ACM MobiCom 2025

QuinID: Enabling FDMA-Based Fully Parallel RFID with Frequency-Selective Antenna

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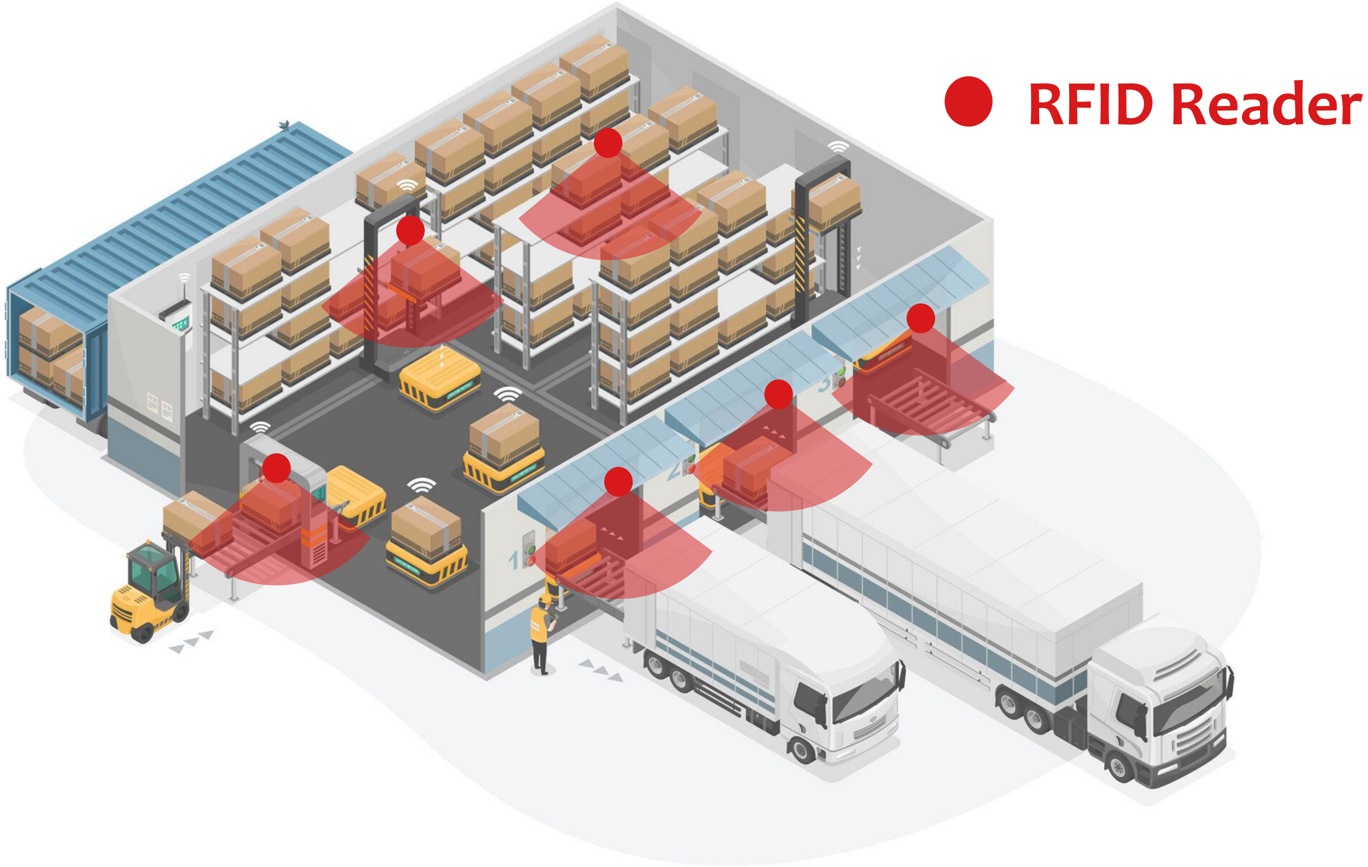
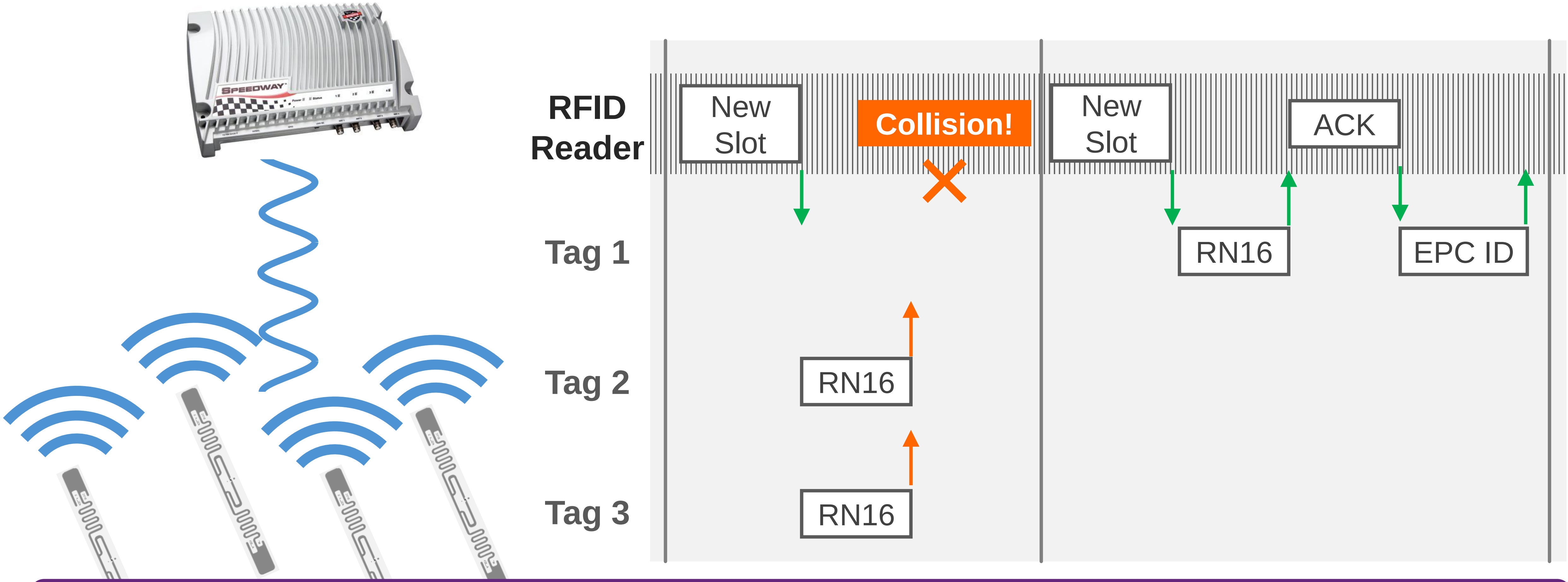
Status Quo: Large Quantity of Tags with Massive Data



Applications require real-time and high-throughput ID collection.

Traditional RFID: Slotted ALOHA-based Protocol

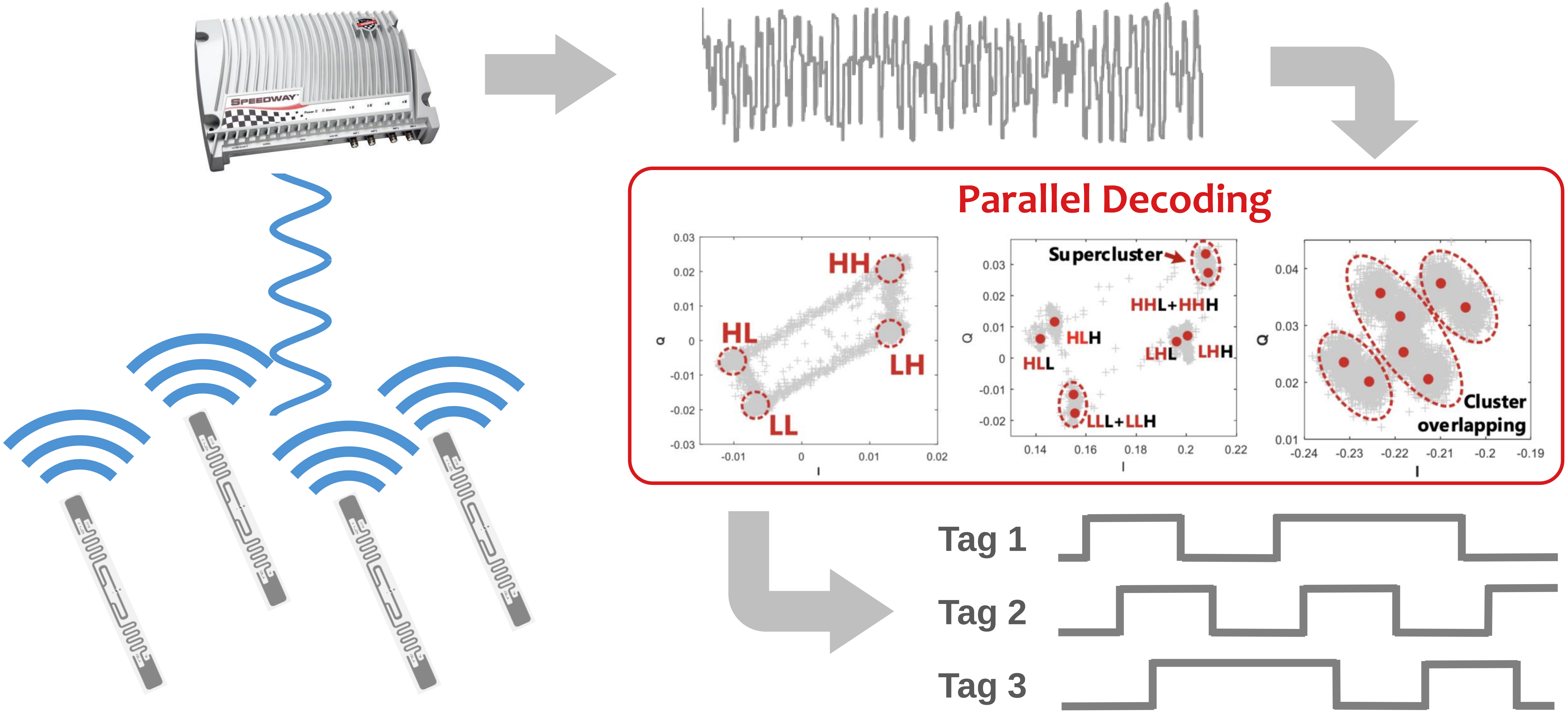
➢ Slotted ALOHA protocol (EPC Gen 2) interrogates tags one by one



Parallel RFID communication has become essential.

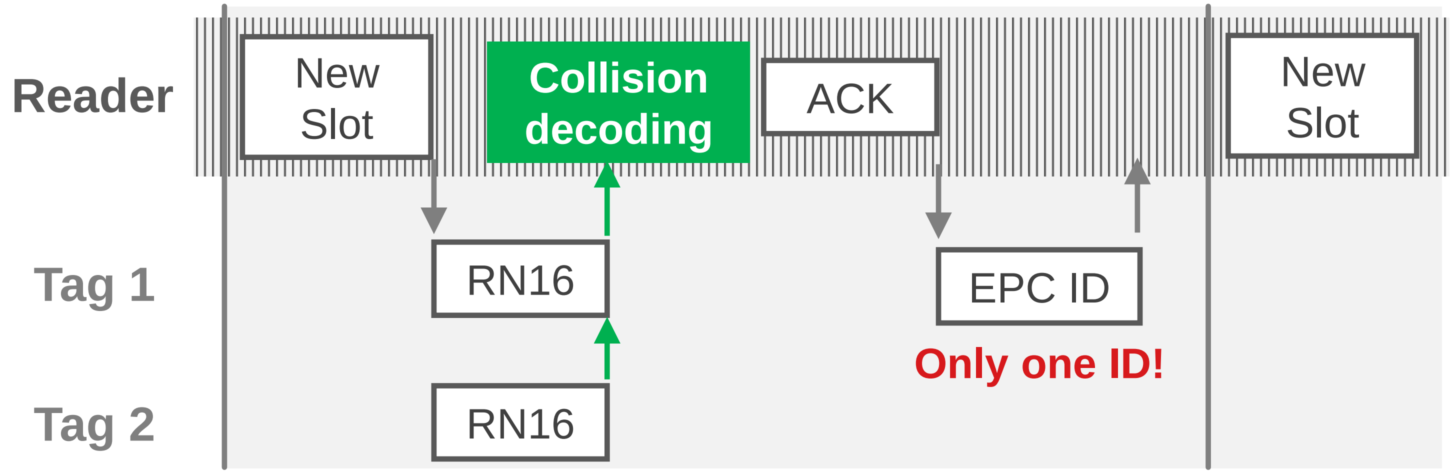
Existing Approach: Parallel Decoding

➢ **This approach lets tags backscatter concurrently and decode collided transmissions**

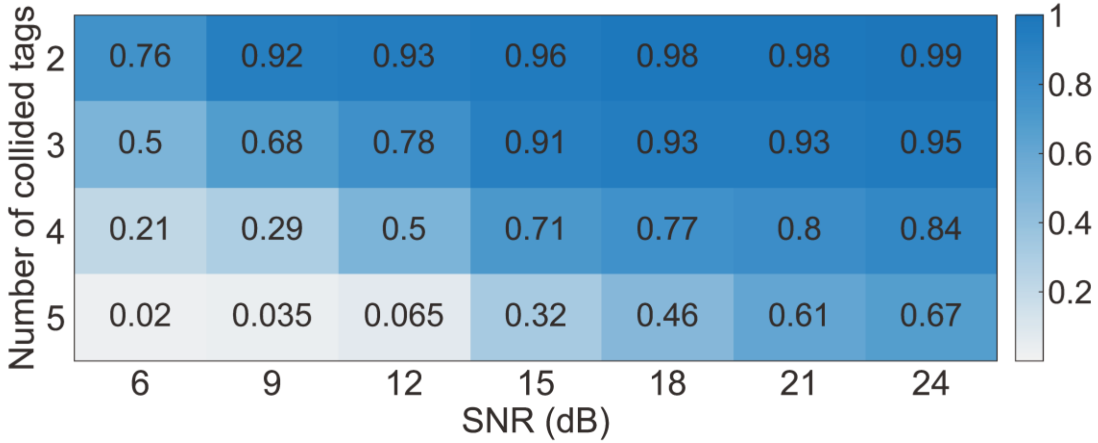


Parallel Decoding cannot achieve genuine and practical parallel RFID

- **Still confines to a TDMA operation**



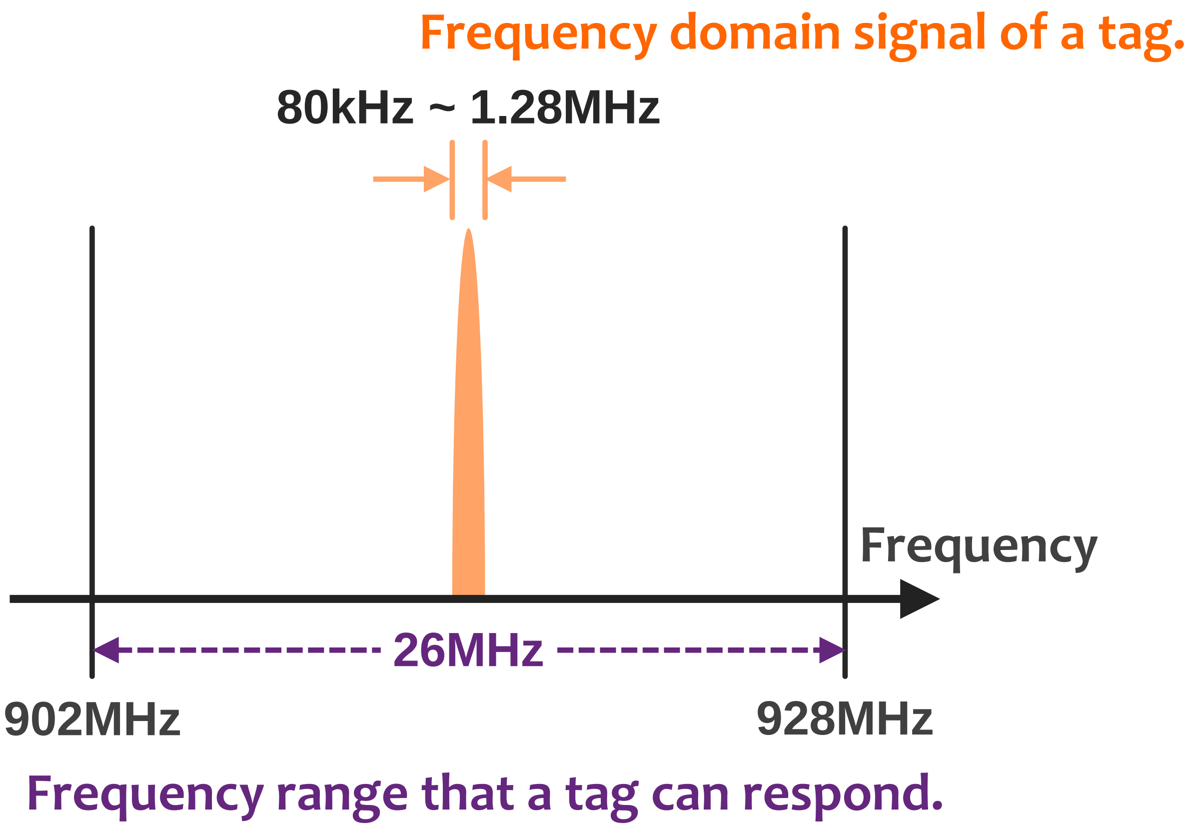
- **Unstable performance in varying conditions**



Successful collided RN16 decoding rate of algorithm from *FlipTracer (MobiCom 17).*

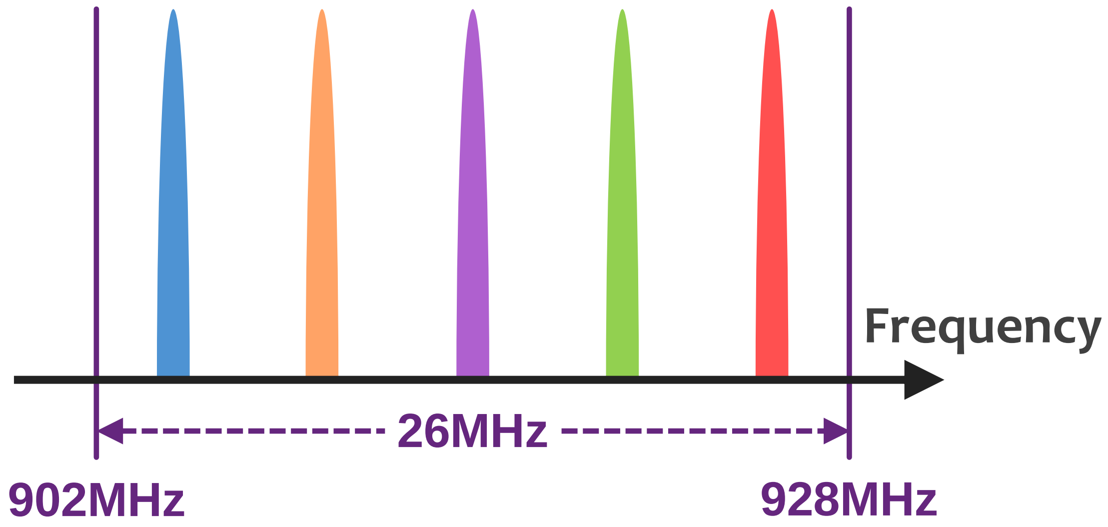
Observation

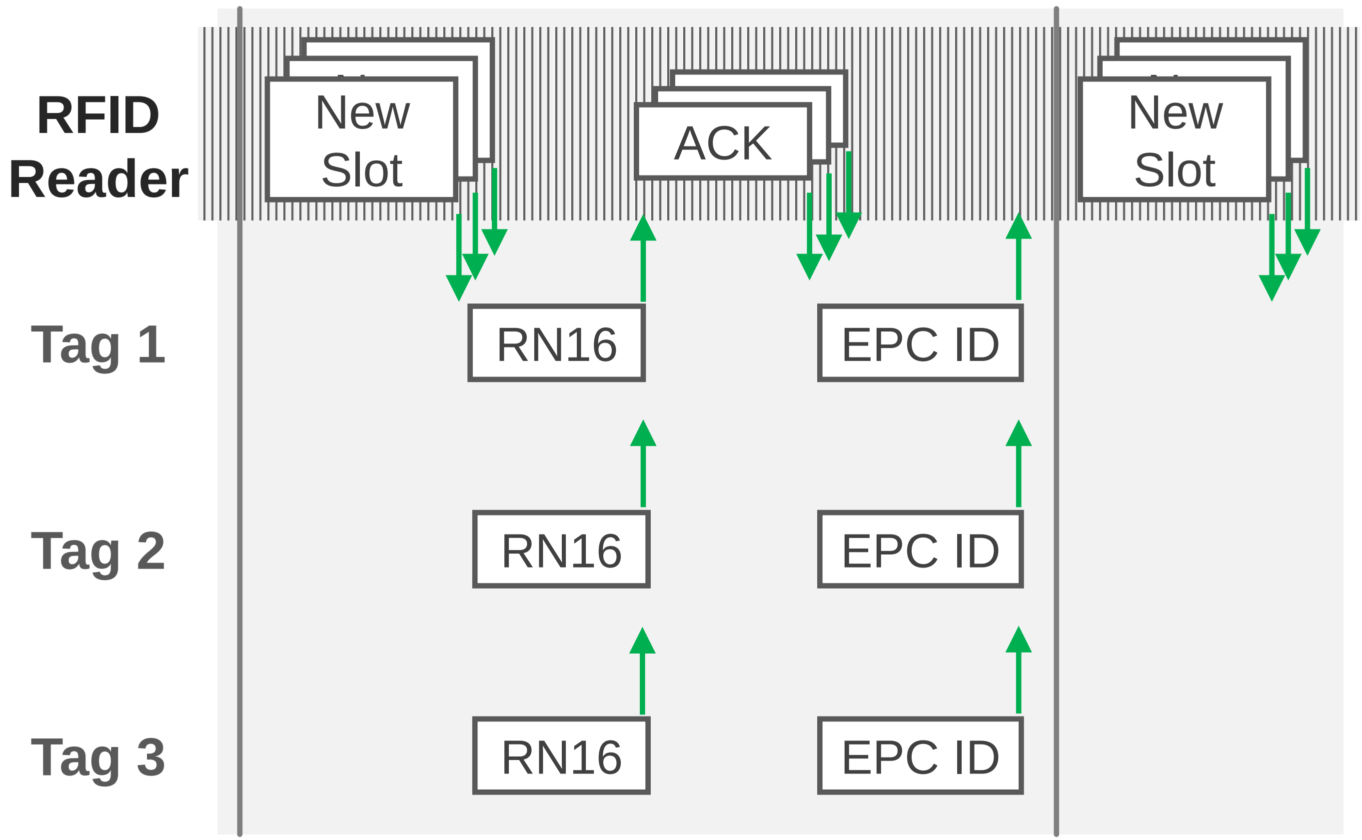
➢ **Tags operate across wide frequencies, but readers excite within a narrow band**



Observation

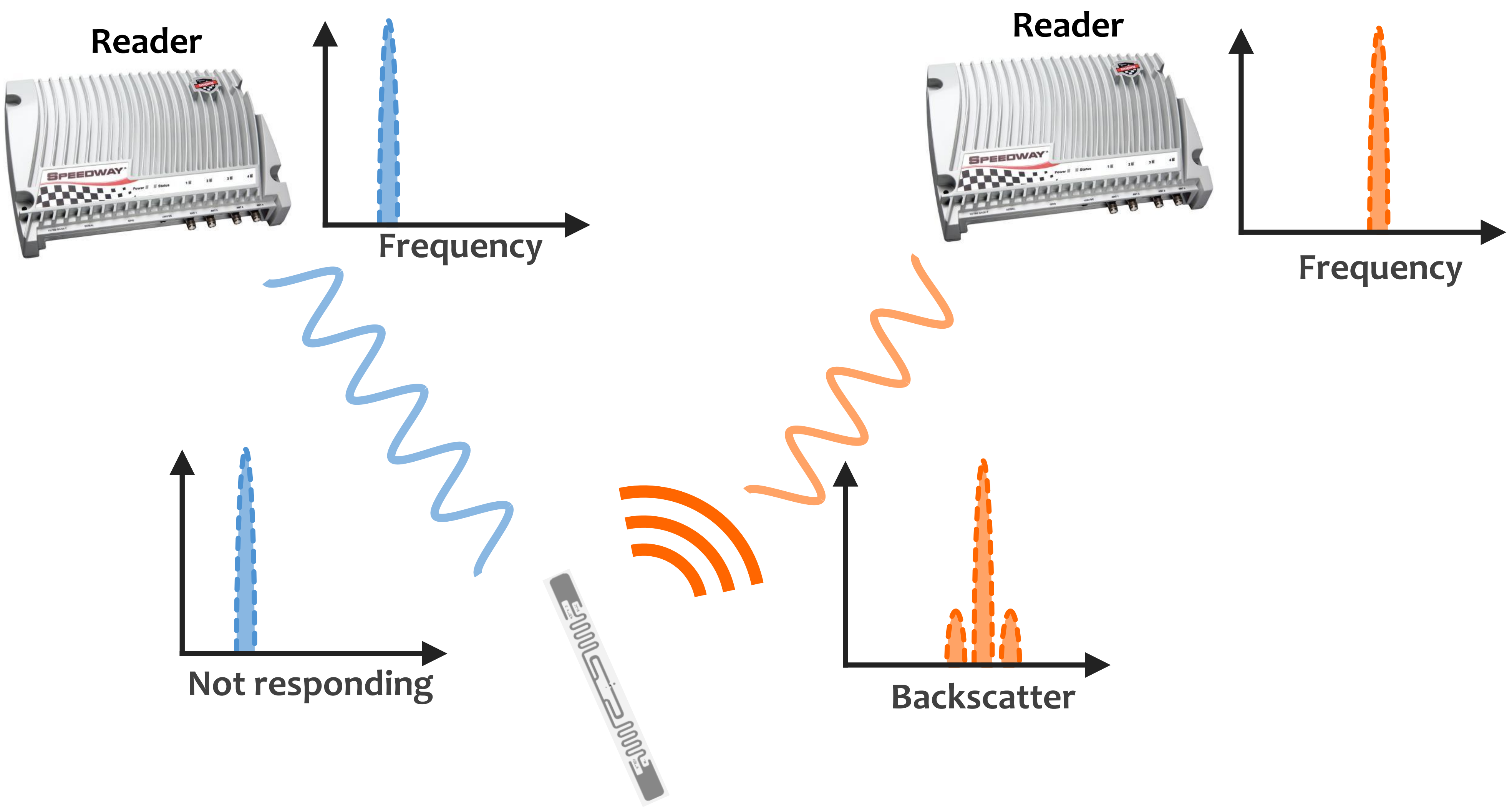
➢ Tags operate across wide frequencies, but readers excite within a narrow band





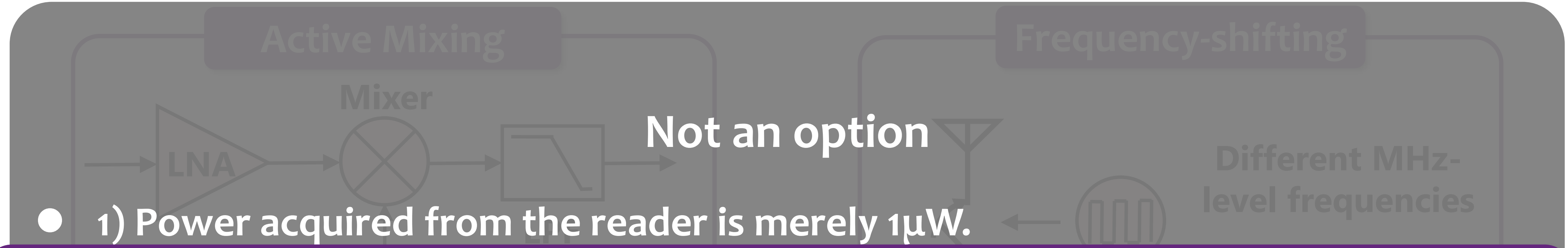
Can we achieve FDMA-based fully parallel RFID communication?

How can a passive tag select its own frequency?



Challenge: High Power Budget and Compatibility

➢ *An FDMA circuit solution*



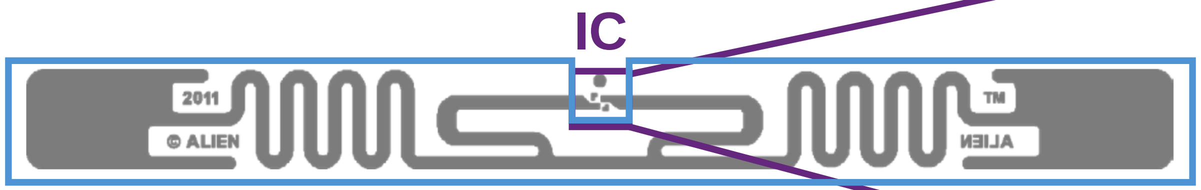
Not an option

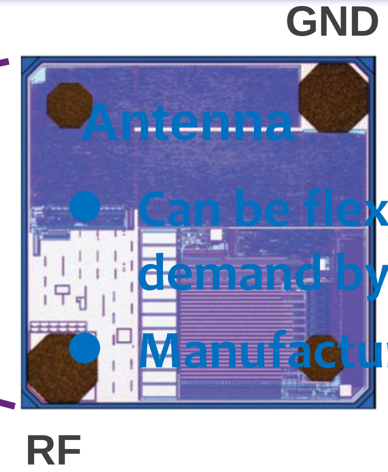
- 1) Power acquired from the reader is merely 1μW.

How can we introduce a frequency-selective antenna while maintaining a battery-free and cost-effective design?

Antenna

- Can be flexibly implemented on demand by service providers.
- Manufacturing is cheap.

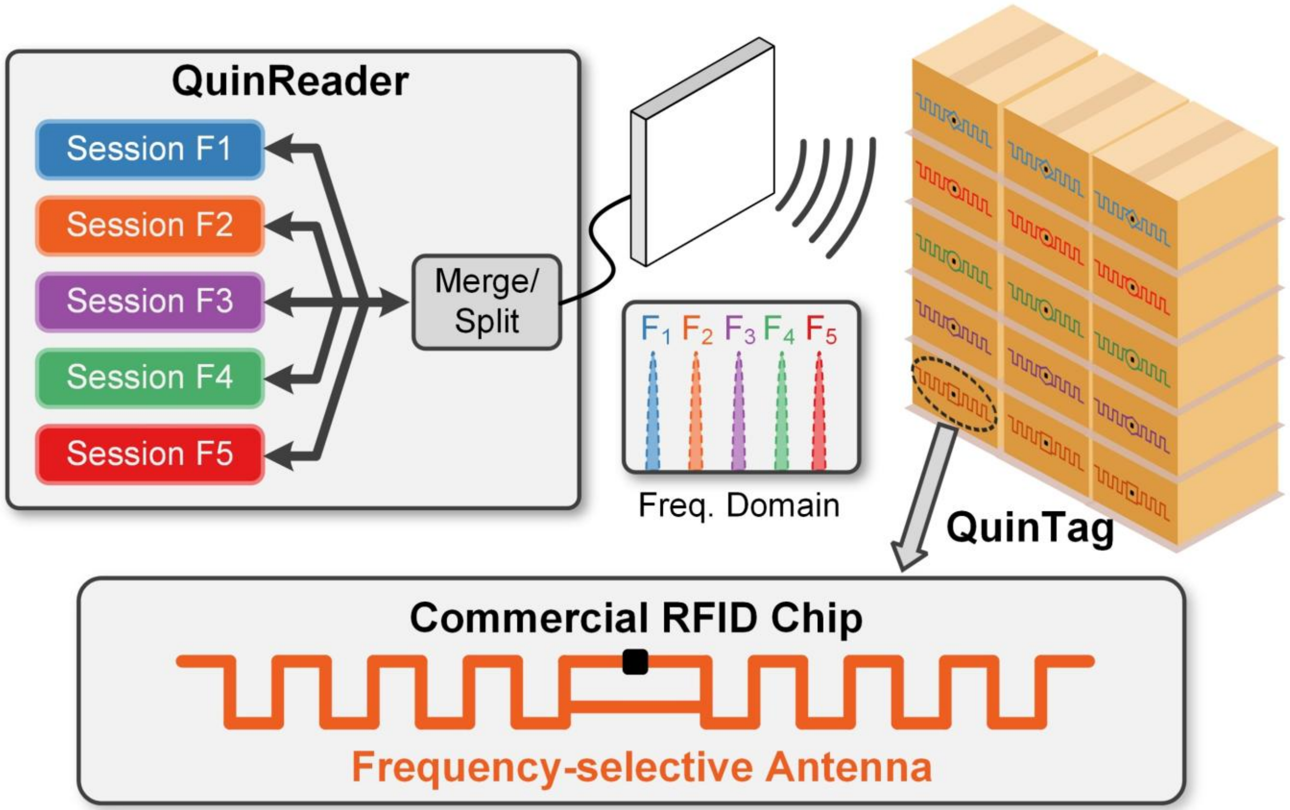


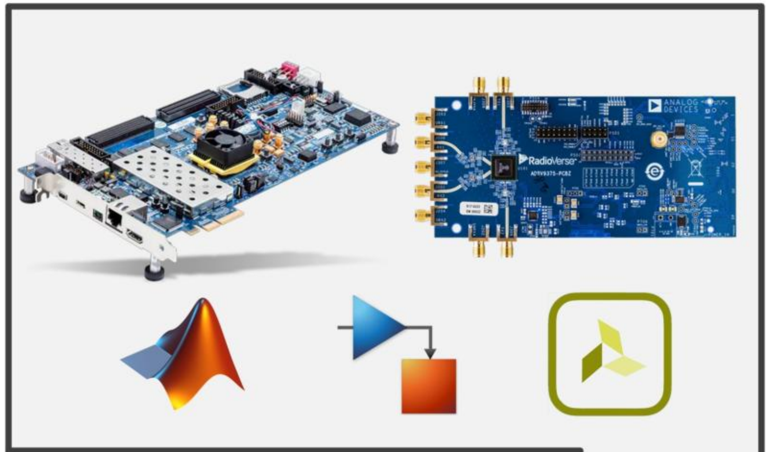


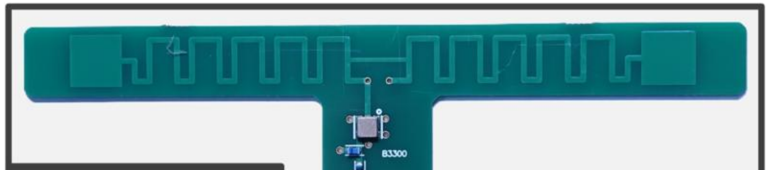
- Nano-scale tag IC chip, already been mass-produced with no carrier distinguishing capability.

QuinID: FDMA-Based Fully Parallel RFID

- ***The first FDMA-based fully parallel RFID system***
  - *Achieves five sub-band FDMA operation, reaching up to 5000 reads per second*
  - *Completely compatible with commercial RFID*




FPGA-based QuinReader


QuinTag

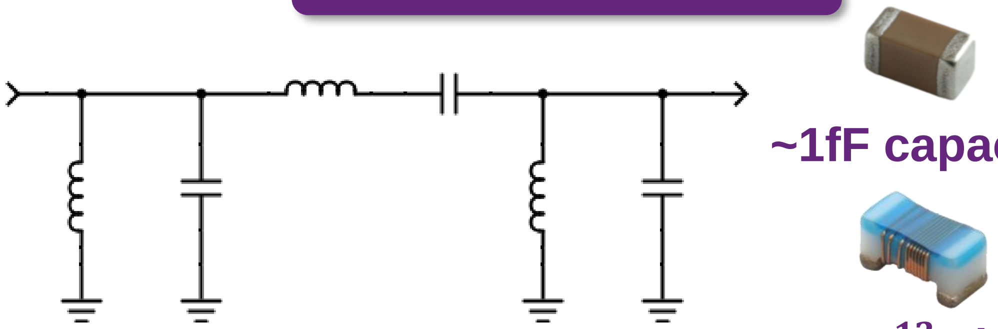
Passive Frequency Selective Antenna in the RF Domain

➢ *Passive filtering capabilities arise from resonant structures*

Quality factor: $$Q = \frac{f_c}{\Delta f} = 2\pi \cdot \frac{\text{energy stored}}{\text{energy dissipated per cycle}}$$

Five sub-bands → 5MHz in 902~928MHz band → Q-factor **at least 200**

LC resonator



~1fF capacitor

$< 10^{-12}$Ohm parasitic resistance

Spec not achievable!

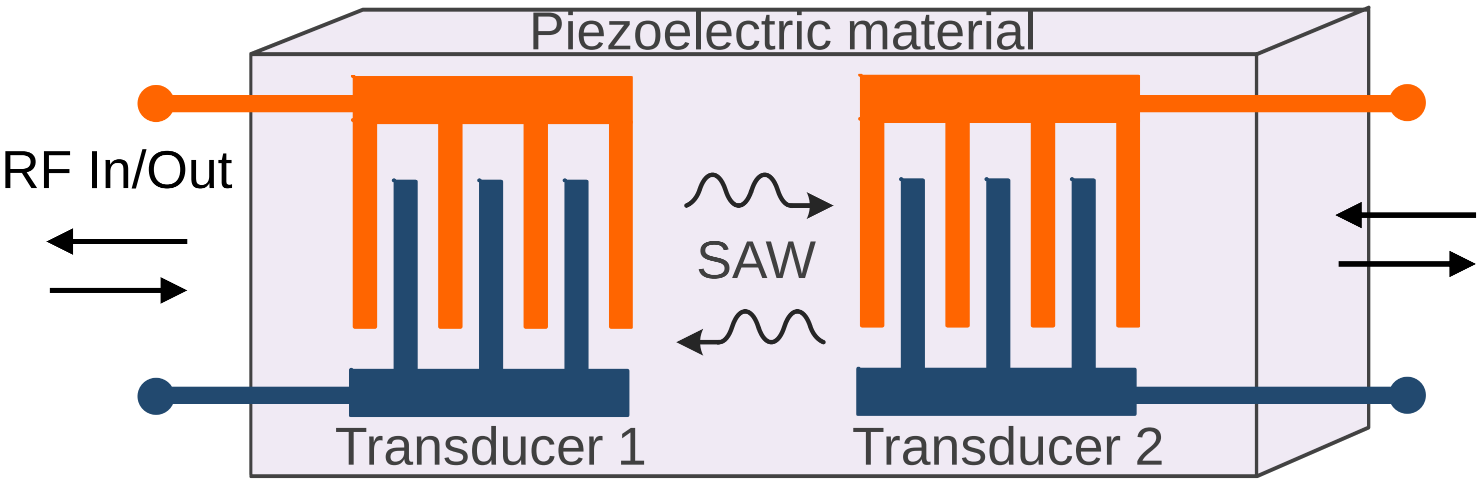
Transmission line resonator

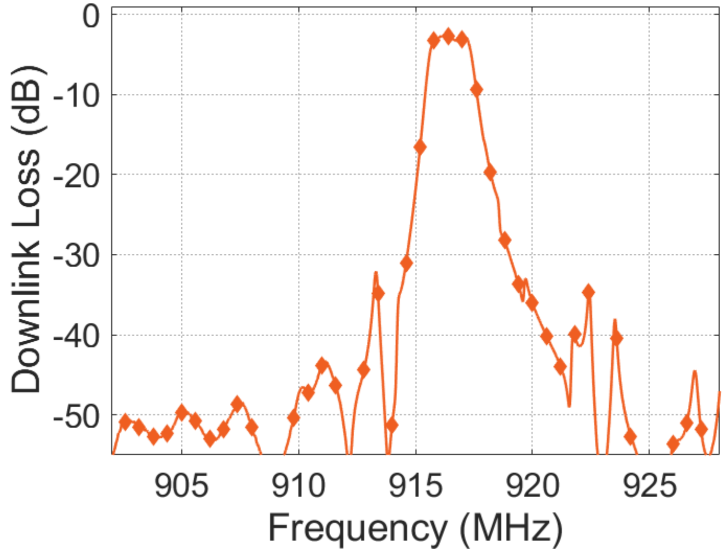
- Radiation dissipation
- Conductor loss

Quality factor limited!

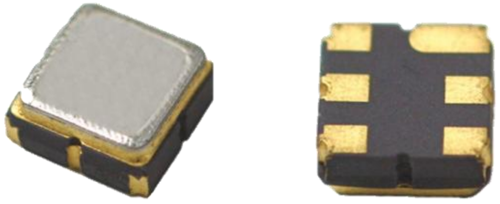
Passive Frequency Selective Antenna in the RF Domain

➢ ***Surface Acoustic Wave (SAW) filter satisfies above requirements***





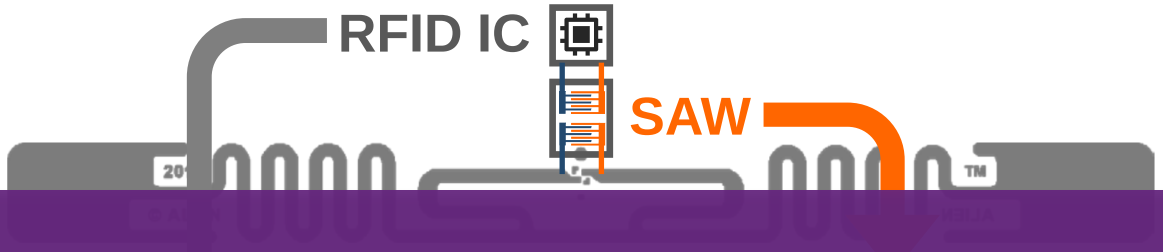
- ***Extremely sharp frequency response with Q-factor up to 1000***
- ***Compact size at IC scale and very low cost***

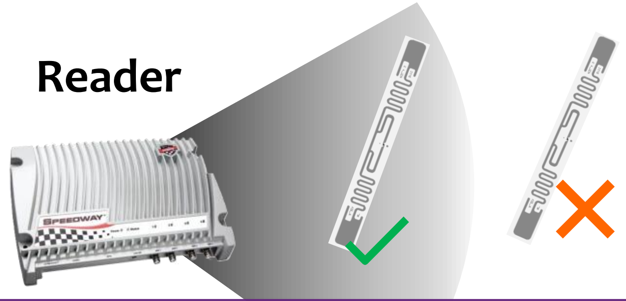


3mm×3mm with package
sub-millimeter die

Designing SAW-based Frequency Selective Antenna

- *Attach the SAW filter directly to RFID antenna*



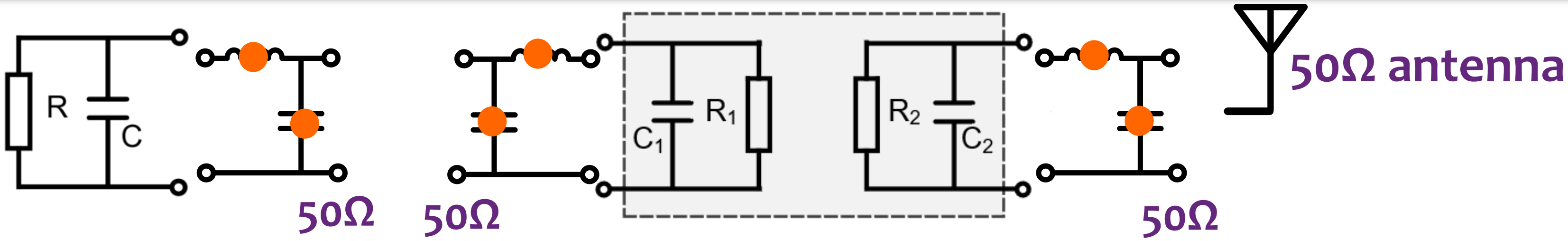


Extremely short read range

not matching

- *Standard approach: uniformly matching all connection ends to standard 50Ω*

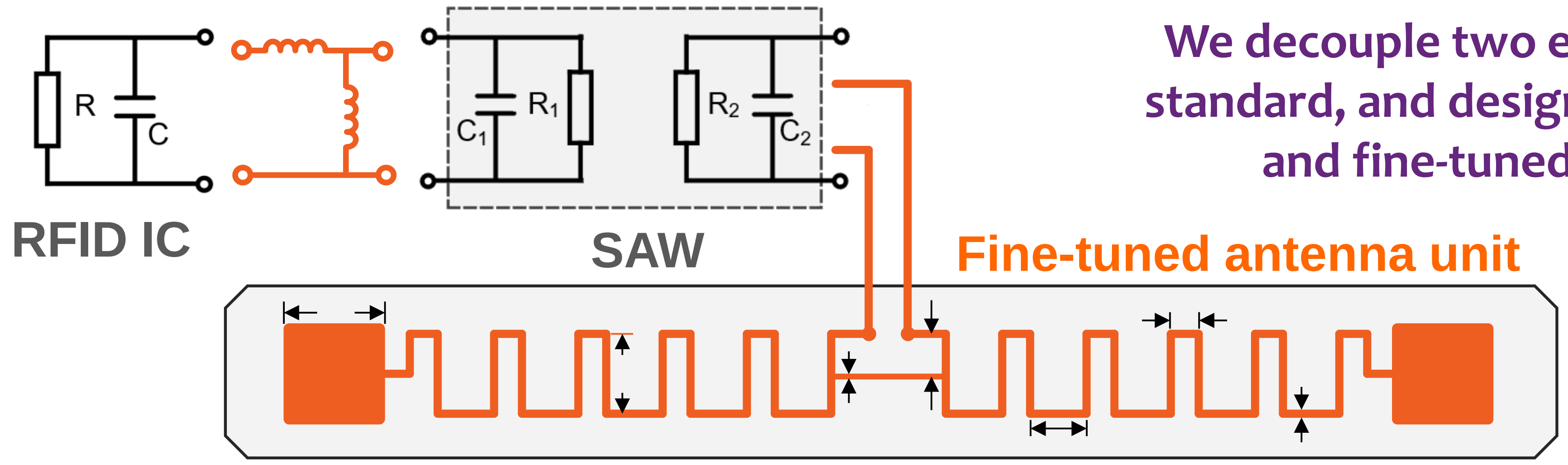
Without matching → Poor energy delivery efficiency
With matching → Much higher cost of the tag



Requires up to 6 matching elements → 4 times cost of the RFID tag!

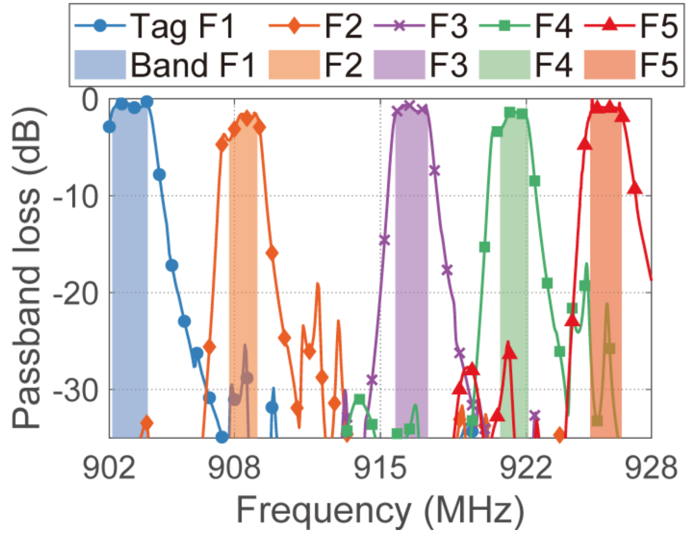
Designing SAW-based Antenna

➢ ***Decoupled impedance matching of the SAW filter***



We decouple two ends of the SAW from the 50Ω standard, and design dedicated matching network and fine-tuned antenna unit separately.

Optimal performance using just 2 inductors!



- Split the whole ISM band into **five** sub-bands
- Gaps are reserved between sub-bands to accommodate the roll-off section
- Each sub-band is associated with a specific type of frequency selective antenna, readable by commercial RFID readers

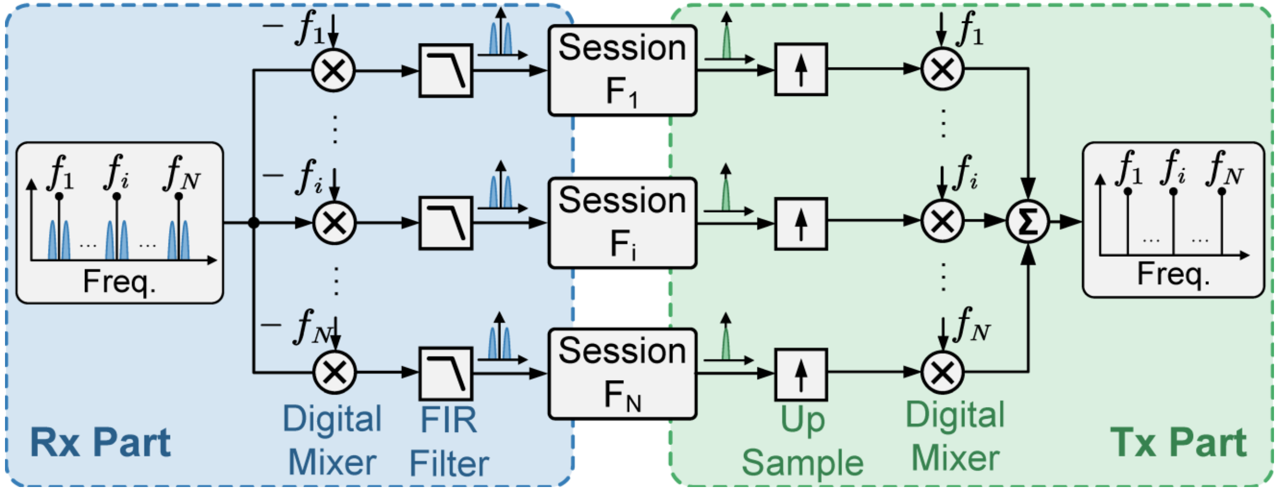
QuinReader Design: Supporting Multi-band RFID sessions

➢ Conventional reader approach

Impractical

- 1) Cost and complexity scale with number of sub-bands.
- 2) Limited usability in mobile applications (handheld readers).

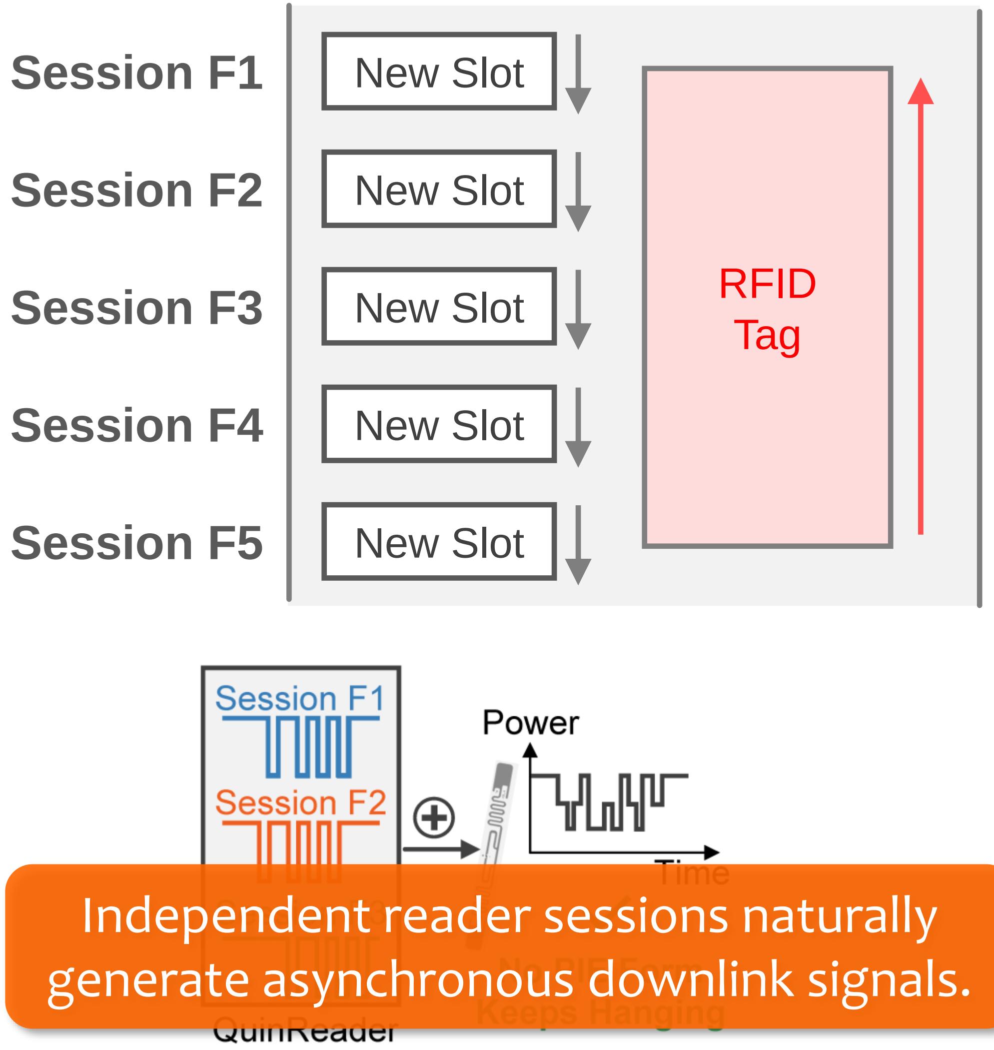
➢ Integrated QuinReader design



- ➢ Digital up/down converters to isolate and merge multi-band signals.
- ➢ Sessions are separated and can run in parallel
- ➢ Standard reader processing along with collision decoding can be seamlessly integrated.

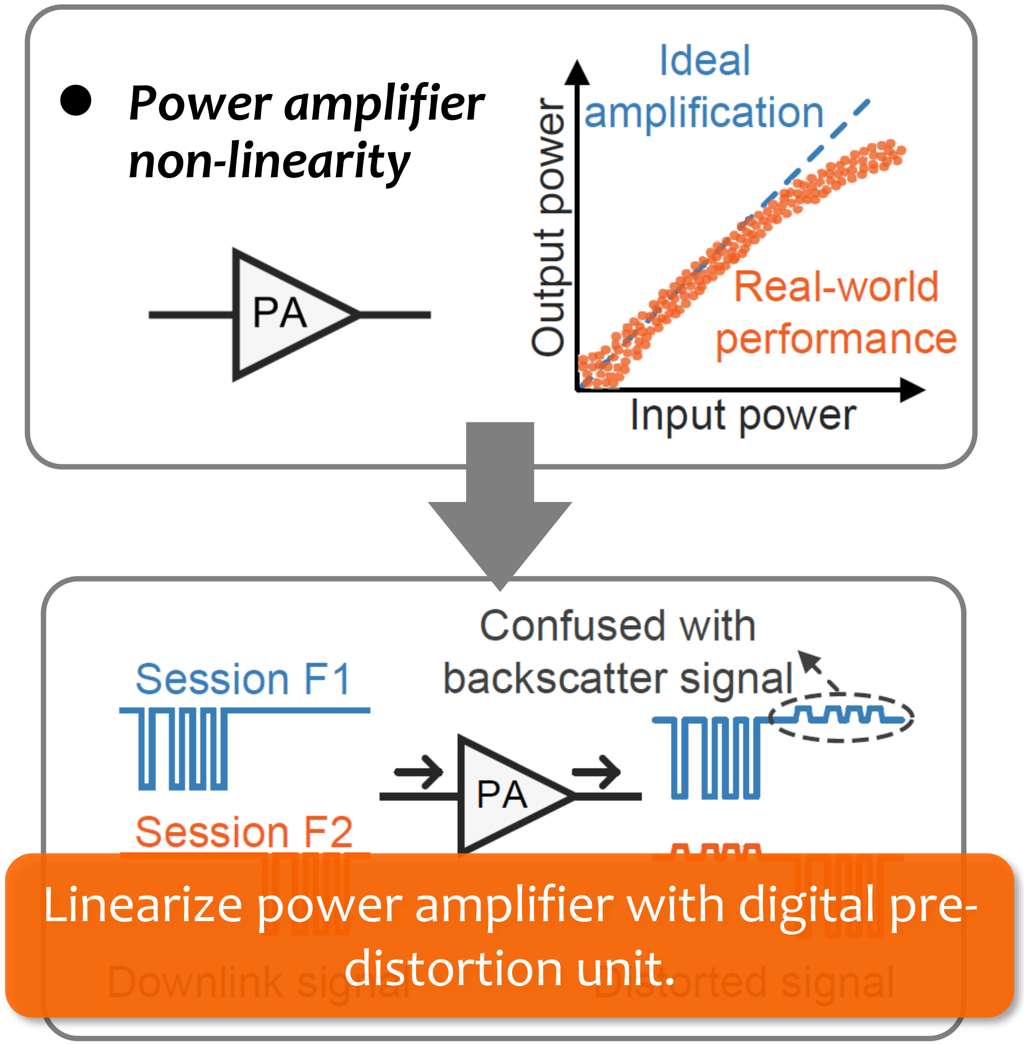
Handling Two Types of Interference

1. Conventional tag's interference



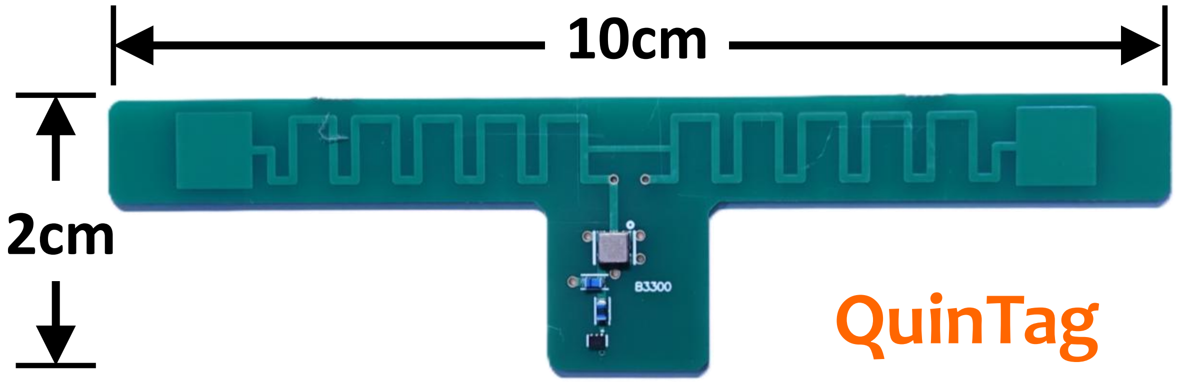
Independent reader sessions naturally generate asynchronous downlink signals.

2. Inter-band interference



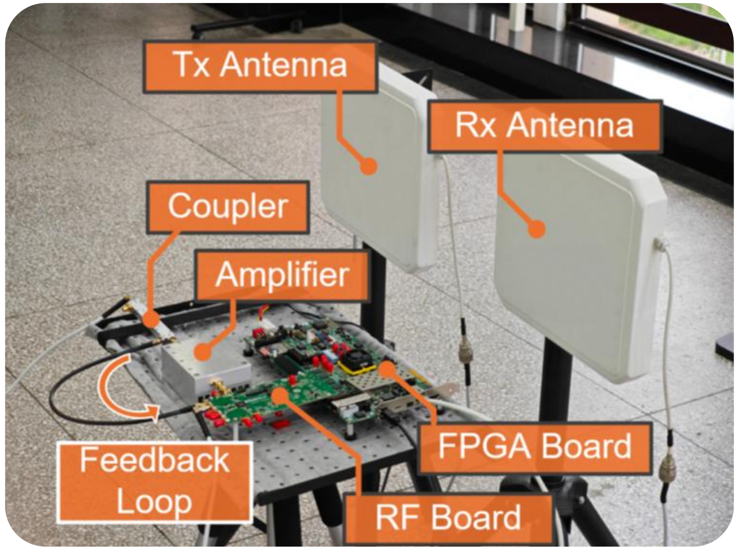
Linearize power amplifier with digital pre-distortion unit.

Implementation



- **Fully battery-free** design with **commercial RFID chips** on two-layer PCB.
- **Five** distinct SAW filters with individually optimized matching network.
- Can also be implemented in **a flexible manner** like commercial RFID tags.

QuinReader

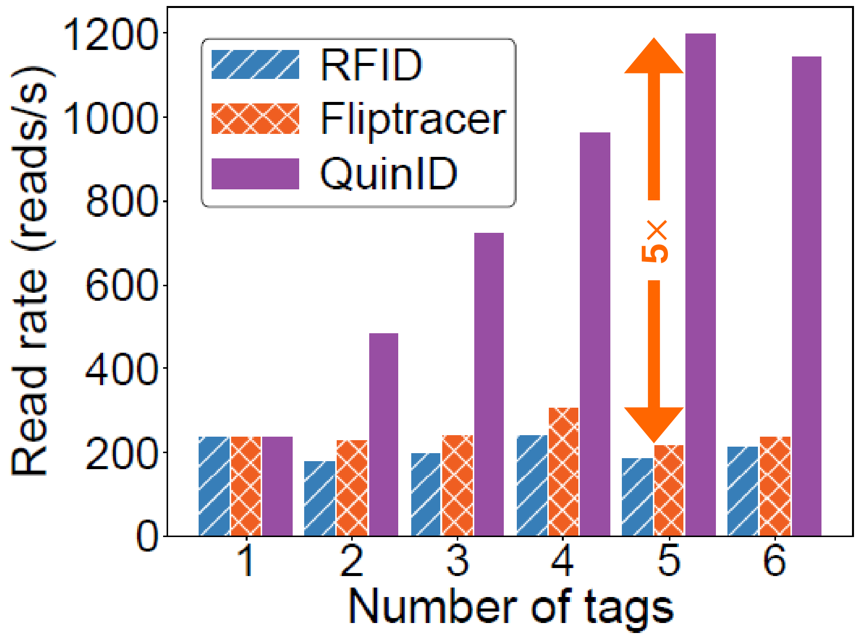


- **FPGA-based SDR** platform with Xilinx ZC706 and ADRV9375 RF board.
- Independent reading sessions with **minimal latency** and zero mutual-interference.

Evaluation

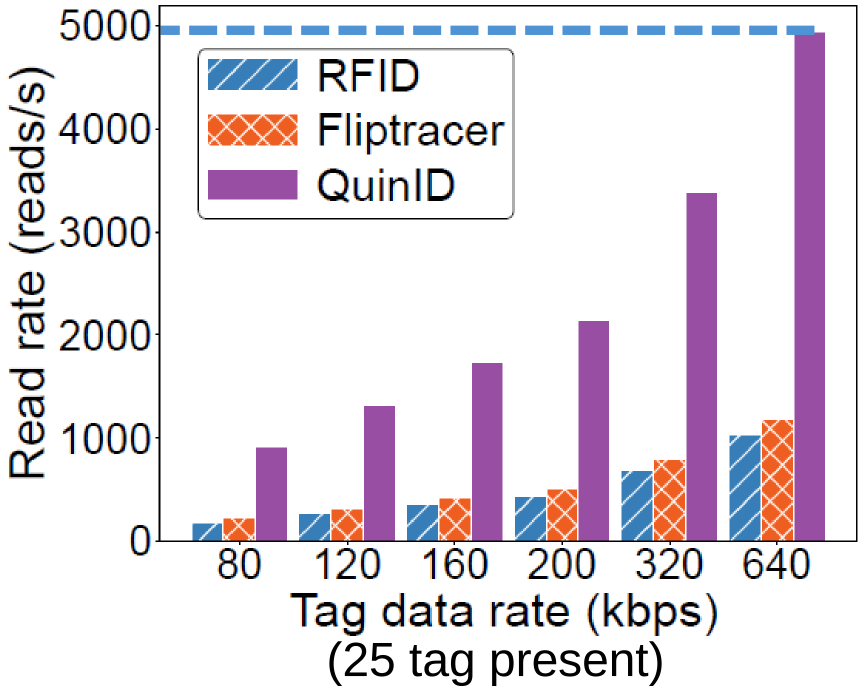
Evaluation - Reading Efficiency

Read rate vs. tag number



FlipTracer – A representative parallel decoding algorithm.

Read rate vs. tag data rate

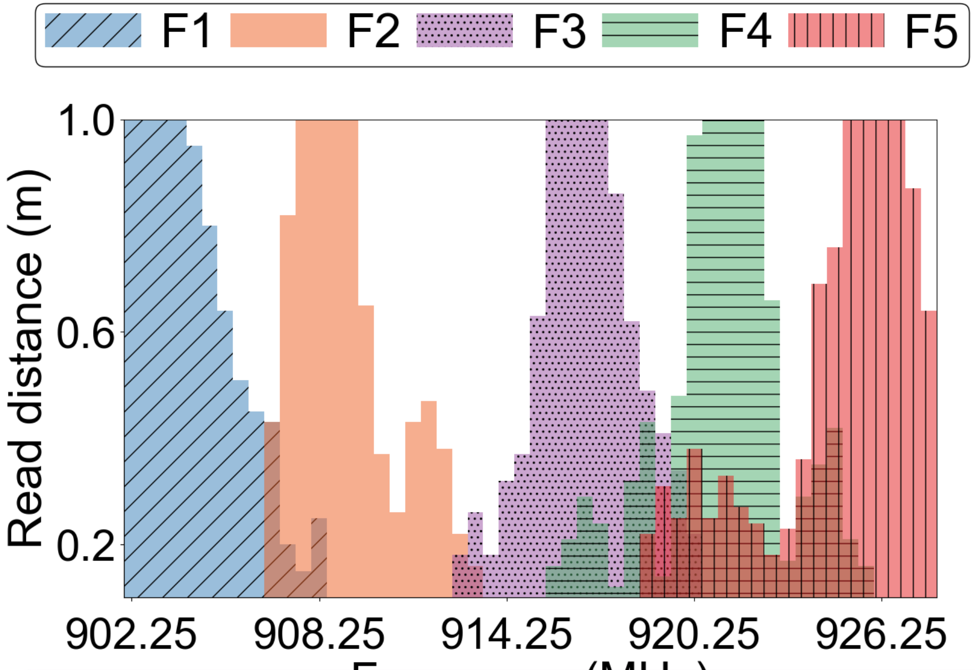


QuinID achieves a fivefold improvement, reaching up to 5000 reads per second.

[FlipTracer]: Meng Jin, Yuan He, Xin Meng, Yilun Zheng, Dingyi Fang, Xiaojiang Chen, "FlipTracer: Practical Parallel Decoding for Backscatter Communication", ACM MobiCom 2017

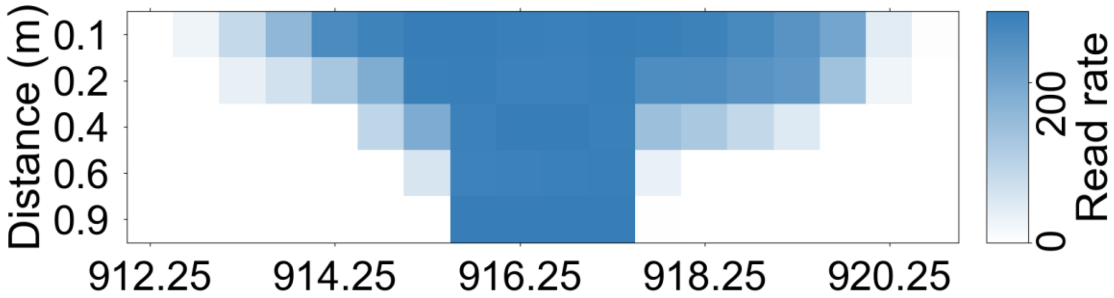
Evaluation - Cross-band misreading

Readability at different range across all frequencies



Impinj R2000 handheld reader

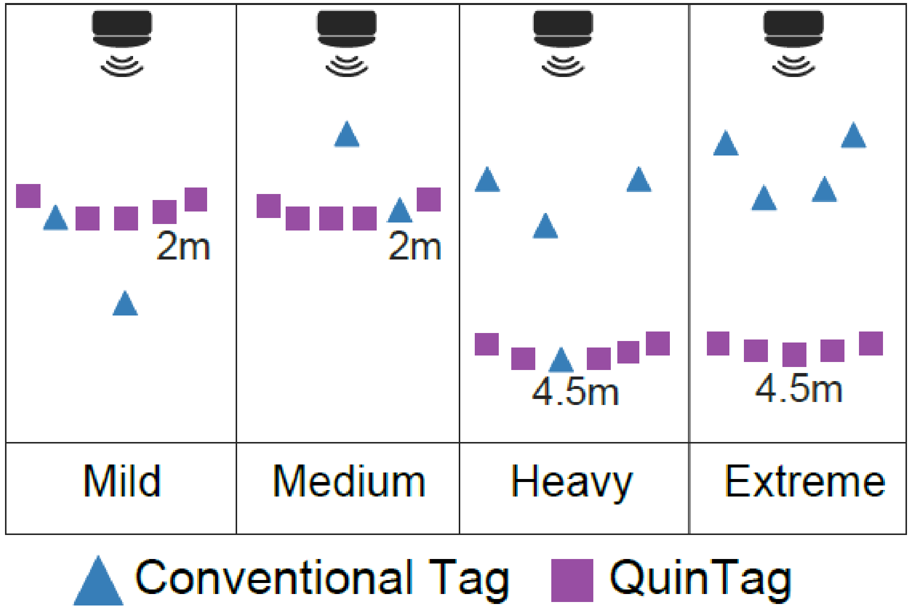
Detailed read rate of QuinTag F3



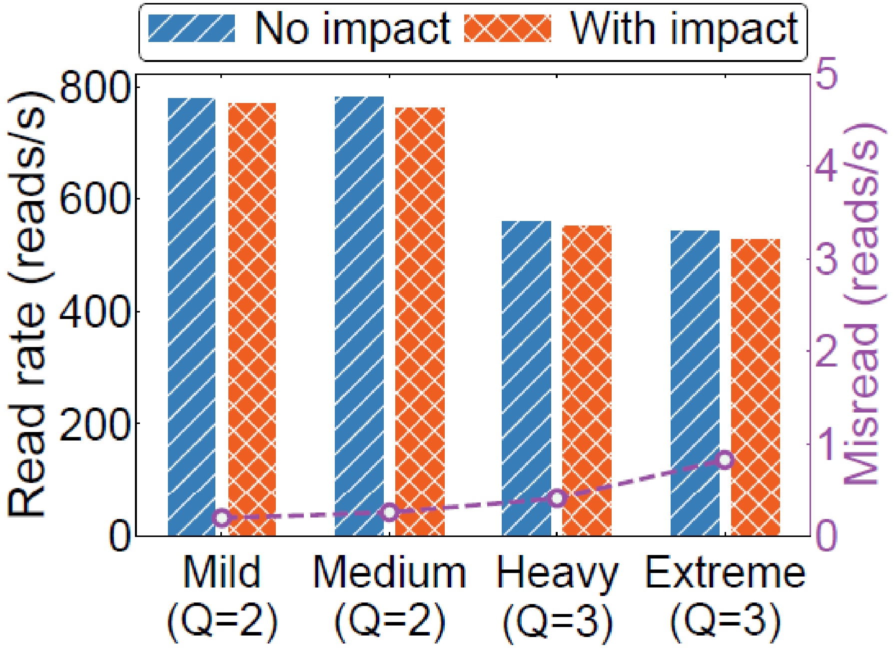
As long as carrier remains within the designated band, cross-band misreading is negligible.

Evaluation - Impact of Conventional Tags

Setup of different scenarios



Comparison of reading performance with or without conventional tags



QuinID is highly robust to conventional tags' impact.

QuinTag - Cost Analysis

A commercial RFID Tag costs 3.4¢

Component	RFID IC	Antenna	Basic Assembly	SAW IC	Inductors	Extra Assembly	Total
Cost in production	1.3¢	1.0¢	1.1¢	1.3¢	2¢	3.3¢	10¢

Further optimization on the assembly cost can be done by integrating all modules on one IC.

Open Access Design and High-Performance RFID Reader

- **QuinID’s hardware schematics and reader implementation can be found at**

  https://github.com/wonderfulnx/QuinID

- **In addition, we also provide a FPGA-based UHF Gen2 RFID Reader implementation, which is the highest-performance SDR-based UHF Gen2 RFID Reader available**

  https://github.com/wonderfulnx/UHF-Gen2-RFID-Reader

	nkargas/Gen2-UHF-RFID-Reader	Our UHF-Gen2-RFID-Reader
Hardware Platform	 USRP N210	 Zedboard + FMCOMMS3
Supported Link Frequency	Only 40kHz	40, 80, 120, 160, 200, 320, 640kHz
Reading Efficiency	< 100 times per second	> 1100 per second
Hardware Cost	~3500$	~1500$

Conclusion

- We present QuinID, the first to enable FDMA-based fully parallel RFID, while maintaining high compatibility with commercial RFID systems.
- QuinID achieves a K-fold increase in the read rate if dividing the bandwidth into K sub-bands. Our evaluation proves a fivefold improvement, reaching up to 5000 reads per second, with a tag manufacturing cost of less than 10 cents.
- We introduce a passive RF computing mechanism that operates directly on the frequency of RF signals.

Visit SUN Group http://tns.thss.tsinghua.edu.cn/sun/ for details.