distance, all sensing applications generally have **limited operation range and/or accuracy.**

Basics of Reconfigurable Intelligent Surfaces (RISs)

- RISs (or Intelligent Reflecting Surfaces- IRS) are expected to be a key enabling physical-layer technology for B5G/6G networks for implementing a **smart radio environment** (i.e., by making the wireless environment programmable and controllable).

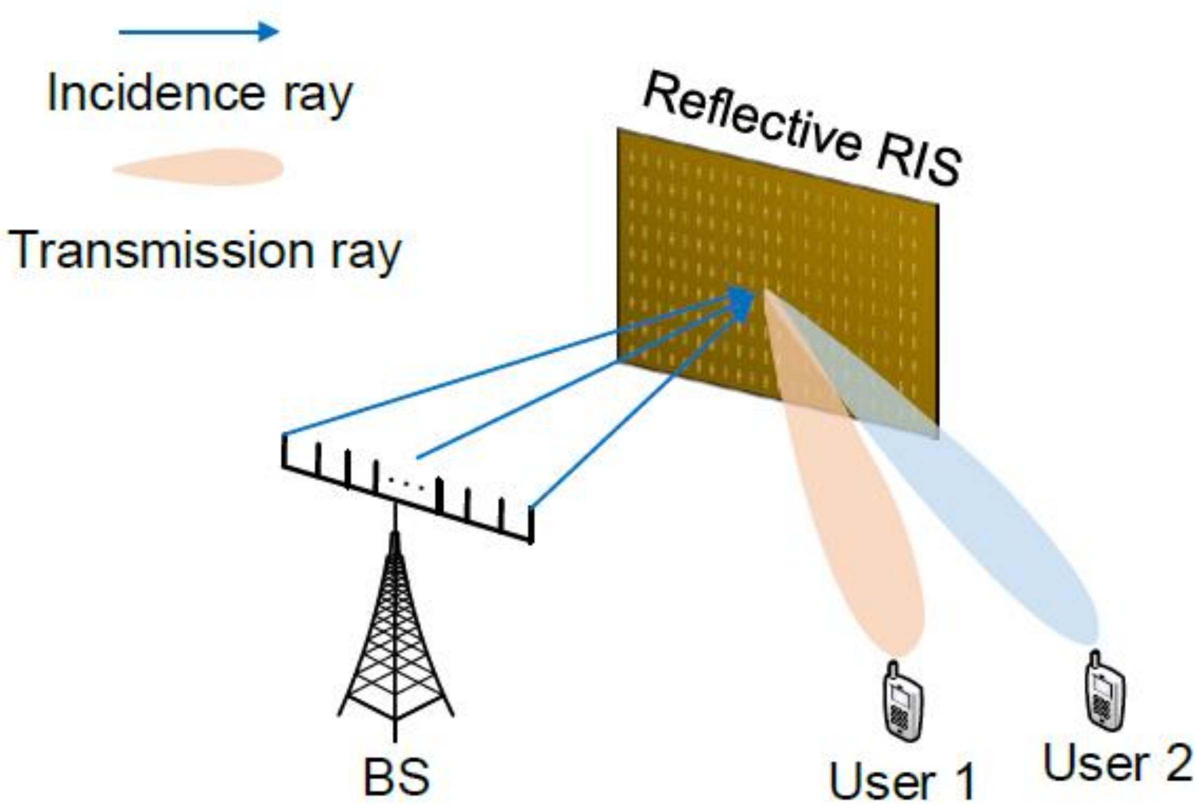
- RISs are, also, referred as **“digital controlled scatterers**” due to their possibility of digitally controlling the electromagnetic behavior of objects coated by them.

- The individual elements of an RIS are viewed as **local scatterers** which contribute to the overall macroscopic scattering model of the RIS.



Main RIS types according to implementation

- **Reflective type RIS:** The RIS only reflects incident signals towards the users on the same side of the Base Station (BS).



Main RIS types according to implementation

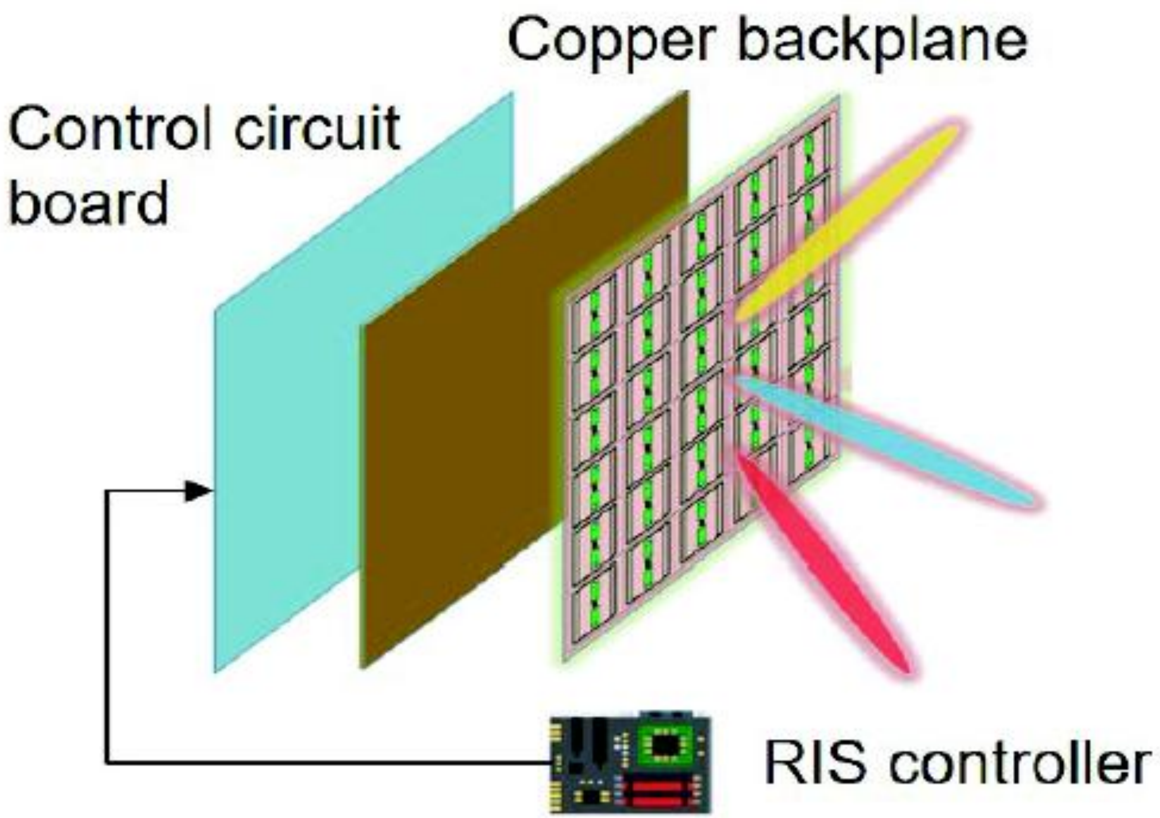
✓ **Components of a reflective type RIS:**

❖ **Outer layer**- A 2D-array of RIS elements, which can directly interact with incident signals.

❖ **Middle layer-** A copper plate that can prevent the signal energy leakage.

❖ **Inner layer-** A printed circuit connecting to the RIS controller, which can control the phase shifts of the RIS elements.

✓



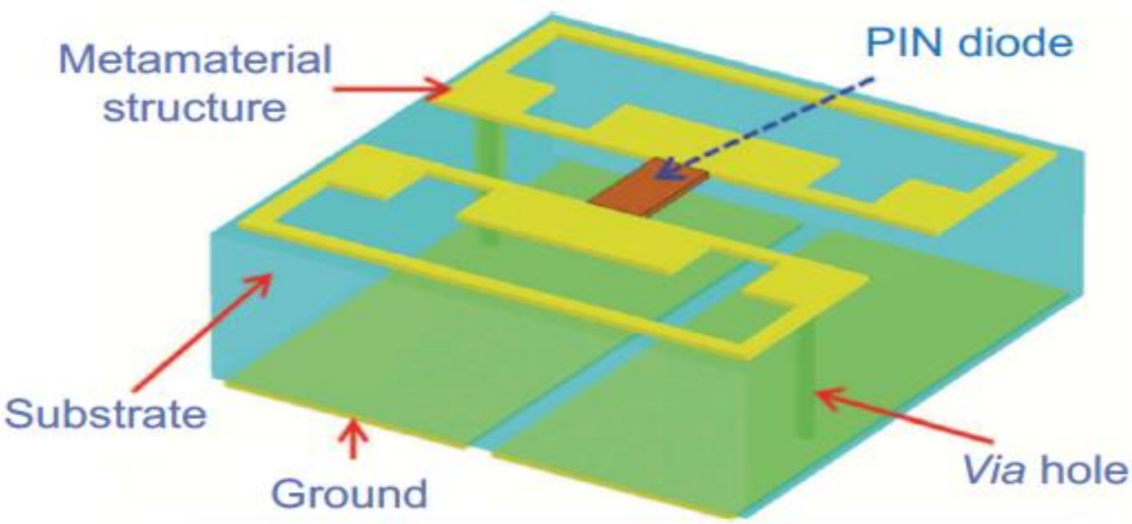
Main RIS types according to implementation

✓ **RIS element:**

❖ Each RIS element is a low-cost sub-wavelength programmable meta-material particle, whose working frequency can vary from sub-6 GHz to THz.

❖ When an EM wave impinges into the RIS element, a current will be induced by the EM wave, and **this induced current will emit another EM radiation** based on the permittivity ε **and** the permeability μ of the RIS.

❖ By controlling the biasing voltage through the via hole, the PIN diode can be switched between “ON” and “OFF” states. The “ON” **and** “OFF” states of the PIN diodes lead to different values of and . As a result, this element will have different response to incident signals by imposing different phase shifts and amplitude.



Main RIS types according to implementation

✓ **Response of a reflective type RIS element:**

$$\gamma = \Gamma e^{-j\theta}$$

✓ Amplitude of the RIS element response: $\Gamma \in [0,1]$

✓ $\Gamma = 1$ indicates that the incident signals are fully reflected.

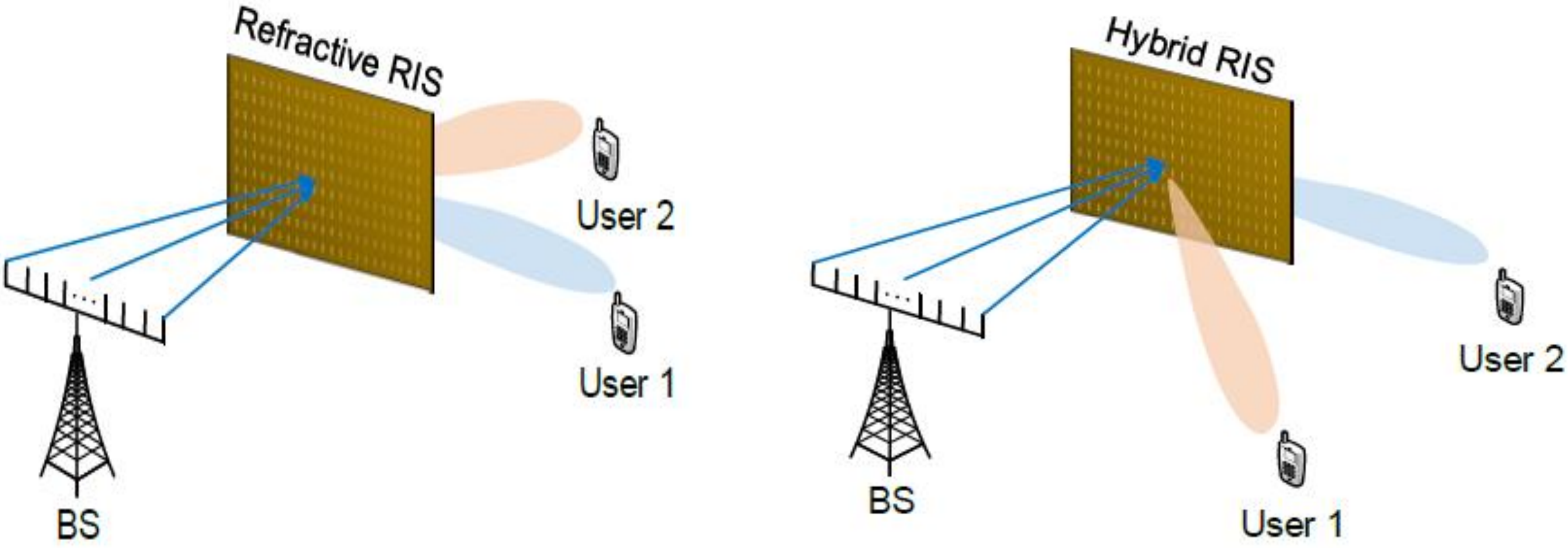
✓ $\Gamma = 0$ implies that the incident signals are fully absorbed.

✓ θ is the additional phase shift introduced by the RIS element.

The response depends on the tuning impedance of the equivalent circuit for each RIS element **and** mutual impedances (if mutual coupling cannot be ignored) at the ports of the RIS, which generally is influenced by azimuth **and** elevation angles for incident **and** reflected signals.

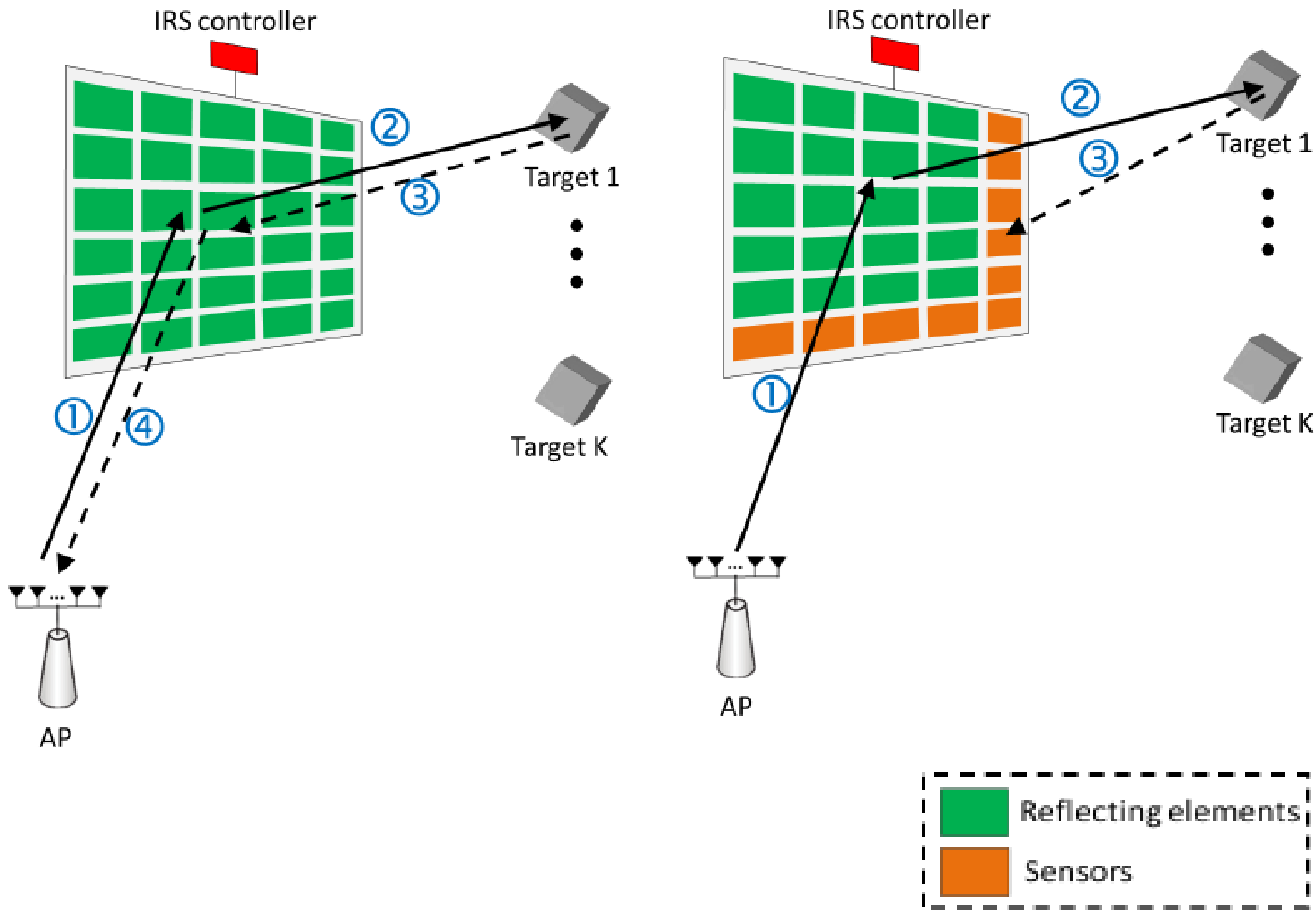
Main RIS types according to implementation

- **Refractive (left) and hybrid (right) type RIS**



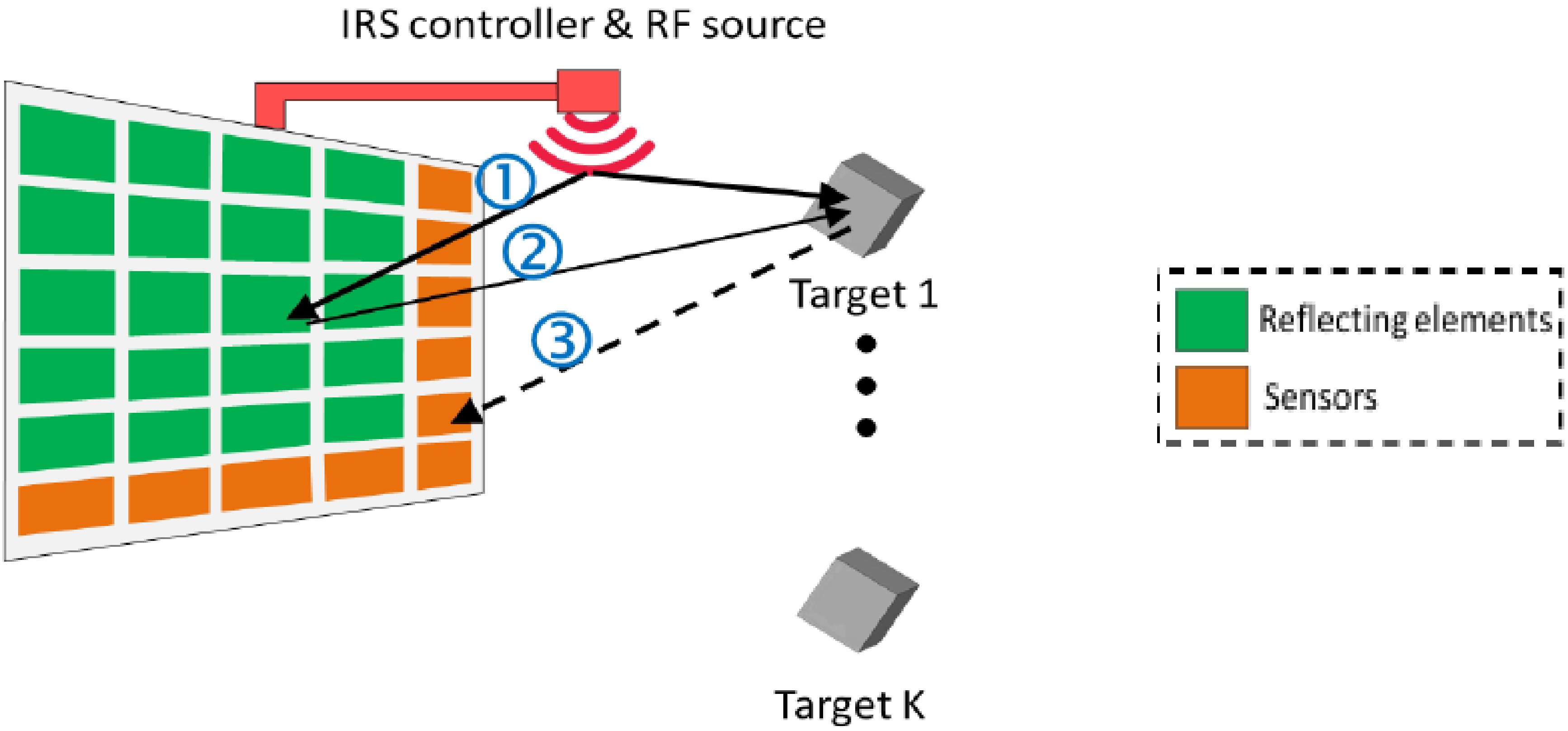
RIS types & RIS-aided radar sensing architectures

- **Passive sensing** with a **triple-reflection link** from the BS/AP's transmitter to its receiver (left) **and semi-passive sensing** whereas **additional low-cost sensors** are installed on the RIS (right).



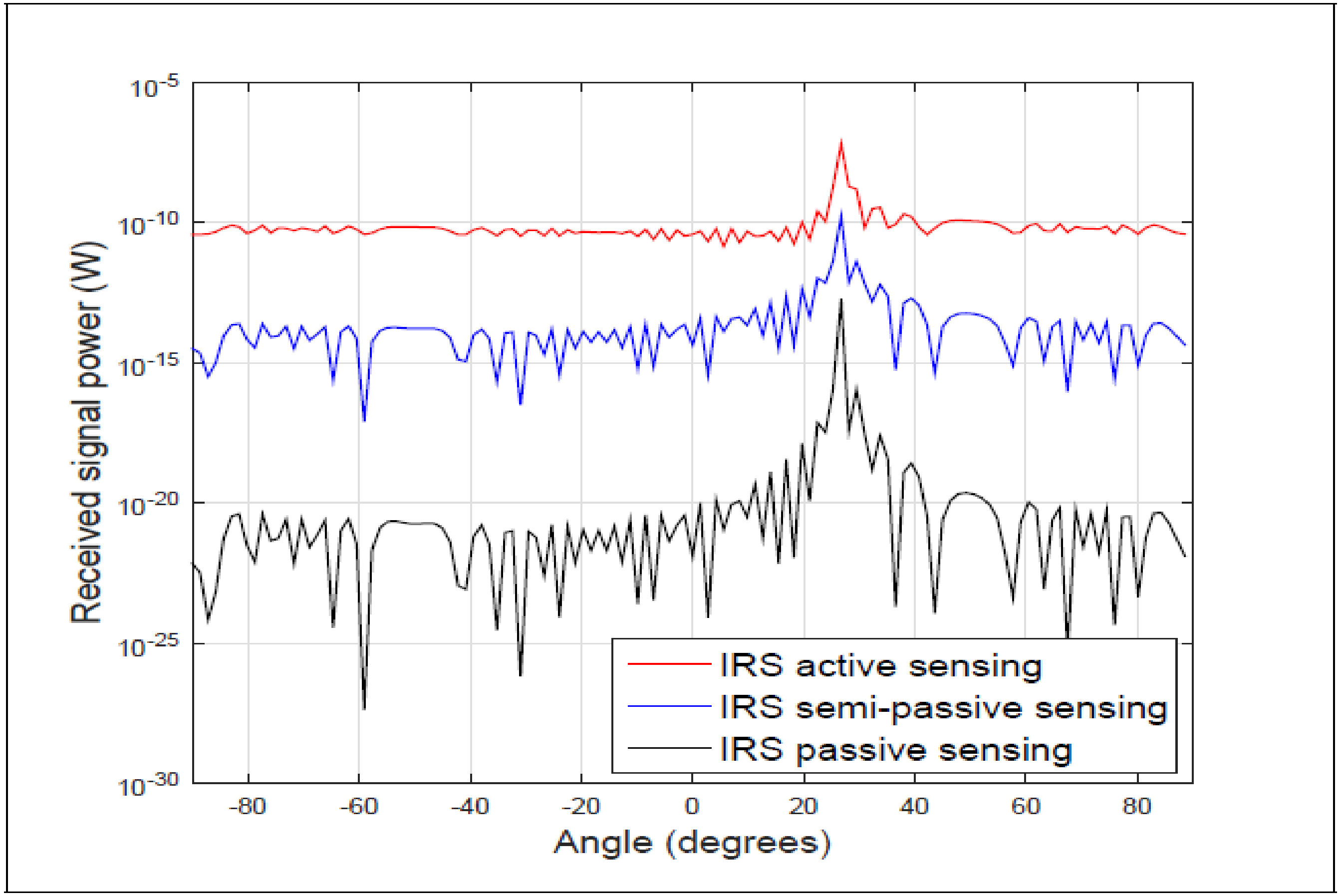
RIS types & RIS-aided radar sensing architectures

- **Active sensing,** whereas the RIS controller also acts as a transmitter (equipped with an RF source) **to send probing signals for sensin**g. Moreover, IRS active sensing can also leverage a **direct echo link**, i.e., RIS controller-target-RIS sensors, which can be combined constructively at the sensors with the **RIS reflected echo link.**

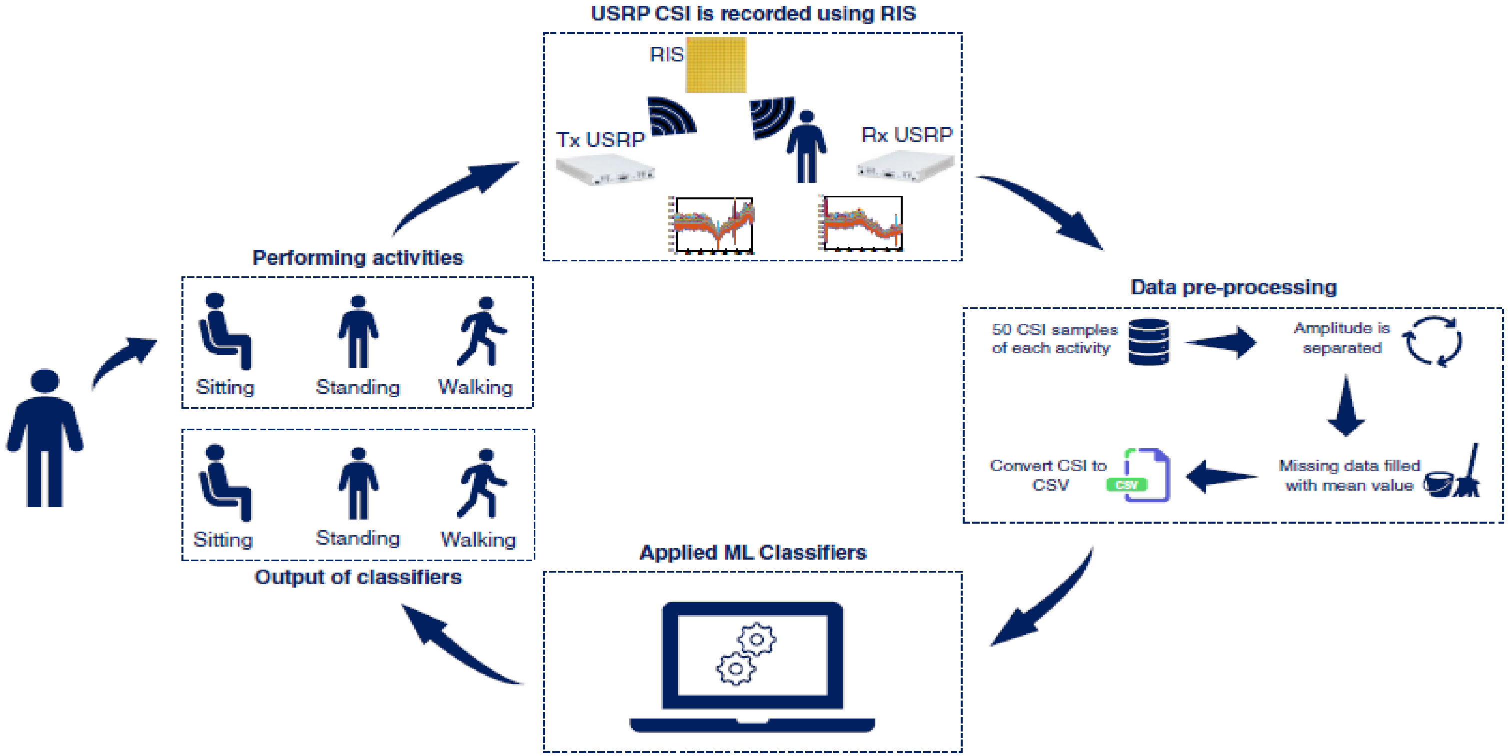


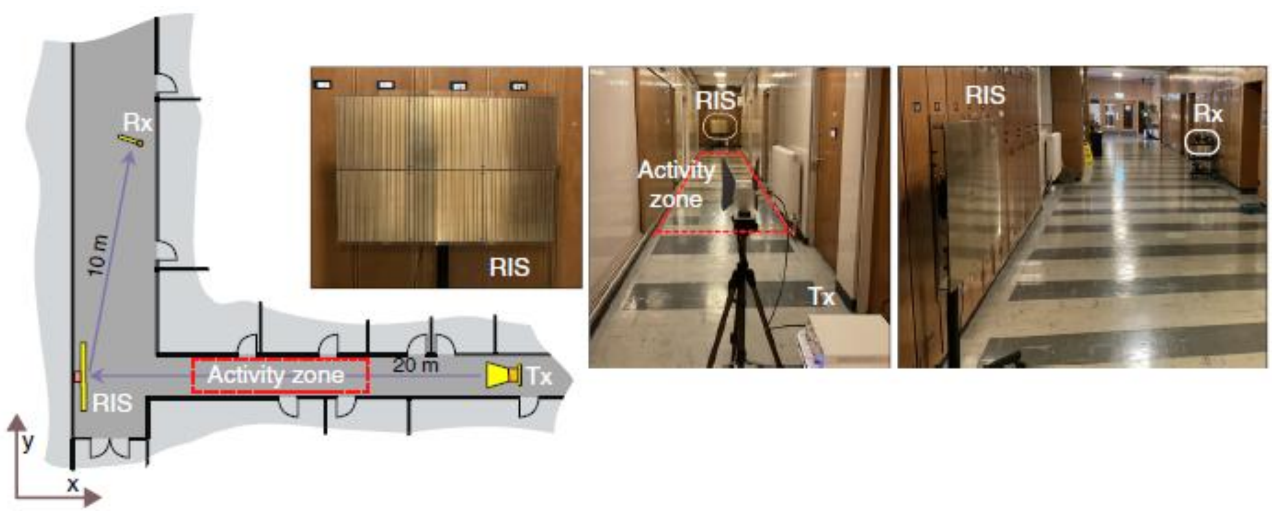
Comparison of RIS-aided radar sensing architectures: Features and Beampatterns

Architecture	Range	Cost	Accuracy	BS/AP needed?	Path Loss
Active sensing	Long	High	High	No	Low
Semi-passive sensing	Medium	Medium	Medium	Yes	High
Passive sensing	Short	Low	Low	Yes	Very high



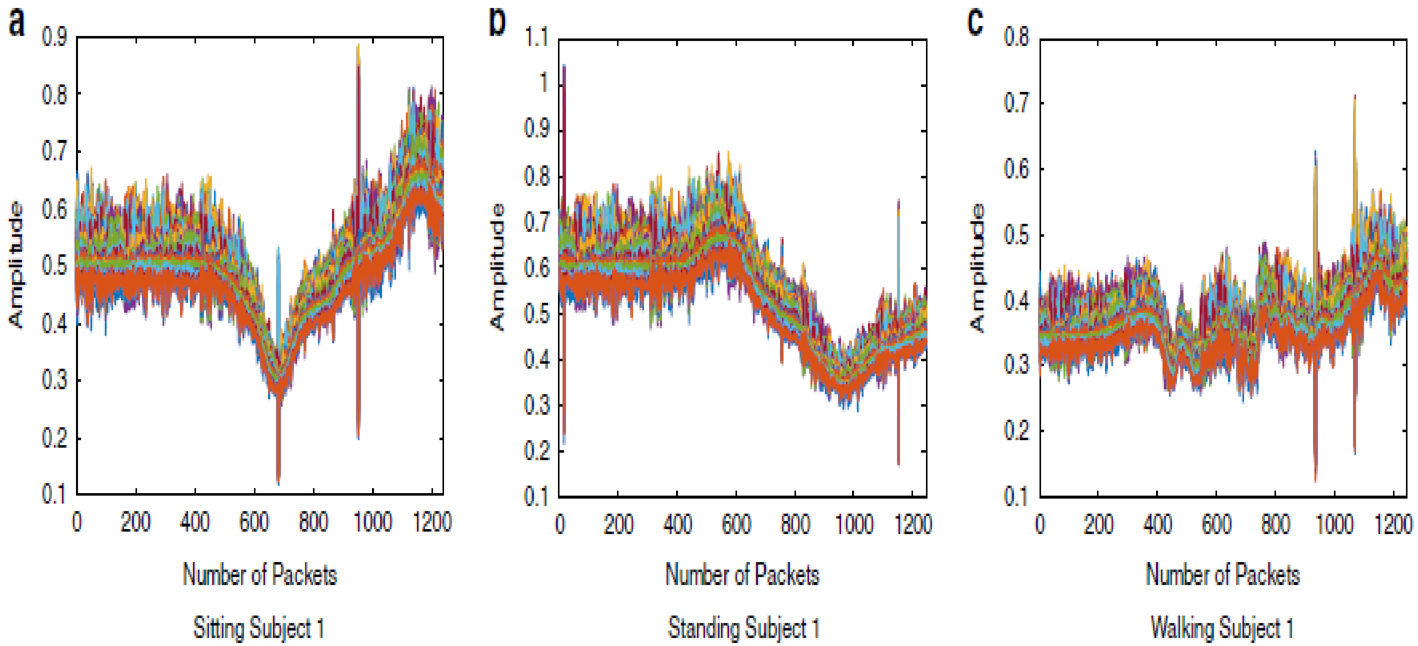
Experimental setup for posture recognition using RIS



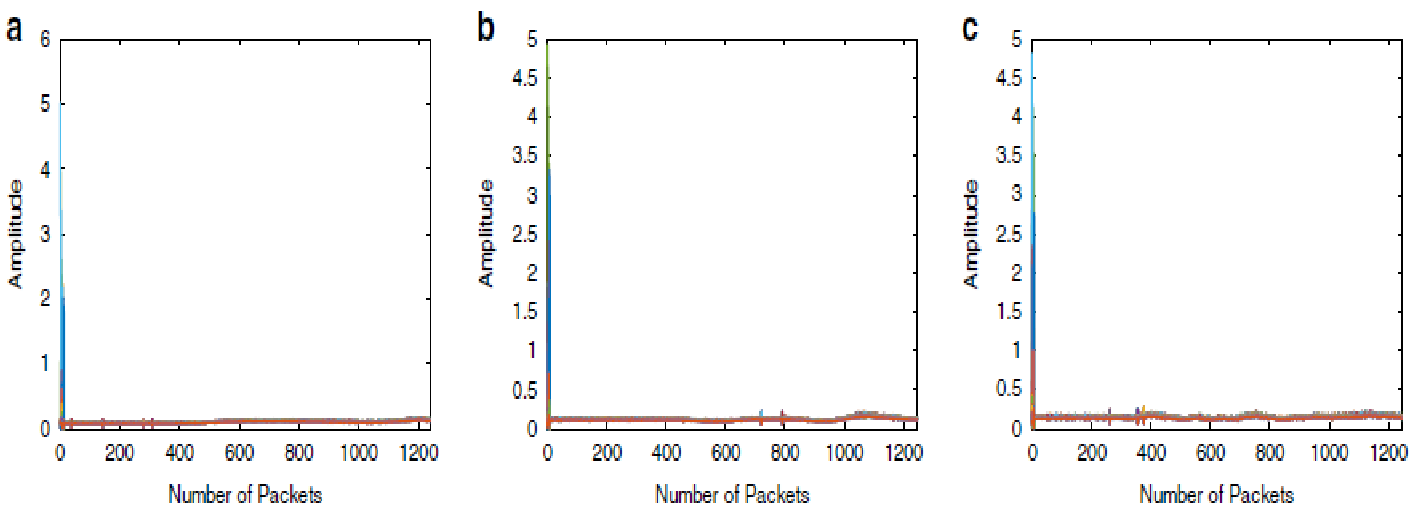


Experimental setup for posture recognition using RIS

RIS-on



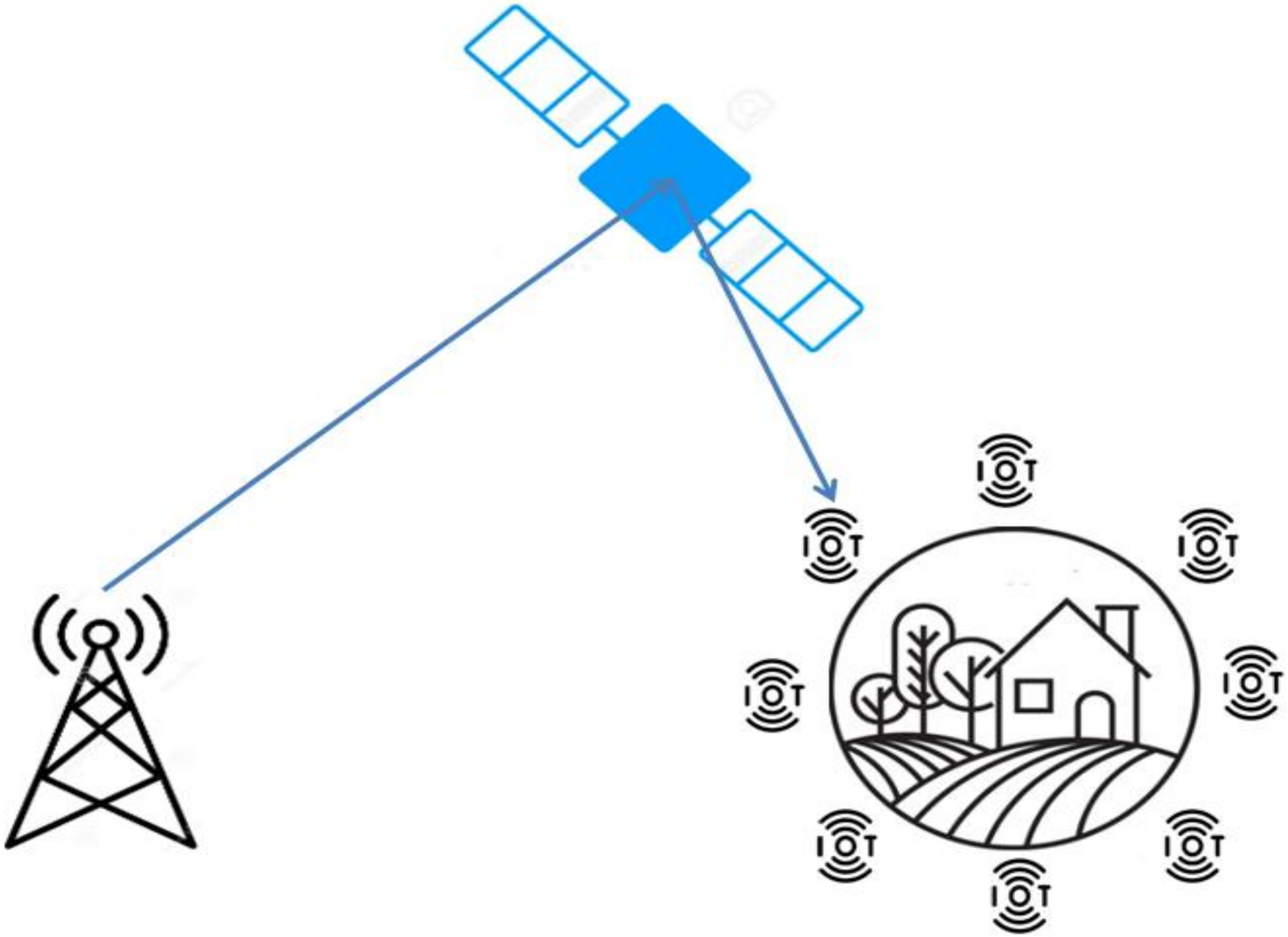
RIS-off



Representative RIS-aided communication use cases

• **Radio coverage enhancement** by creating **virtual Line-of-Sight link**s in low coverage areas or dead-zones for outdoor or indoor users.

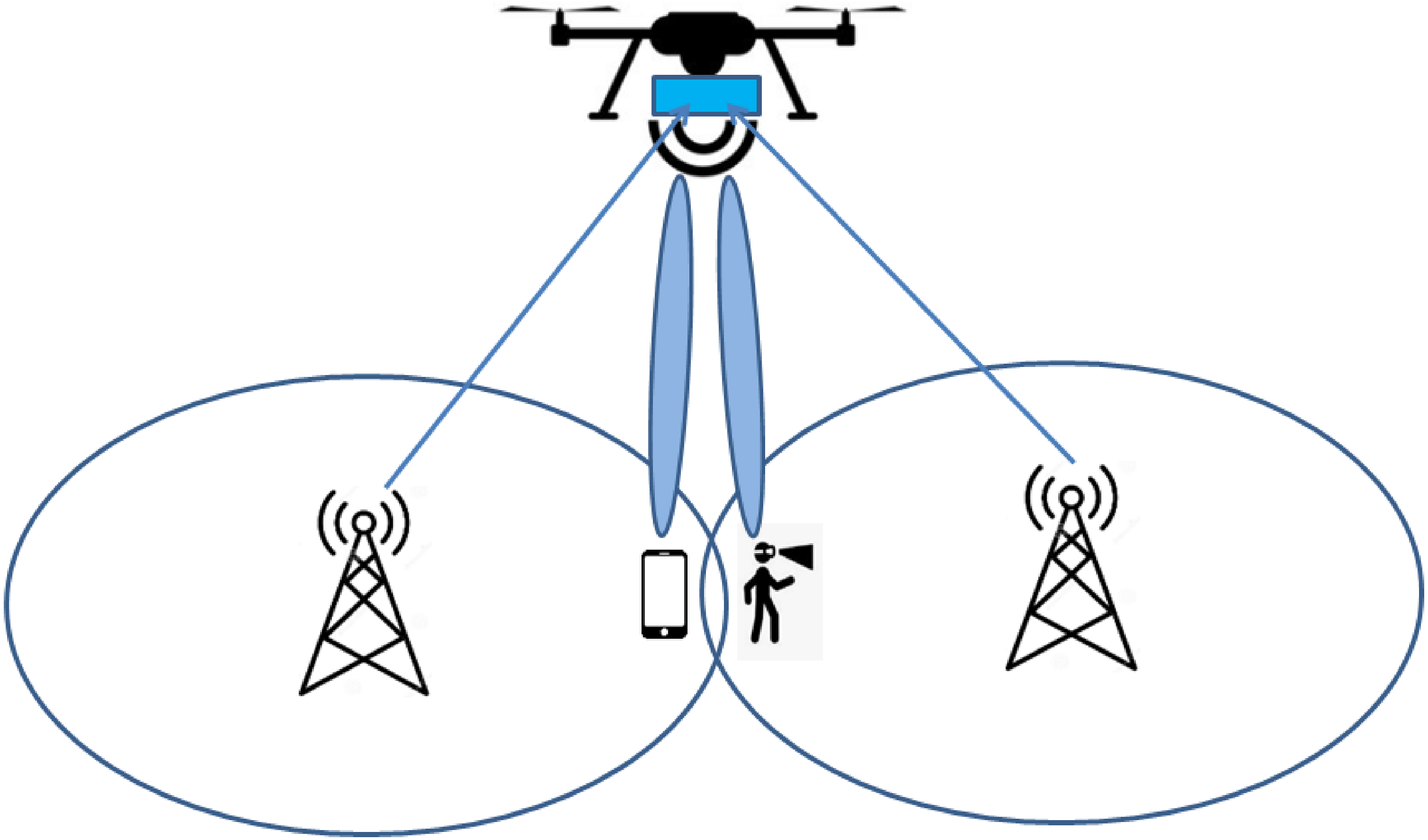
✓Example: Coverage enhancement of IoT devices through **space-to-ground communications.**



Representative RIS-aided communication use cases

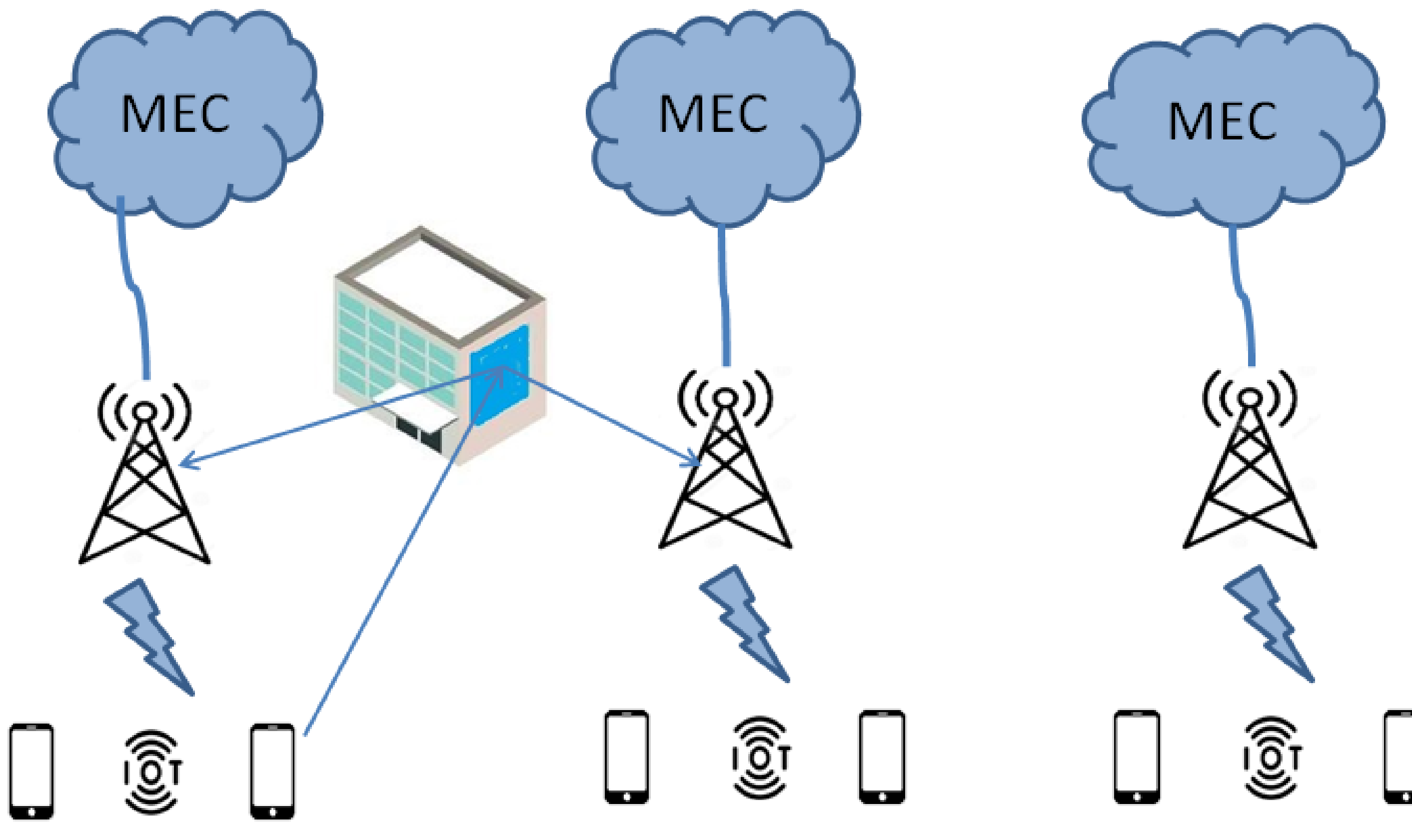
- **Increase of channel capacity** as calculated by the ergodic achievable rate R= E{log2(1+SINR)}.

✓Example: Higher achievable rates with RIS-equipped UAVs through air-to-ground communications **for cell-edge and AR/VR users**.



Representative RIS-aided communication use cases

• **Energy efficiency,** mainly due to the nearly-passive operation of RISs.
✓ Example: Higher Energy efficiency through minimizing the network power consumption through **RIS-aided MEC** for computing tasks performed by multiple BSs (Optimization variables: Set of tasks performed by each BS, the transmit and receive beamforming vectors, the transmit power of the mobile devices, the RIS phase shifts).



Integrated Communication and Sensing (ICAS)

- **ICAS** refers to the introduction of sensing capability as part of a wireless communication network in order to alleviate:

✓ Additional costs for infrastructure
✓ Inefficiencies in spectrum usage

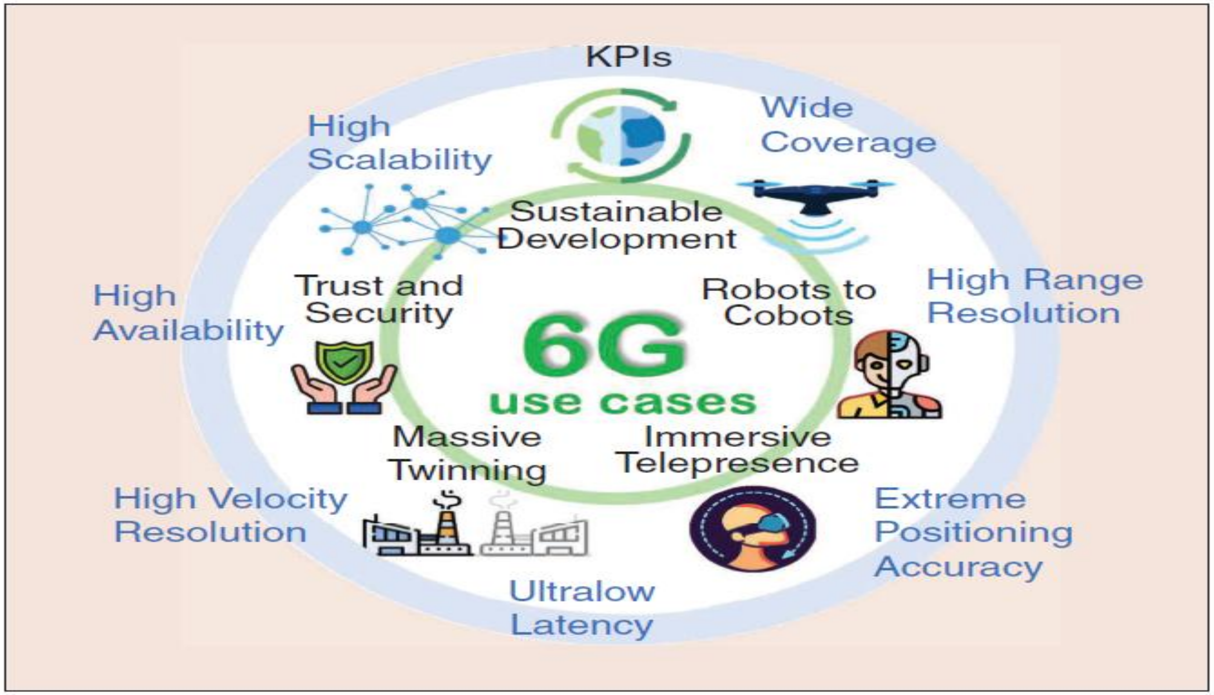
- Implementation of sensing for ICAS has to adapt to design aspects determined by the communication needs (although some enhancements and modifications are needed). For example:

✓ **Hardware-** Different time scales of sensing *and* data transmission may lead to mono-static, bi-static or multi-static scenarios for sensing *and* the introduction of RISs as a new network element.

✓ **Spectrum-** As better sensing accuracy is achieved in higher frequencies, it is expected that sensing will be supported from low frequencies up to sub-THz in order to be, also, in line with the spectrum to be exploited for data communication.

✓ **Waveform design-** The waveform used for sensing has to be, also, processed by communication transceivers (e.g., OFDM).

ICAS and 6G use case families



6G use case family	
Sustainable development	Drone deployment for health care, remote sensing and monitoring of weather conditions, asset tracking.
Immersive telepresence	Gesture recognition for human-machine, augmented reality.
Trust and security	Telesurgery, patient tracking and monitoring, provision of local trust zones for humans and machines.
Massive twinning	Manufacturing, Smart building, Smart City.
Robots to Cobots	Cobot positioning, mapping of cobots’ environment.

Research challenges-Conclusions

- The wireless sensing environment may be **enhanced through various types of RISs**, in order to facilitate the sensing processes by creating virtual LoS links, establishing controllable multipath propagation and enabling flexible passive beam scanning to compensate path loss.

- The information obtained through sensing **could improve communication performance and reliability** by facilitating channel estimation, beam alignment and user tracking.

- Determination of **suitable performance metrics for the various wireless sensing applications** should be devised (such as “sensing coverage probability” and “sensing ergodic capacity” for the radar sensing case by generalizations of coverage probability and ergodic capacity metrics).

- **The general design approach** in ICAS should be **reusing** the elements of communication and sensing as much as possible.

- Summing up, it is envisaged that an **ambient sensing environment** will be available by the deployment of the 6G mobile systems.

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