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Non-Intrusive Item Authentication with High Robustness for RFID-Enabled Logistics

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Background

Problem: Incidents of damaged, lost, or replaced goods can occur during the express transportation

Current Solutions

Lacks the capability to detect item conditions

Authenticate the legitimacy of item tags

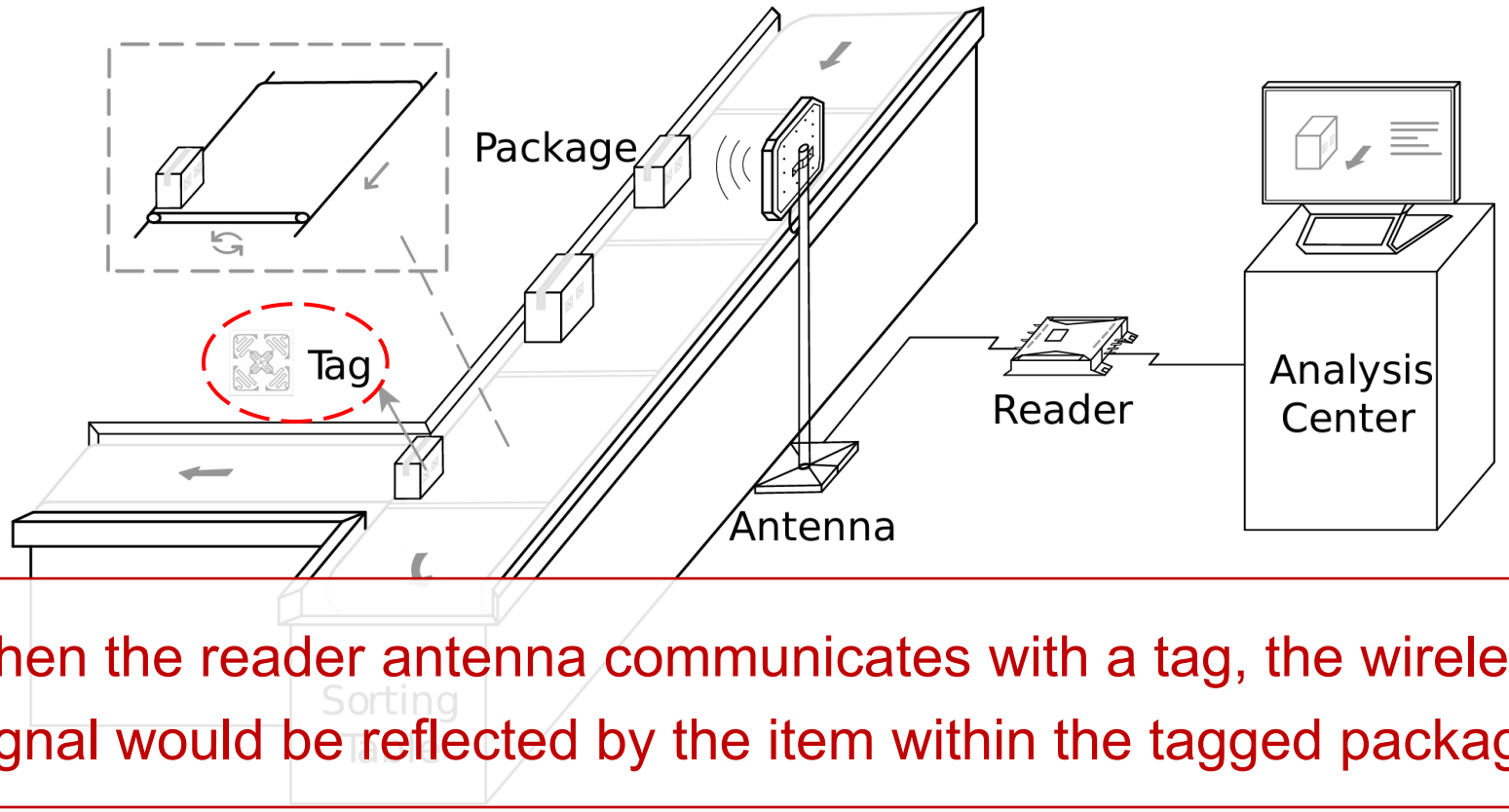
Wrap RFID antennas around packages

Confined to stationary scenarios

Extract features from signals penetrating package interiors

Our Scheme

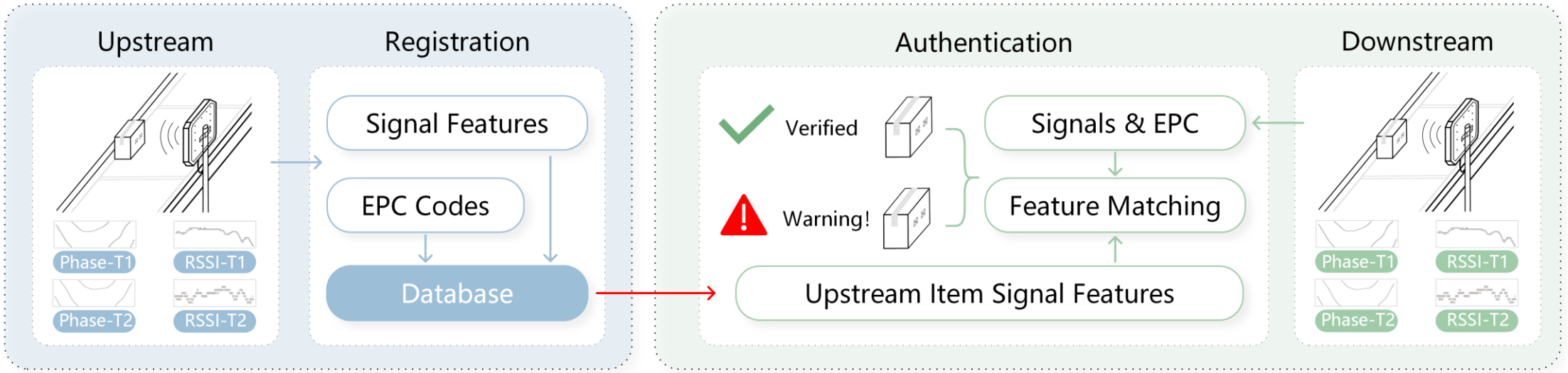
- Operating scenario of RF-Express



When the reader antenna communicates with a tag, the wireless signal would be reflected by the item within the tagged package

Our Scheme

➢ Operating process of RF-Express



Data acquisition and registration

Data acquisition and feature matching

Challenge #1

Problem: How to characterize the relationship between the item within the package and the collected RF signals?

Item Feature Extraction

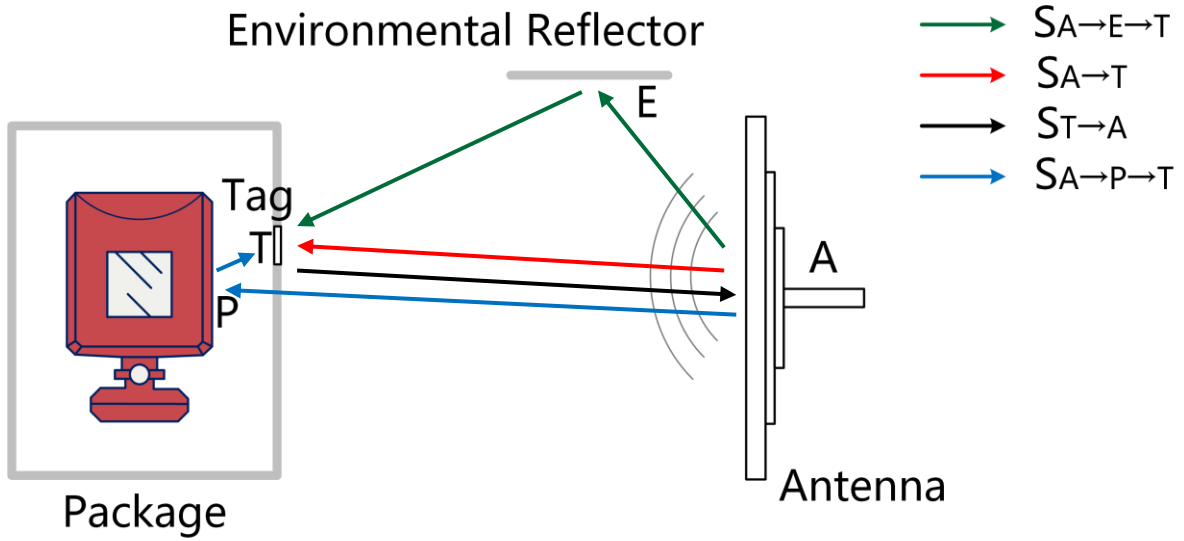
- Signal Propagation Model

Channel parameter

$$S' = \boxed{h} \cdot S$$

$$\begin{aligned} S_T &= (S_{A\to T} + S_{A\to E\to T} + S_{A\to P\to T}) \cdot h_T \\ &= (h_{A\to T} + h_{A\to E\to T} + h_{A\to P\to T}) \cdot S_0 \cdot h_T \end{aligned}$$

$$S_{T\to A} = h_A \cdot h_{T\to A} \cdot S_T$$



RF signal propagation in sorting scenarios

Item Feature Extraction

➢ Channel Parameters

Item features:

- ✓ Medium depth
- ✓ Material type
- ✓ Shape of item

When the status of the item changes, the radio frequency signal will also change accordingly

- Signal refraction:

$$h_b = \frac{1}{d_b} e^{-\mathbf{J}2\pi f \frac{d_b \sqrt{\epsilon_{rb}}}{c}}$$

(Penetration depth)

(Dielectric constant of m_b)

- Signal reflection:

$$h_{\text{refl},a\to b\to a} = \sqrt{R_{\text{refl}}} \cdot e^{-\mathbf{J}\theta_{\text{refl}}}$$

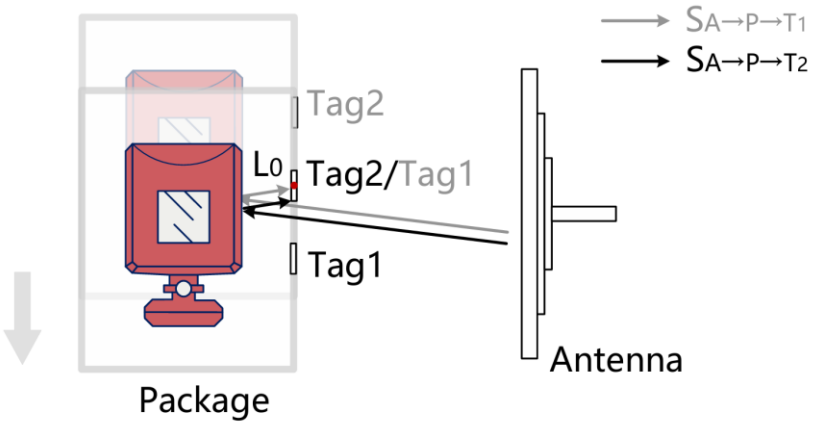
(Related to the incident angle of the signal and the dielectric constants of mediums)

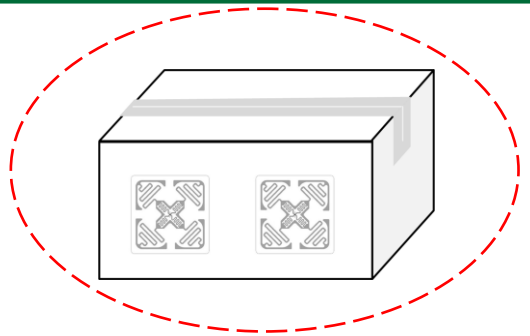
Challenge #2

Problem: How to minimize the adverse impact of indoor multipath itself and its variations?

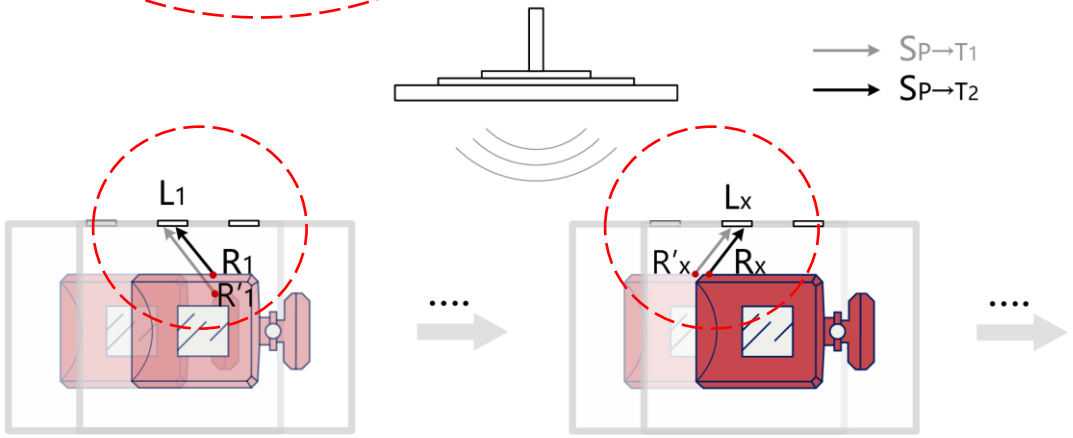
Item Feature Extraction

- Dealing with Multipath Variations





(Parallel deployment)



The difference between the signals of the two tags will be able to retain the feature of the item

Challenge #3

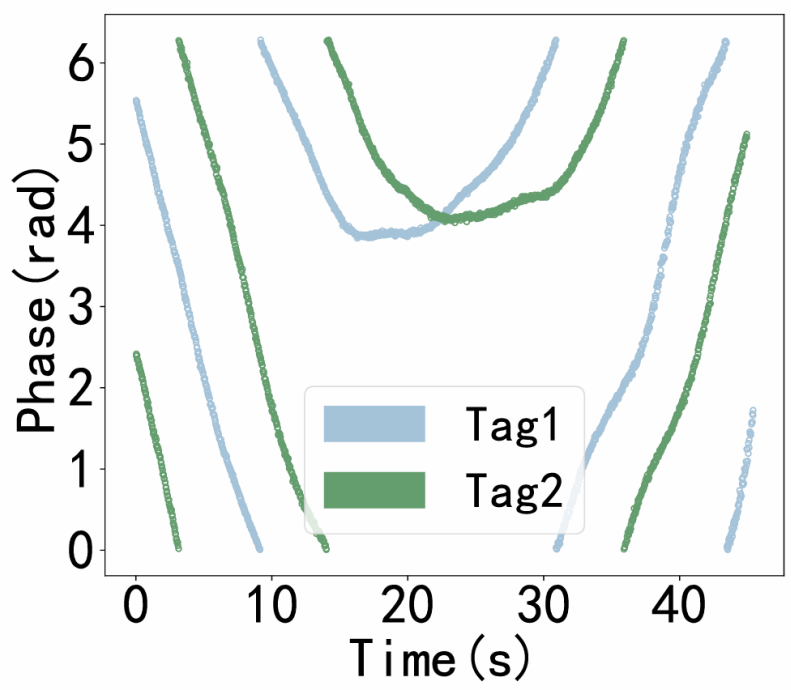
Problem: How to handle the inconsistent signal data lengths between upstream and downstream nodes?

Data Preprocessing

- V-zone Detection

$$\theta = (\frac{2\pi f}{c} \times 2d + \theta_{\text{refl}} + \theta_{\text{hdw}}) \bmod 2\pi$$

The relationship between phase and the distance from the tag to the reader antenna



Original sequence

Data Preprocessing

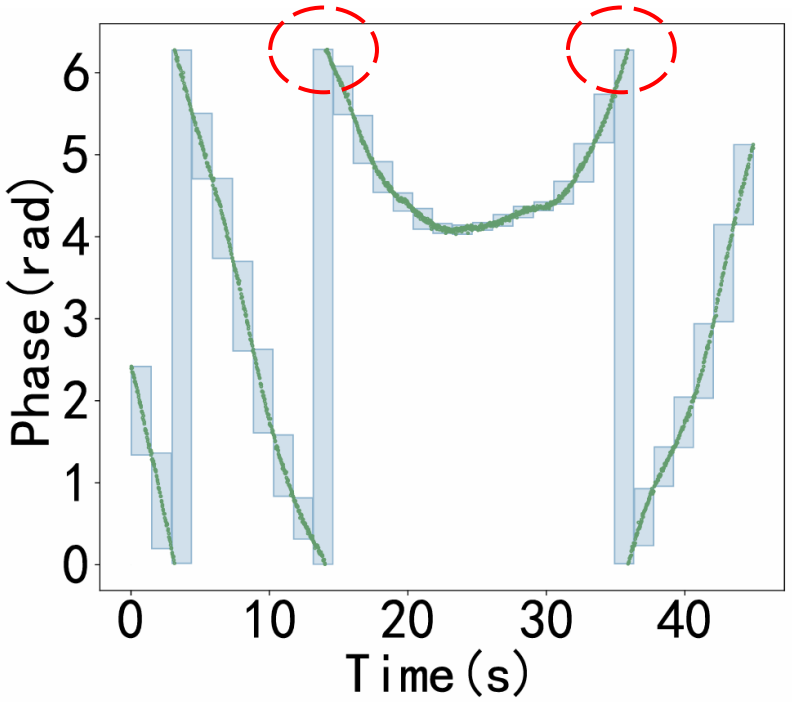
- V-zone Detection (Phase jump: 0 → 2π or 2π → 0)

Jump sub-sequence:

$$\max(\Theta_i) - \min(\Theta_i) > \tau \quad \text{or}$$
$$|\texttt{last}(\Theta_i) - \texttt{first}(\Theta_{i+1})| > \tau.$$

Endpoints of V-Zone:

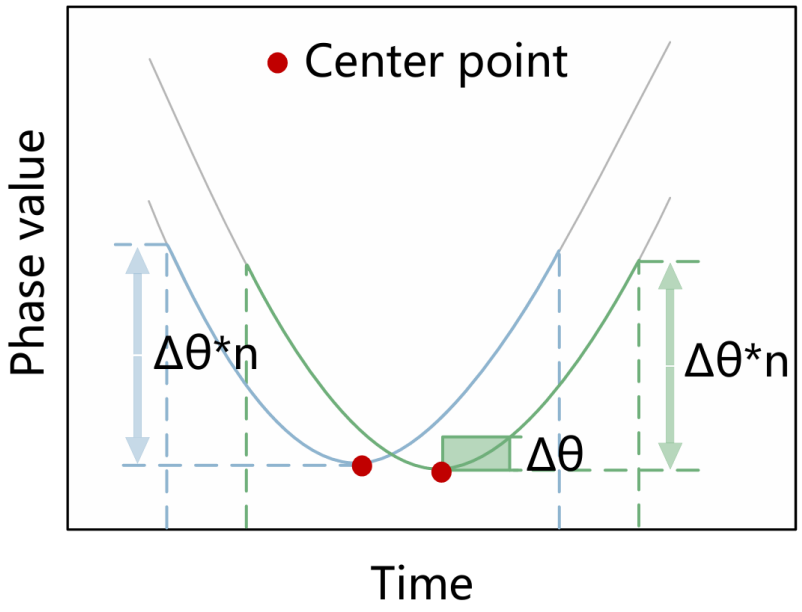
$$2\pi - \theta_{j,i_2} \leq \eta \quad \text{and}$$
$$2\pi - \theta_{j,(i+1)_1} \leq \eta,$$



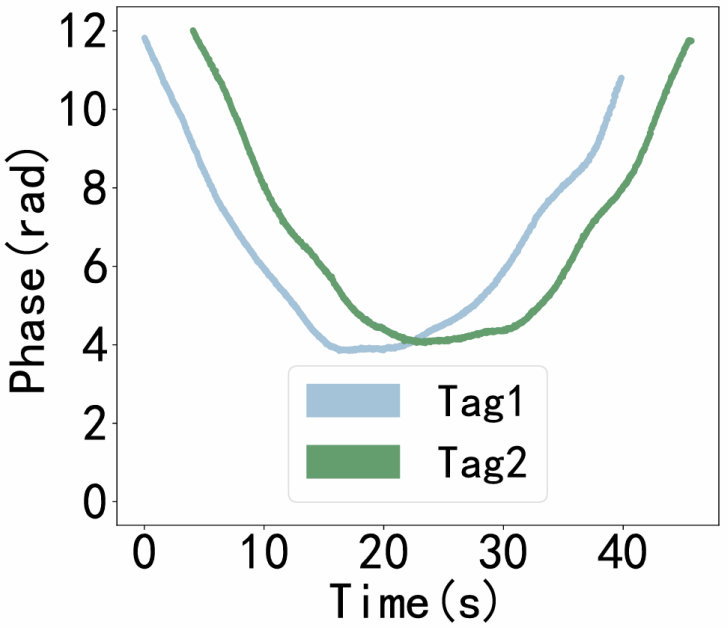
Sliding window

Data Preprocessing

- Signal Selection & Data Interpolation



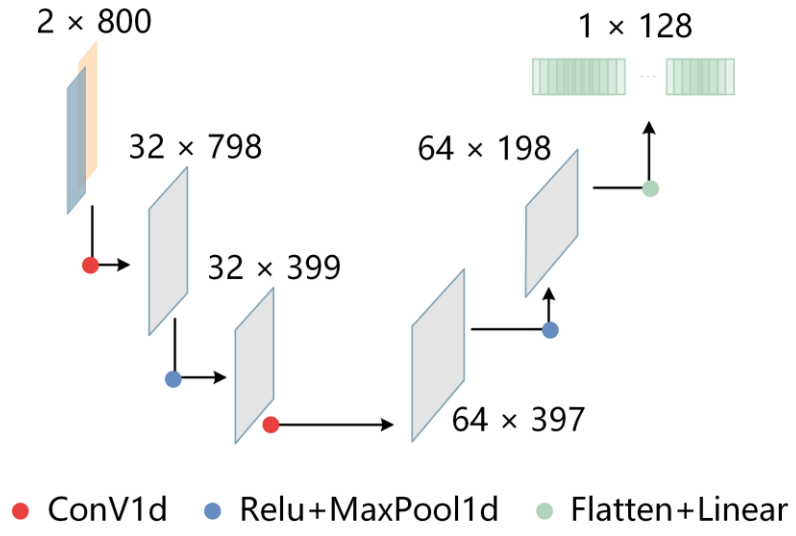
Signal selection



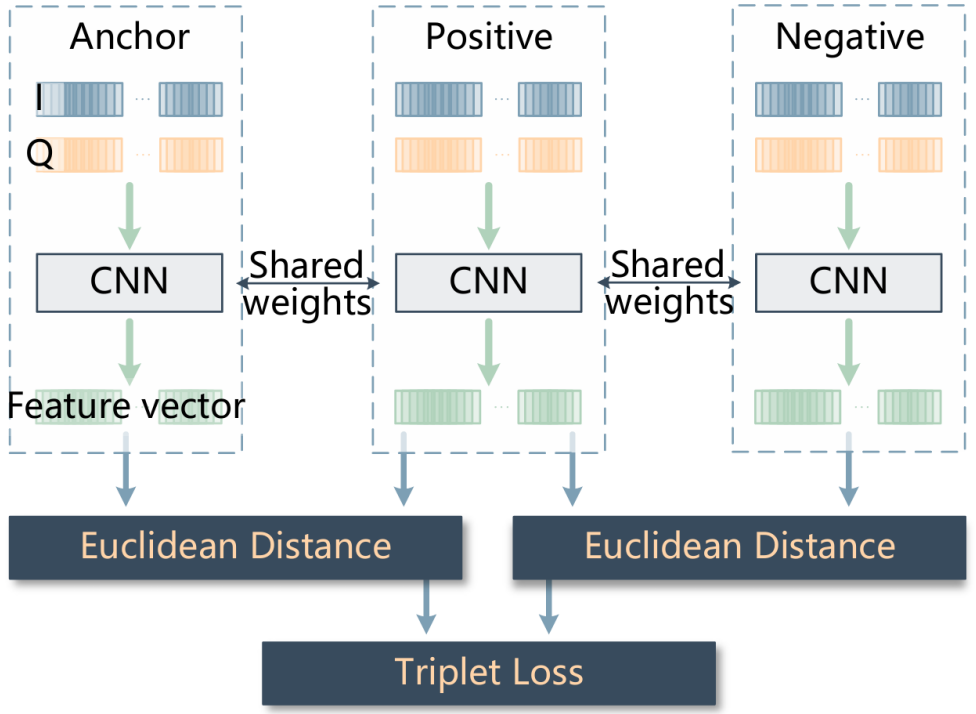
Concatenated sequence

Feature Matching

- Triplet Network



CNN framework



Training process of the triplet network

Implementation

- Prototype

  ImpinJ R420 reader, Laird S9028PCL antenna

  ImpinJ Monza H47 tags

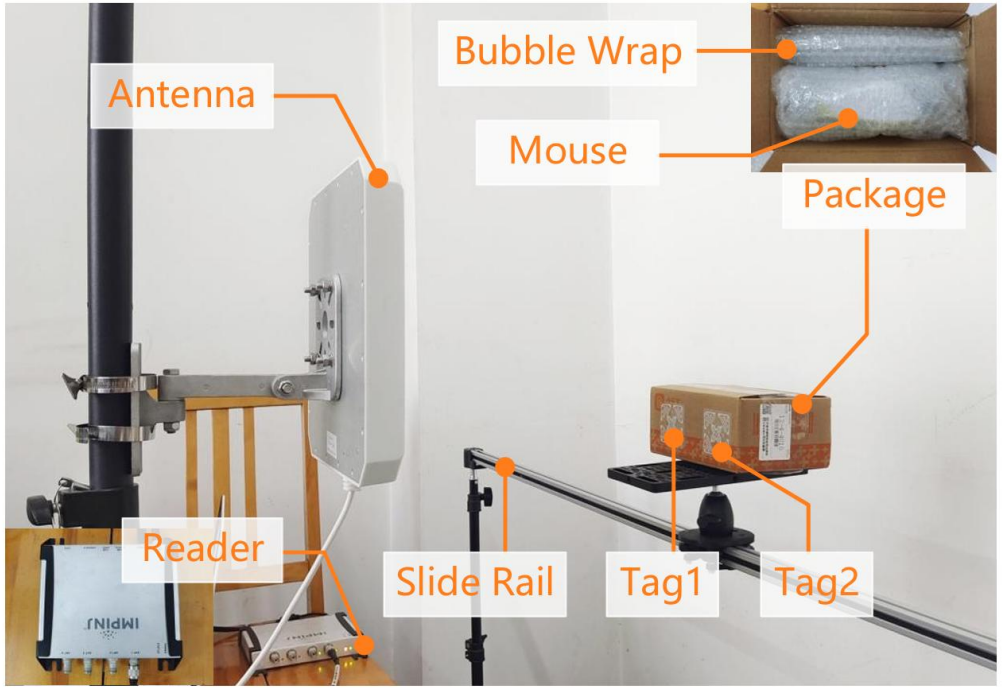
  Low Level Reader Protocol (LLRP)

  Photography slide rail

- Data collection

  5 liquids, 5 smartphones

  2 mice, 2 building blocks



Evaluation

Metrics

- True Acceptance Rate (TAR)

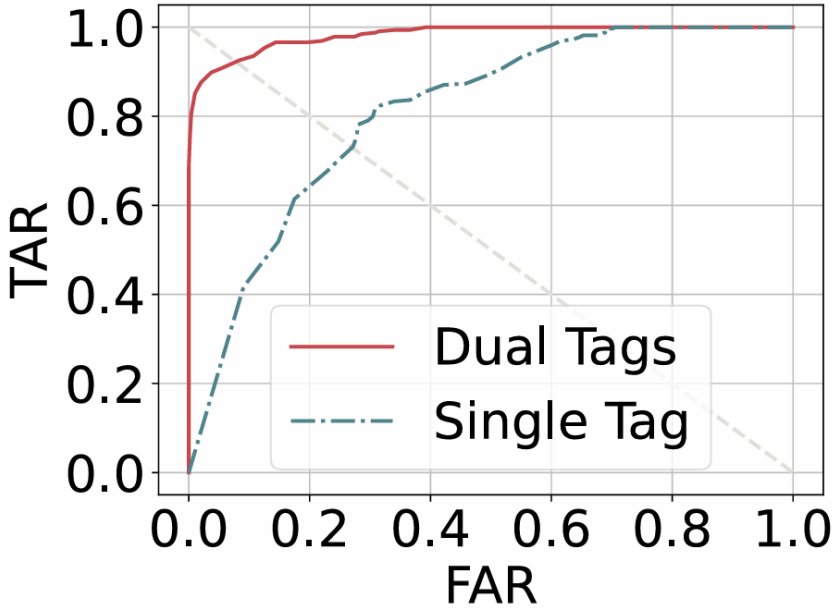
  N_{accept} / N_{same}

- True Rejection Rate (TRR)

  N_{reject} / $N_{different}$

- Equal Error Rate (EER)

  The point where TAR and FAR are equal



ROC curves for dual-tag and single-tag cases,

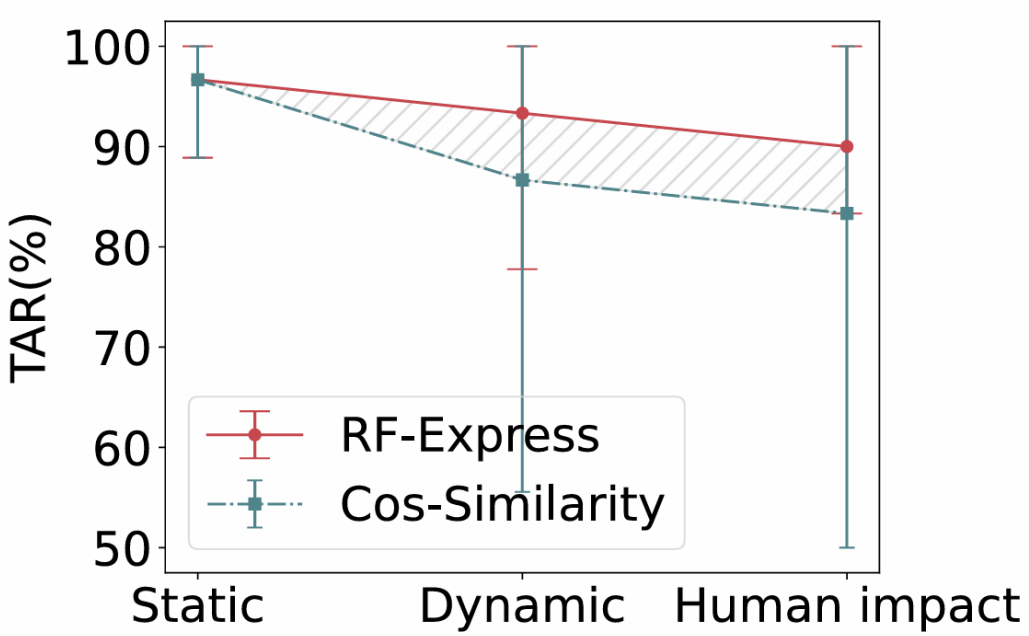
with EERs of **7.79%** and **27.02%** respectively

Evaluation

- Overall accuracy

  - Average TAR: 90.97%
  - Average TRR: 94.38%
    - ✓ Loss: 100%
    - ✓ Replacement: 91.36%
    - ✓ Damage: 91.77%

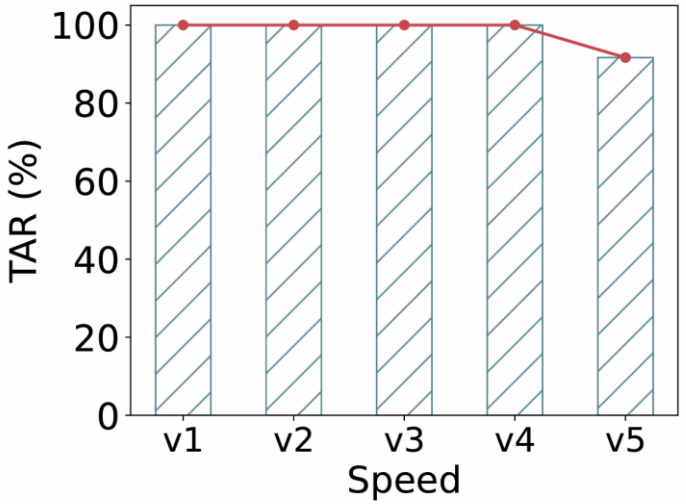
- Impact of Different Environmental Changes



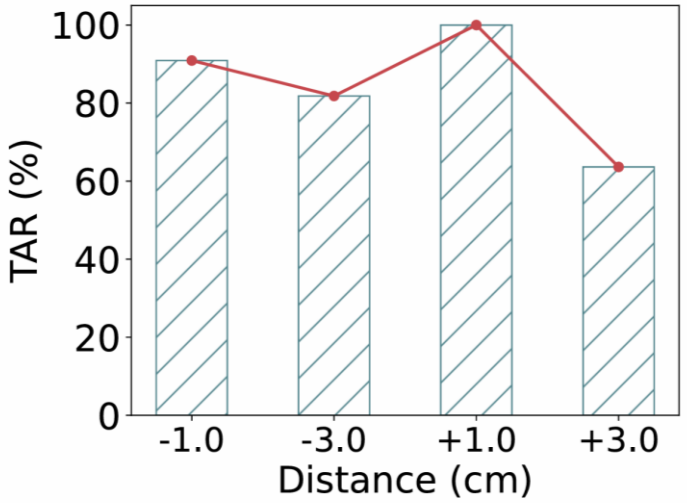
Evaluation

- Impact of Factors

Conveyor speed



Package-antenna distance

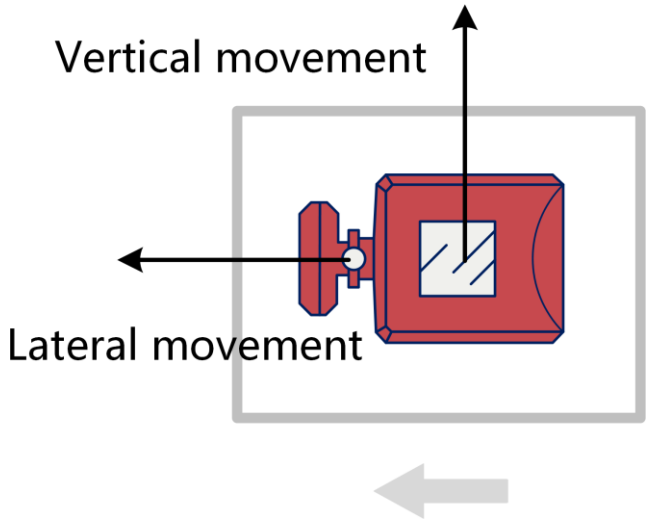


The interpolation approach can successfully handle changes in speed

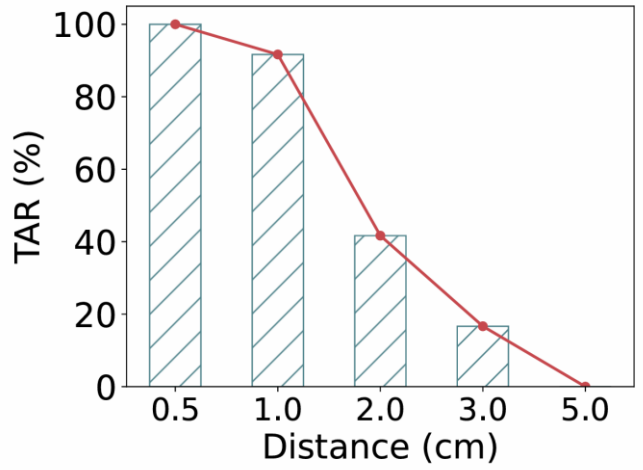
RF-Express can resist the impact of minor changes in package-antenna distance

Evaluation

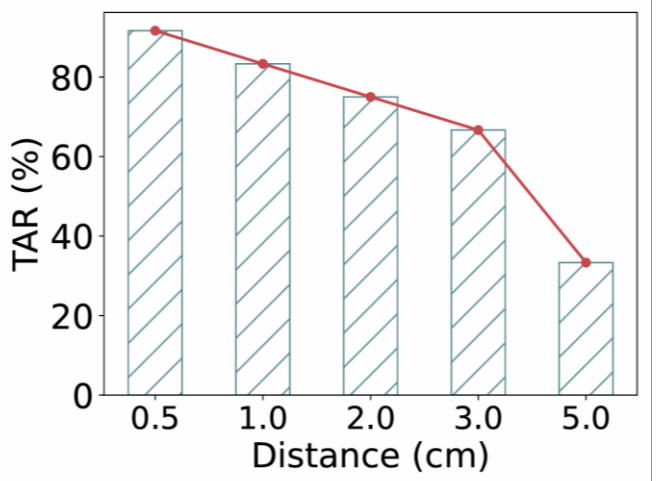
- Impact of Factors



Item's lateral movement



Item's vertical movement



Minor item movement has a relatively small impact on the system

Conclusion

Current limitations:	Item status not visible	Logistics process interrupted
Our target:	Accurate item authentication	Non-intrusive & highly robust
Our solutions:	Dual tagging	V-Zone detection	Triplet network

Results: The prototype experiments showcased the high accuracy and robustness of RF-Express

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