RFID+: Spatially Controllable Identification of UHF RFIDs via Controlled Magnetic Fields

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nsdi '24

Background

Spatially Controllable RFID Inventory has many applications

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Two Anomalies of UHF RFID Systems

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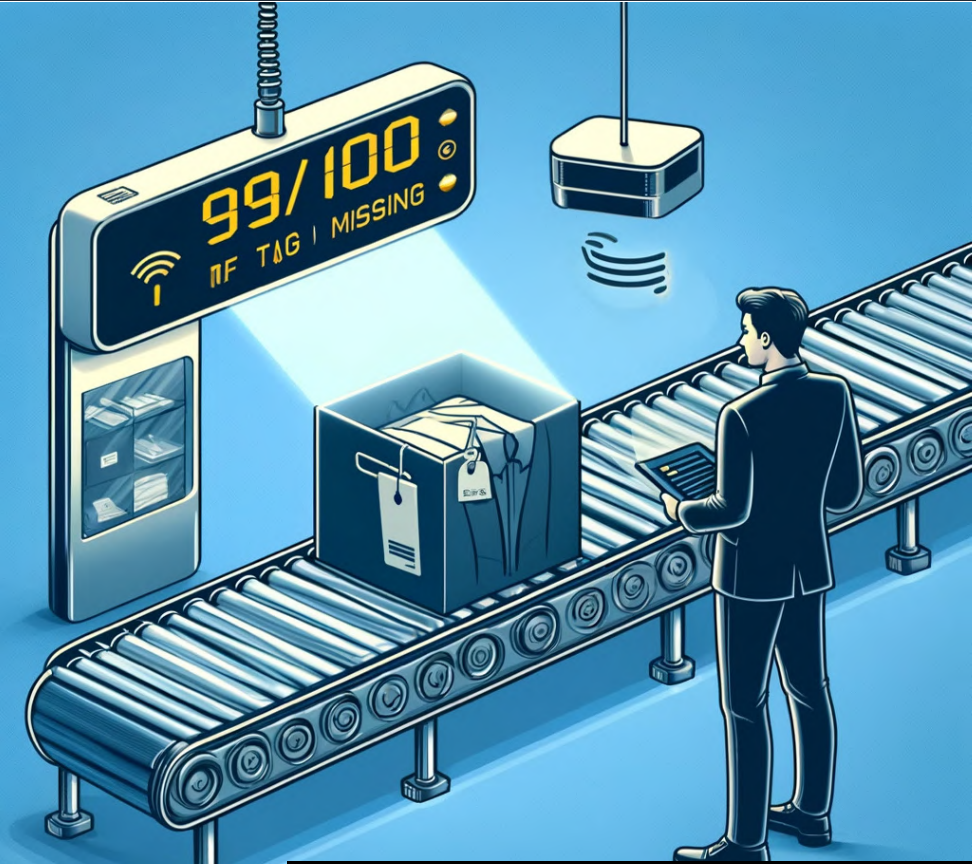

miss-reading anomaly

Two Anomalies of UHF RFID Systems

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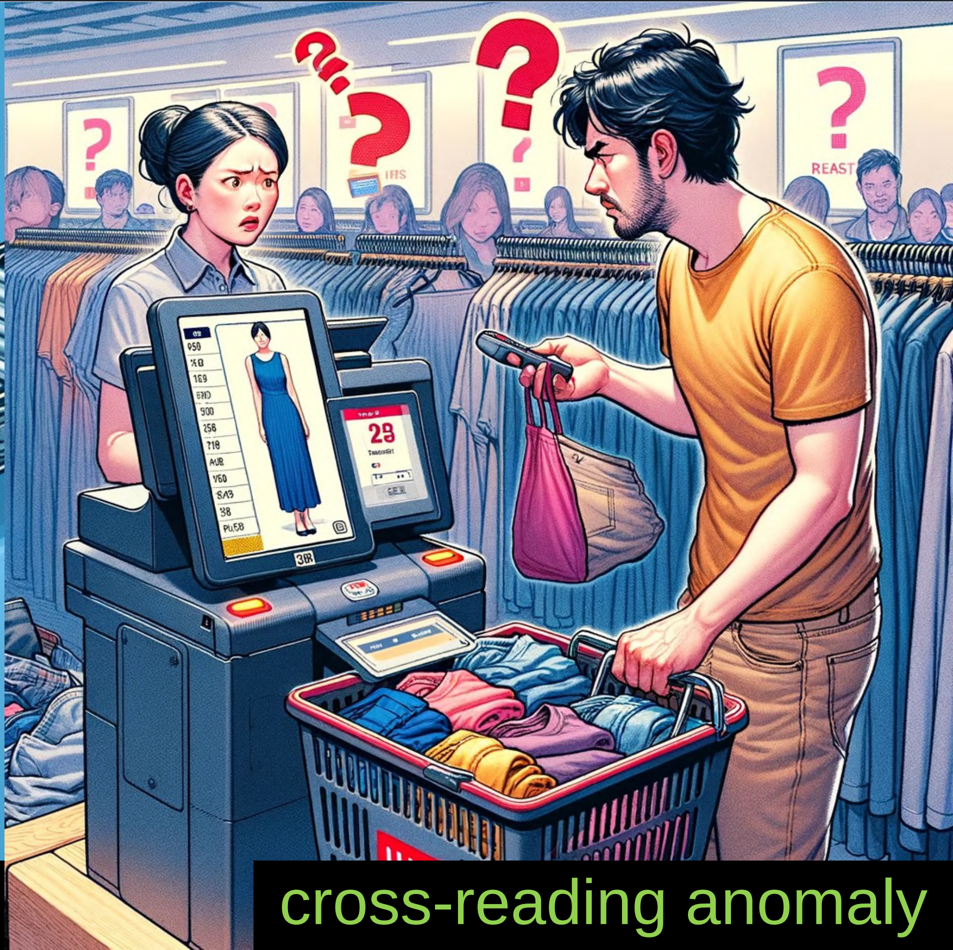
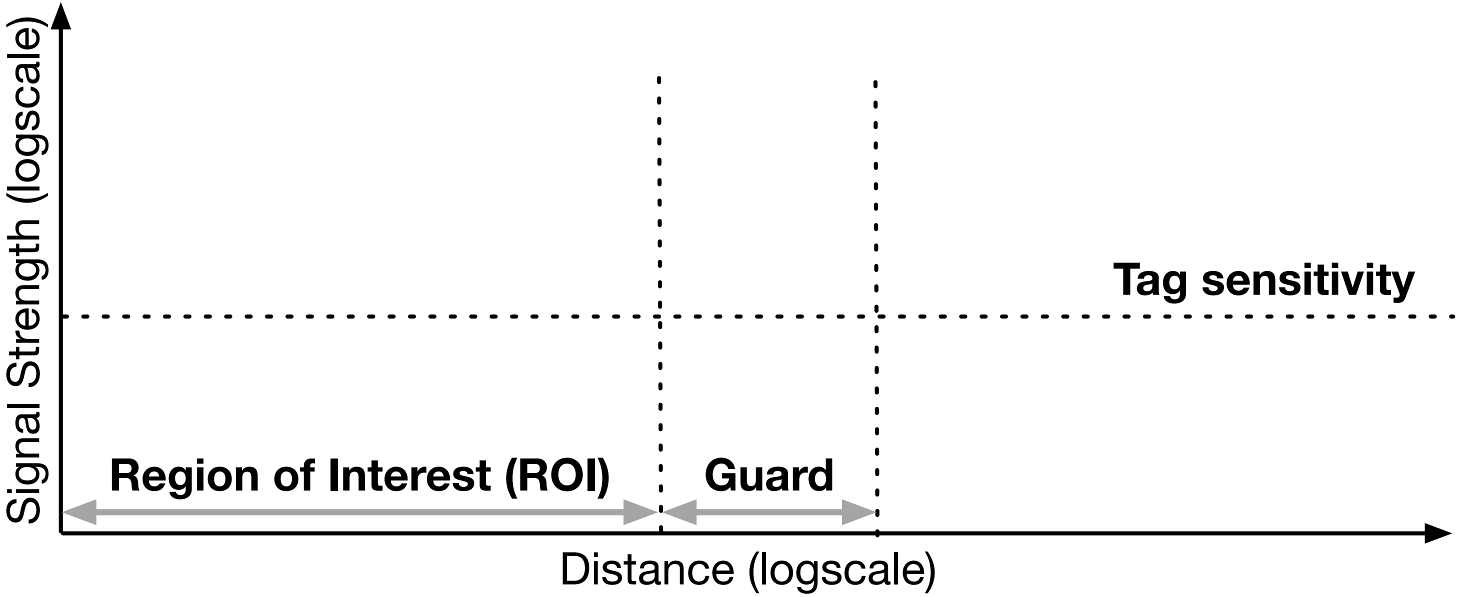


cross-reading anomaly

Two Anomalies of UHF RFID Systems

The propagation behavior of ultra-high frequency RF signals



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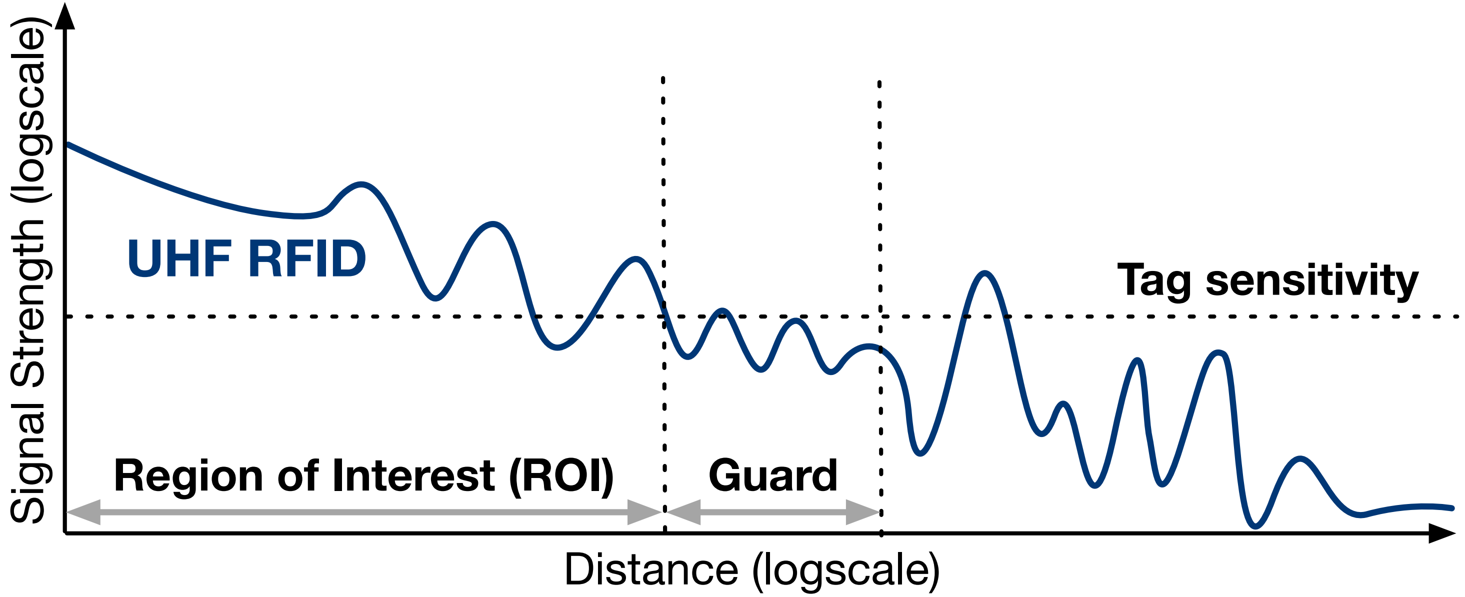

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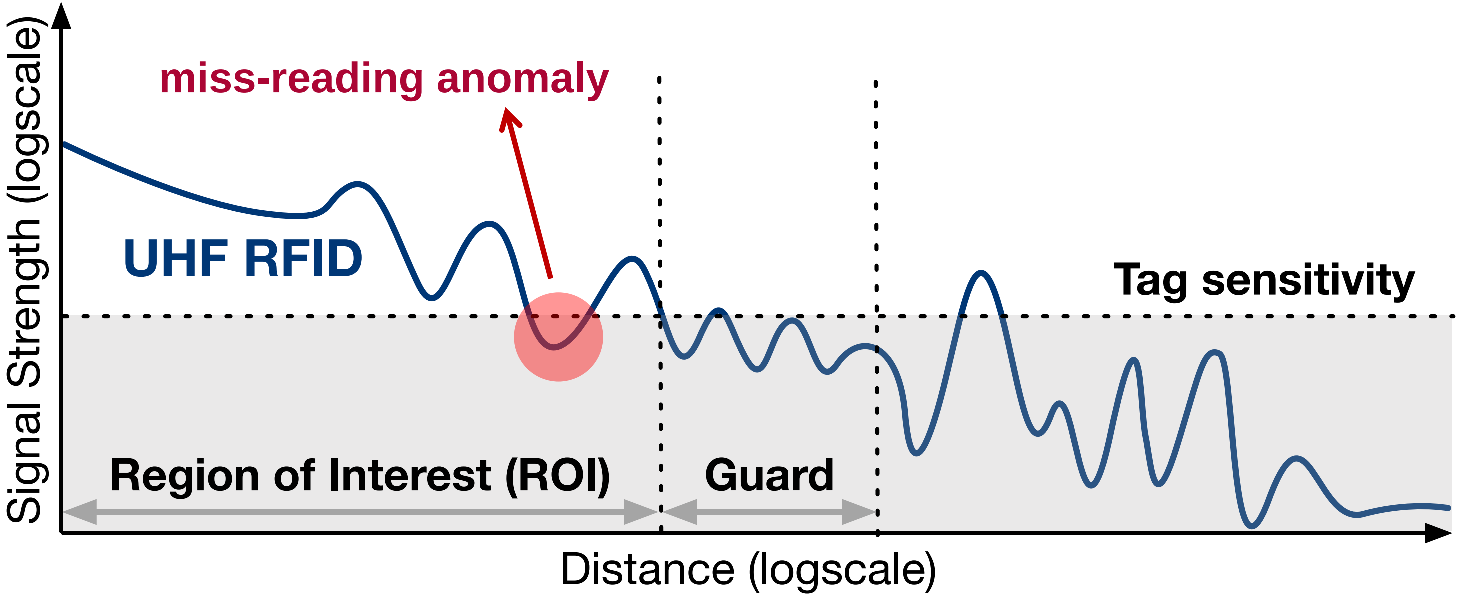

miss-reading: multipath signals destructively combine within ROI

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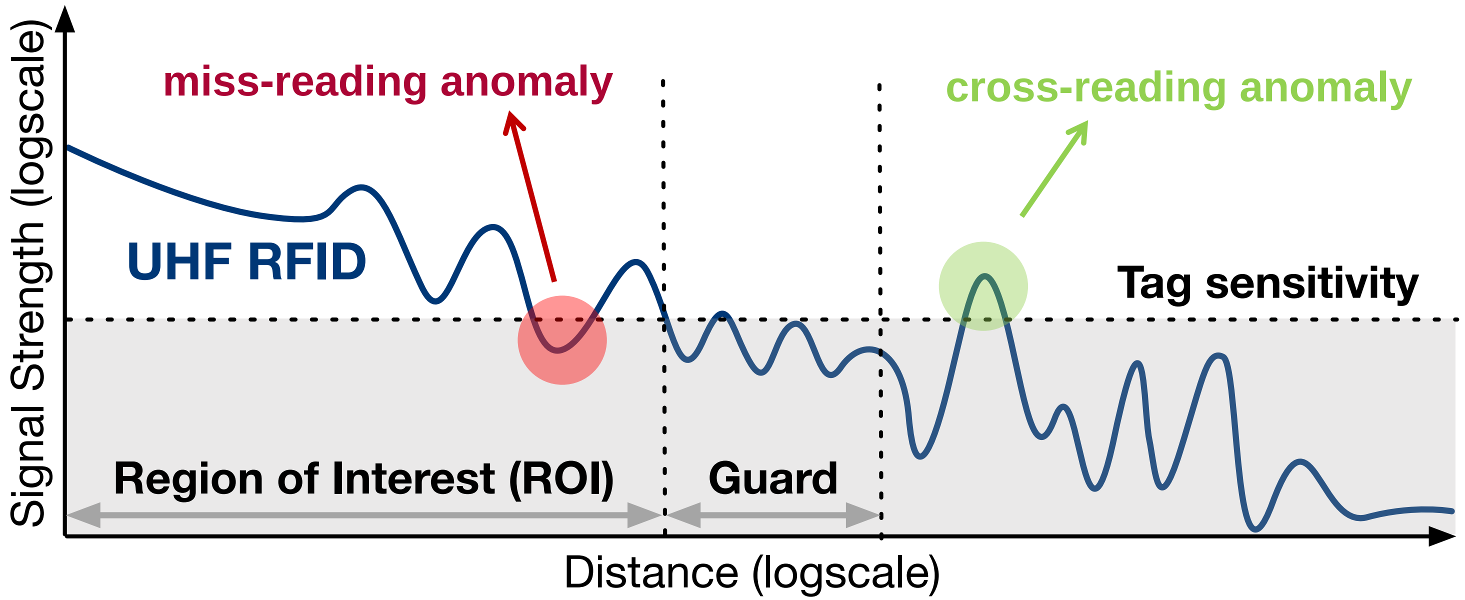

miss-reading: multipath signals destructively combine within ROI

cross-reading: multipath signals constructively combine beyond ROI

Two Anomalies of UHF RFID Systems

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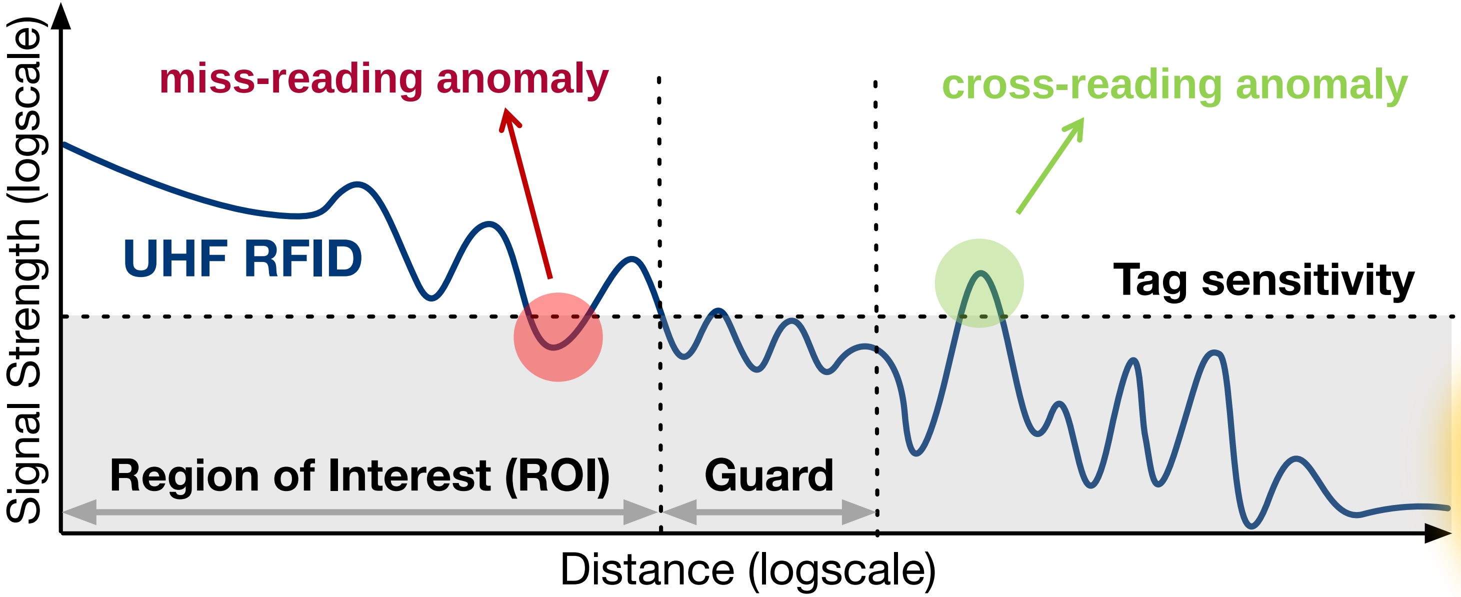
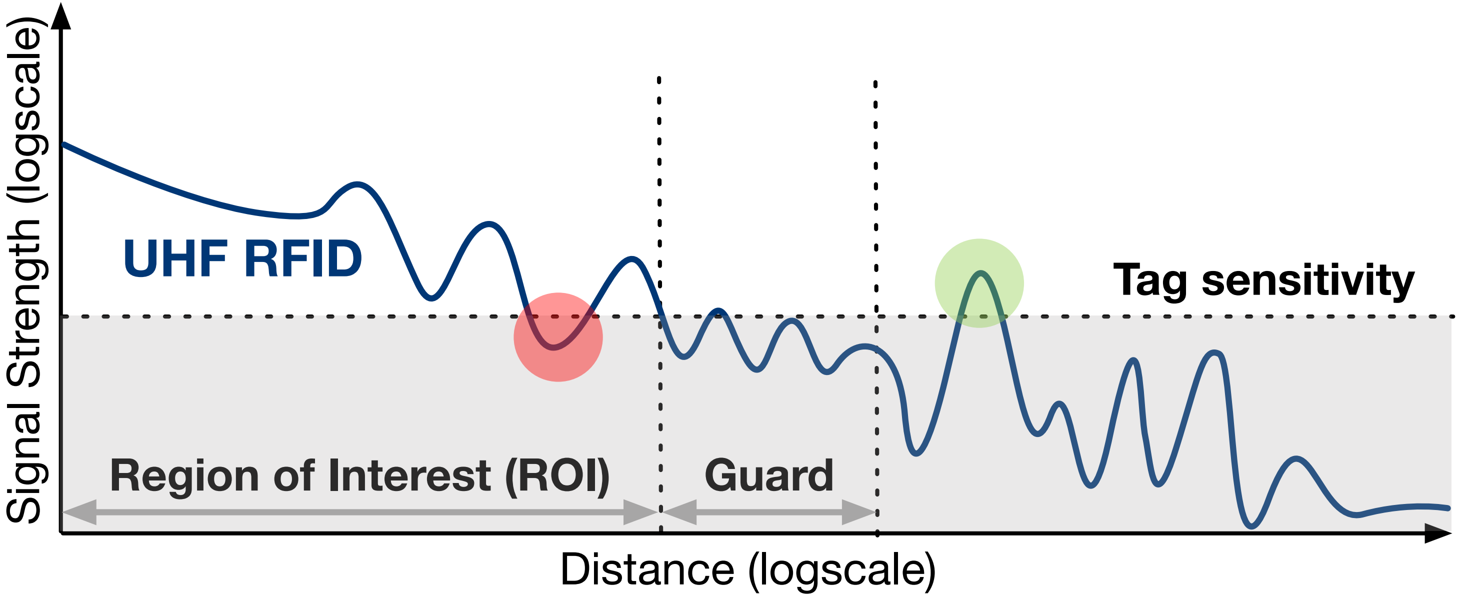


How to address miss-reading and cross-reading anomalies simultaneously?

Magnetically-driven UHF RFID Systems

The propagation behavior of magnetic signals



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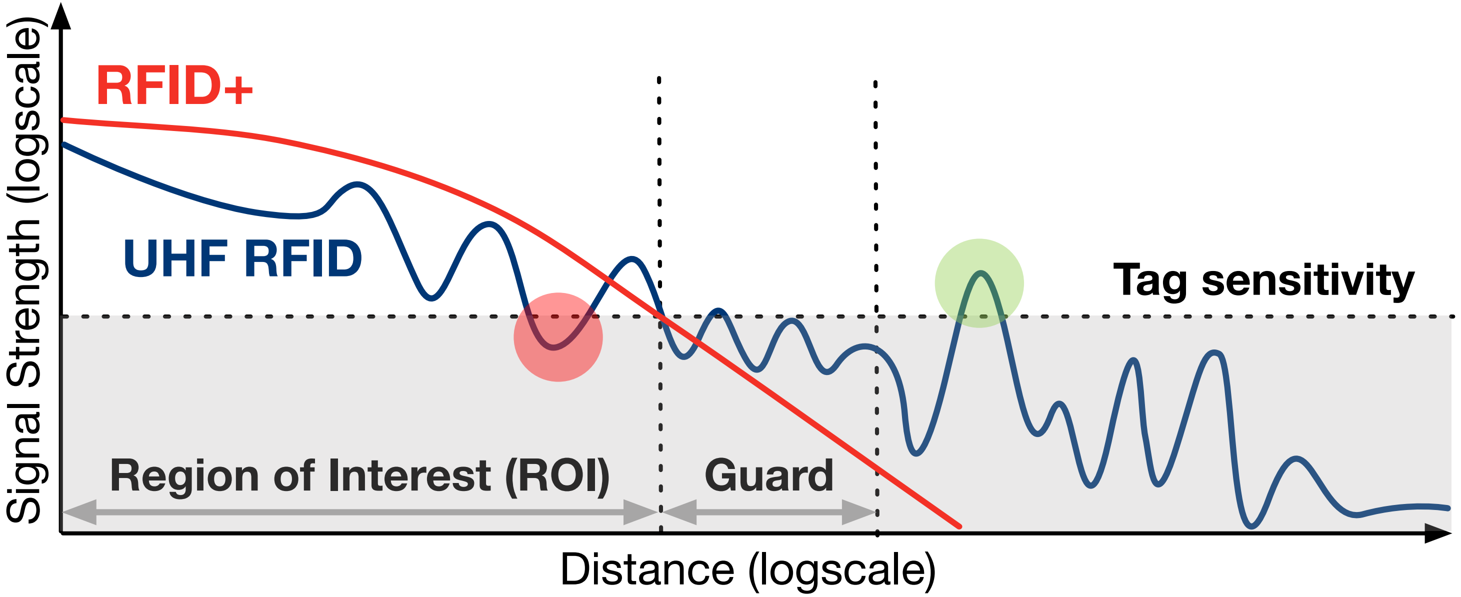

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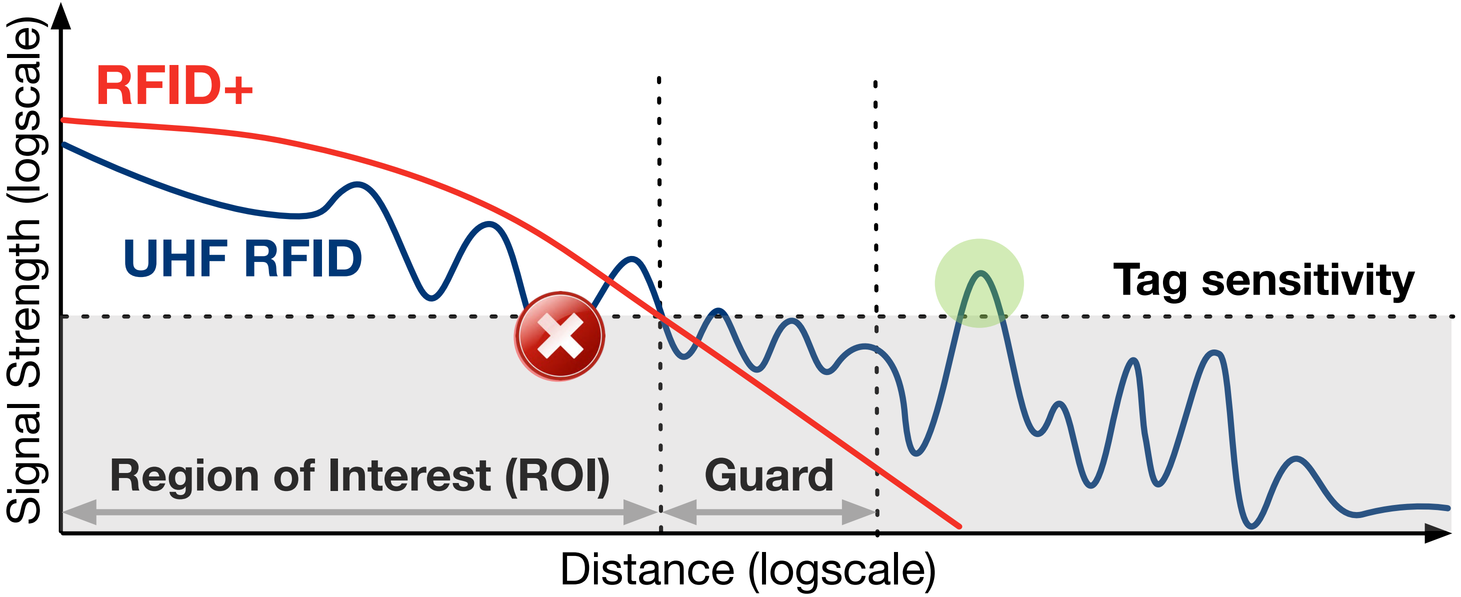

High penetrability: **no destructively combined signals within ROI**

Magnetically-driven UHF RFID Systems

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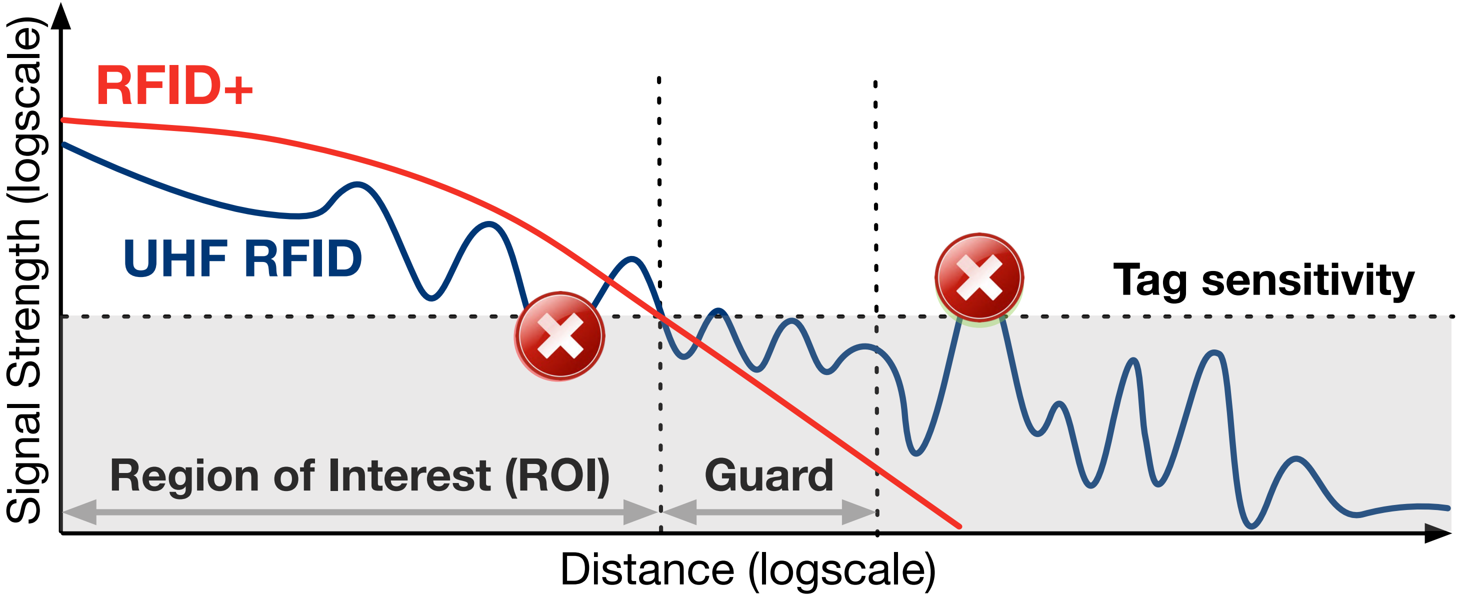
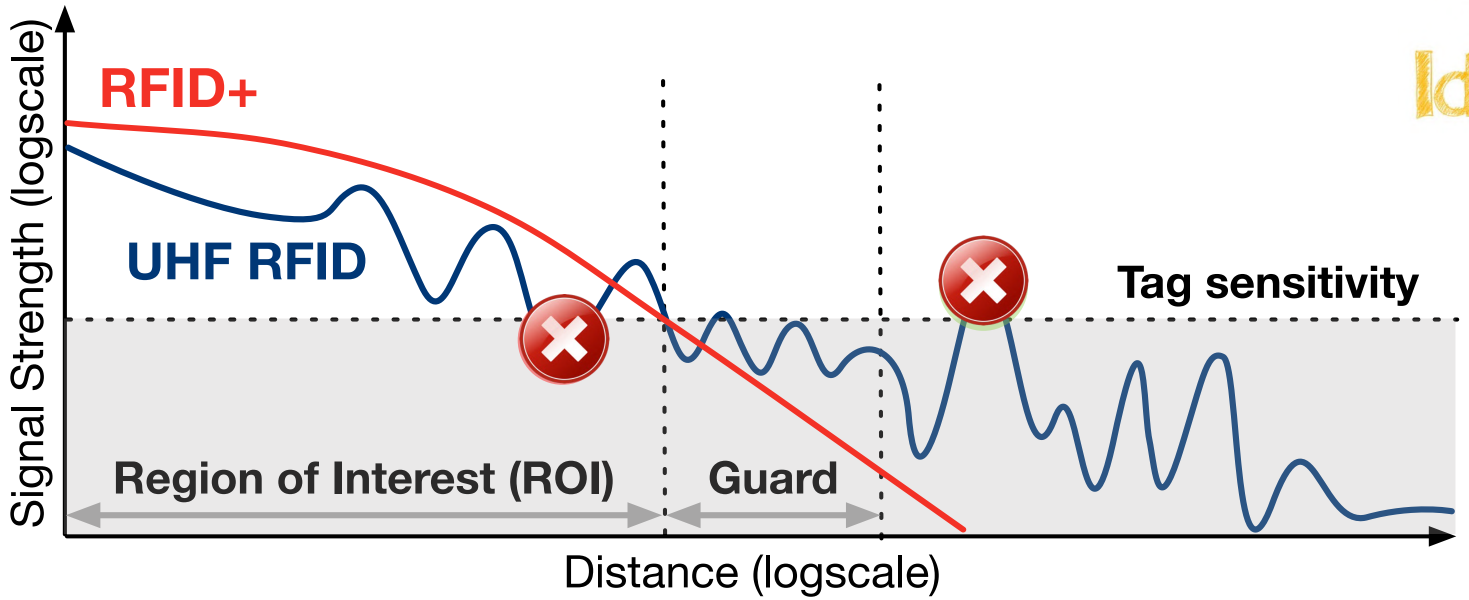


High penetrability: no destructively combined signals within ROI

Rapid attenuation: no constructively combined signals beyond ROI

Magnetically-driven UHF RFID Systems

The propagation behavior of magnetic signals



Is it possible to utilize a magnetic field in powering the inventory process of UHF RFIDs?

Inductive Coupling via Matching Loops

Every RFID tag inherently incorporates a single-turn coil, i.e., a matching loop.

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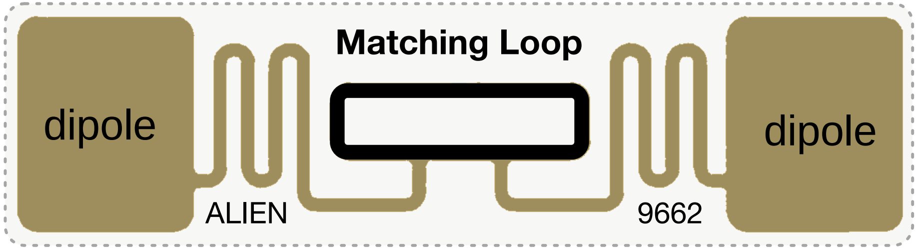
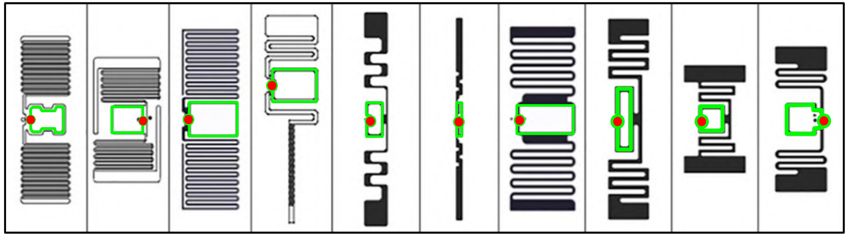


Structure of a Typical UHF RFID Tag



10 Popular UHF RFID Tags

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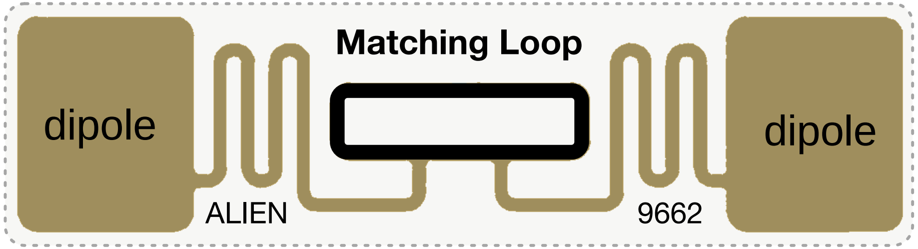

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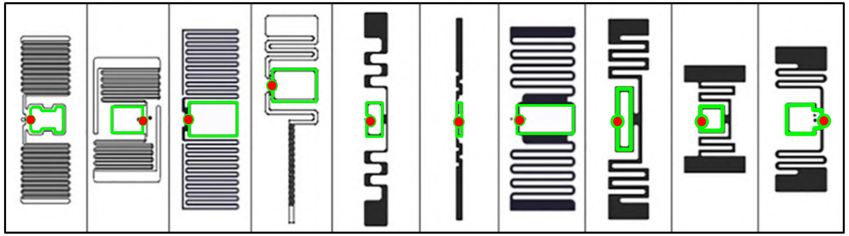

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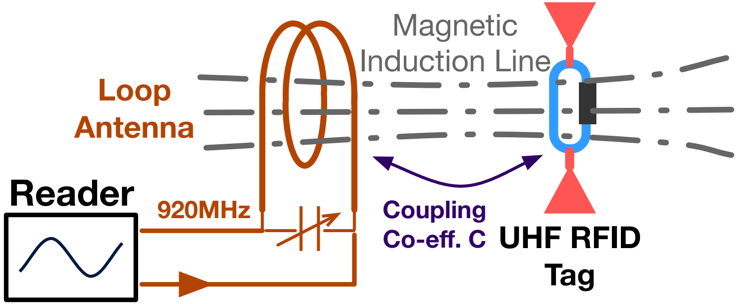
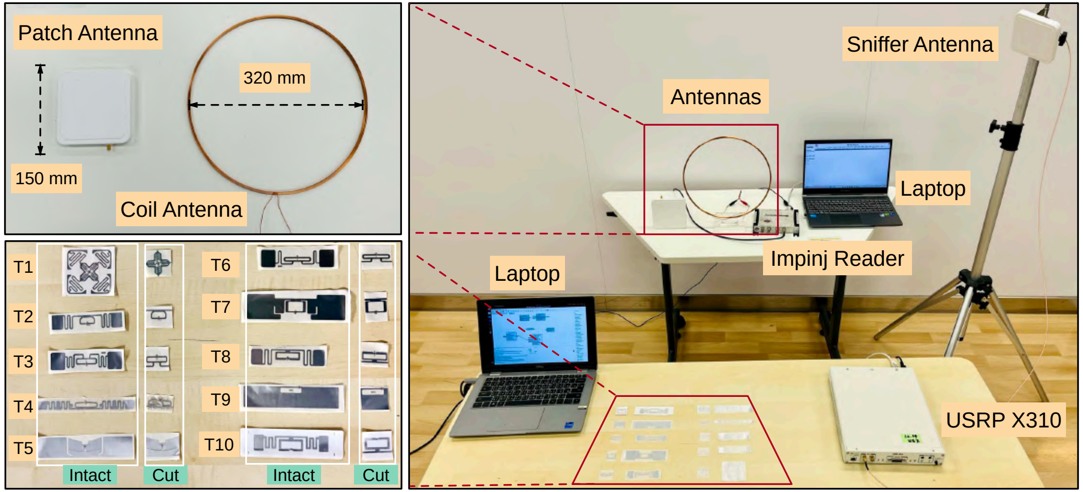


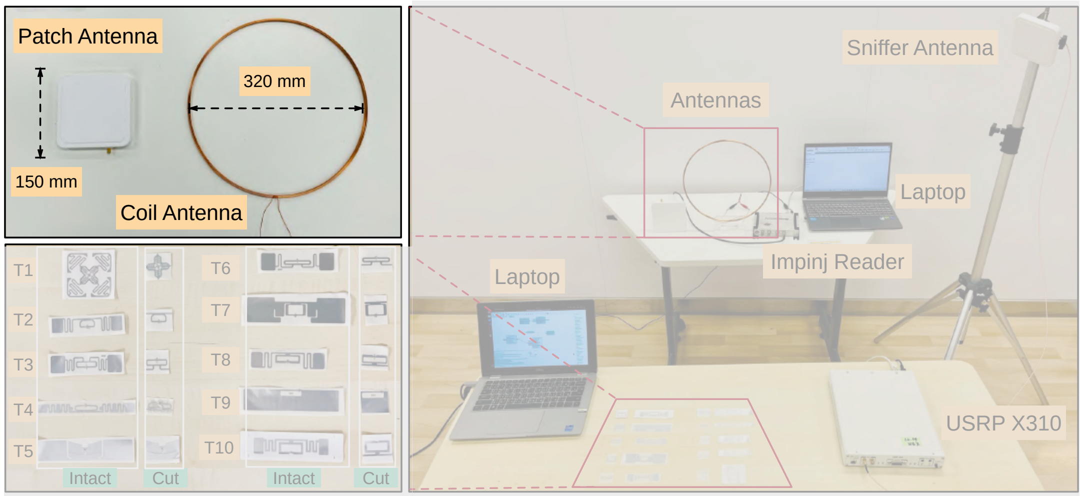
Inductive coupling: the matching loop can capture magnetic field energy and then power the tag for communication.

Preliminary Verification



Experiment Validation

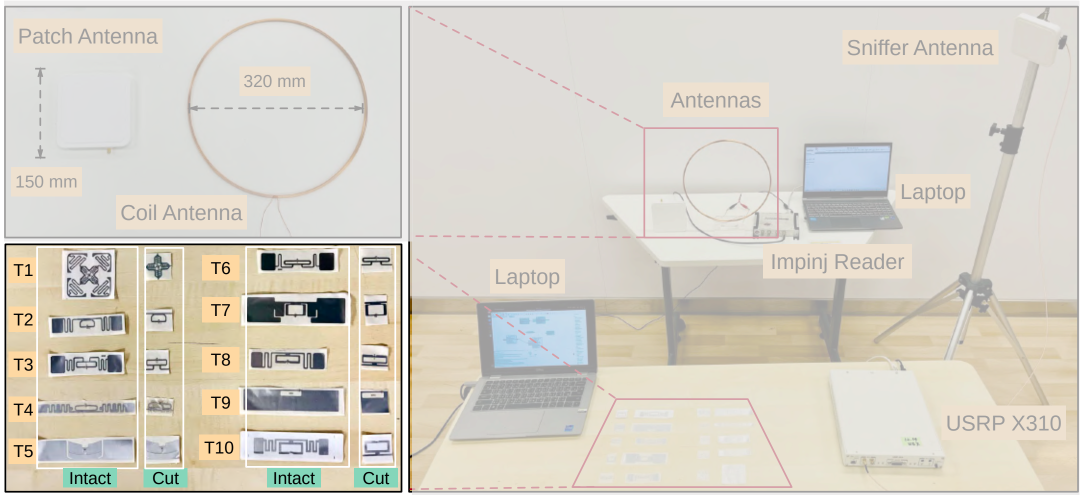
Preliminary Verification



Experiment Validation

- **Tx:** Coil antenna and Patch antenna, respectively

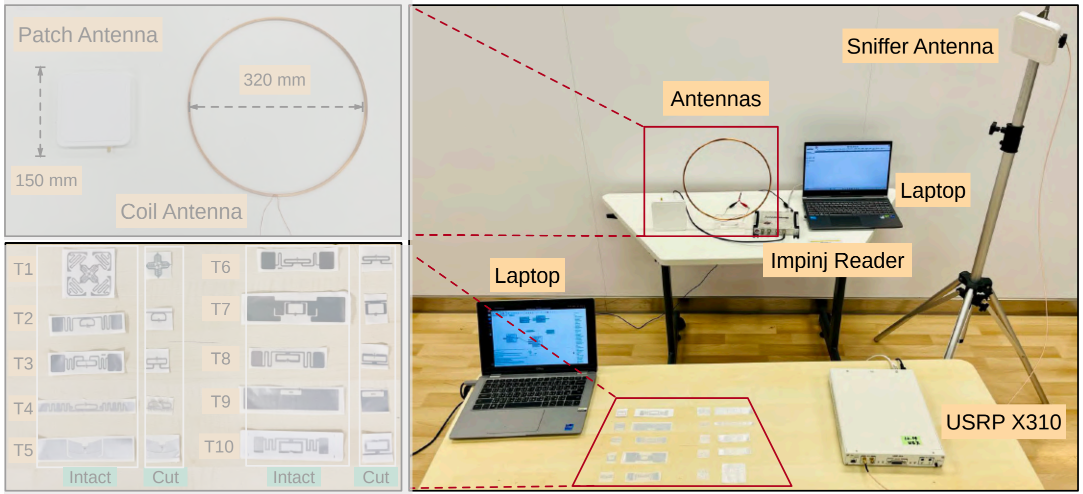
Preliminary Verification



Experiment Validation

- **Tx:** Coil antenna and Patch antenna, respectively
- **Tags:** modified tag whose dipole antenna is cut off

Preliminary Verification



Experiment Validation

- **Tx:** Coil antenna and Patch antenna, respectively
- **Tags:** modified tag whose dipole antenna is cut off
- **Rx:** USRP X310 as Receiver to sniff communication

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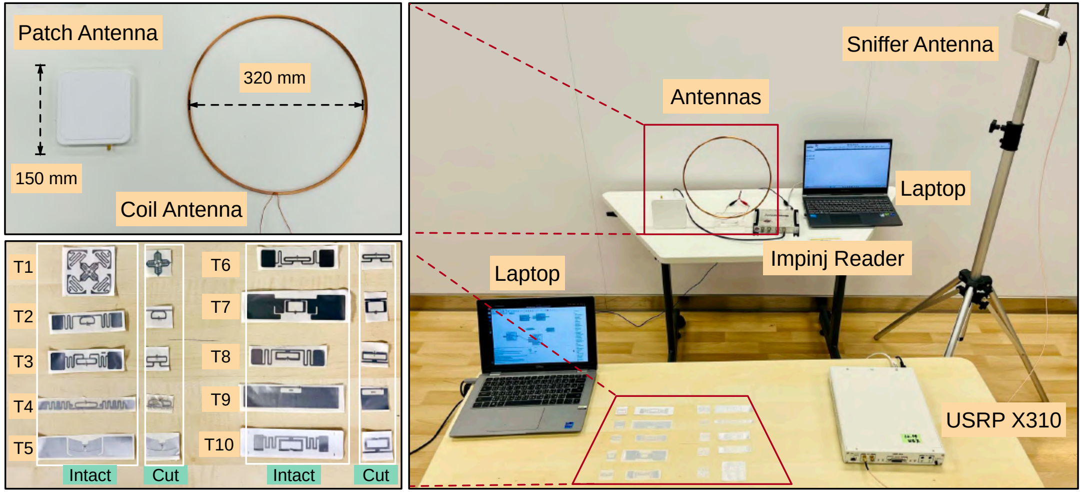

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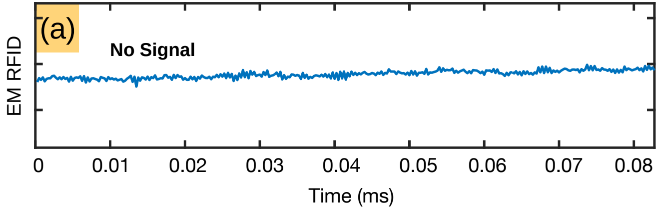
Tx: Patch Antenna (Electrical)



No signal can be detected because the tags' dipole antenna is cut off

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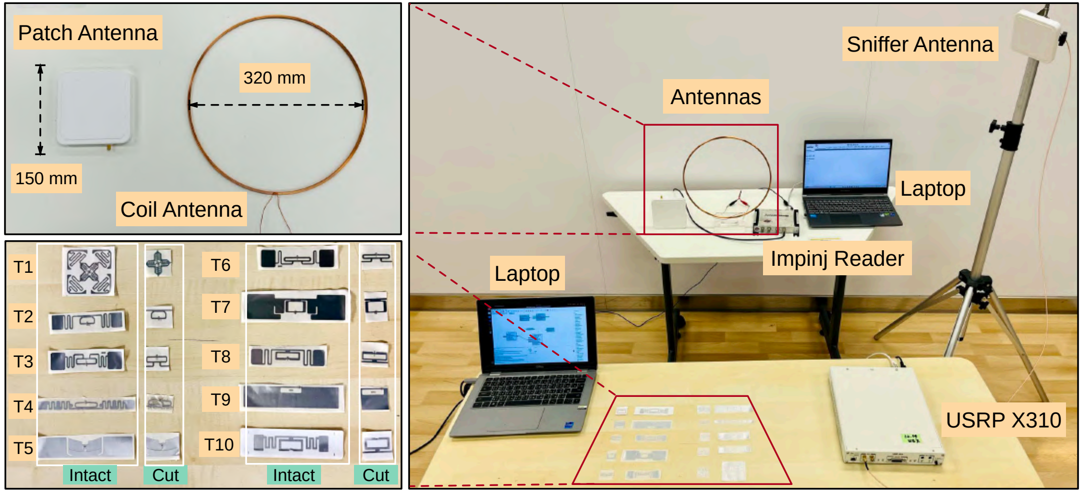

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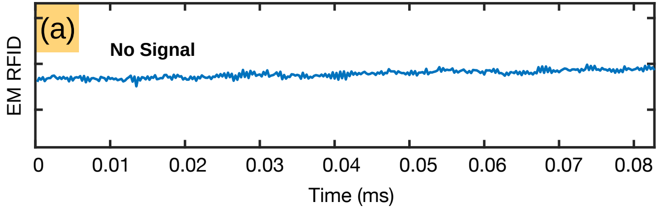

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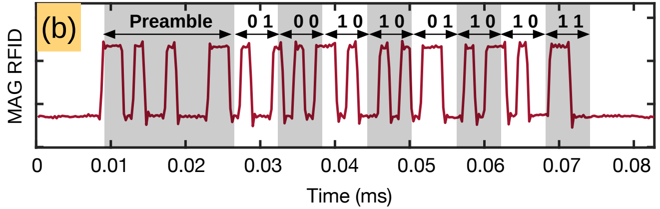
Tx: Coil Antenna (Magnetic)



Reply signal can be detected even when the tags' dipole antenna is cut off

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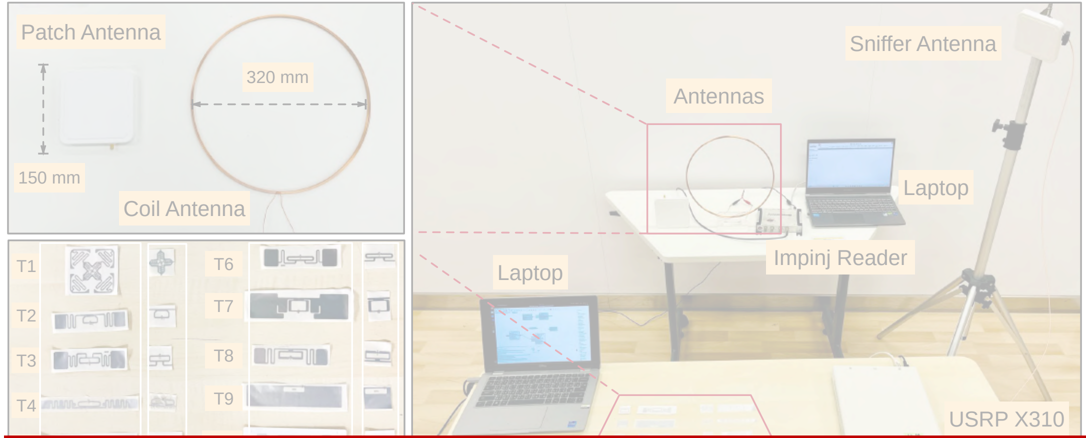

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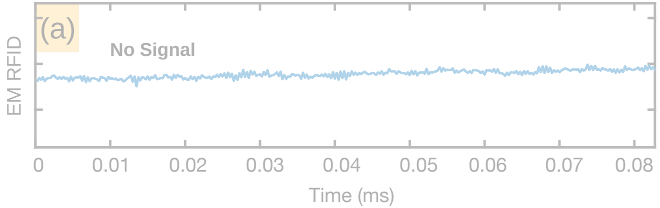
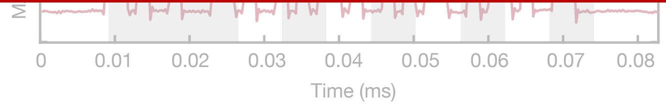


No signal can be detected because the tags' dipole antenna is cut off

COTS RFID tags can be activated and queried using magnetic fields while the protocol remains consistent

- **Tx:** Coil antenna and Patch antenna, respectively
- **Tags:** modified tag whose dipole antenna is cut off
- **Rx:** USRP X310 as Receiver to sniff communication



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RFID+

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RFID+

- **First spatially controllable magnetically-driven UHF RFID inventory system**

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- Introduce techniques for innovative coil antenna designs and a fast inventory algorithm

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- **First spatially controllable magnetically-driven UHF RFID inventory system**
- **Introduce techniques for innovative coil antenna designs and a fast inventory algorithm**
- **Achieves a 99% discovery rate and nearly zero crossing-reading within the region of interest (ROI)**

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Challenge 1:

How to generate a uniformly distributed magnetic field at the UHF band?

Magnetically Blind Zones at UHF band

Simulated magnetic intensity distribution at HF and UHF bands

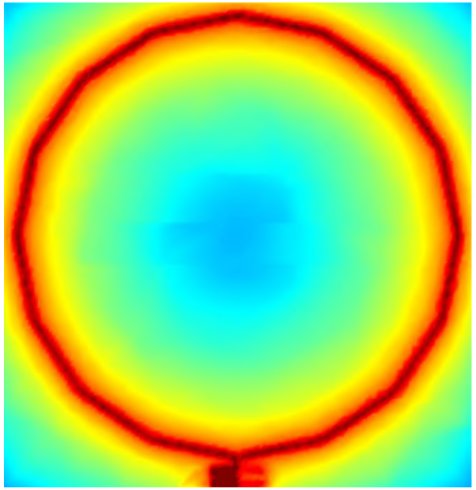
Magnetically Blind Zones at UHF band

Simulated magnetic intensity distribution at HF and UHF bands

Wavelength: λ
Coil Perimeter: C

$\lambda \approx 22\text{m}$

$\lambda \gg C$



HF: 13.56MHz

HF band: the current around the loop **can** remain almost in phase and of the same sign; thus, it **can** produce a uniform strong magnetic field.

Magnetically Blind Zones at UHF band

Simulated magnetic intensity distribution at HF and UHF bands

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Coil Perimeter: C

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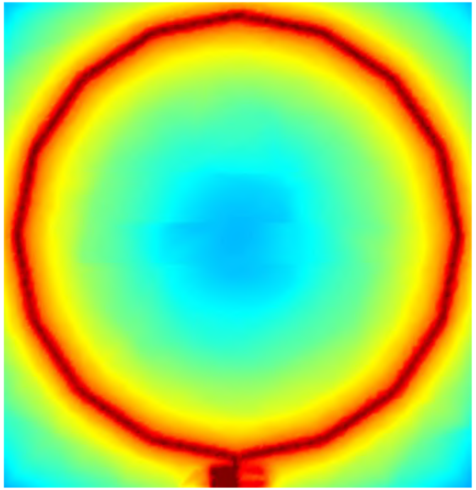

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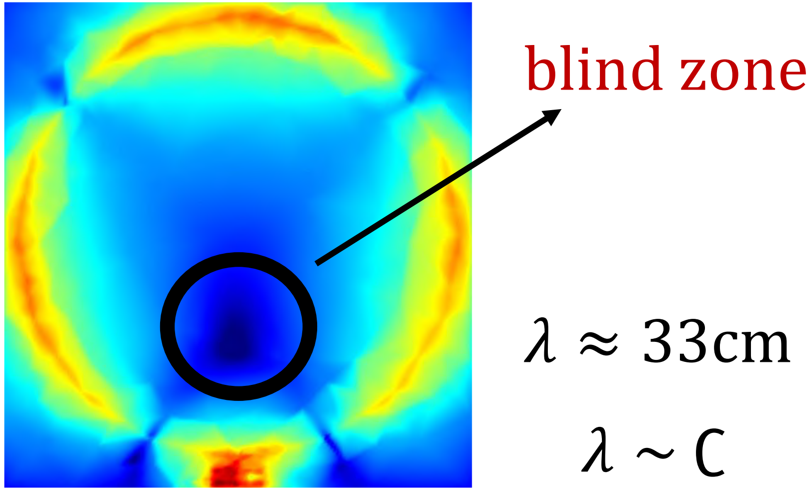


UHF: 920MHz

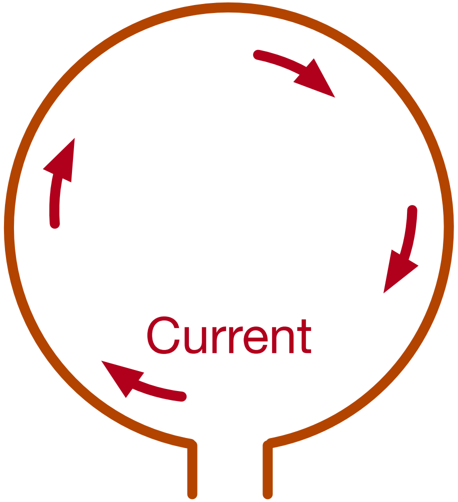
$\lambda \approx 33\text{cm}$

$\lambda \sim C$

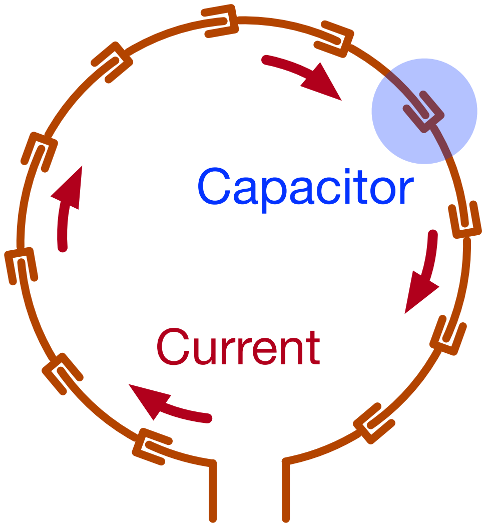
UHF band: the current around the loop **cannot** remain almost in phase and of the same sign; thus, it **cannot** produce a substantial magnetic field.

Capacitor-Segmented Coil Antenna

Capacitor-Segmented Coil Antenna



Traditional Coil



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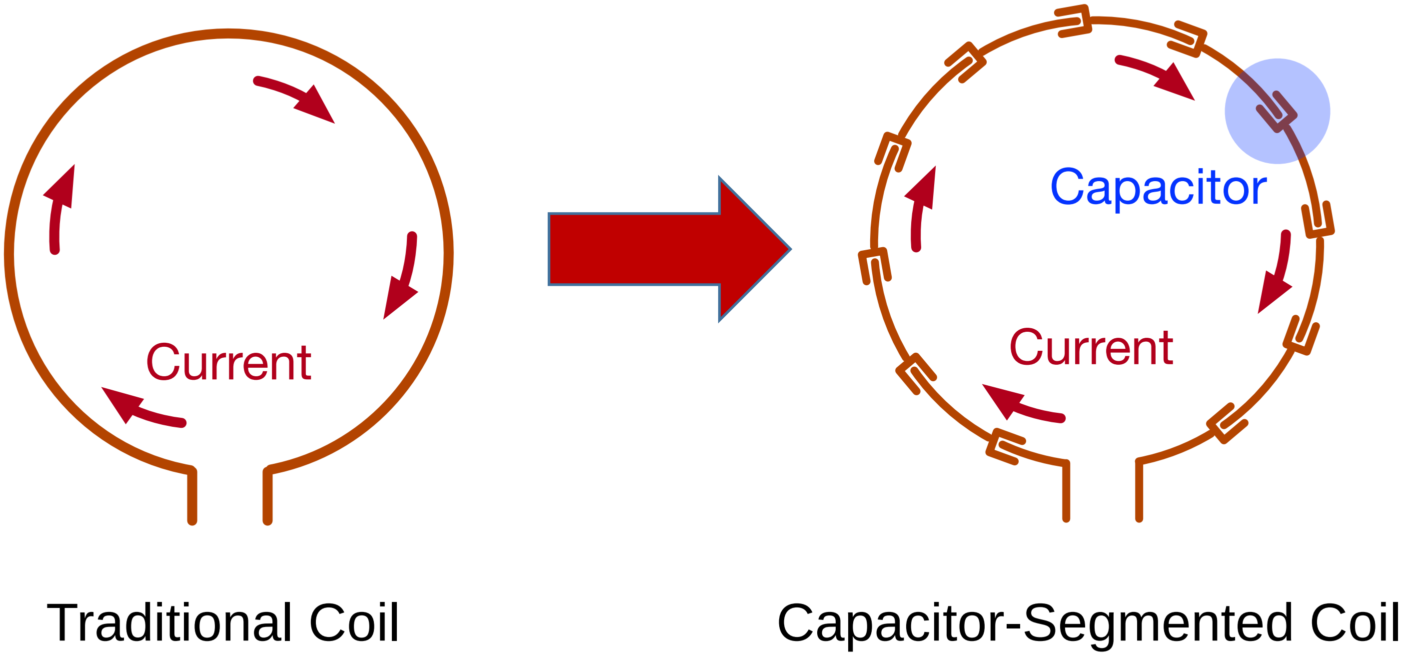
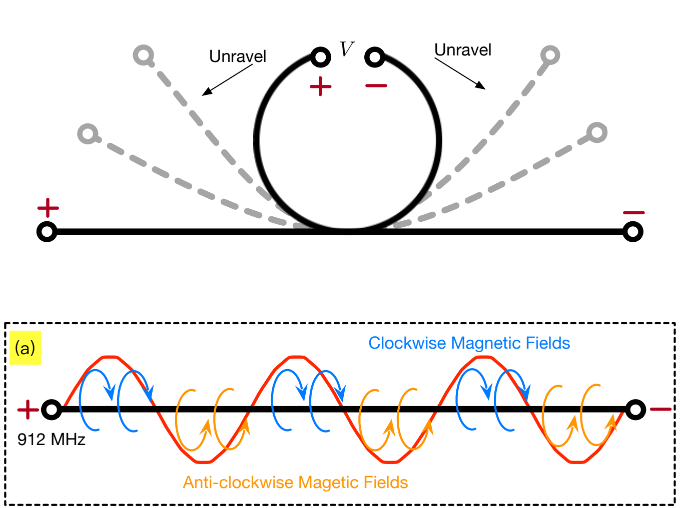


Segmenting the loop physically and inserting capacitors between adjacent segments. Each segment can be modeled as an equivalent RLC circuit.

Capacitor-Segmented Coil Antenna



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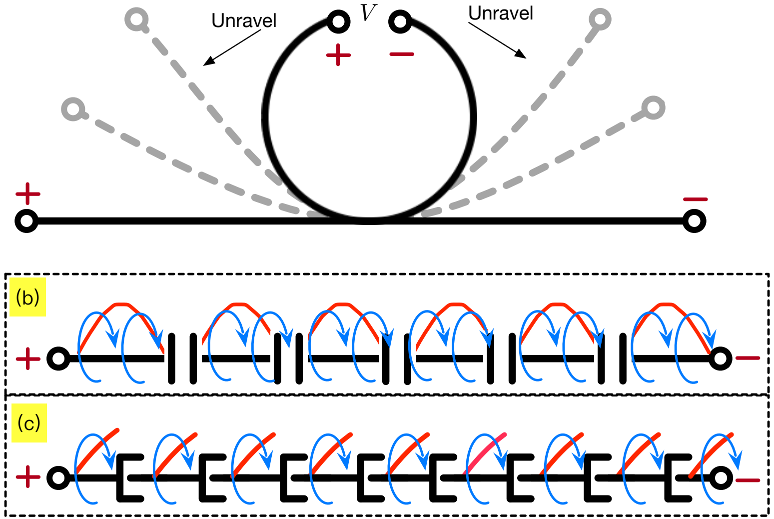
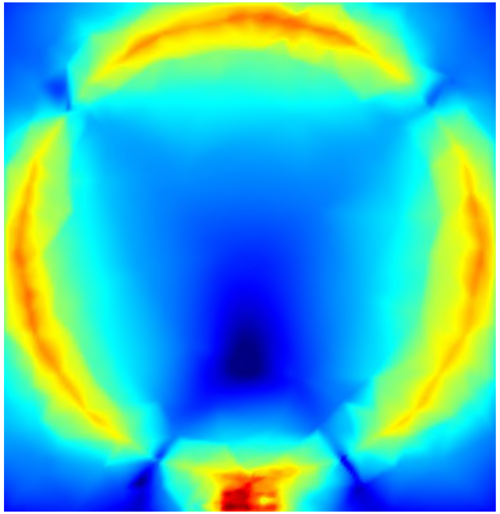
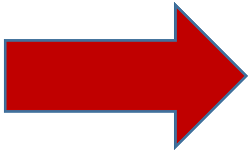


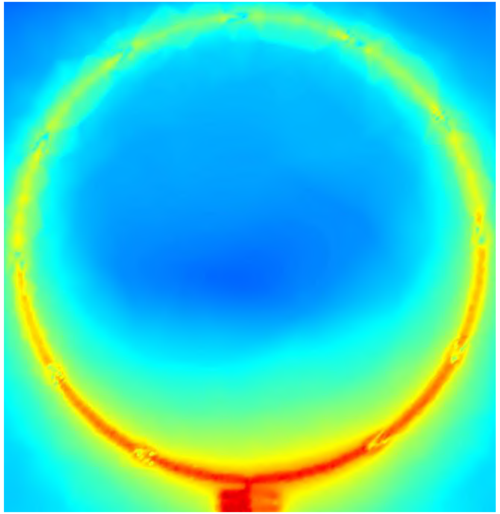
Capacitor-Segmented Coil

Such RLC circuits guarantee that the RF signal retains a uniform initial phase shift across segments and no out-of-phase magnetic field is generated.

Capacitor-Segmented Coil Antenna







Traditional Coil

Capacitor-Segmented Coil

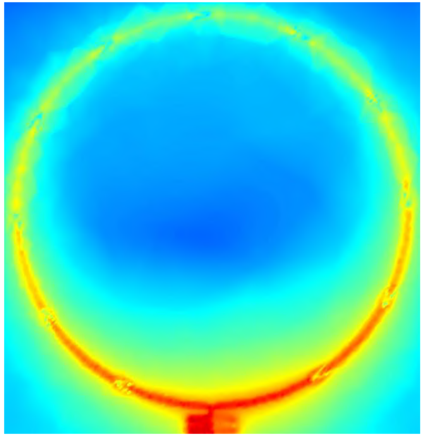
The capacitor-segmented coil can maintain the loop’s small size while guaranteeing a uniform magnetic field distribution

Multi-turn Spiral Coil Antenna

Multi-turn coils can spread magnetic energy more uniformly

Multi-turn Spiral Coil Antenna

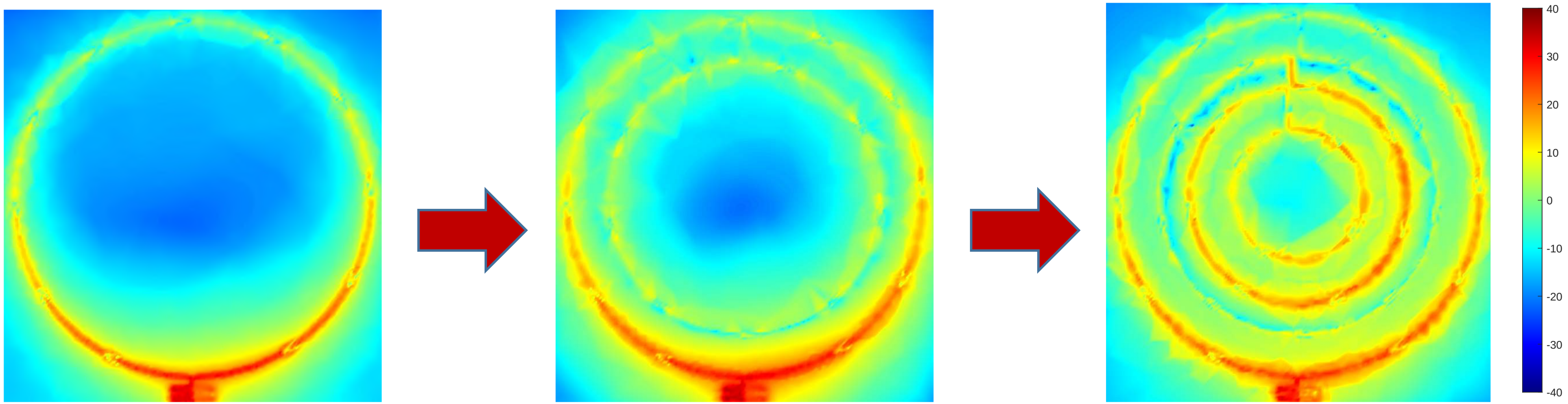
Multi-turn coils can spread magnetic energy more uniformly



One Coil

Multi-turn Spiral Coil Antenna

Multi-turn coils can spread magnetic energy more uniformly



One Coil

Two Coils

Four Coils

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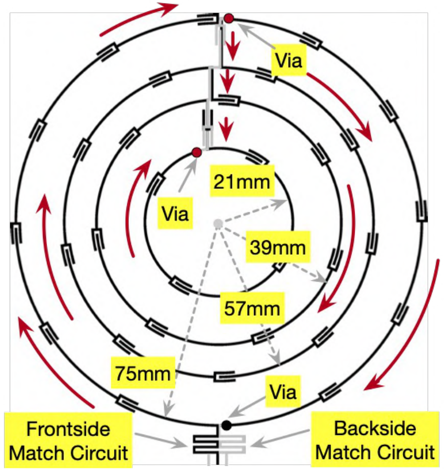
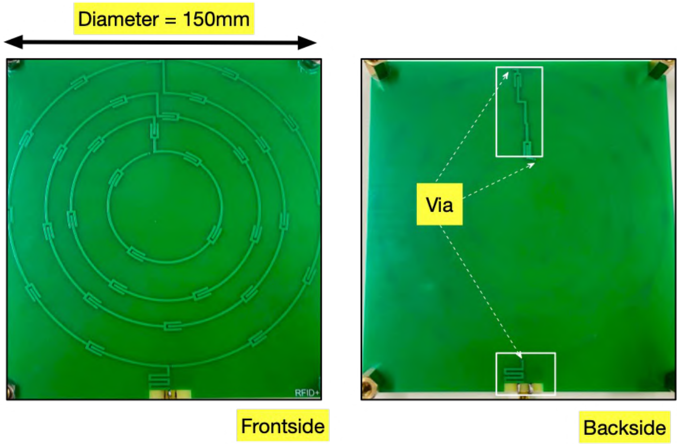
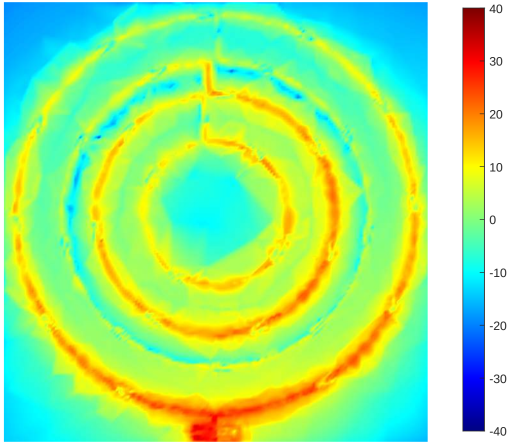




Prototype



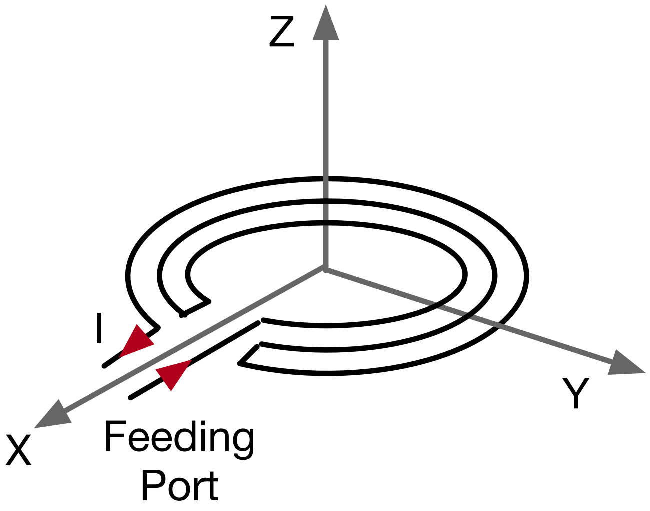
Four Coils

A four-turn design can achieve a balance between maximum magnetic intensity and minimizing the mutual coupling effect among coils.

Challenge 2:

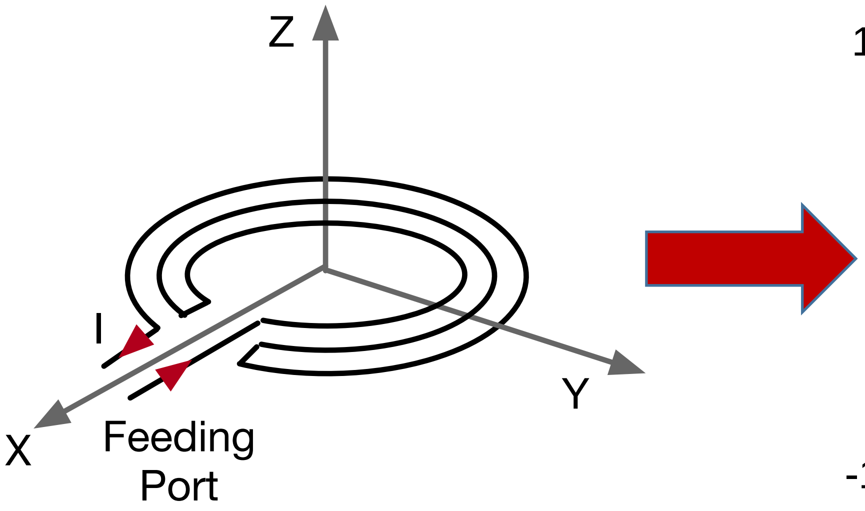
How to precisely manipulate the magnetic field to achieve spatially controllable reading?

Bi-directional Magnetic Field Distribution



A coil antenna

Bi-directional Magnetic Field Distribution



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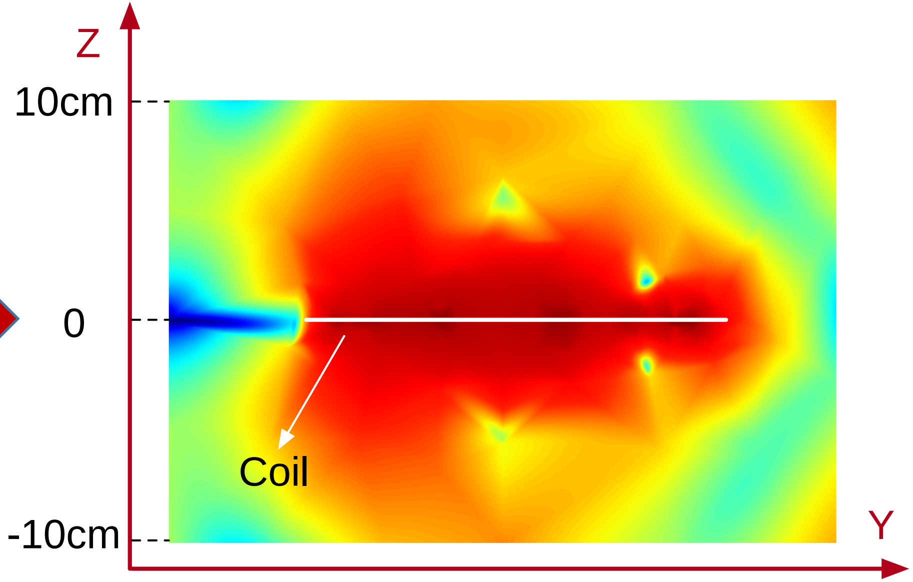
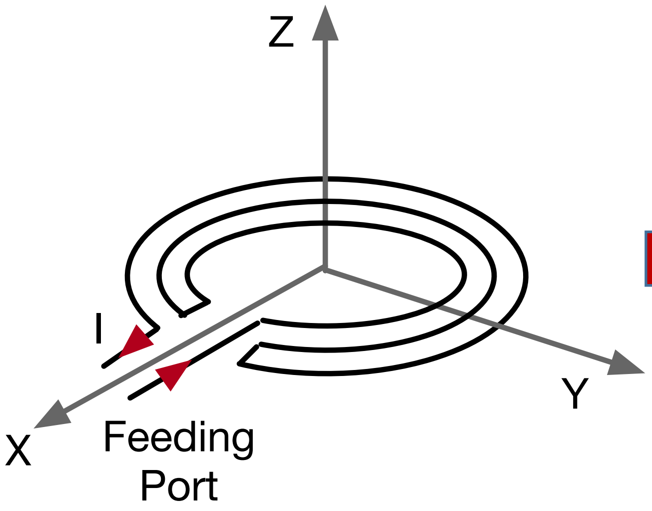


Simulated magnetic intensity of a coil antenna in Z-axis

Bi-directional Magnetic Field Distribution



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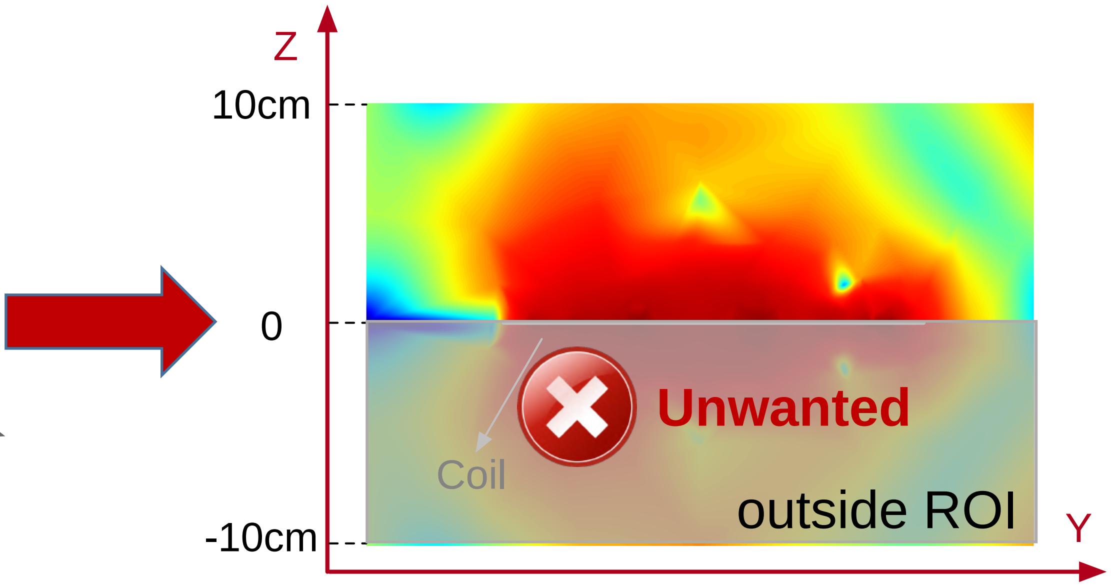


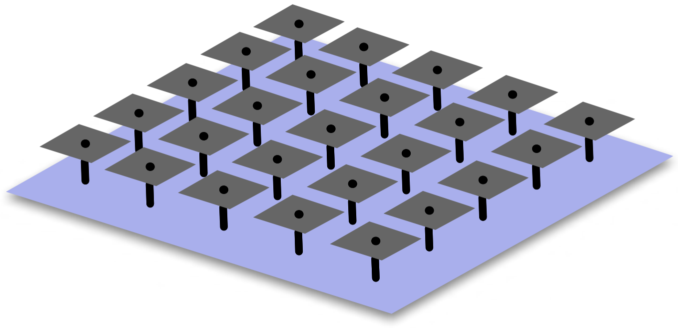
Simulated magnetic intensity
of a coil antenna in Z-axis

How to confine the bi-directional magnetic field distributed in one direction only?

Mushroom-like High-Impedance Surface

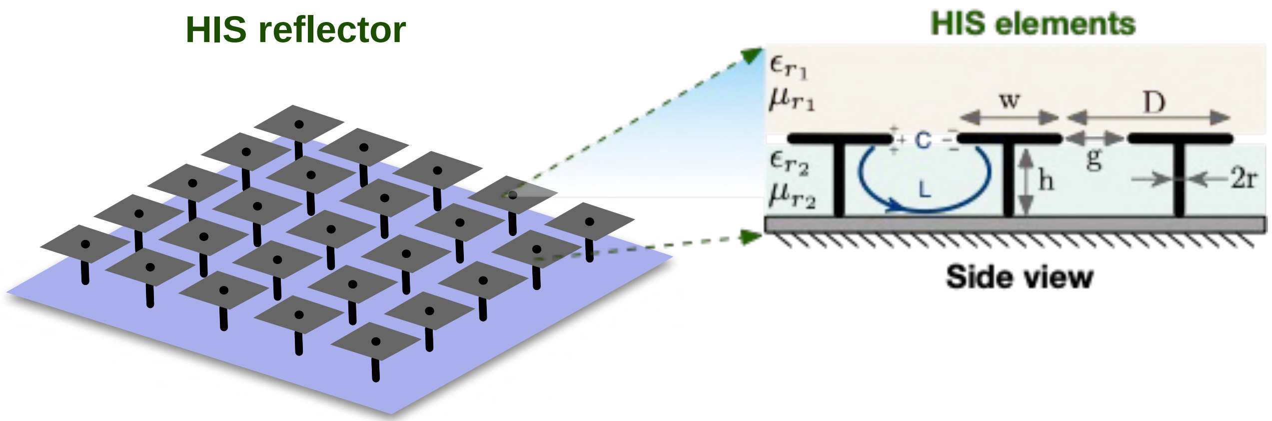
Mushroom-like High-Impedance Surface

HIS reflector



Bird‘s-eye view

Mushroom-like High-Impedance Surface

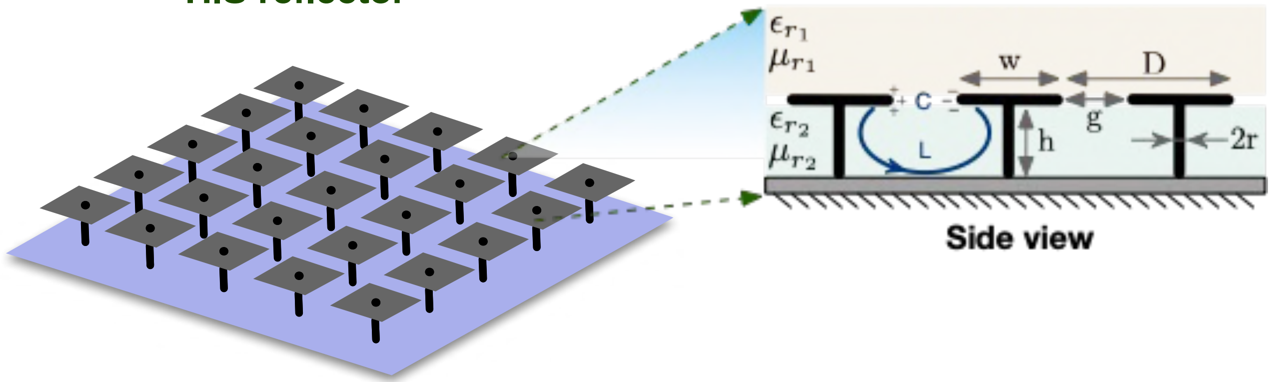


Bird's-eye view

Mushroom-like High-Impedance Surface

HIS reflector

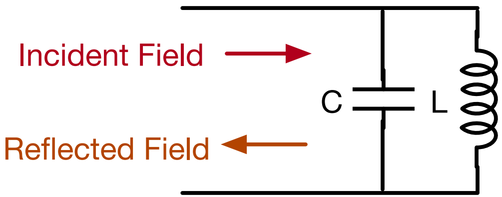
HIS elements



Side view

Bird‘s-eye view

Parallel LC circuit

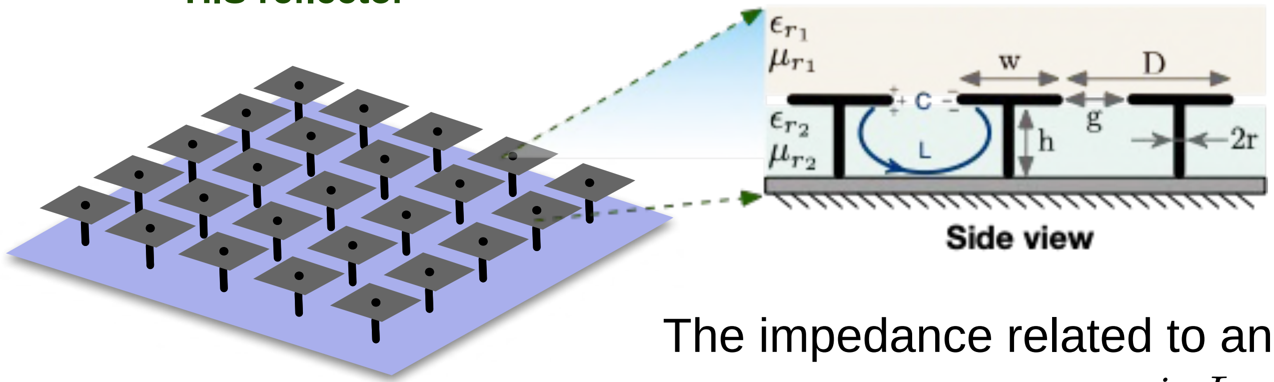


Equivalent circuit

Mushroom-like High-Impedance Surface

HIS reflector

HIS elements



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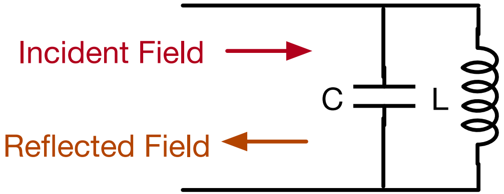
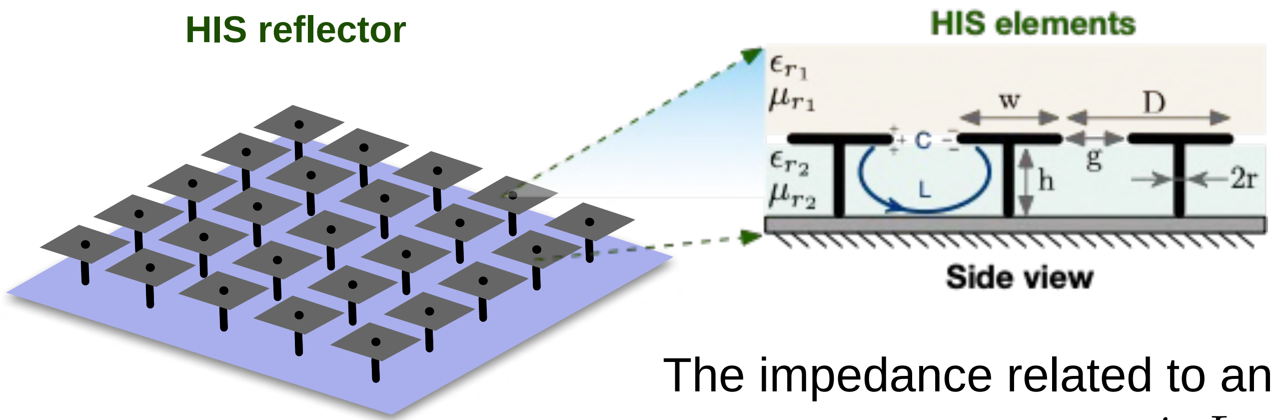


Equivalent circuit

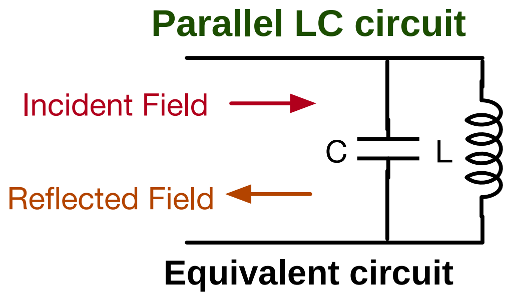
The impedance related to an HIS can be expressed as:

$$Z_{\mathrm{HIS}} = \frac{j\omega L}{1-\omega^2 LC} = \frac{j\omega L}{1-(\omega/\widehat{\omega})^2}$$

Mushroom-like High-Impedance Surface



Bird's-eye view



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The magnetic field's reflected phase by the HIS is $\theta = \mathrm{Im}\left(\ln \left(\frac{Z_{\mathrm{HIS}} - \eta_0}{Z_{\mathrm{HIS}} + \eta_0} \right) \right)$

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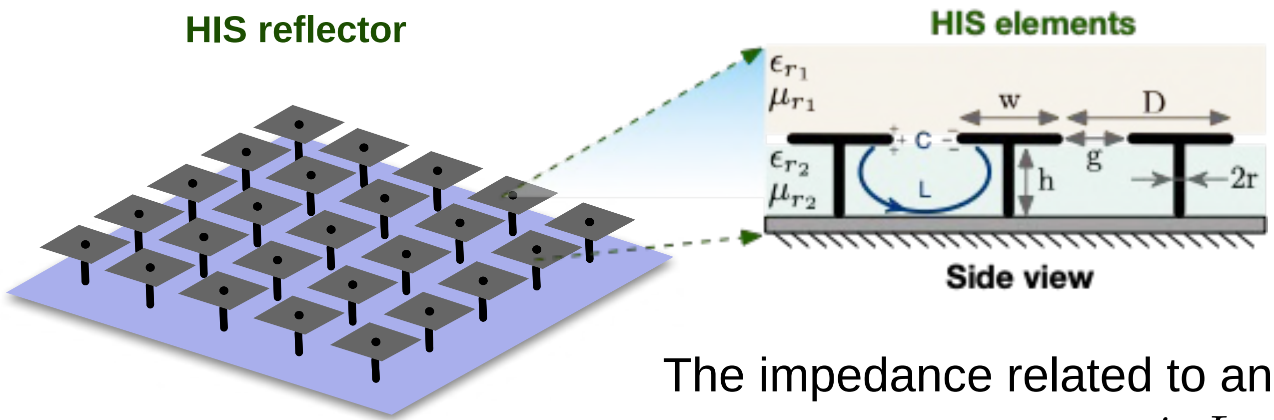

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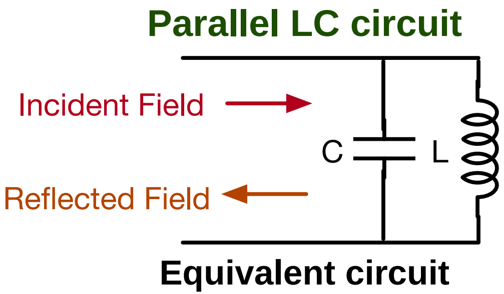

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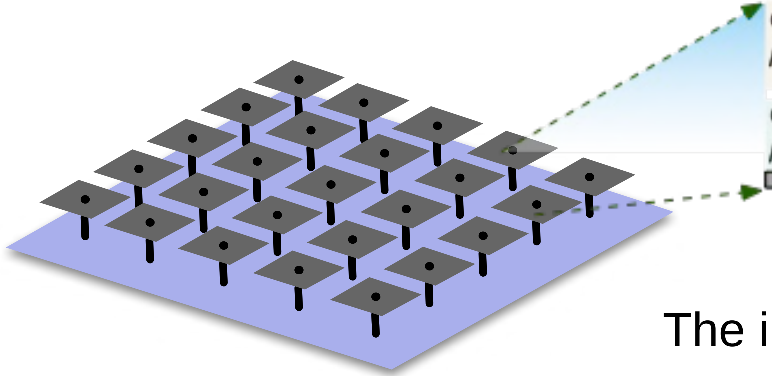
At resonant frequency, $\omega = \widehat{\omega}$

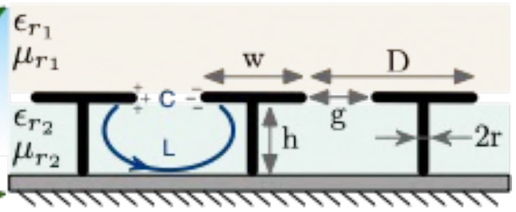
Mushroom-like High-Impedance Surface

HIS reflector



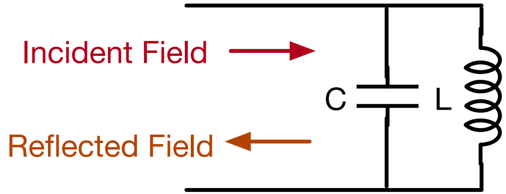
Bird's-eye view

HIS elements



Side view

Parallel LC circuit



Equivalent circuit

The impedance related to an HIS can be expressed as:

$$Z_{\text{HIS}} = \frac{j\omega L}{1 - \omega^2 LC} = \frac{j\omega L}{1 - (\omega/\widehat{\omega})^2}$$ **Infinity**

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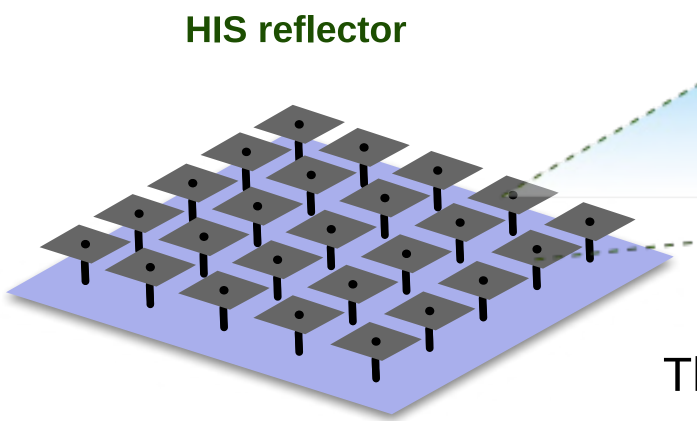
Mushroom-like High-Impedance Surface



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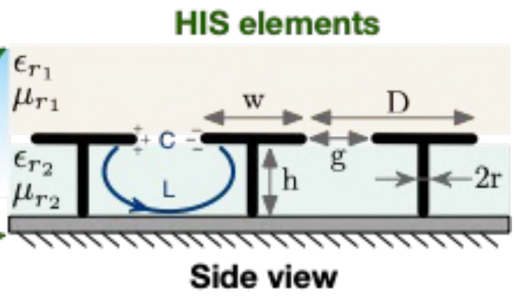

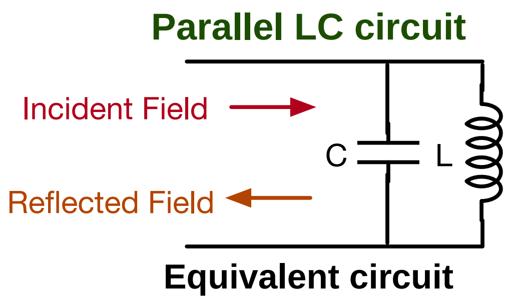

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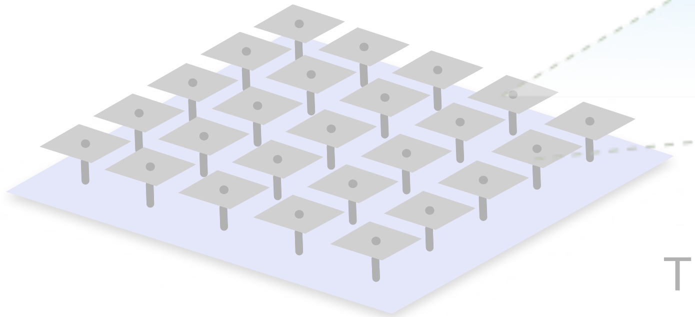
At resonant frequency, $\omega = \widehat{\omega}$ ➡ $Z_{\text{HIS}} \to +\infty$ ➡ $\theta \approx 0$

Mushroom-like High-Impedance Surface

HIS reflector



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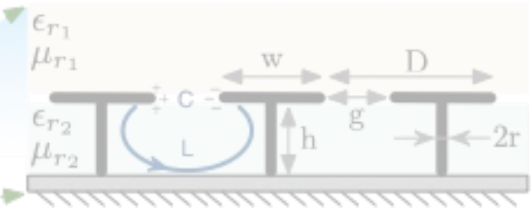

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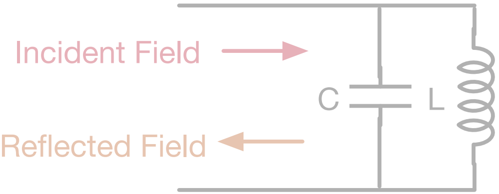

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Infinity

The reflected magnetic field has zero phase shift and thus it can constructively combine with the forward-propagating field

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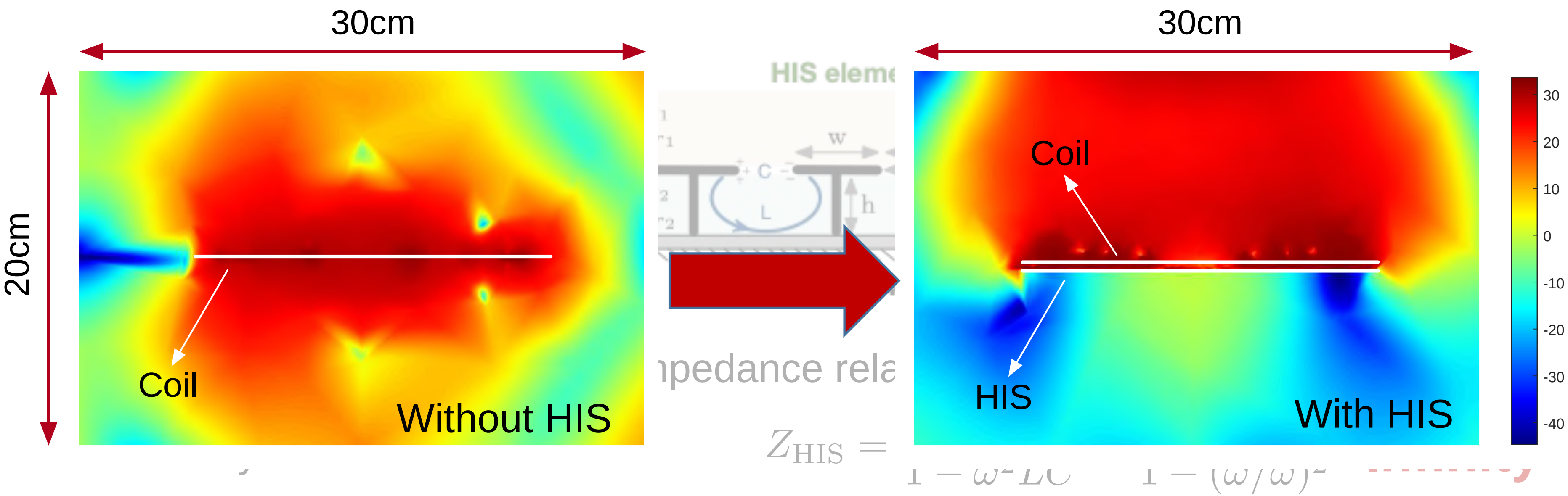

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More Precisely Spatial Controllability

A coil array can further enhance RFID+’s spatial controllability in fine-grain

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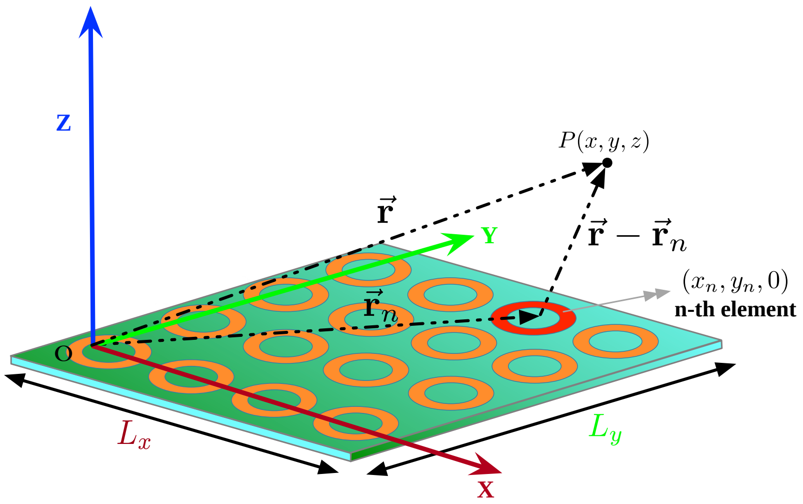

Magnetic Beamforming

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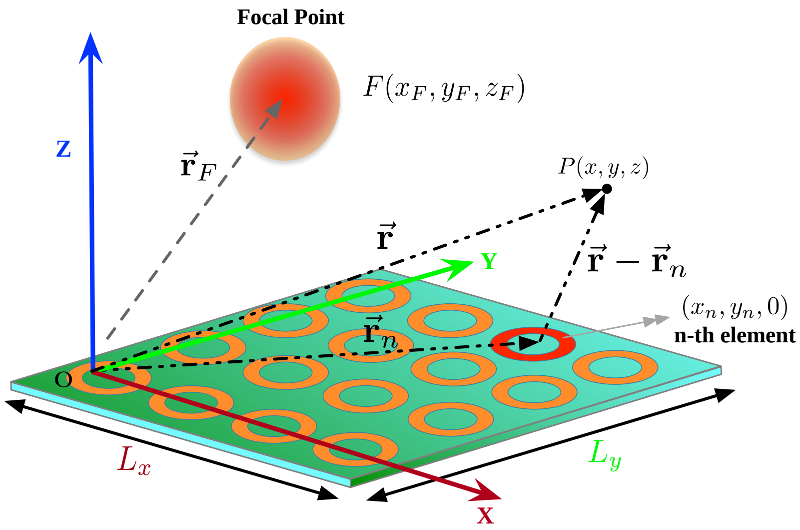
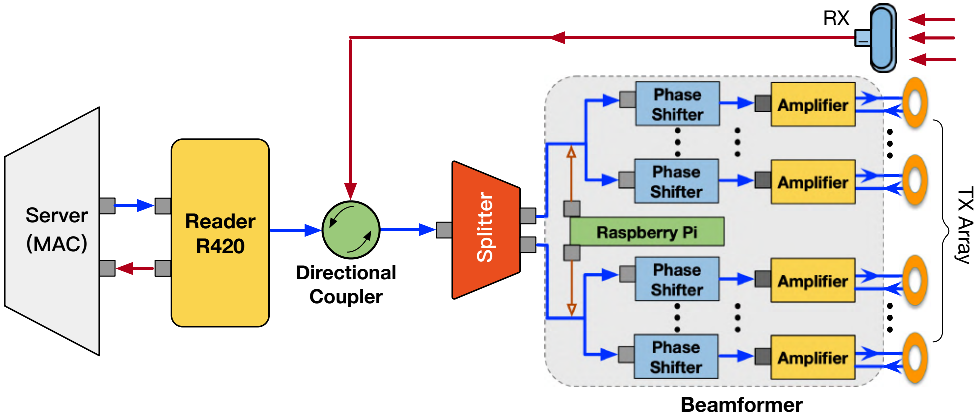


Magnetic Beamforming

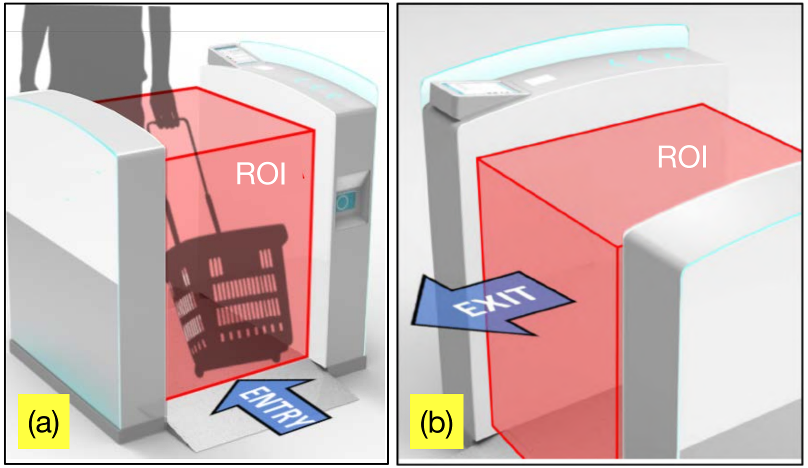


Architecture of Near-Field Reader

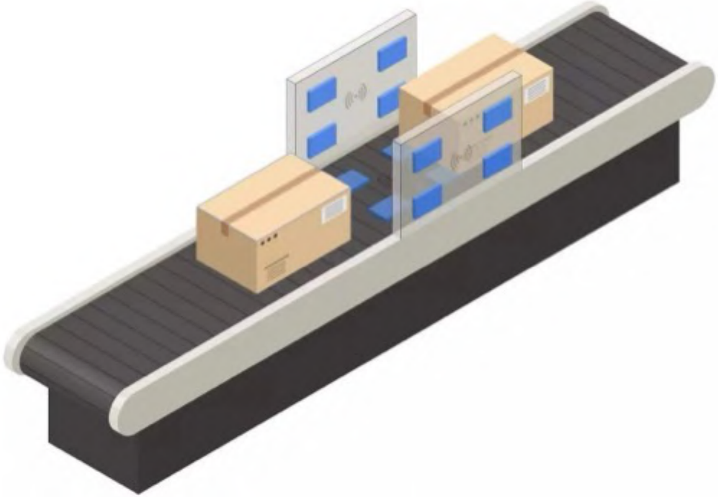
Challenge 3:

How to quickly detect all tags in a brief timeframe to ensure a smooth customer experience?

Fast Inventory: Desirable Yet Unachievable



Scenario1: Checkout Lane



Scenario2: Belt Conveyor

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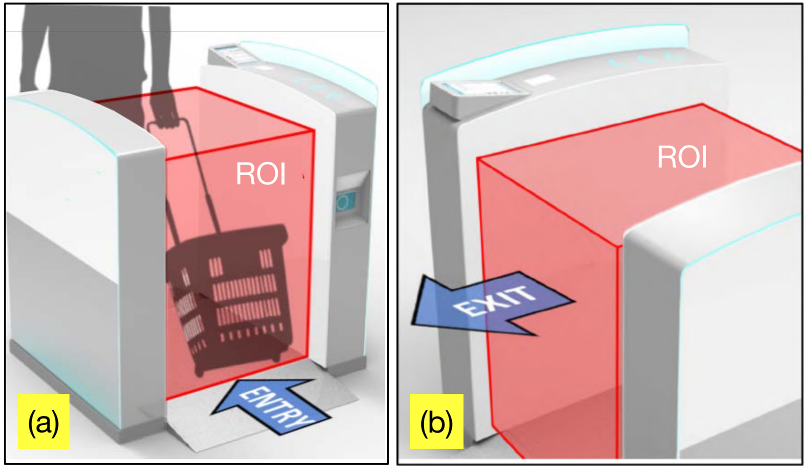

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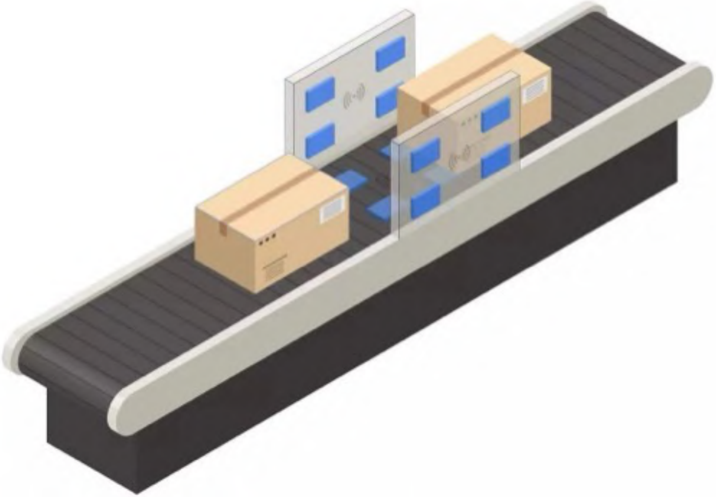

Scenario2: Belt Conveyor

- **Short Response Time:** RFID system has only several seconds to react

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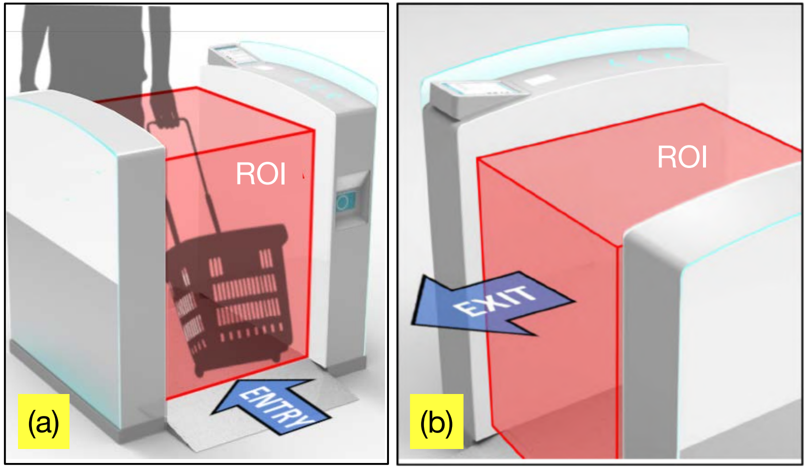

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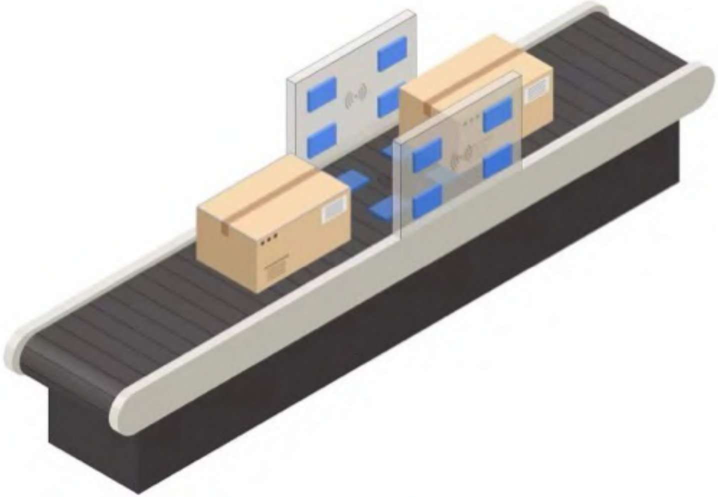

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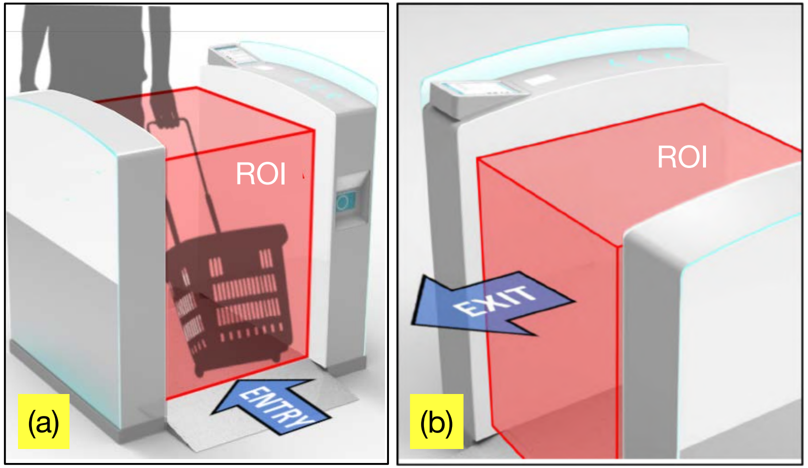

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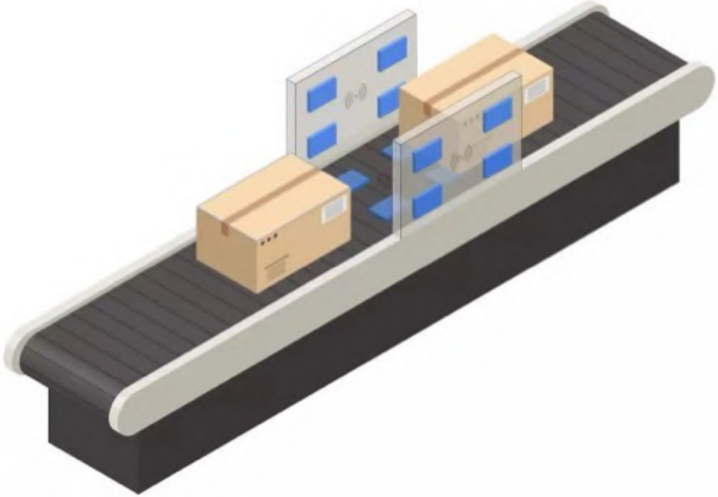

Scenario2: Belt Conveyor

- **Short Response Time:** RFID system has only several seconds to react
- **High Throughput:** About 100-200 tags need to be detected at each time
- **Massive Collision:** Nearly 74% of the time is lost to channel contention

Dual-Coupling Inventory Strategy

Prefetching: combines both radiatively- and magnetically-driven RFID systems together to enhance the reading speed within ROI.

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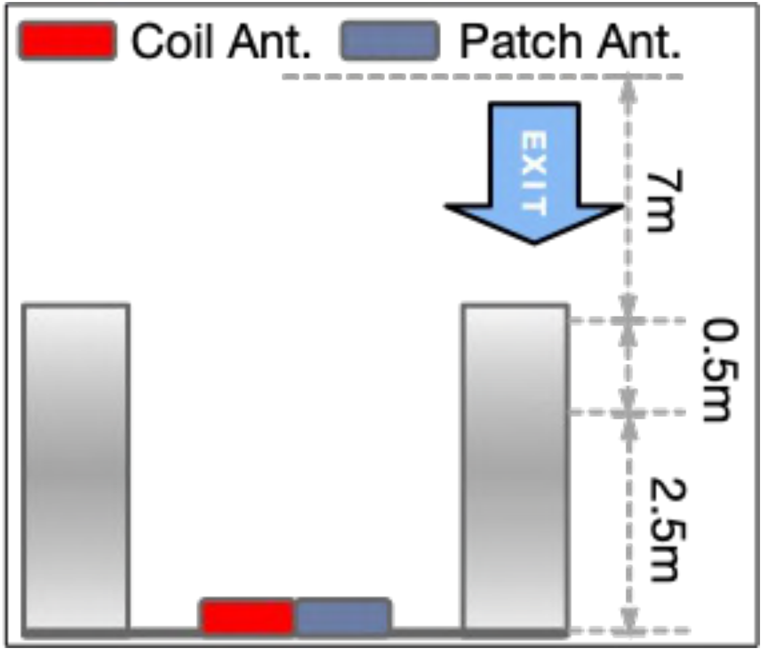

Top View of a Checkout Lane

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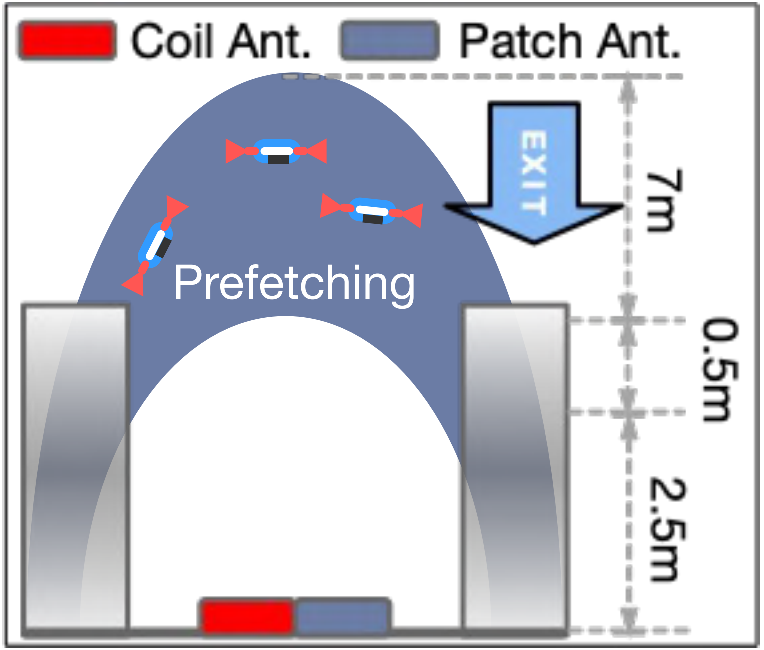

Top View of a Checkout Lane

- **Phase 1:** the far-field reader identifies a set of candidate tags in advance. The collected EPCs are then used to construct a Candidate Bloom Filter (BF).

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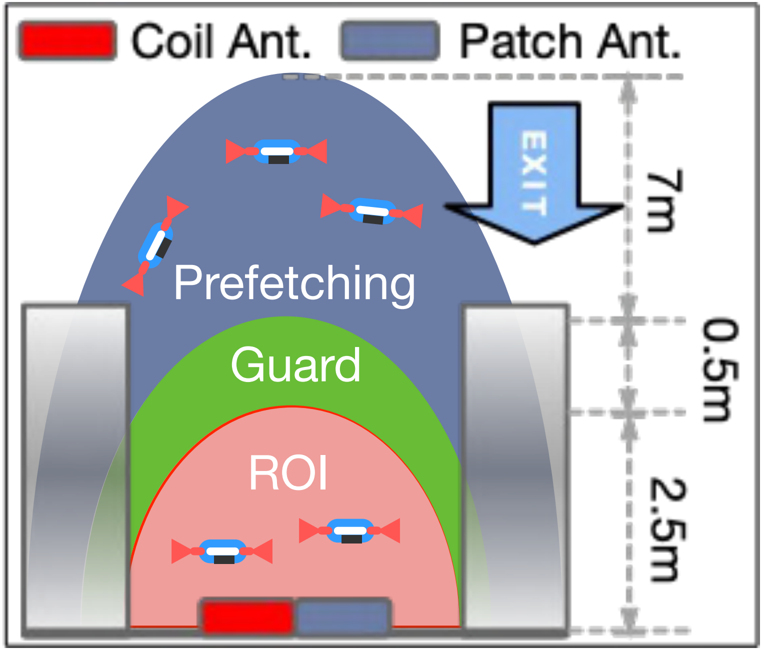

Top View of a Checkout Lane

- **Phase 1:** the far-field reader identifies a set of candidate tags in advance. The collected EPCs are then used to construct a Candidate Bloom Filter (BF).
- **Phase 2:** the near-field reader uses previously obtained BF to check for the presence of tags within the ROI quickly.

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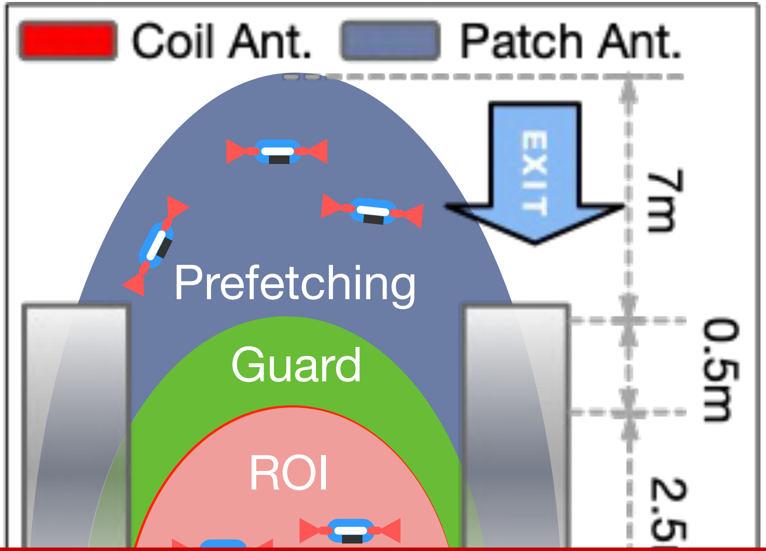

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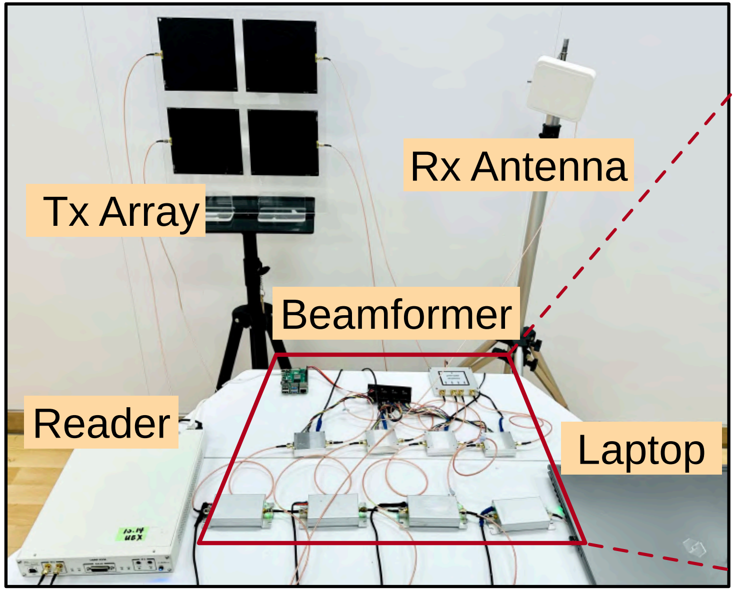
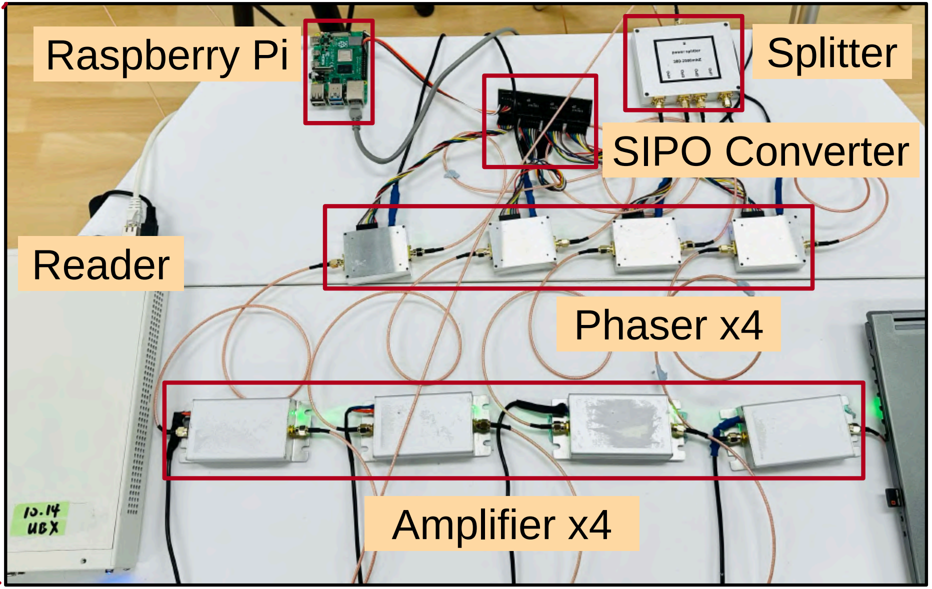
The acquisition overhead is reduced by approximately 60% by using Bloom Filter to speed up the inventory process

Implementation





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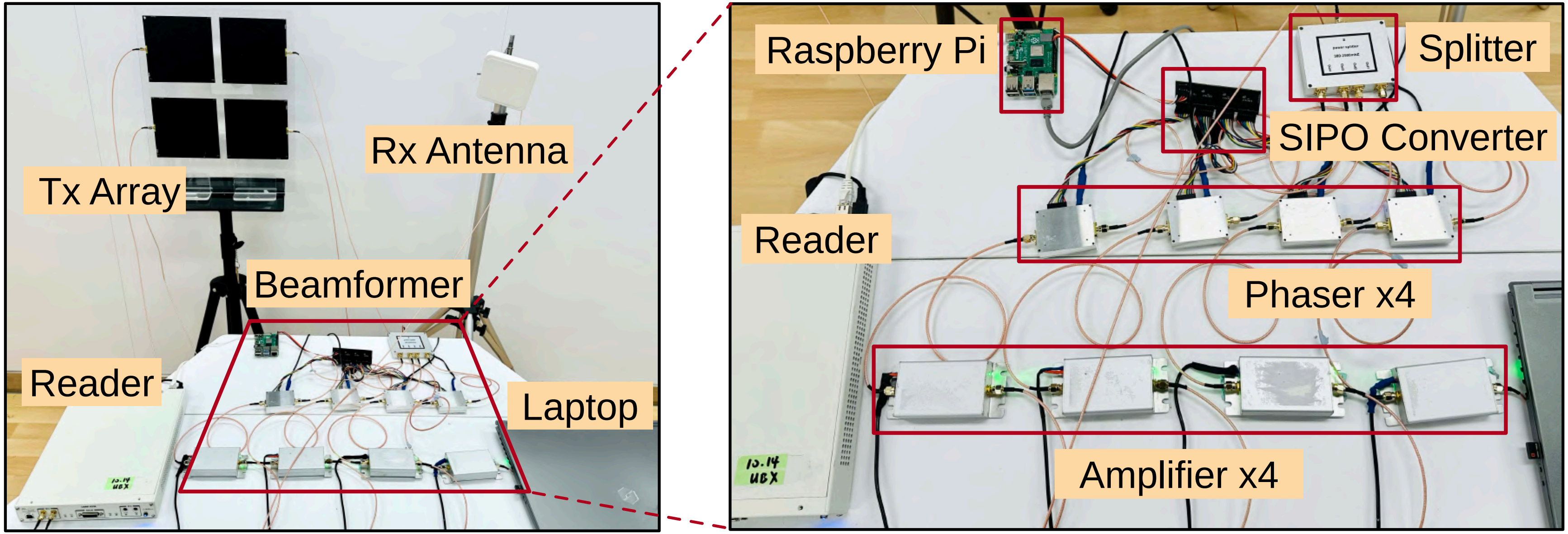
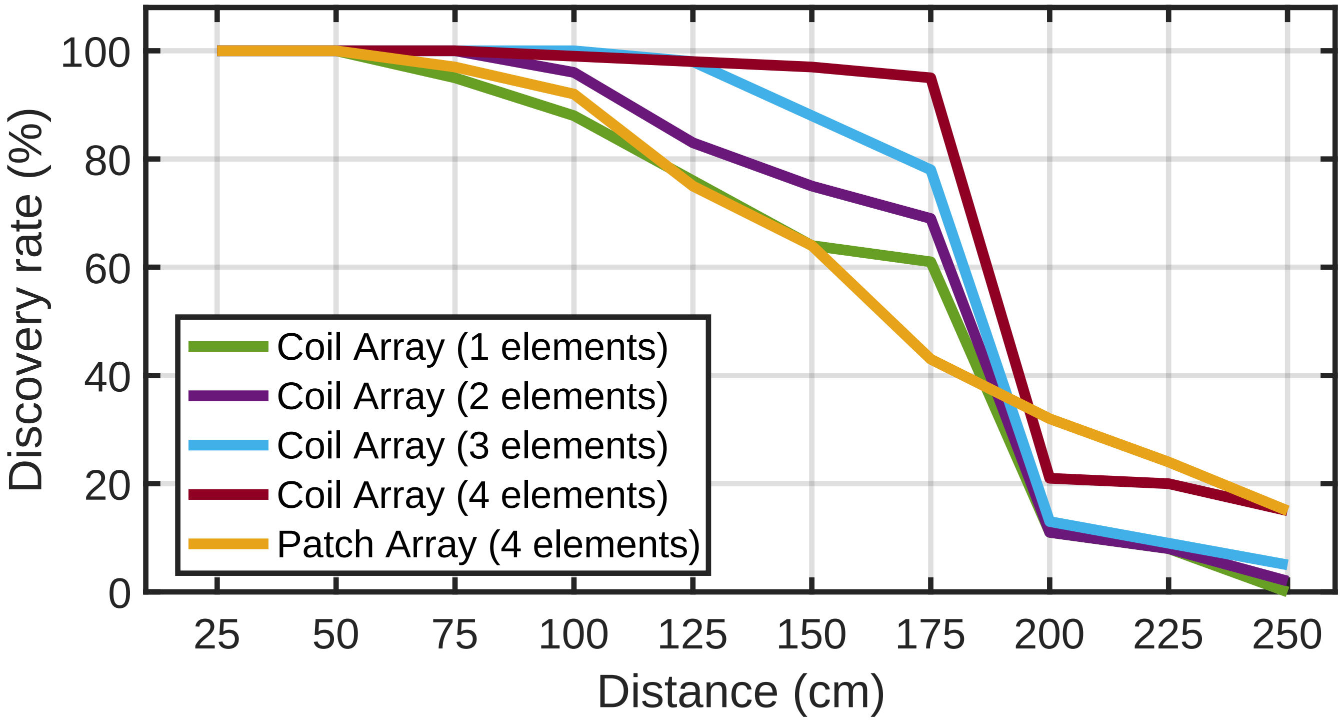


- **Reader:** USRP X310 software-defined radios
- **Beamformer:** Raspberry Pi 4 Model B + Phase Shifter (PHSA-152)
- **Tx:** Custom-designed 2 × 2 coil antenna array + HIS reflectors

Inventory Accuracy

Inventory Accuracy

In the test, a dense collection of 100 tags was fixed to a flat surface. The accuracy was measured based on the discovery rate



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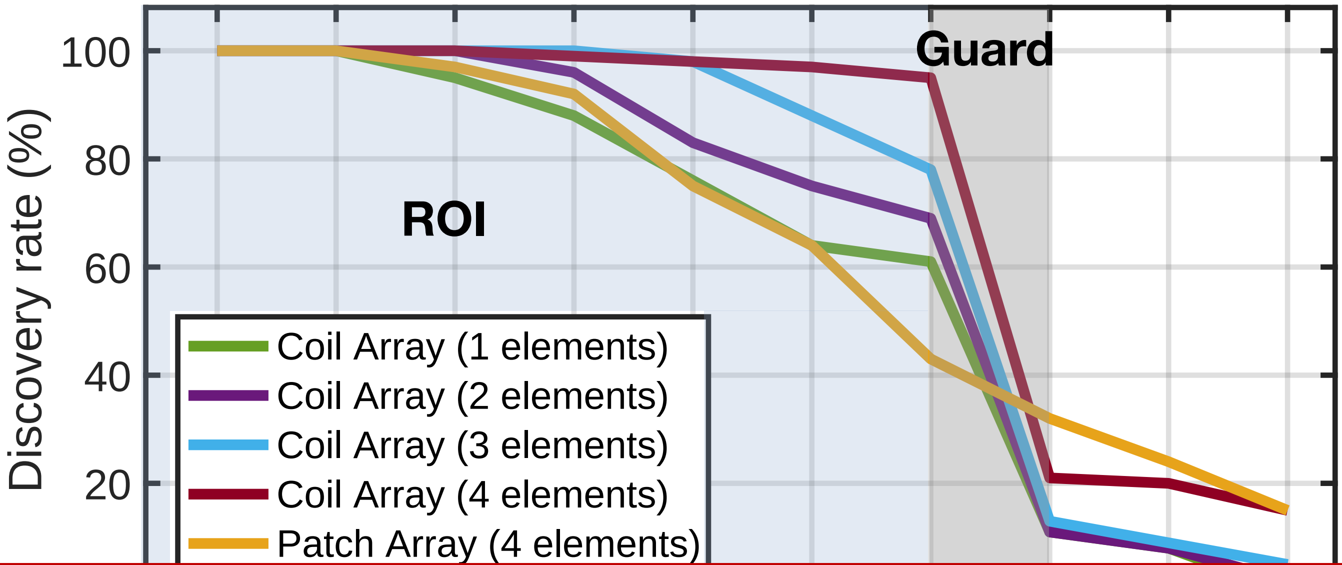
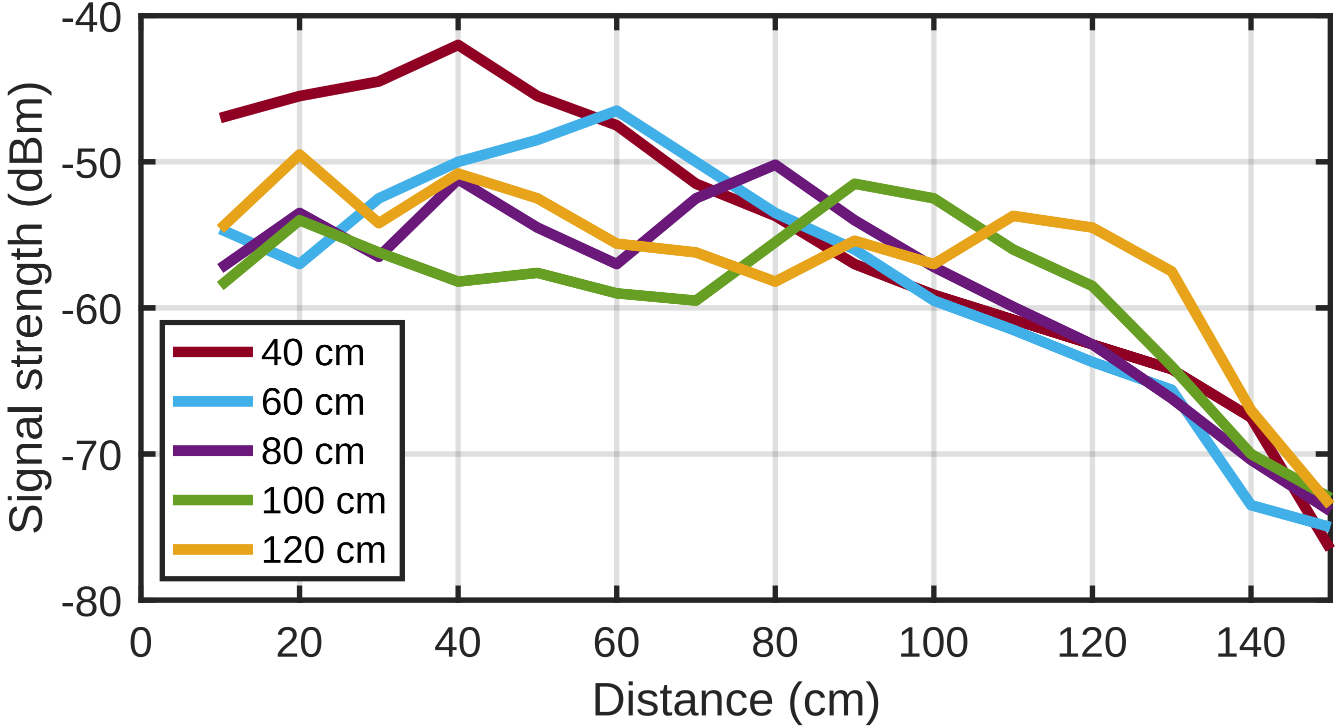


RFID+ excels in detecting tags within ROI up to 175cm (>95%), and performance significantly declines beyond this range.

Spatial Manipulation

Spatial Manipulation

We directed the beamforming's focus to five positions along the Z-axis. For each position, the tag's backscattered signal strength was measured.



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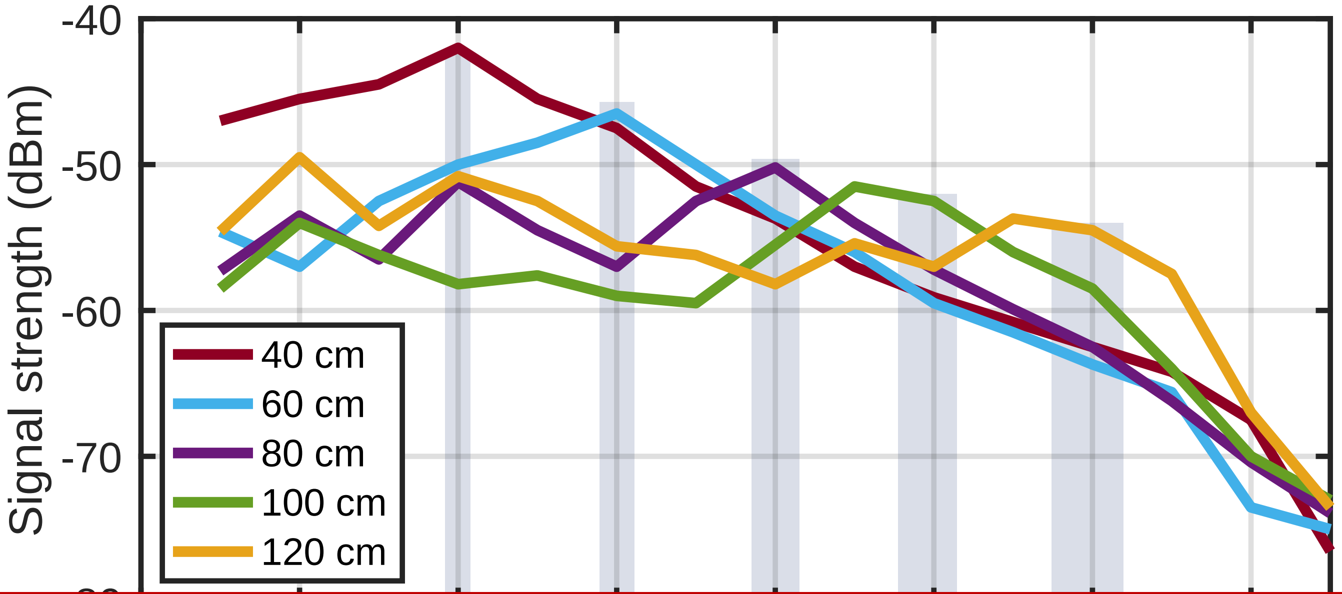
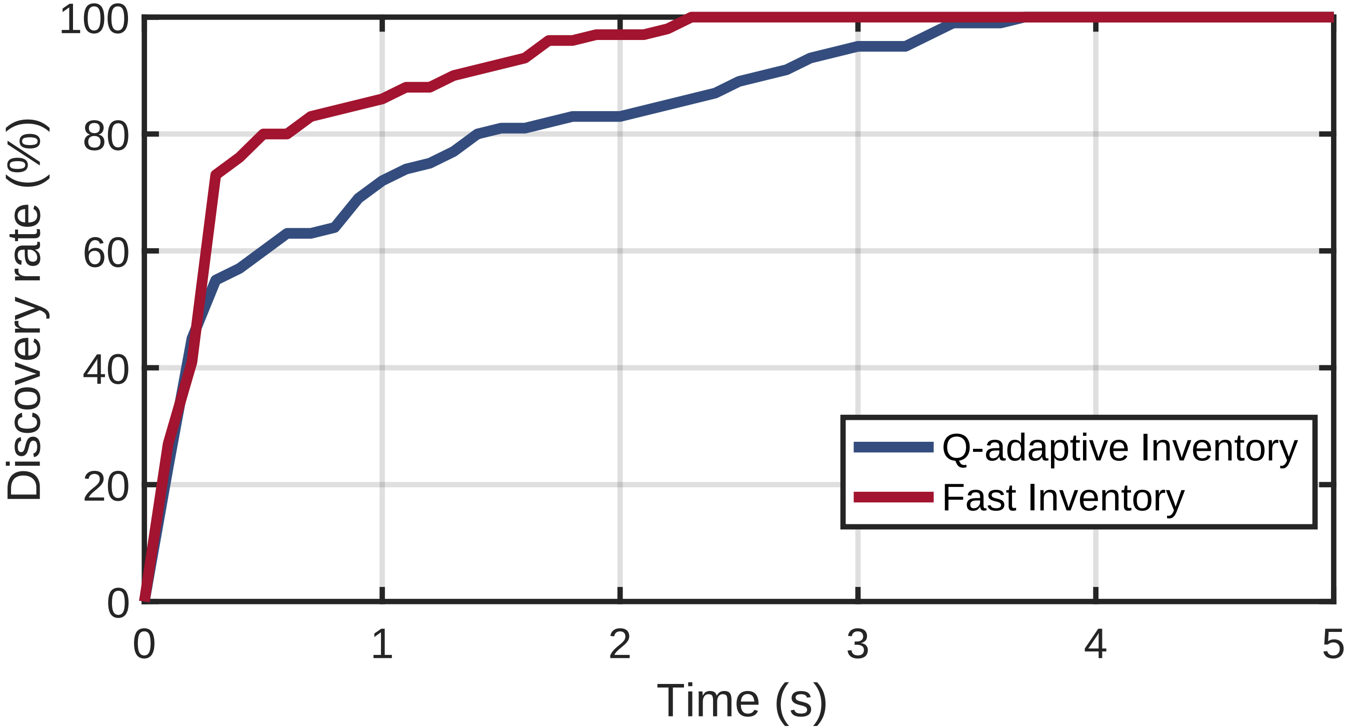


The beamforming focal point increases the average received signal strength by approximately 7.73 dB at these locations.

Inventory Efficiency

Inventory Efficiency

We compared the proposed dual-coupling fast inventory algorithm against the conventional Q-adaptive inventory method.



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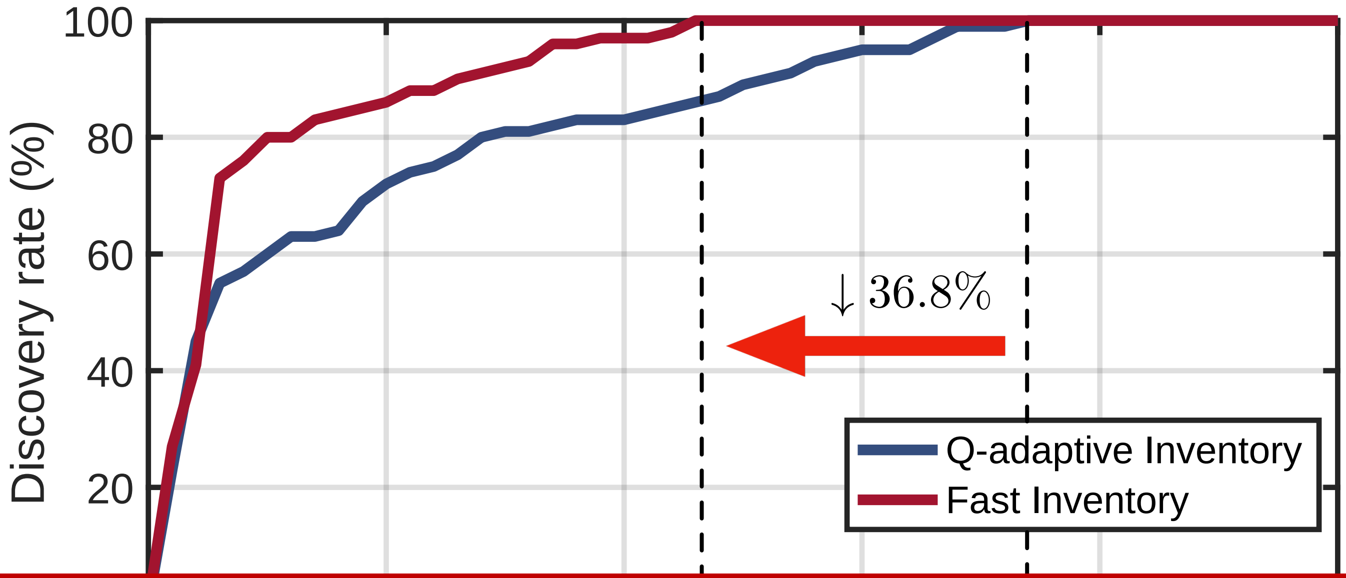

The fast inventory achieves discovery in just 2.4 seconds, saving 36.8% of the time compared to the Q-adaptive algorithm.

Pilot Study: Logistic Network Evaluation

We tested RFID+ in a textile factory warehouse and a conveyor scanning gateway.

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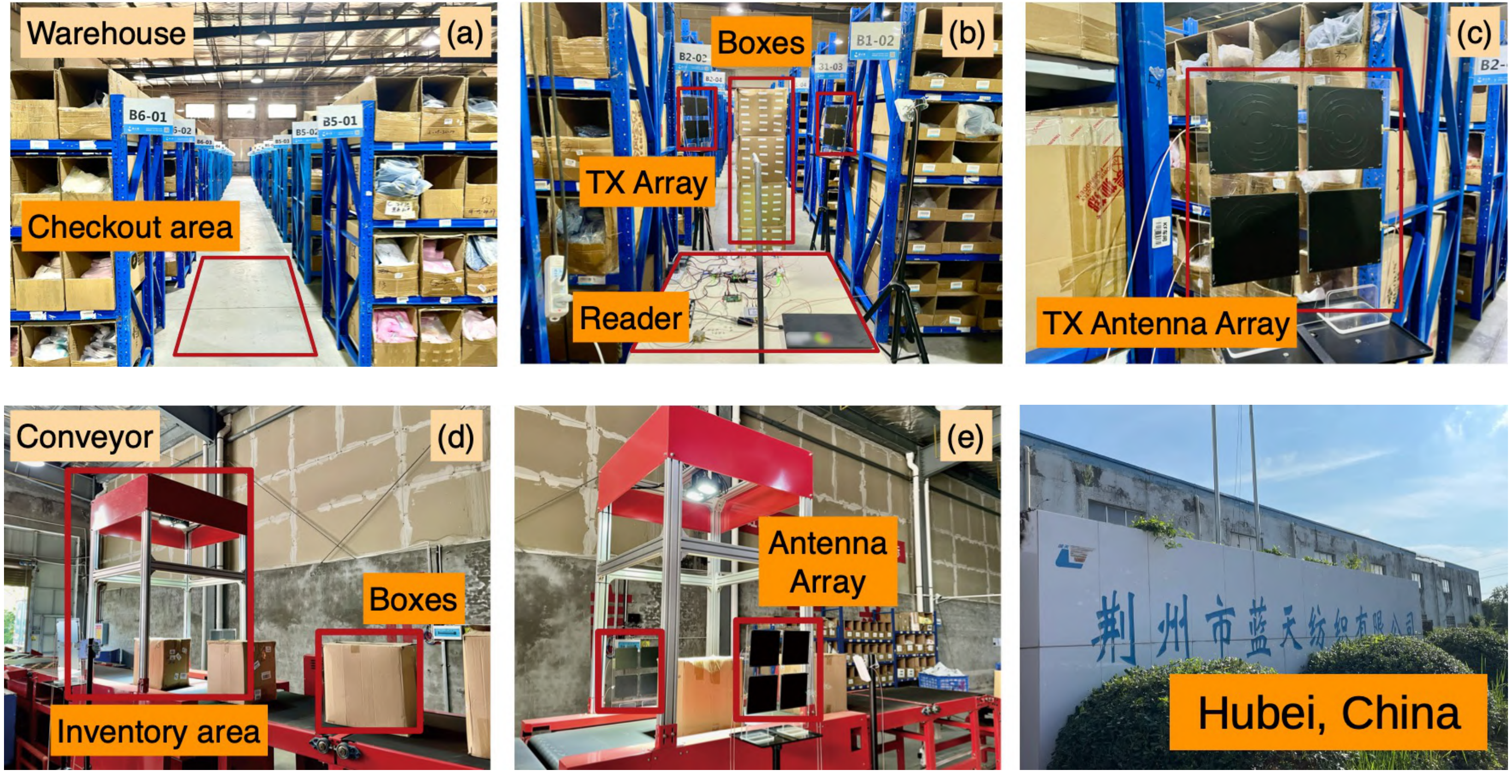

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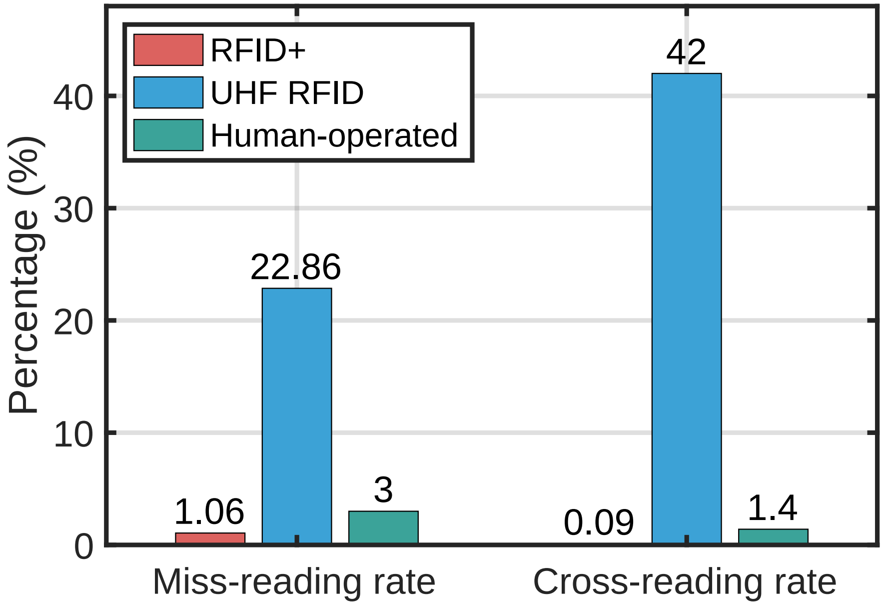
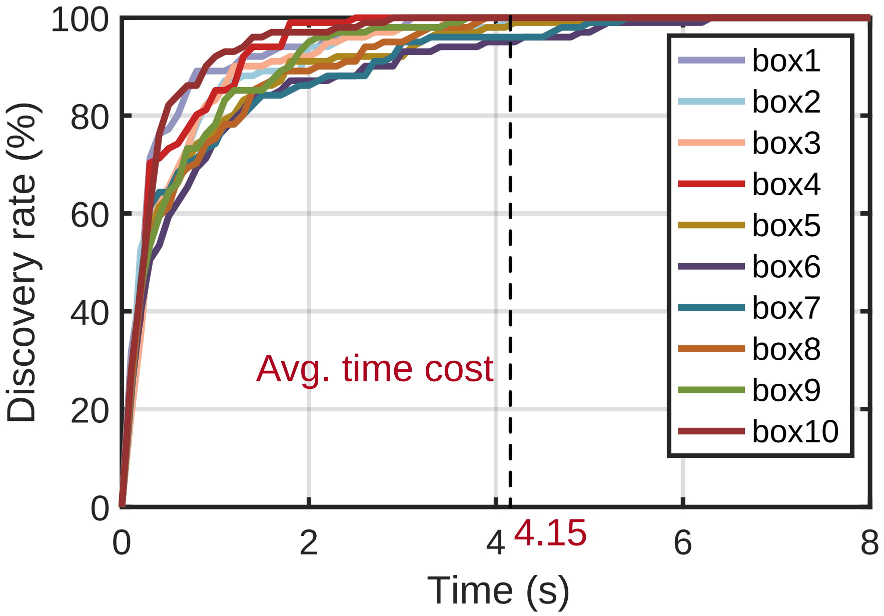


Warehouse



Conveyor

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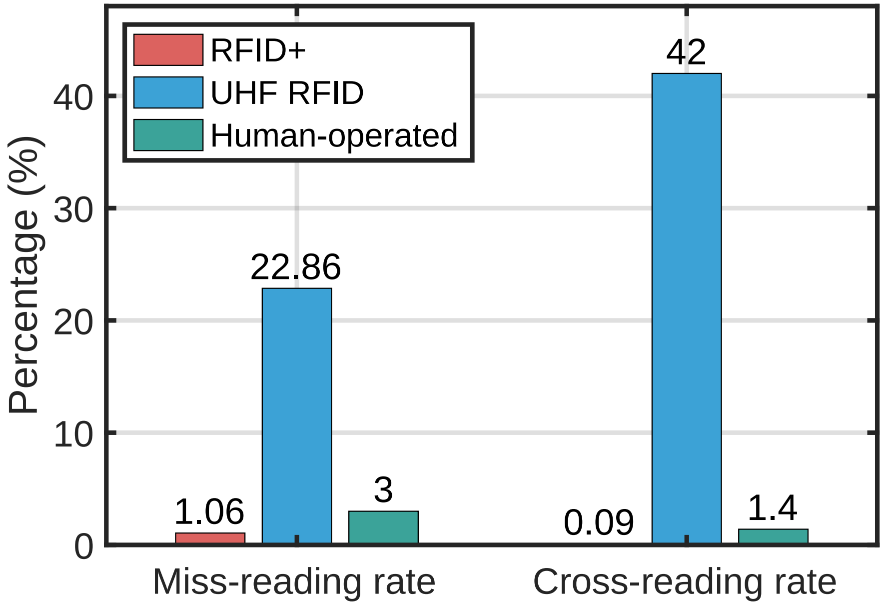

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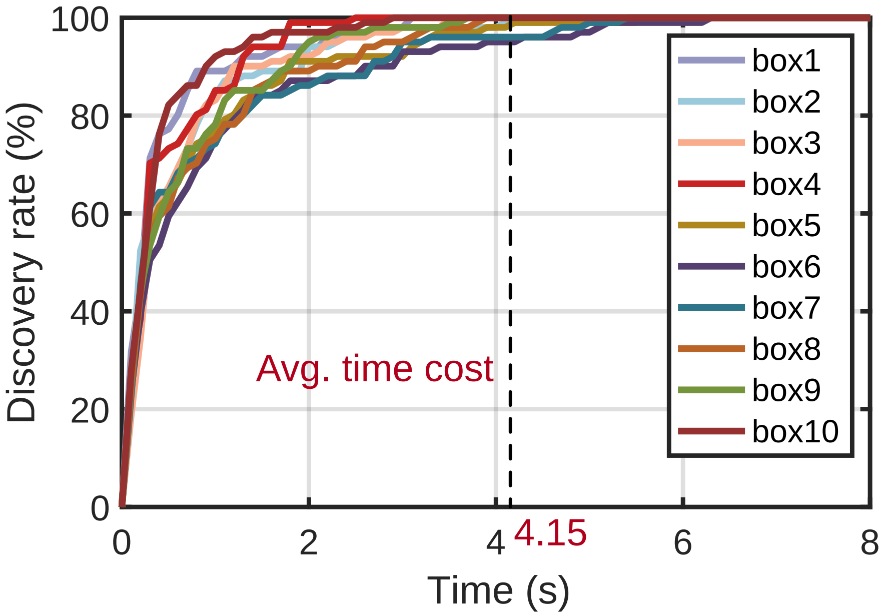

Conveyor

RFID+ achieved about 1.95% miss-reading rate and nearly 0.1% cross-reading rate within a reasonable time slot.

Conclusion

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- We first demonstrate that a **magnetically-driven UHF RFID** system is feasible and valuable.

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Conclusion

- We first demonstrate that a **magnetically-driven UHF RFID** system is feasible and valuable.
- We first integrate disparate elements (e.g., **capacitor-segmented loops, multi-turn coils, HISs, coil arrays**, etc.) into a unified practical RFID inventory system.
- We achieve a **1.95%** miss-reading rate and nearly **0.1%** cross-reading rate in a pilot study.