Reliable and Efficient RFID Networks

Jue Wang

with Haitham Hassanieh, Dina Katabi, Piotr Indyk

Massachusetts Institute of Technology

Machine-Generated Data

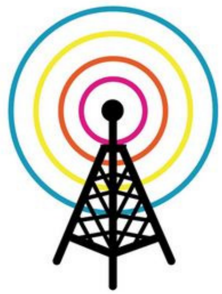
RFID will be a major source of such traffic

- In Oil & Gas – about 30% annual growth rate
- In Healthcare – $1.3B revenue annually
- "number of RFID tags sold globally is projected to rise from 12 million in 2011 to **209 billion** in 2021."

– McKinsey Big Data Report 2011

Are Our Wireless Protocols Ready?

- Wireless protocols require power and computation



- **RFIDs are very wimpy**
  - No power source
  - Ultra-low cost → not much circuitry

RFIDs can't perform typical functions like carrier sense or rate adaptation

How Do we Deal with RFID Wimpy Nodes?

The traditional approach to deal with wimpy technologies is to dial down functionality
- e.g., client can't adapt bit rate → fixed rate

RFIDs are Inefficient and Unreliable

[P05, JZF06, RZH07, BW08, BVG09, GZG12]

Our Approach

Do not give up on functions that make communication reliable and efficient

- e.g., if one RFID can't adapt rate, maybe collectively can perform rate adaptation

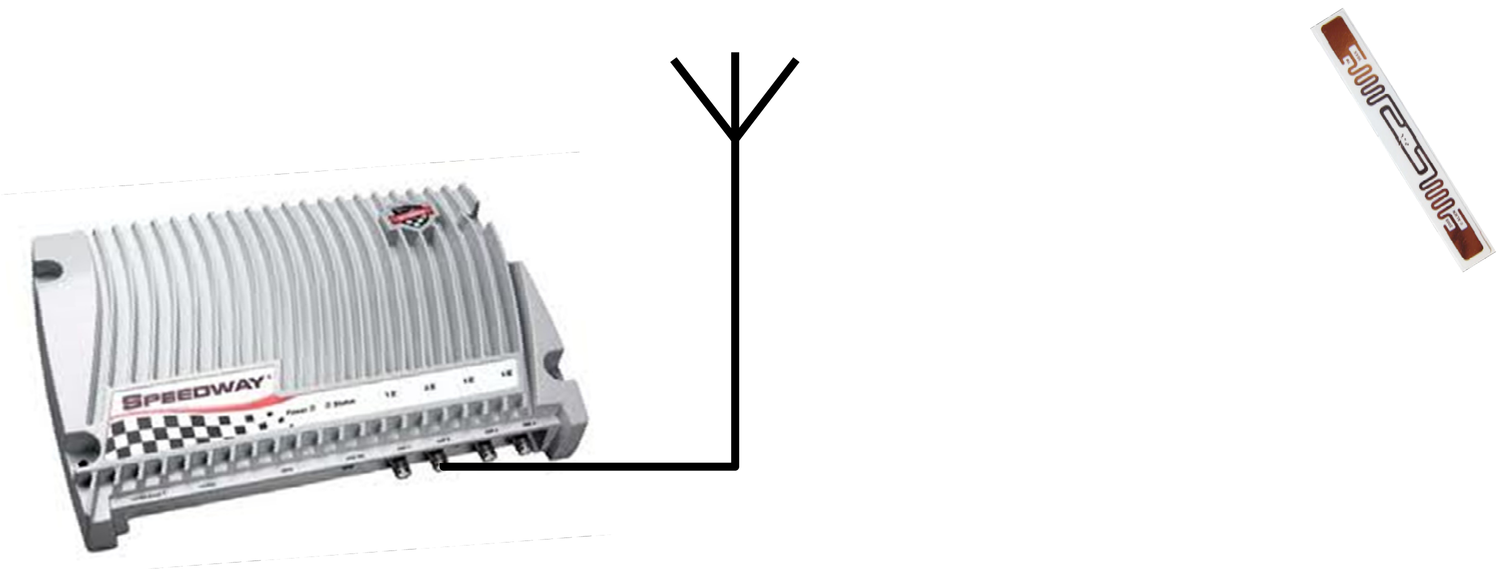
Network As a Node:

Build sophisticated protocols by making many wimpy RFIDs emulate one powerful node

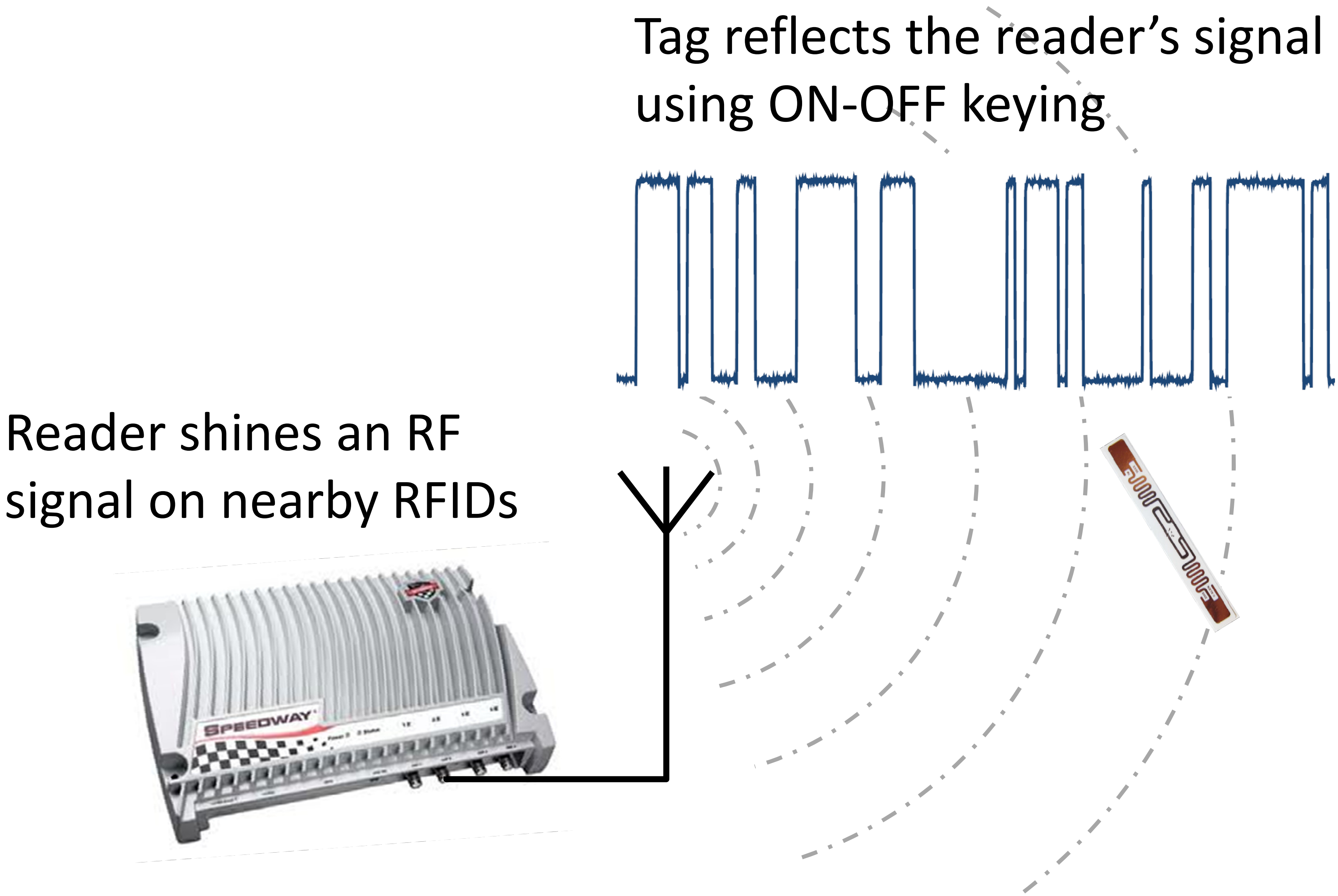
Rest of the Talk

- Understanding RFID communication
- Network As a Node
- Empirical evaluation

Backscatter Communication

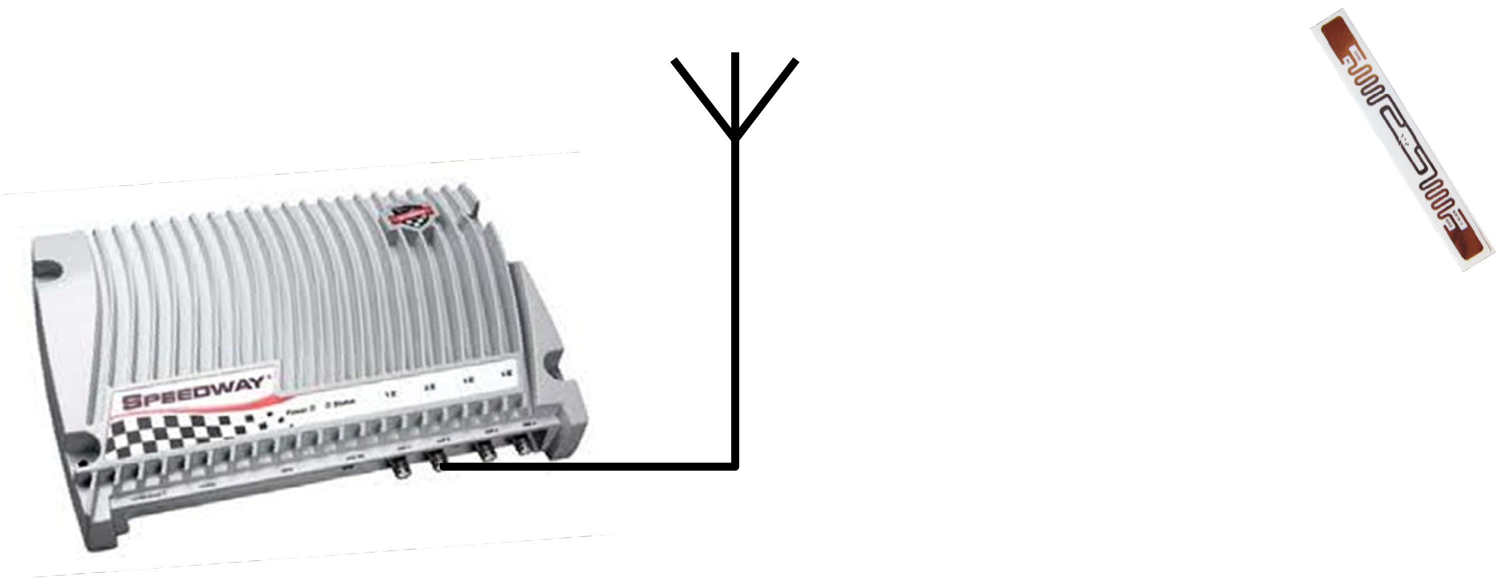


Backscatter Communication



Backscatter Communication

RFIDs are synced by the reader's signal



Challenges of Backscatter

RFIDs cannot hear each other

→ Collisions

Cannot adapt modulation to channel quality

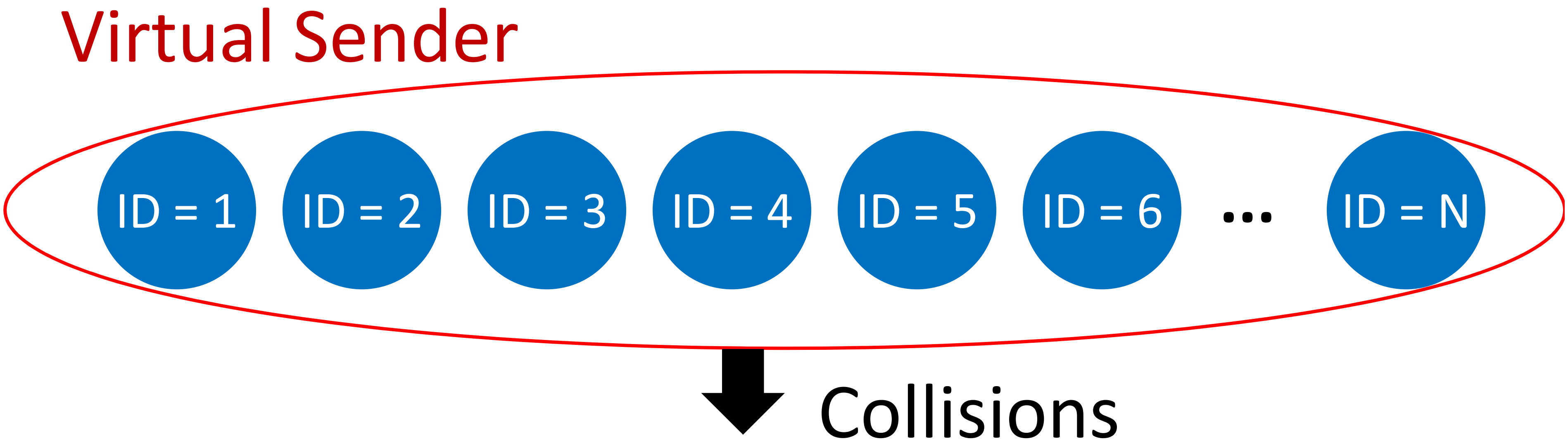
→ Don’t exploit a good channel to send more bits per symbol

→ Don’t react to a bad channel

Rest of the Talk

- Understanding RFID communication
- Network As a Node
- Empirical evaluation

Network As a Node



Collision becomes a code across the virtual sender's bits

- Deals with collision by decoding collision-code
- Adapts the rate by making collision-code rateless

Network-As-a-Node

Node Identification

Data Communication

The Node Identification Problem

Each object has an ID
Reader learns IDs of nearby objects

Applications

- Inventory management
- Shopping cart

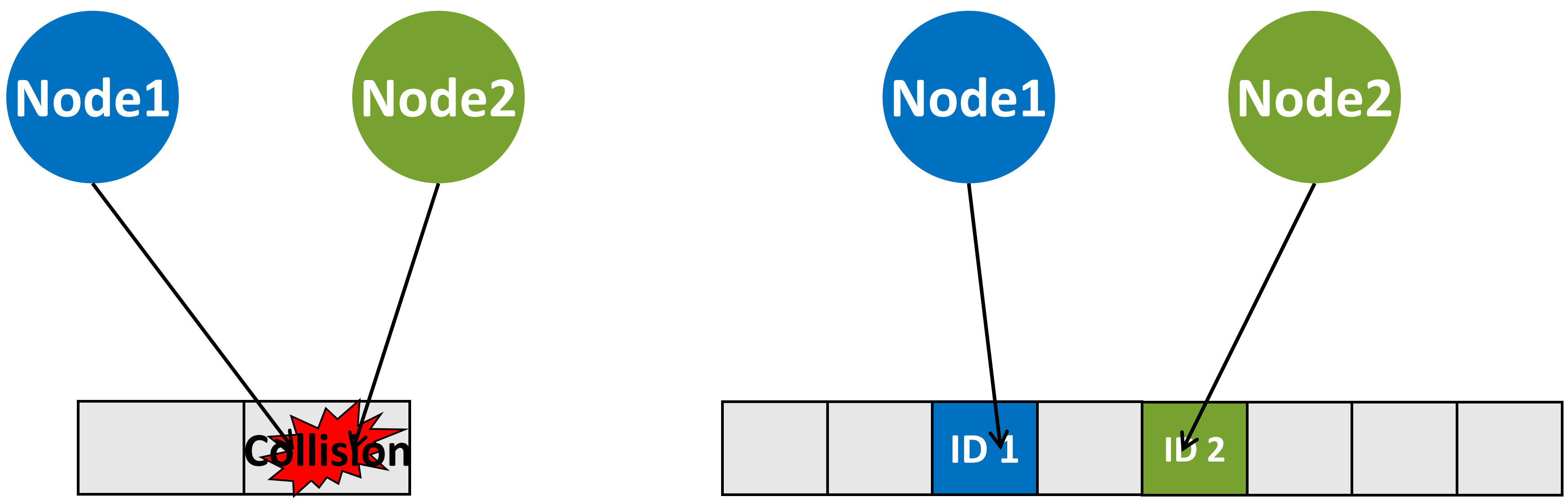
Challenge: RFIDs cannot hear each other

→ Collisions

Current Approach: Slotted Aloha

Time is divided into slots;

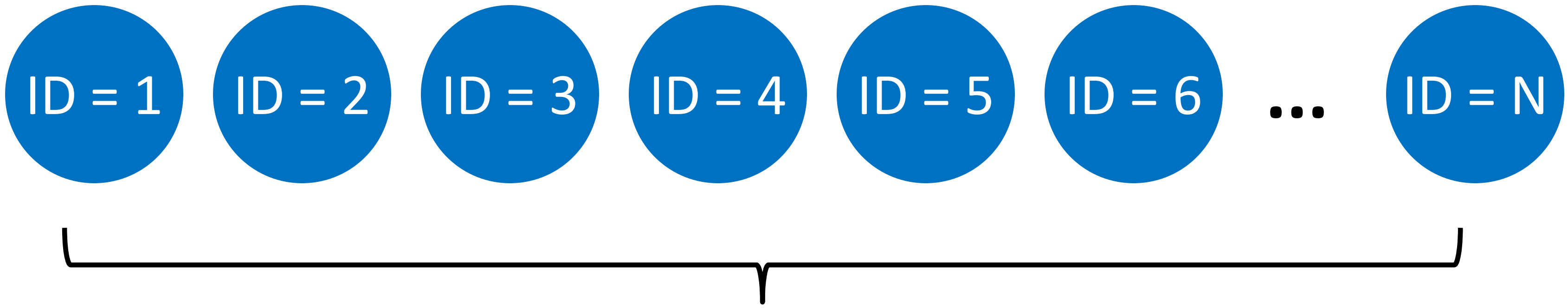
Each RFID transmits in a random slot



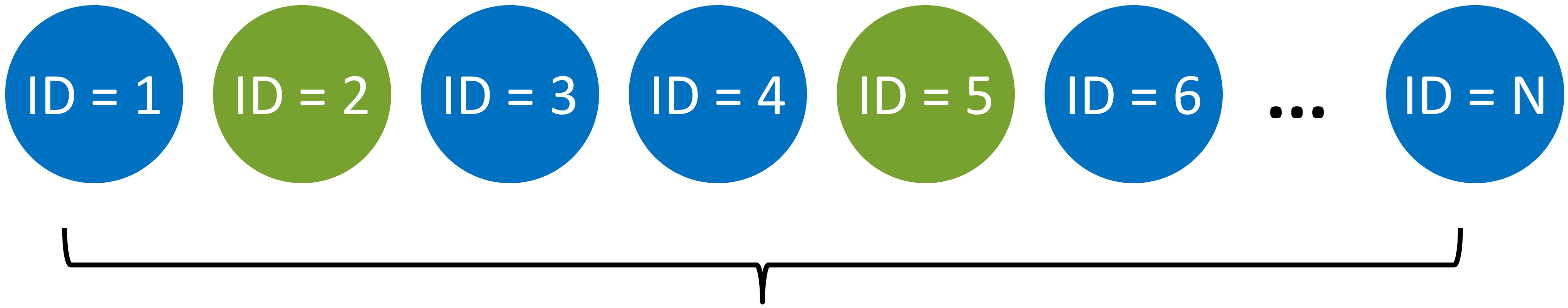
Few Time Slots **OR** Many Time Slots

Unreliable **Inefficient**

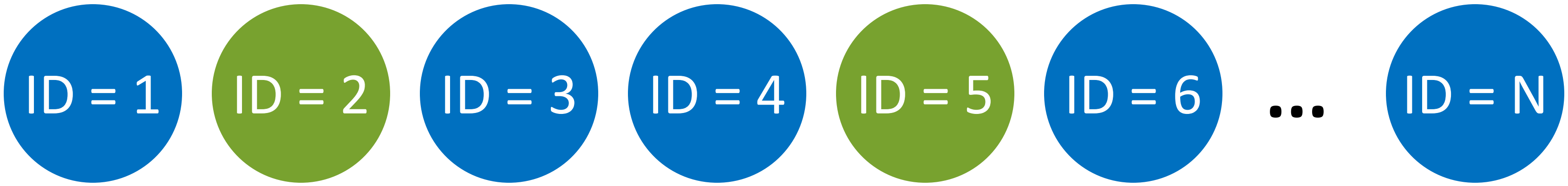
How can network-as-a-node help?



A million RFIDs in the Wal-Mart store



But only a few (e.g., 20) in the shopping cart

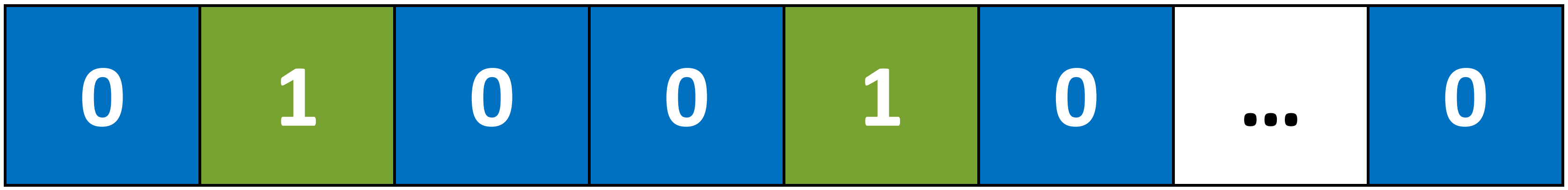


System is represented by a vector $\mathbf{x}$

$x_i = 1$ if node with ID = i is in cart

0	**1**	**0**	**0**	**1**	**0**	**…**	**0**

vector $\mathbf{x}$



Ideally, want to compress $\mathbf{x}$ and send it to the reader

But $\mathbf{x}$ is distributed across all nodes!

vector $\mathbf{x}$

0	1	0	0	1	0	…	0

$\mathbf{x}$ is Sparse

↓

Want the network to emulate a compressive sensing sender

A Virtual Compressive Sensing Sender

Compressive sensing matrix

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \overset{\boldsymbol{A}}{\begin{bmatrix} 0 & 1 & 1 & 1 & & 0 \\ 0 & 0 & 1 & 0 & \cdots & 1 \\ 1 & 1 & 1 & 0 & & 1 \end{bmatrix}} \times \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix}$$

- Virtual sender sends $\boldsymbol{y}$
- Reader decodes $\boldsymbol{x}$ using a compressive sensing decoder

A Virtual Compressive Sensing Sender

Compressive sensing matrix

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \overset{\boldsymbol{A}}{\begin{bmatrix} 0 & 1 & 1 & 1 & & 0 \\ 0 & 0 & 1 & 0 & \cdots & 1 \\ 1 & 1 & 1 & 0 & & 1 \end{bmatrix}} \times \begin{matrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{matrix}$$

- Virtual sender sends $\boldsymbol{y}$

How to implement this virtual sender using a network of RFIDs?

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 1 & & 0 \\ 0 & 0 & 1 & 0 & \cdots & 1 \\ 1 & 1 & 1 & 0 & & 1 \end{bmatrix} \times \begin{matrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{matrix}$$

Virtual sender mixes information in $\mathbf{x}$

Network can mix information using Collisions

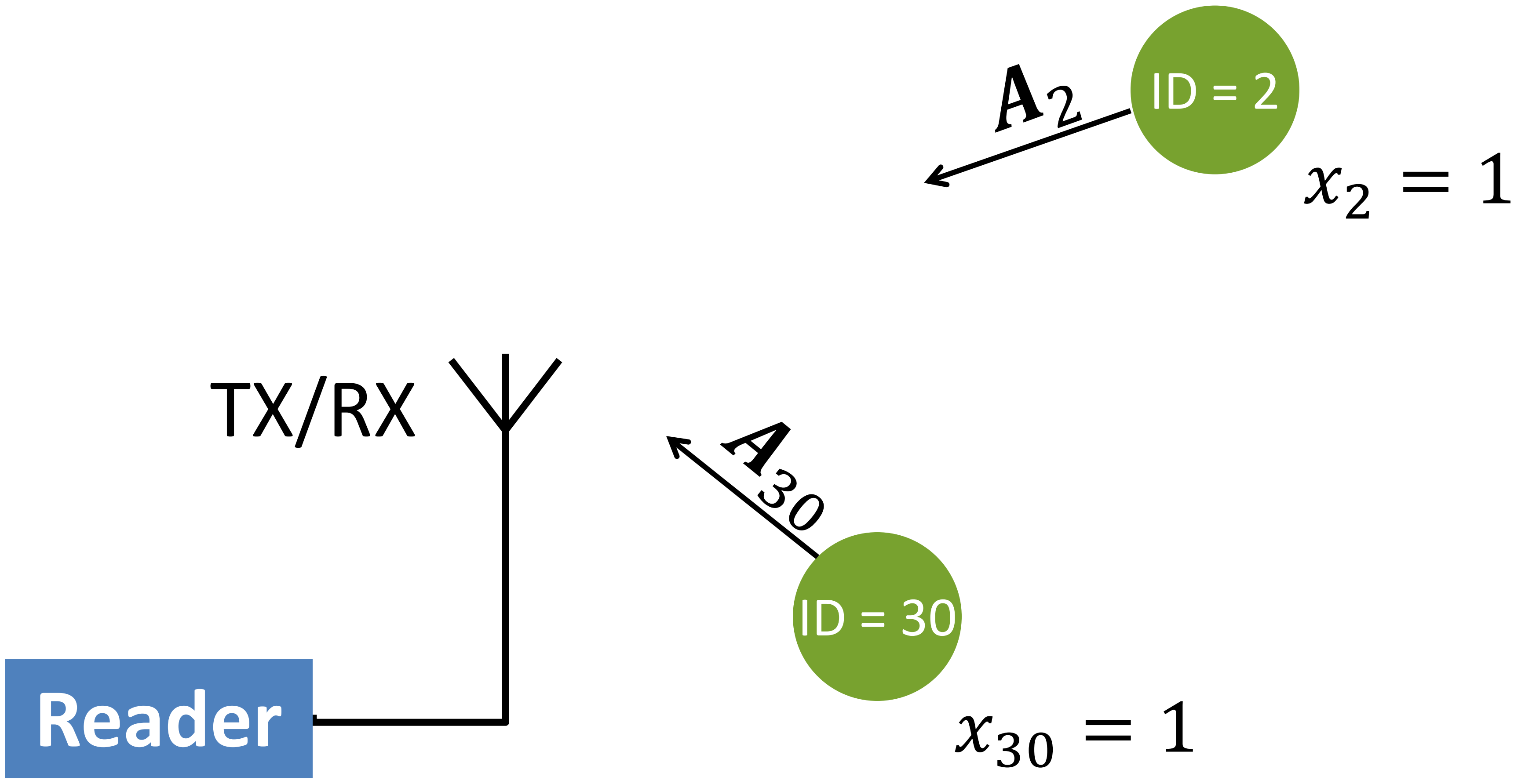
Network Compressive Sensing Using Collisions

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \overset{\quad \boldsymbol{A}_1 \quad \boldsymbol{A}_2 \quad \boldsymbol{A}_3 \quad \boldsymbol{A}_4 \qquad\quad \boldsymbol{A}_N}{\begin{bmatrix} 0 & 1 & 1 & 1 & & 0 \\ 0 & 0 & 1 & 0 & \cdots & 1 \\ 1 & 1 & 1 & 0 & & 1 \end{bmatrix}} \times \begin{matrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{matrix}$$

Node with ID = i transmits $\boldsymbol{A}_i$

Collisions mix on the air

Example: Cart has only ID 2 and ID 30



The reader receives a collision:

$$\boldsymbol{y} = \boldsymbol{A}_2 x_2 + \boldsymbol{A}_{30} x_{30}$$

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{A}_2 & \cdots & \boldsymbol{A}_{30} & \cdots & \boldsymbol{A}_N \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{30} \\ \vdots \\ x_N \end{bmatrix}$$

The reader receives a collision:

$$\boldsymbol{y} = \boldsymbol{A}_2 x_2 + \boldsymbol{A}_{30} x_{30}$$

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{A}_2 & \cdots & \boldsymbol{A}_{30} & \cdots & \boldsymbol{A}_N \end{bmatrix} \times \begin{bmatrix} 0 \\ x_2 \\ \vdots \\ x_{30} \\ \vdots \\ 0 \end{bmatrix}$$

$$\boldsymbol{y} = \boldsymbol{A}\mathbf{x}$$

Network-based compressive sensing solves node identification

Network-As-a-Node

Node Identification

Data Communication

Data communication in RFID networks performs poorly because it lacks rate adaptation

RFIDs always send 1 bit/symbol

Can’t exploit good channels to send more bits

→ Inefficiency

Can’t reduce rate in bad channels

→ Unreliability

Can network-as-a-node help?

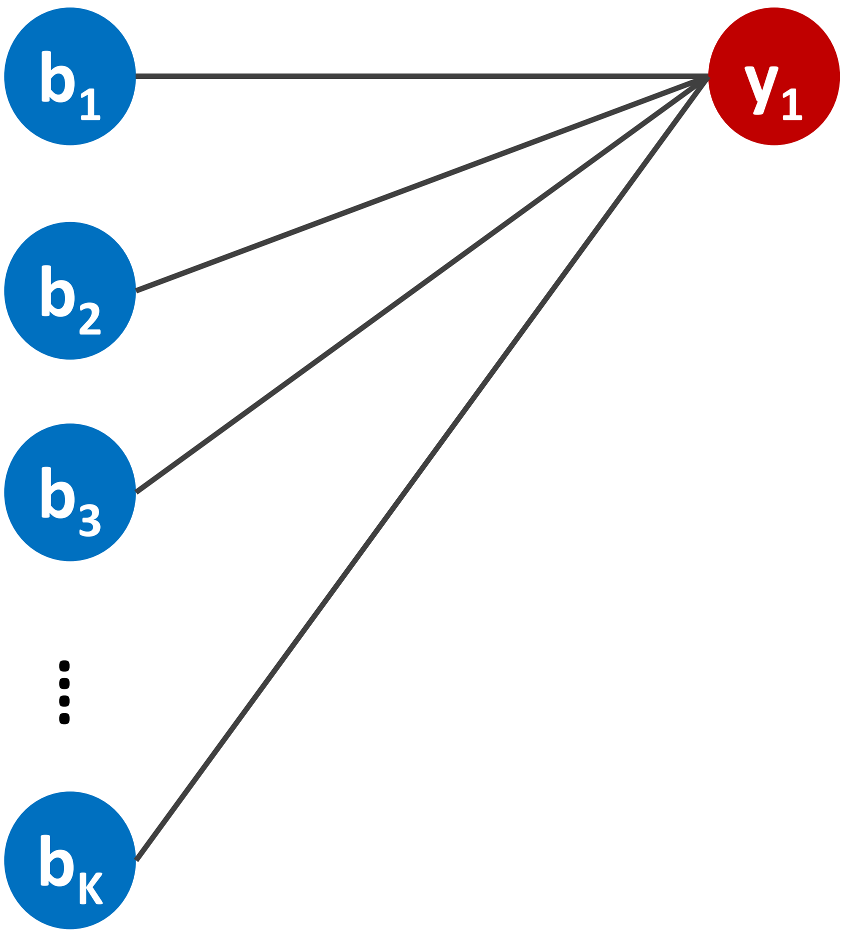
Network-Based Rate Adaptation

- Nodes transmit messages and collide
- Reader collects collisions until it can decode
  - **good channel** → decode from **few collisions**
  - **worse channel** → decode from **more collisions**

Adapts bit rate to channel quality without feedback

Collisions as a Distributed Code

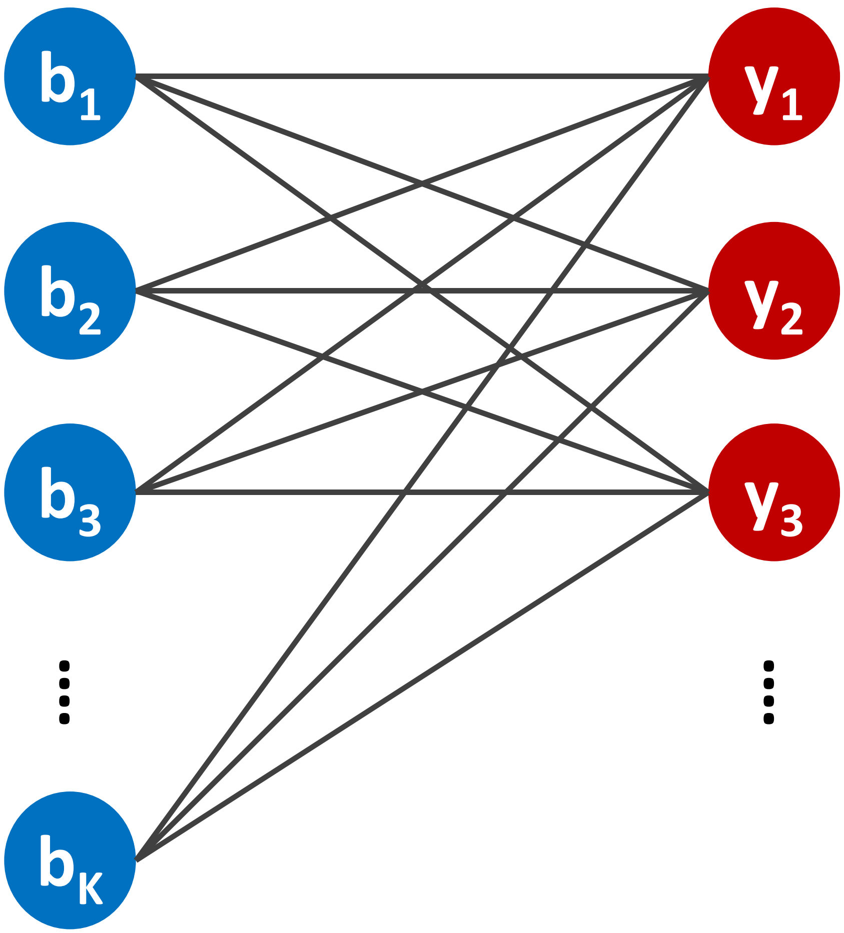
Collisions naturally act like a linear code



$y_1 = h_1 b_1 + h_2 b_2 + \ldots + h_K b_K$

But simply colliding is not a good code

Repetition Code → Bad Code!



$$y_1 = h_1\, b_1 + h_2\, b_2 + \ldots + h_K\, b_K$$

$$y_2 = h_1\, b_1 + h_2\, b_2 + \ldots + h_K\, b_K$$

$$y_3 = h_1\, b_1 + h_2\, b_2 + \ldots + h_K\, b_K$$

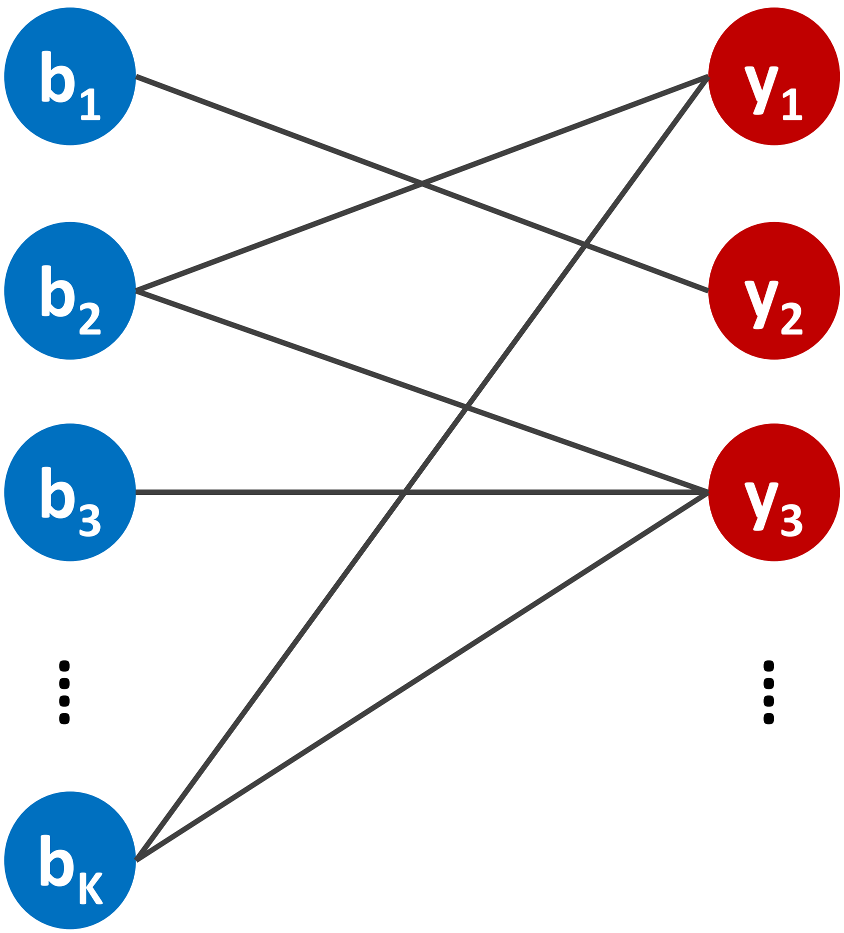
A good code for RFIDs

- ✓ Different linear equations
- ✓ Sparse → Easy to decode (e.g., LDPC)

Collisions as Sparse Random Code

Each node has a different pseudo random sequence

Node transmits in a collision if bit in sequence is "1"



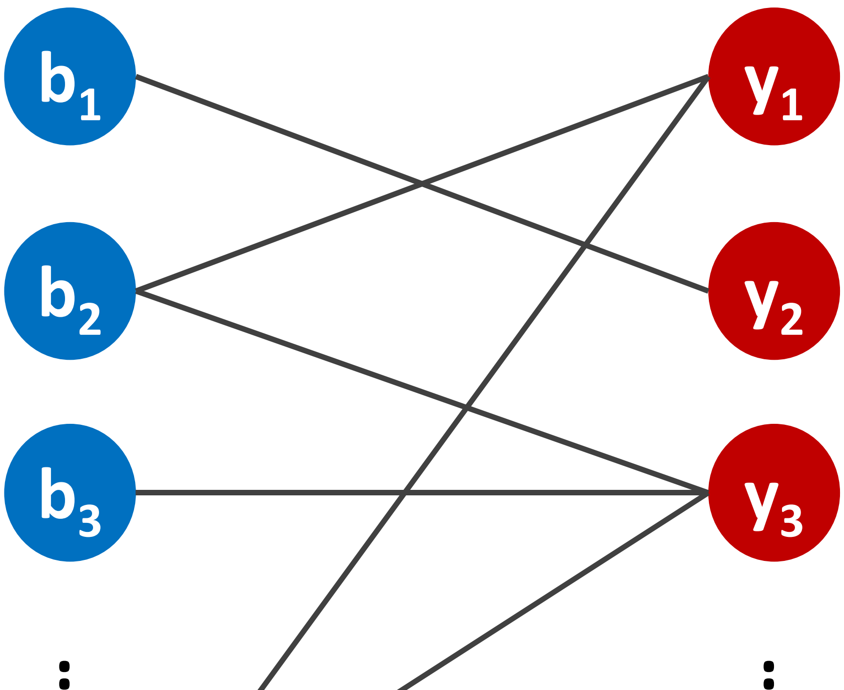
$y_1 = h_2\, b_2 + h_K\, b_K$

$y_2 = h_1\, b_1$

$y_3 = h_2\, b_2 + h_3\, b_3 + h_K\, b_K$

How Does the Reader Decode?

Sparse Code → Leverage ideas from LDPC



Belief Propagation enables the reader to decode quickly

Treat network of RFIDs as a single virtual node

→ Rate adaptation via rateless collision-code

Rest of the Talk

- Understanding RFID communication
- Network as a node
- Empirical evaluation

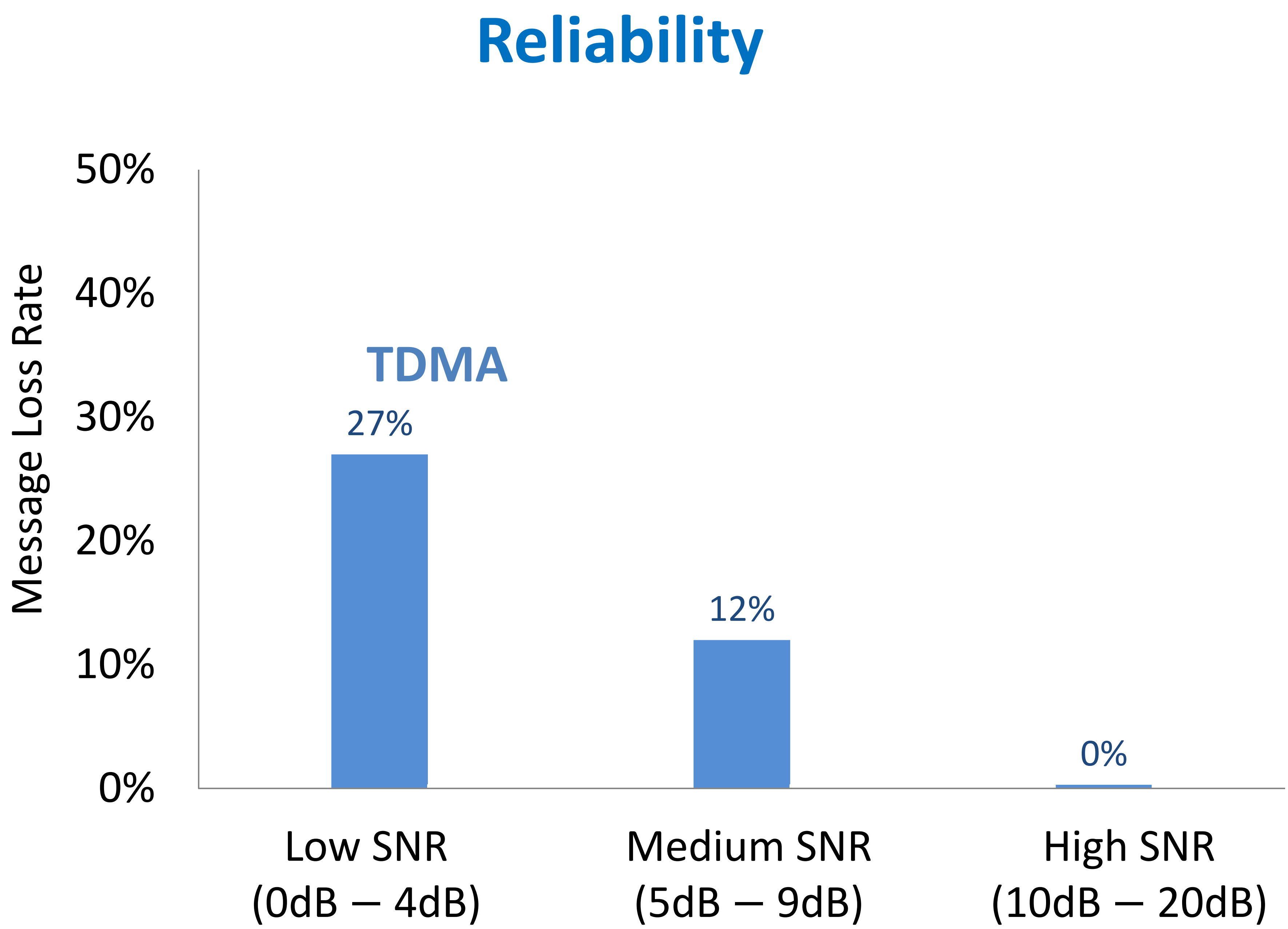
Evaluation

- Reader implementation on GNURadio USRP
- 16 UMass Moo programmable RFIDs

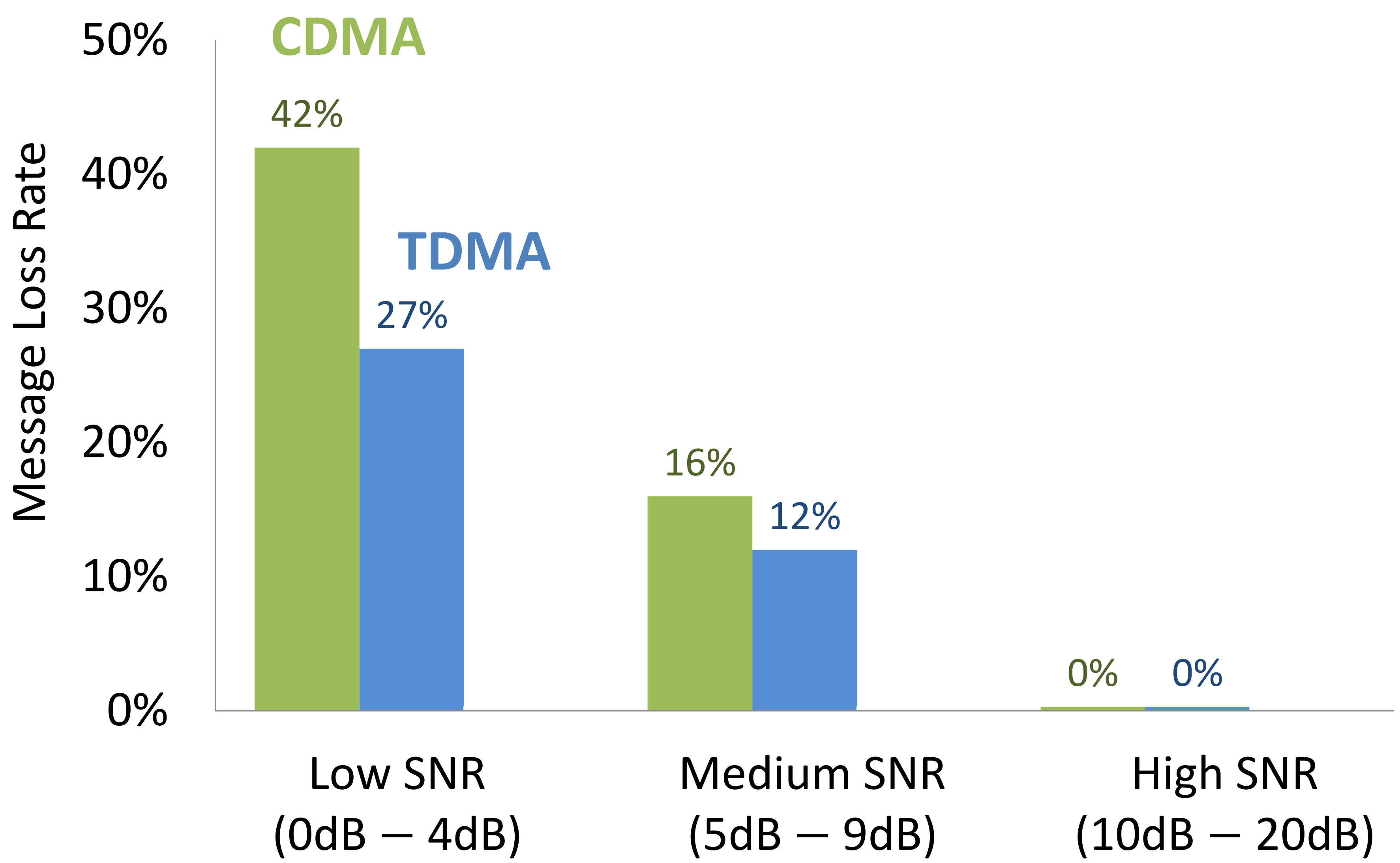
Evaluate Data Communication

Compared schemes

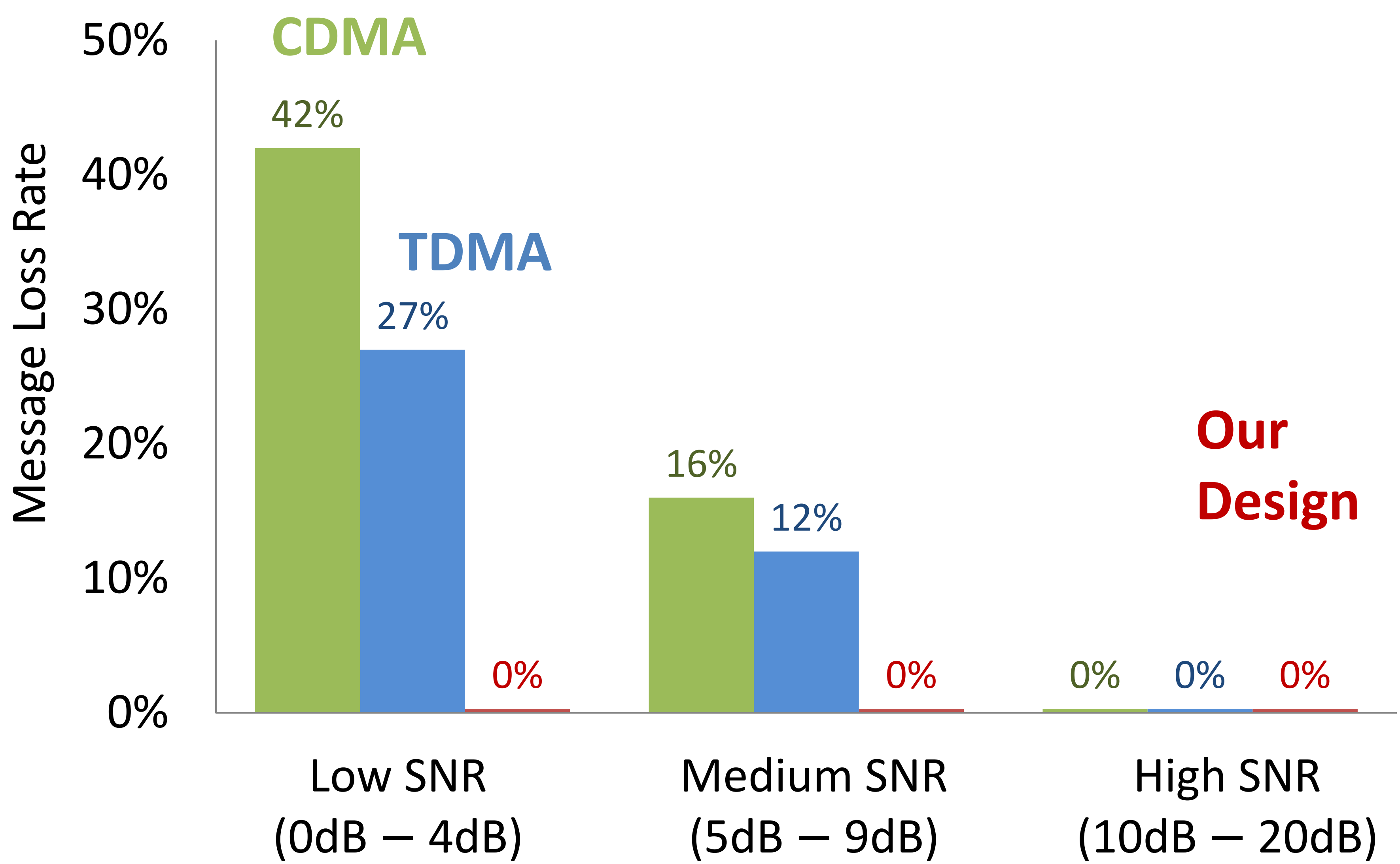
1. Network-based Rate Adaptation
2. TDMA
3. CDMA

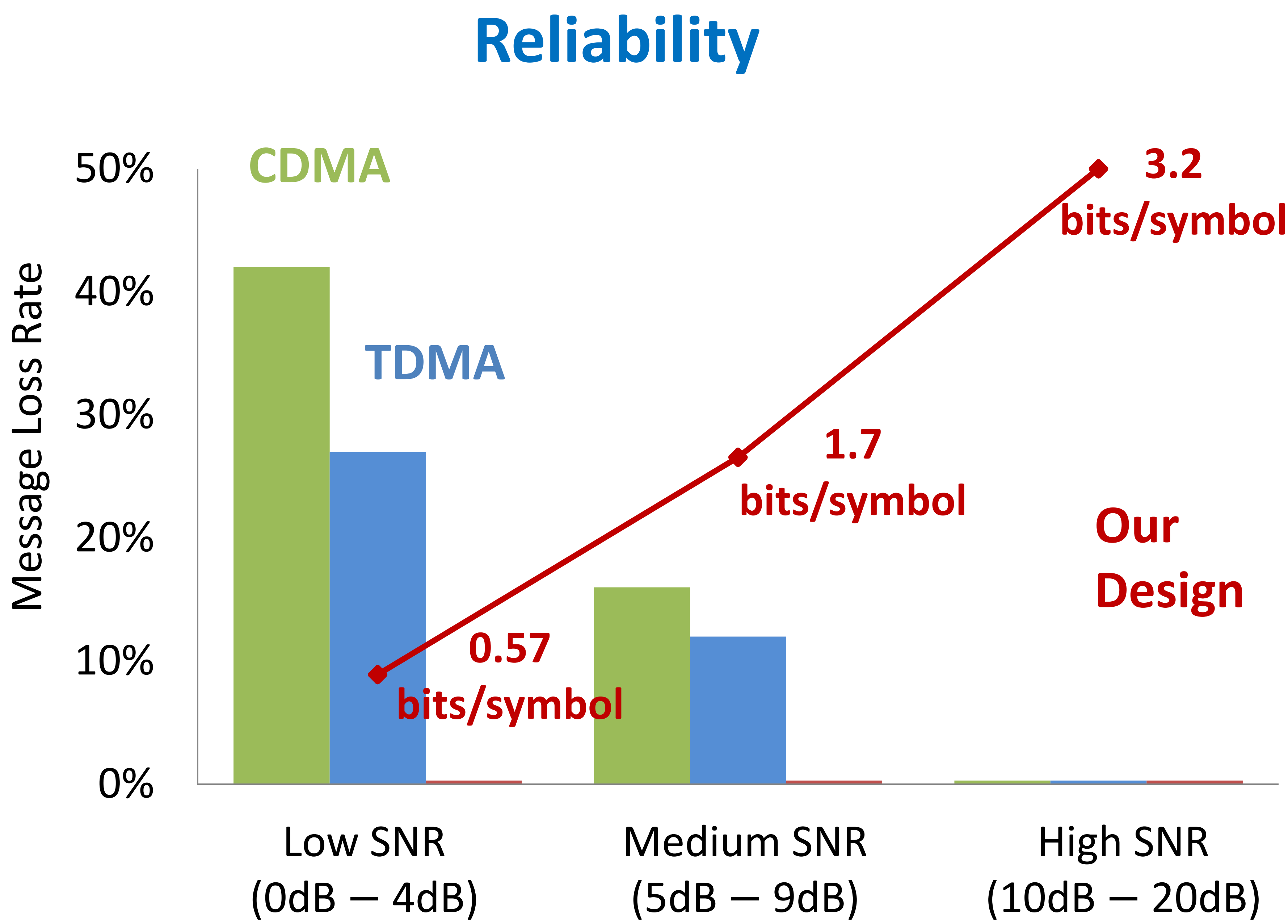

Reliability
Message Loss Rate
50%
40%
30%
20%
10%
0%
TDMA
27%
12%
0%
Low SNR
(0dB – 4dB)
Medium SNR
(5dB – 9dB)
High SNR
(10dB – 20dB)

Reliability

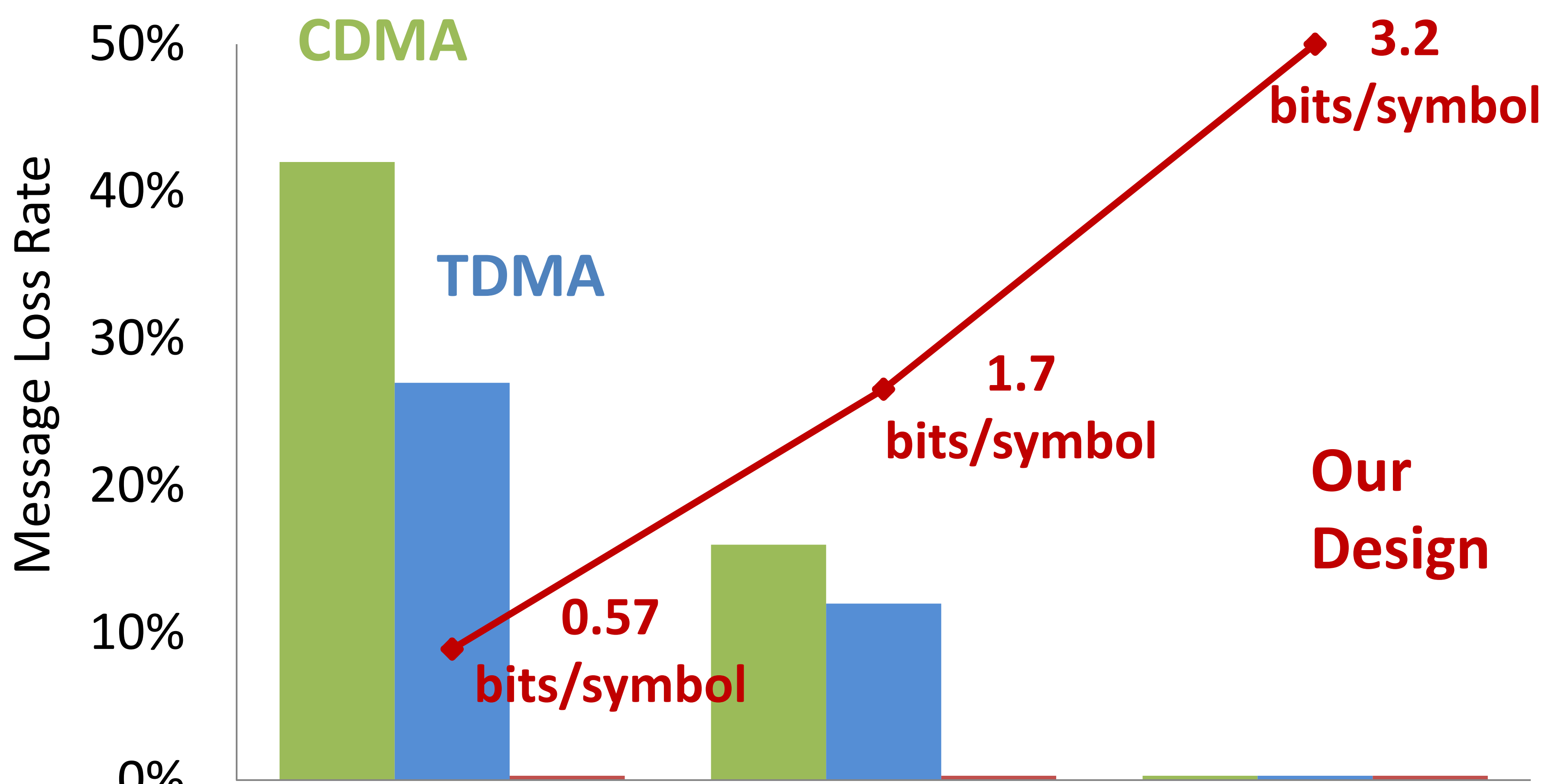


Reliability




Reliability
Message Loss Rate
50%
40%
30%
20%
10%
0%
CDMA
TDMA
Our Design
0.57 bits/symbol
1.7 bits/symbol
3.2 bits/symbol
Low SNR (0dB – 4dB)
Medium SNR (5dB – 9dB)
High SNR (10dB – 20dB)

Reliability

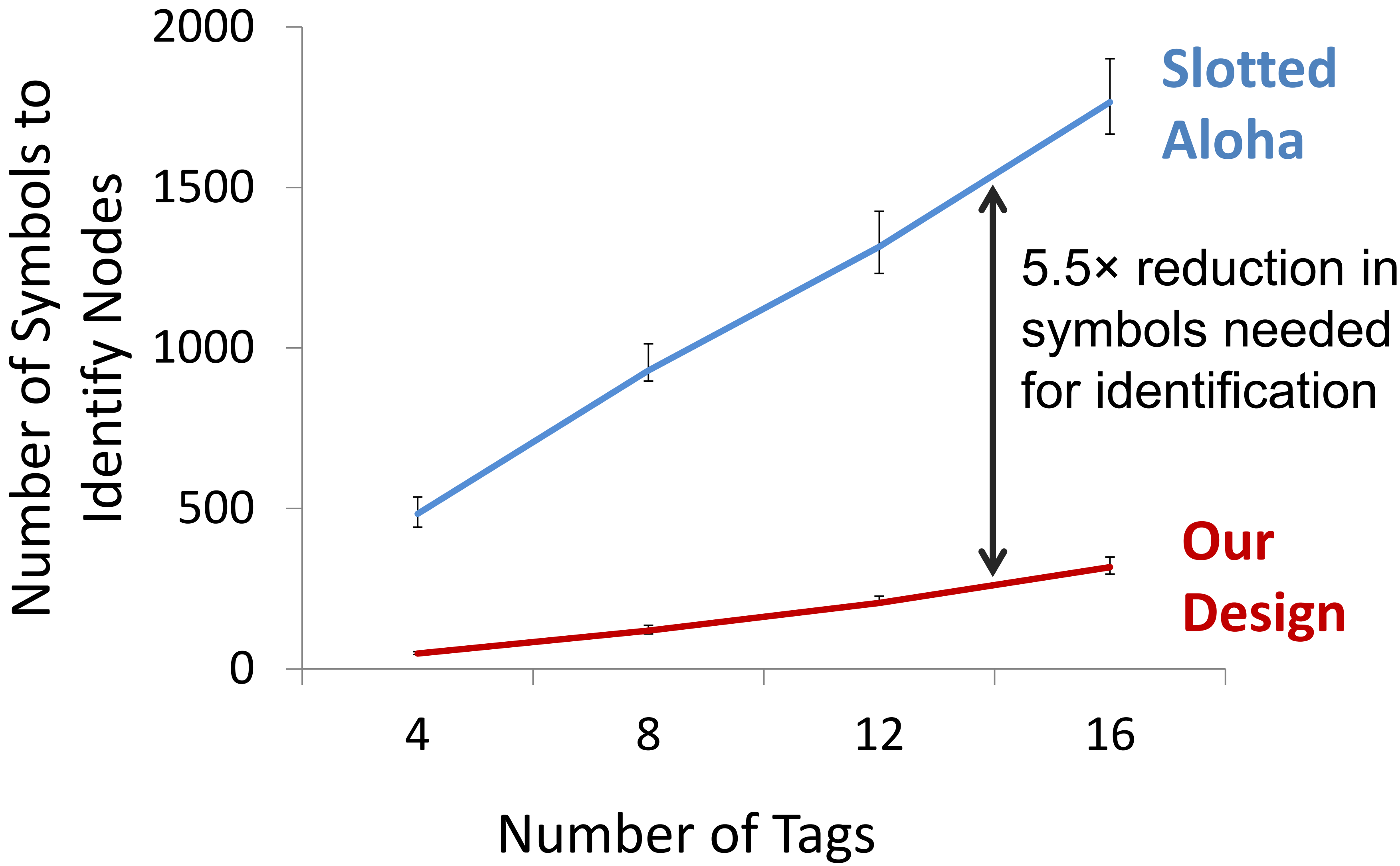


Network as a node adapts bit rate to eliminate message loss

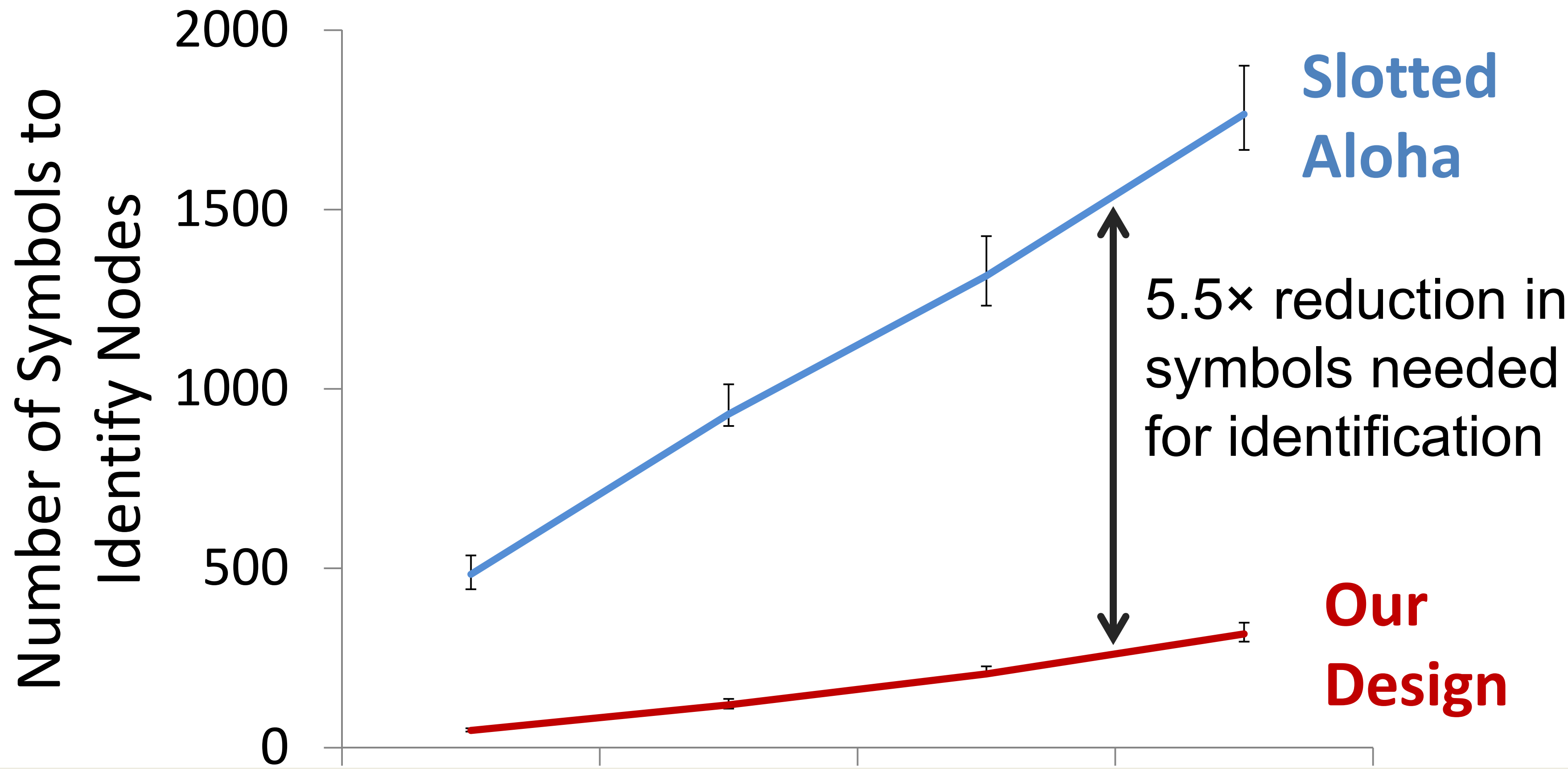
Node Identification

Compared Schemes
- Network-based Compressive Sensing
- Framed Slotted Aloha (standard)

Node Identification



Node Identification



Network compressive sensing improves efficiency of node identification by 5.5×

Conclusion

- Network as a node enables wimpy RFIDs to implement sophisticated protocols
- Efficient node identification via compressive sensing
- Network-based rate adaptation using collisions as a rateless code
- Empirical results show significant gains in efficiency and reliability