### Multi-Tag RFID Systems

- **Attach more than one tag to an object**
  - Redundant Tags
  - Dual-Tags
  - Private memory only
  - Shared memory only
  - Shared and private memory
- **Benefits of Multi-tags**
  - Increased expected voltage on a tag
  - Increased expected communication range
  - Increased memory
  - Increased reliability
  - Increased durability

### Reader-Tag Communication

- **Optimal Tag Positioning**
- **Voltage on a tag**
- **Expected Largest Angle of Incidence**
- **Applications of Multi-Tags**
  - Supply chain management
  - To increase chances of object detection
  - Luggage tracking
  - Regulations require different algorithms
  - Preventing illegal deforestation
  - Tagging of trees to prevent illegal logging

### Effect on Singulation Algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Randomized Tags</th>
<th>Dual-Tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary</td>
<td>No Effect</td>
<td>No Effect</td>
</tr>
<tr>
<td>Binary Variants</td>
<td>No Effect</td>
<td>No Effect</td>
</tr>
<tr>
<td>Randomized Doubles Time</td>
<td>No Effect*</td>
<td>No Effect*</td>
</tr>
<tr>
<td>STAC</td>
<td>Causes DOS</td>
<td>No Effect*</td>
</tr>
</tbody>
</table>

*If Dual-Tags communicate to form a single response
**No Effect**

### Security Enhancement

- n-Tags send “chaff” hiding the real IDs
- Recycled IDs are good “chaff” source
- “Chaffing and winnowing” has a cost
- Extra tag functionality
- Overhead to create and filter “chaff”

### Properties

- Allows tags addition and removal from the system
- Provides security against active eavesdroppers
- Offers security against active readers
- Enables dynamic tradeoff between security, privacy, and singulation time
- Effective against active attacks:
  - Stealing a tag
  - Tracking and billhisting

### Time and Space Complexity

- In the total number of tags in the system
- \( \text{O}(\text{r}) \), \( \text{O}(\text{d}) \), \( \text{O}(\text{d}2) \), \( \text{O}(\text{d}2) \)

### Introduction to Radio Frequency Identification (RFID) Systems

- **RFID Primer**
  - Three types of RFID tags
    - Passive
    - Active
    - Semi-Active
  - Operational Frequencies
    - 125KHz - 5.8GHz
  - Operational Range
    - 5mm - 15m
  - Standardization Bodies
    - International Organization for Standardization
    - EPCglobal, Inc

- **EPC System Architecture**

- **Applications**

- **Reader-Tag Communication**

- **Multi-Tag RFID Systems**

- **Randomized PRF Tree Walking Algorithm**

- **Randomized Number Generation Hardware**

- **Optimal Random Number Length**

- **Expected Relative Voltage Increase Factor**

- **Inductive Coupling**

- **Inductive Propagation**

- **Major Research Issues**
  - Reducing the cost of tags
  - Providing security and privacy
  - Standardizing the technology

- **Forward Range**

- **Backward Range**

- **Inductive Coupling**

- **Far-Field Propagation**

- **Applications of Multi-Tags**
  - Supply chain management
  - To increase chances of object detection
  - Luggage tracking
  - Regulations require different algorithms
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- **Steps of the algorithm**

1. Each tag generates a random number, and the reader performs a tree-walk on these numbers
2. If collision on b detected:
   - Suspended all tags with \( b = 1 \)
   - Each suspended tag stores \( \text{Traverse}(1, 0) \)
   - Wake up tags suspended on bit \( 1 \)
   - Traverse(1, 0)
3. Else if no collision on bit detected:
   - Traverse(1, 0)
   - Randomized PRF Tree Walking Algorithm

- **Expected Factor of Distance Increase**

- **Goal**: Efficiently solve reader-tag authentication problem in the presence of many tags

- **Properties**
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- **Time and Space Complexity**

- **Random Number Generation Hardware**

- **Future Work**
  - Field testing of Multi-tags
  - Identifying new applications of Multi-tags
  - Improving hardware complexity of the algorithm
  - Developing new efficient authentication algorithms