ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 14: Backscatter Communications

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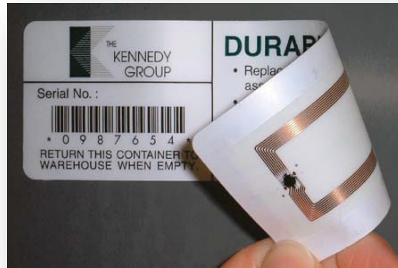
RFIDs


VISA
4000 1234 5678 9010
VISA


THE KENNEDY GROUP
Serial No. :
RETURN THIS CONTAINER TO WAREHOUSE WHEN EMPTY


ILLINOIS
HART, BRADLEY ASHTON
Undergraduate


PASSPORT
United States of America


UNITED STATES OF AMERICA
PASSPORT CARD
UNITED STATES DEPARTMENT OF STATE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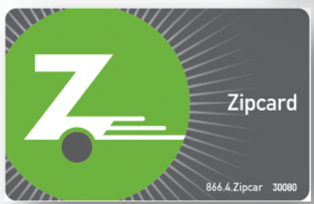
Zipcard
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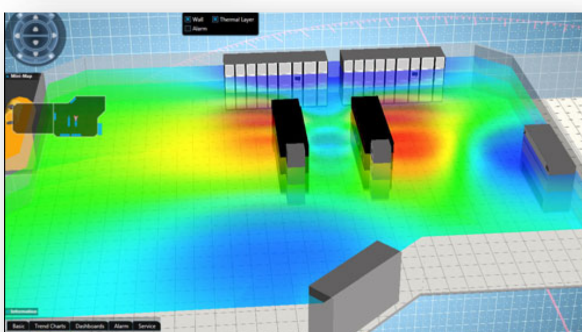
E-ZPass



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*

Can we use current wireless protocols for these low power networks?

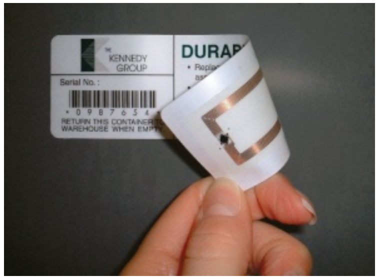
RFID Requirements

- Small form factor
- Massive scale
- Lifetime

RFID Constraints

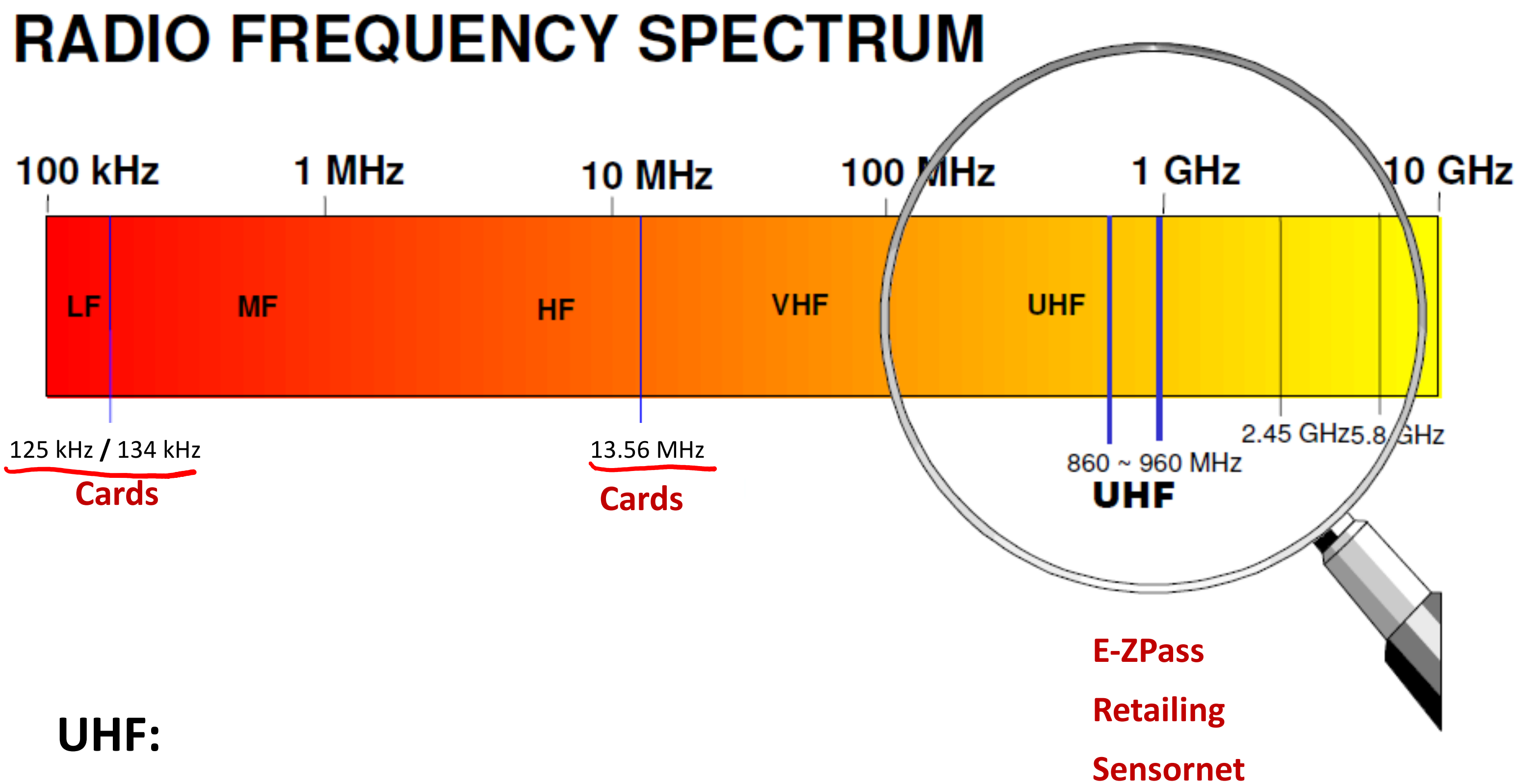
- No battery
- Ultra-low cost
- Simple circuitry

- Wireless protocols require power and computation



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

RFID Background

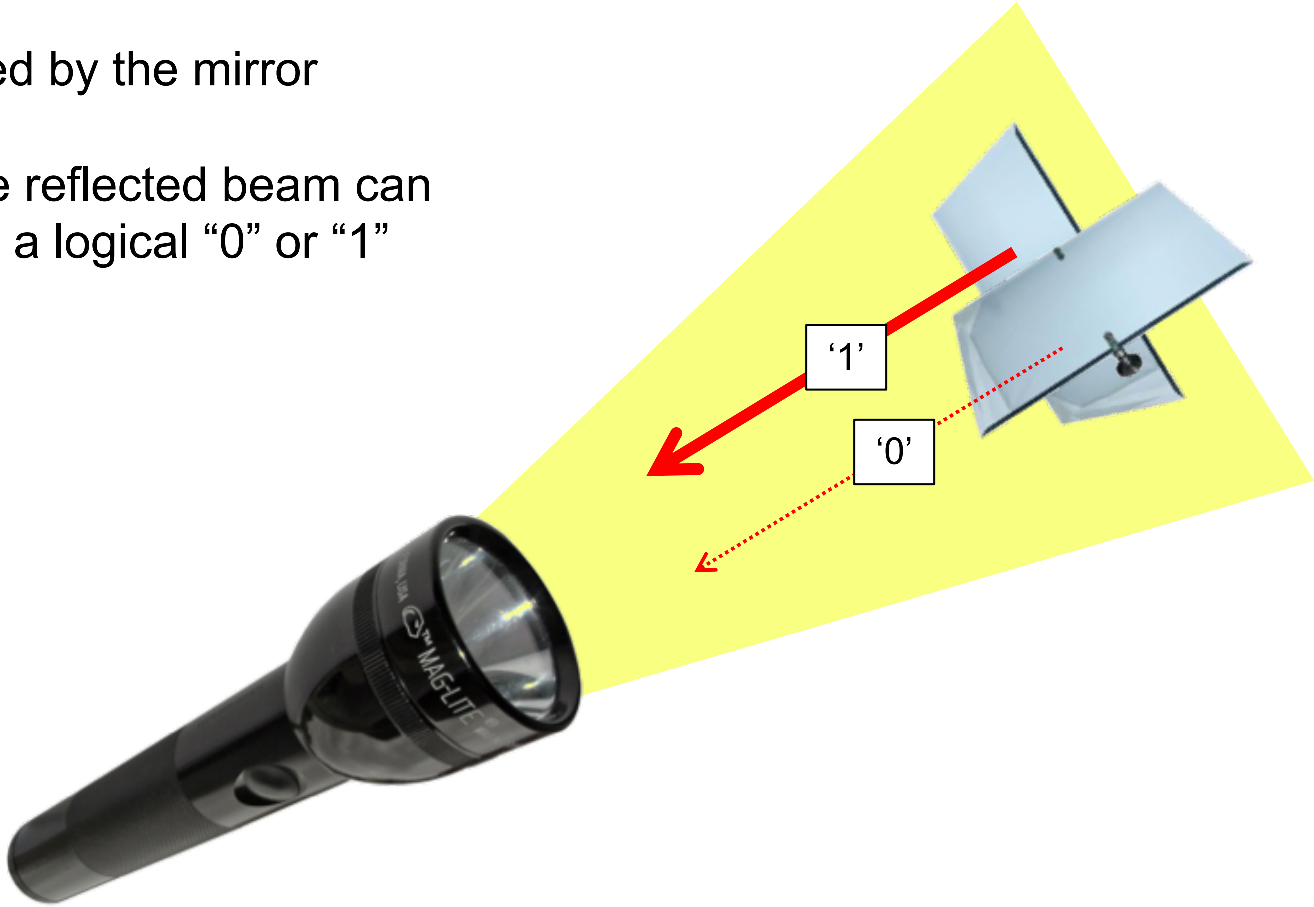


UHF:

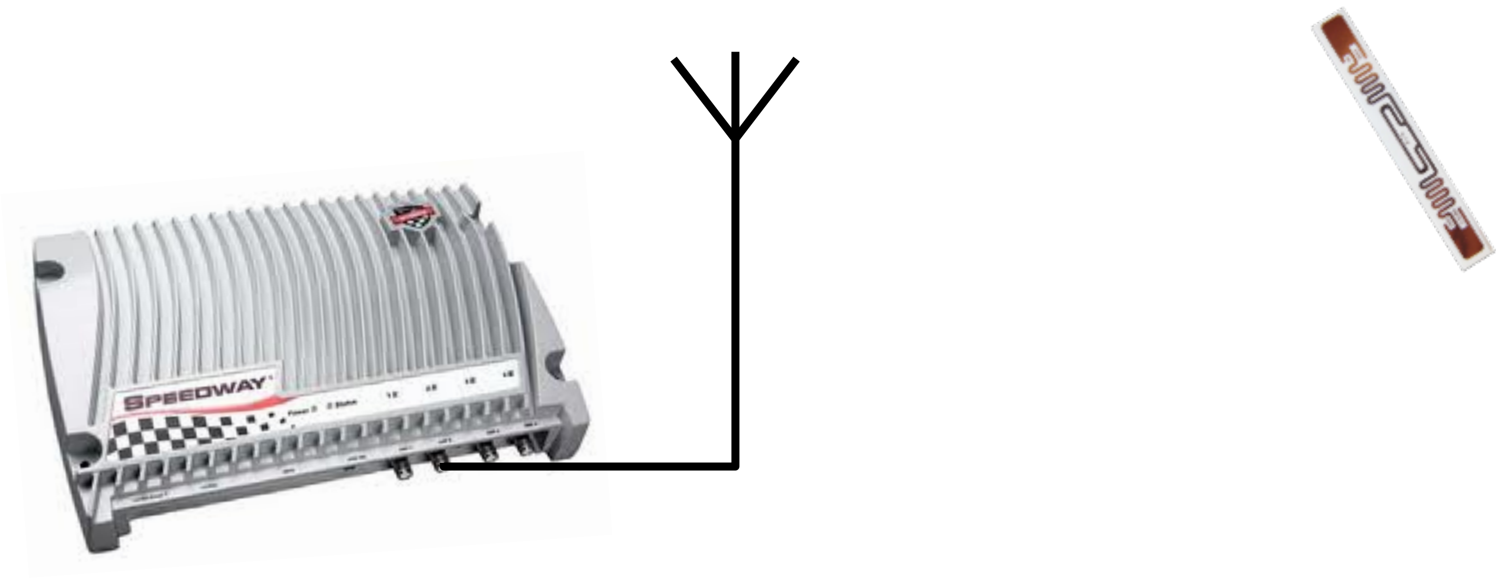
- Achieves higher range (few meters v.s. cm)
- Uses backscatter communication instead of inductive coupling

Backscatter Communication

- A flashlight emits a beam of light
- The light is reflected by the mirror
- The intensity of the reflected beam can be associated with a logical “0” or “1”



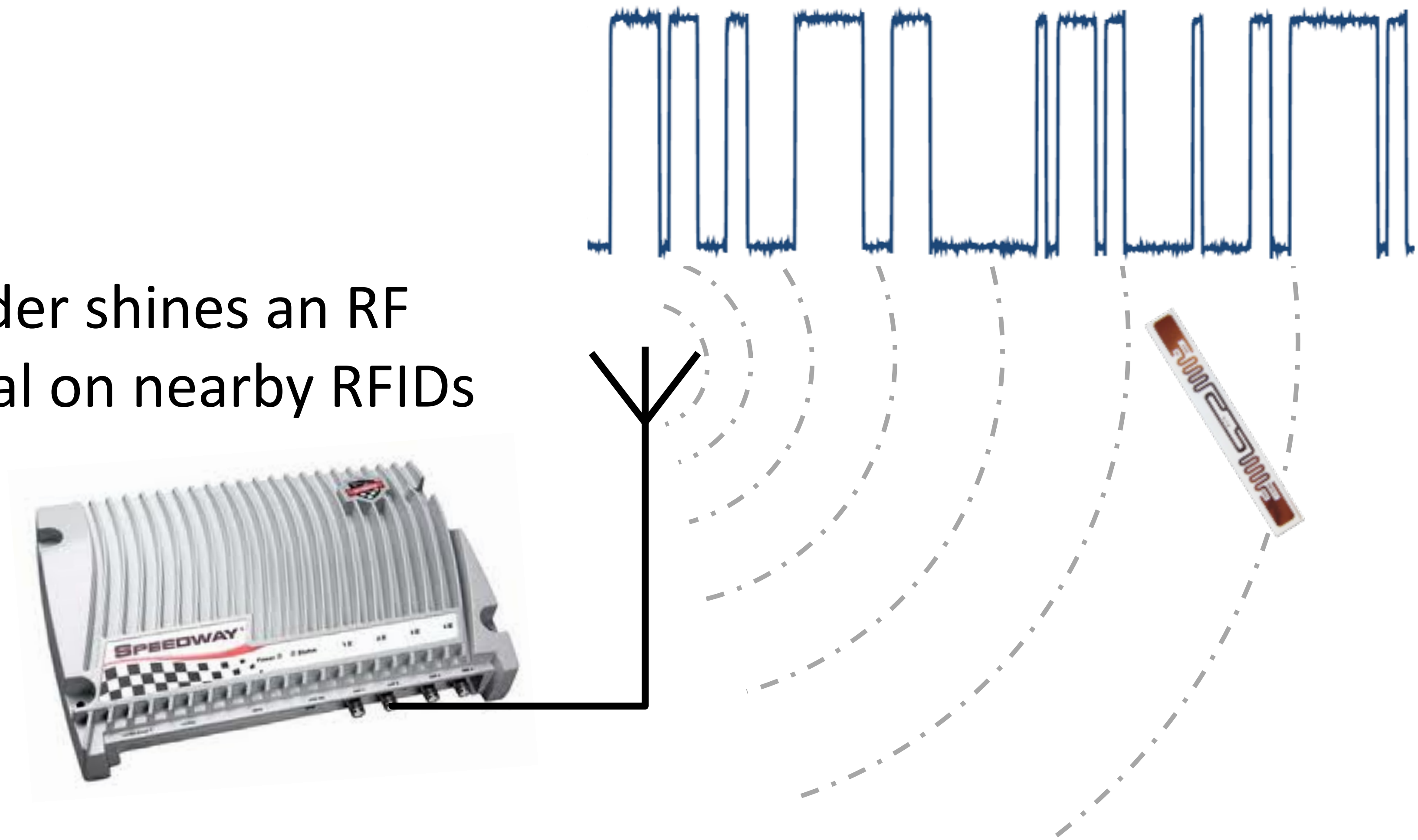
Backscatter Communication



Backscatter Communication

Tag reflects the reader's signal using ON-OFF keying

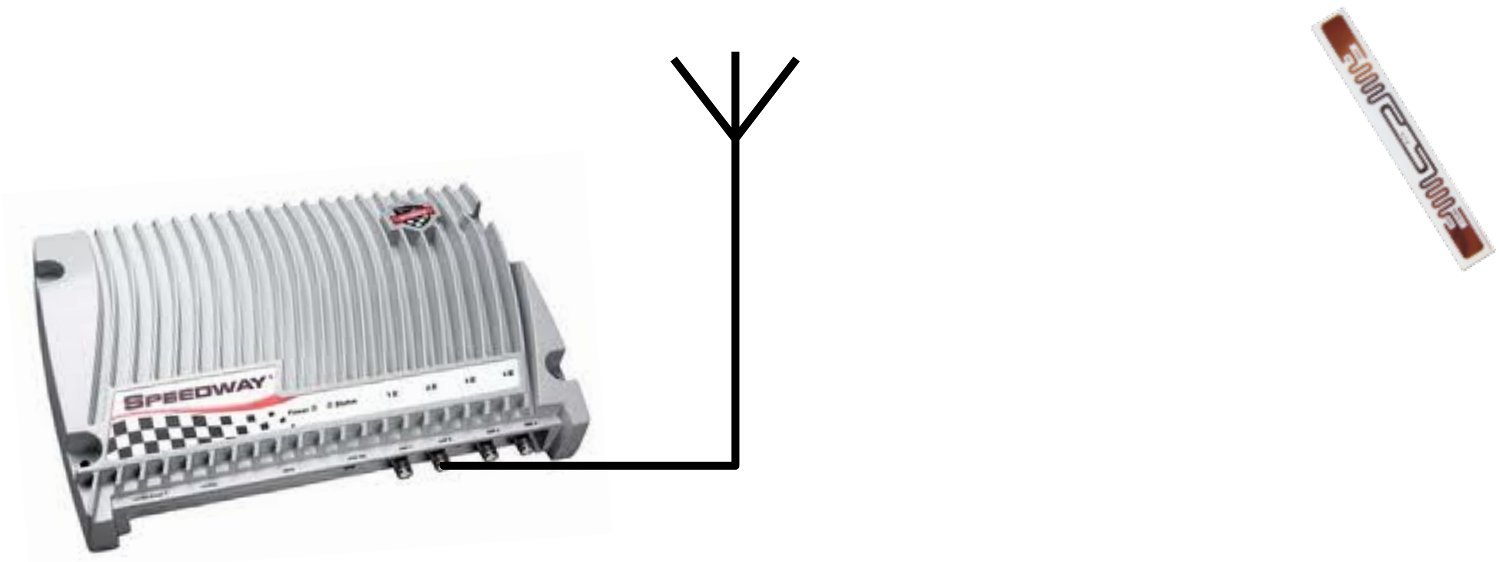
Reader shines an RF signal on nearby RFIDs



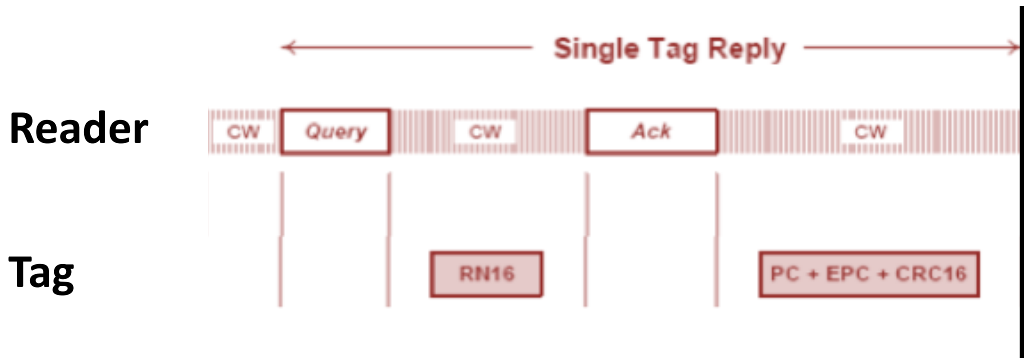
Backscatter Communication

RFIDs are synced by the reader's signal:

- Time synchronization
- Frequency synchronization



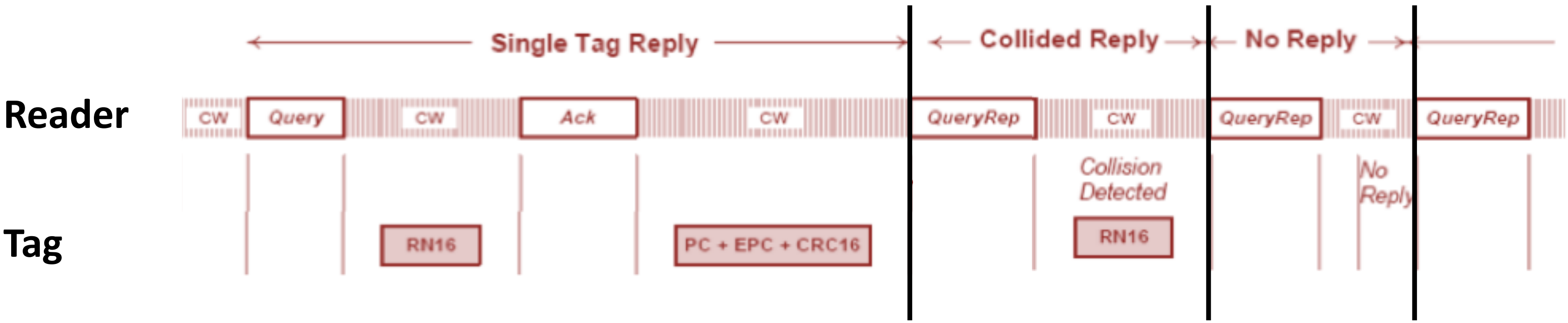
EPC Gen2 Standard – MAC



Slotted Aloha:

- Reader allocates Q time slots and transmits a query at the beginning of each time slot
- Each tag picks a random slot and transmits a 16-bit random number
- In each slot:
  - RN16 decoded → Reader ACKs → Tags transmits 96-bit ID
  - Collision → Reader moves on to next slot
  - No reply → Reader moves on to next slot

EPC Gen2 – MAC



Inefficient:

- If reader allocates large number of slots → Too many empty slots
- If reader allocates small number of slots → Too many collisions

EPC Gen2 – MAC

- N RFID Tags & K Time slots
- Each tag picks a slot uniformly at random to transmit in.

Probability that a tag transmits in a give slot: $p = \frac{1}{K}$

Probability that all tags transmit without collision:

$$E = N \cdot p \cdot (1 - p)^{N-1}$$

To maximize E, set

$$\frac{dE}{dp} = 0$$

$$\rightarrow N(1-p)^{N-1} - Np(N-1)(1-p)^{N-2} = 0$$

$$\rightarrow 1 - p - pN + p = 0$$

$$\rightarrow p = \frac{1}{N} \rightarrow K = N$$

EPC Gen2 – MAC

- N RFID Tags & K Time slots
- Each tag picks a slot uniformly at random to transmit in.

Probability that a tag transmits in a give slot: $p = \frac{1}{K}$

Probability that all tags transmit without collision:

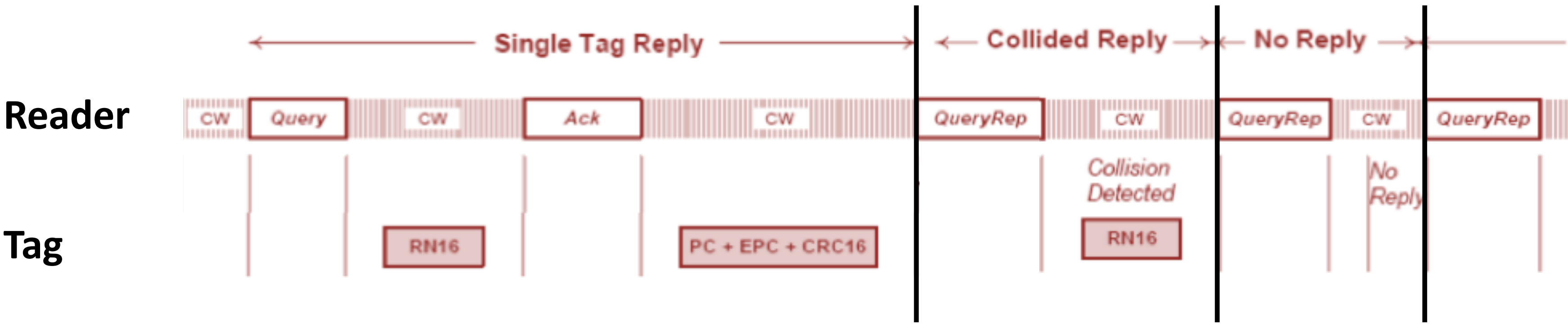
$$E = N \cdot p \cdot (1 - p)^{N-1}$$

To maximize E, set $K = N$

$$Efficiency = E = \left(1 - \frac{1}{N}\right)^{N-1}$$

$$Efficiency \leq \lim_{N \to \infty} E = \lim_{n \to \infty} \left(1 - \frac{1}{N}\right)^{N-1} = \frac{1}{e} = 0.37$$

EPC Gen2 – MAC



Inefficient:

- If reader allocates large number of slots → Too many empty slots
- If reader allocates small number of slots → Too many collisions
- If reader knows number of tags = N → Allocate K=N slots → 37% efficiency
- Downlink overhead

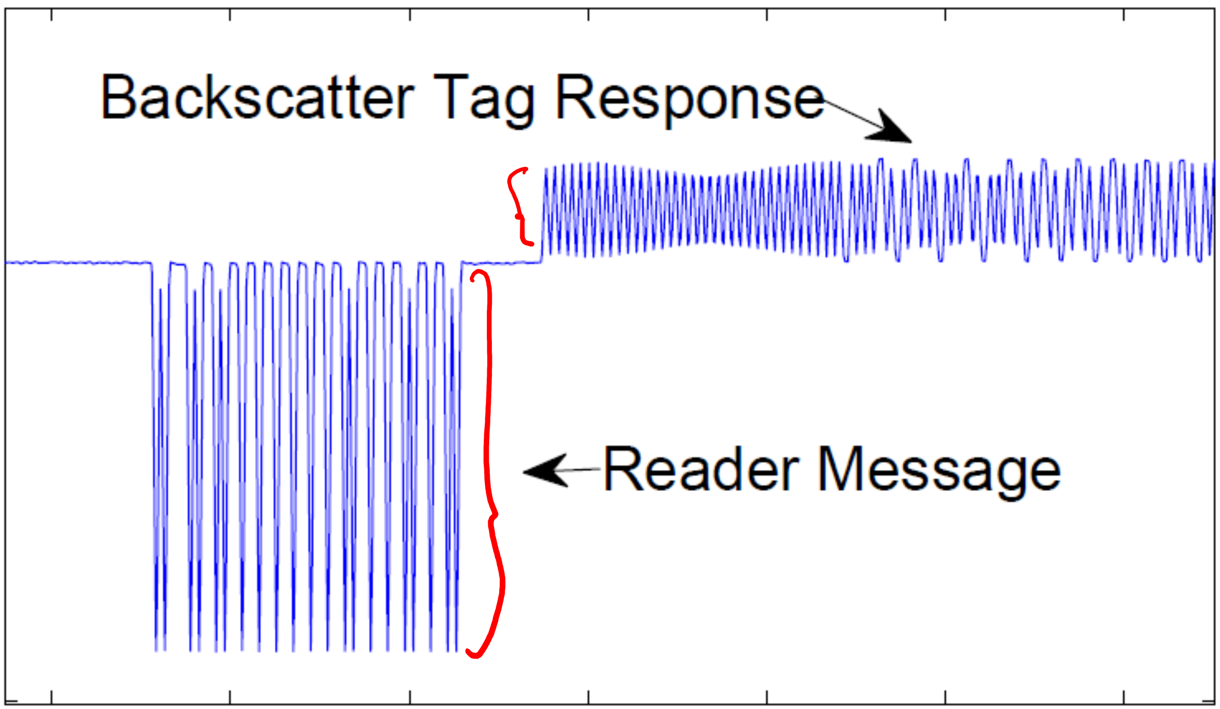
EPC Gen2 – Rate Adaptation

- TDMA
- Fixed modulation: 1 bit/symbol ON-OFF keying (ASK)
- Miller-4 encoding
- No effective adaptation → message loss

Challenges of Backscatter

RFIDs cannot hear each other

→ Collisions



Challenges of Backscatter

RFIDs cannot hear each other

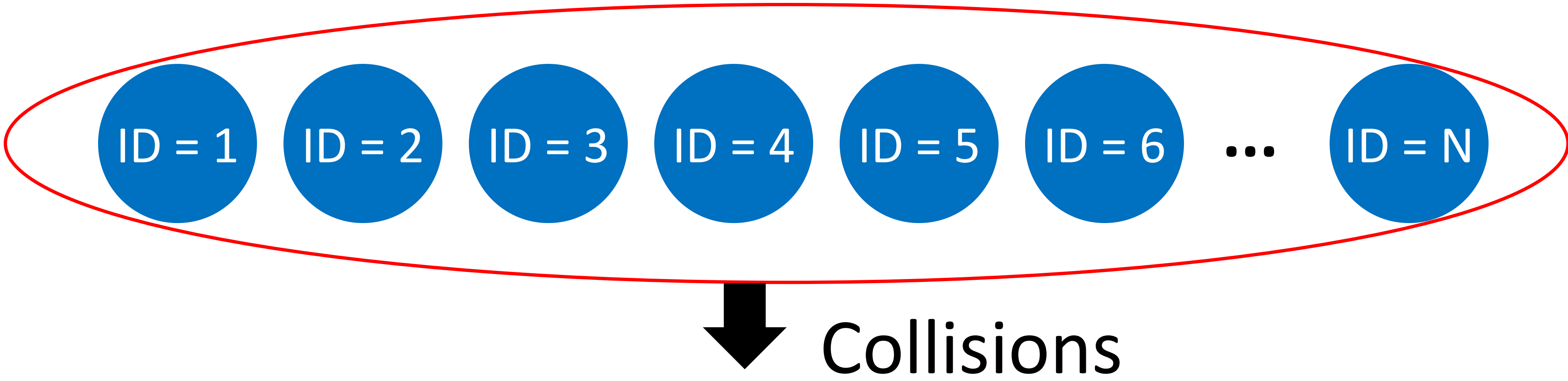
→ Collisions

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

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

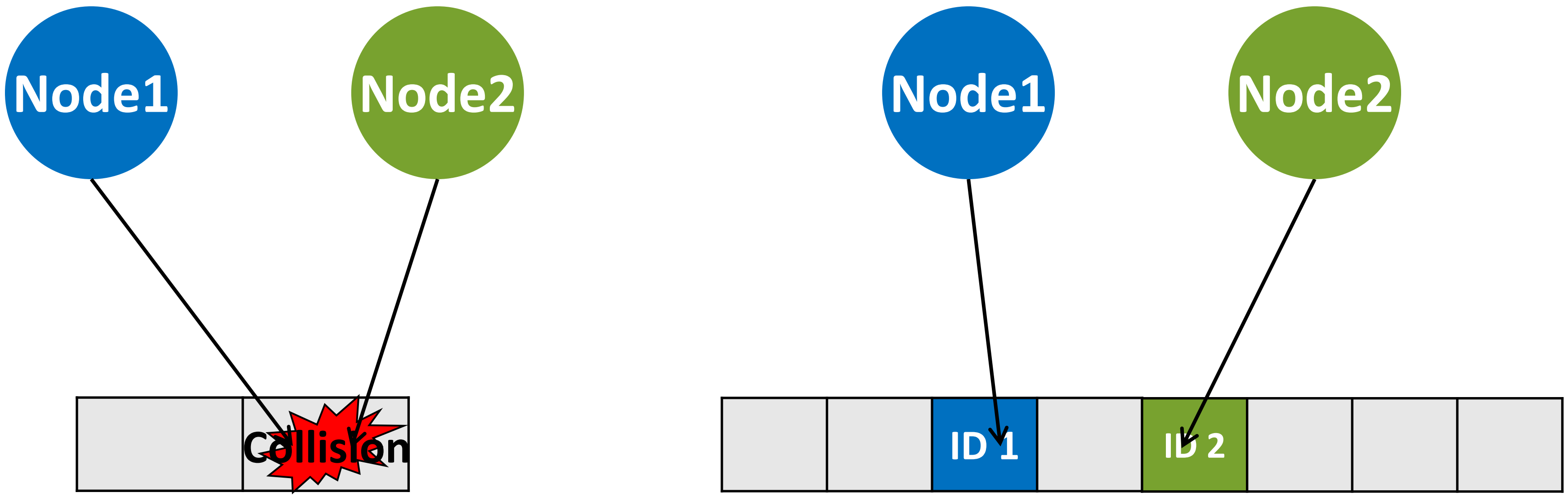
Challenge: RFIDs cannot hear each other

→ Collisions

Current Approach: Slotted Aloha

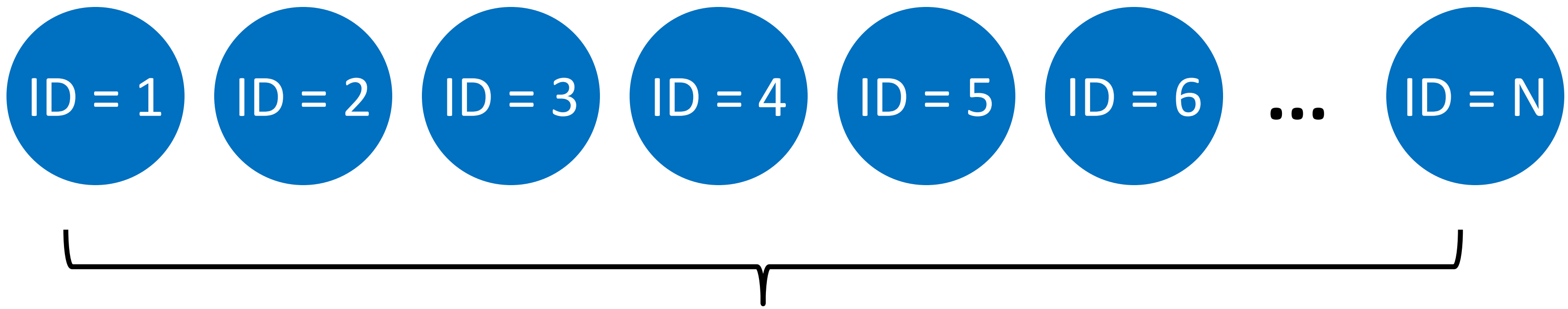
Time is divided into slots;

Each RFID transmits in a random slot

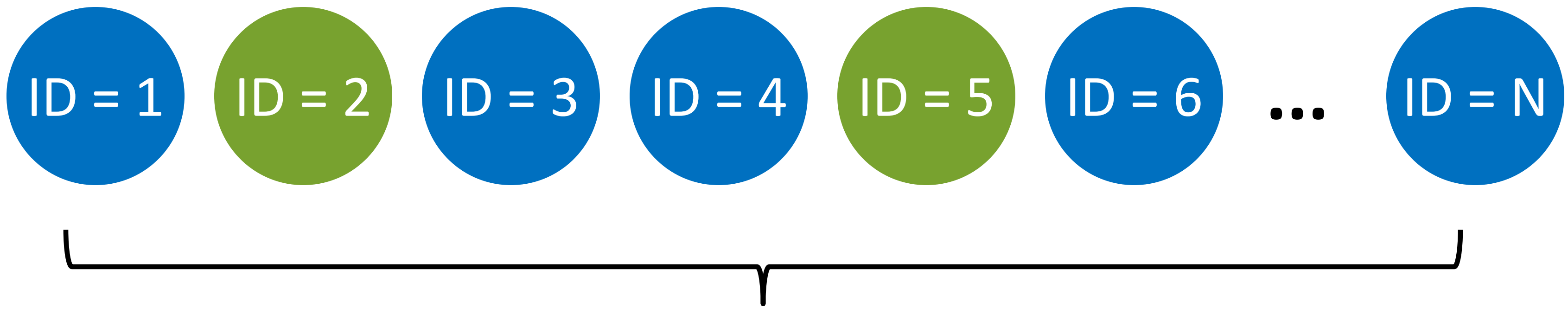


Few Time Slots **OR** Many Time Slots

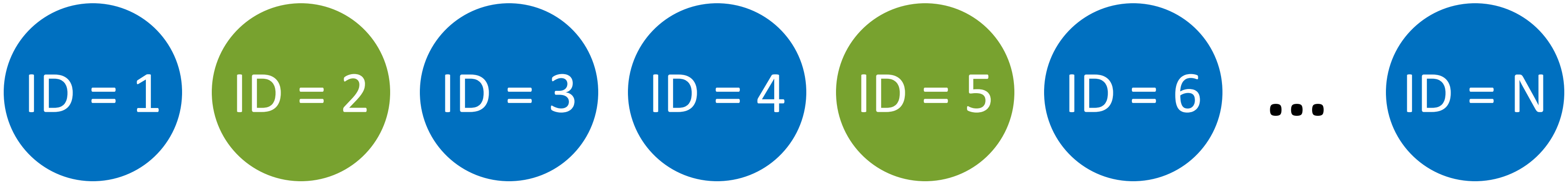
Unreliable **Inefficient**



A million RFIDs in the Wal-Mart store



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

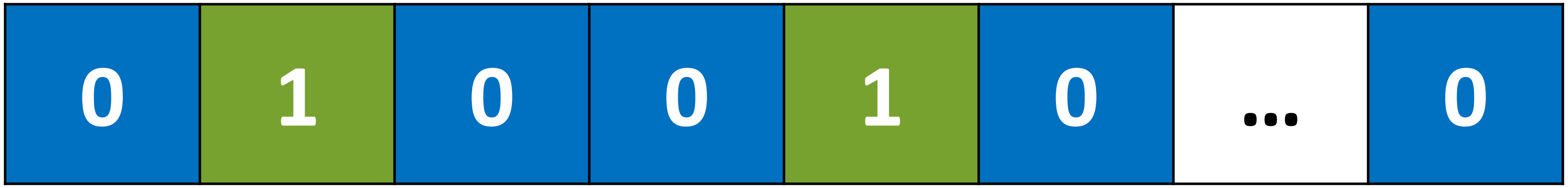


System is represented by a vector $\mathbf{x}$

$x_i = 1$ 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

Use Compressive sensing to compress and send $\mathbf{x}$

Compressive Sensing

Linear Equations:

$$y = Ax$$

- M equations and N unknowns: $y_{M \times 1} = A_{M \times N} x_{N \times 1}$
- Solve for: x
- If M<N → Cannot solve for x

Compressive Sensing

Compressive Sensing: $\mathrm{y} = A\mathrm{x}$

- If x has at most K << N non-zero entries: i.e. x is sparse
  → Can recover x from M << N measurements
  → $M = O(K \log N/K)$

- A must satisfy Restricted Isometry Property (RIP)
  - E.g. Random 0/1 or +1/-1
  - E.g. Fourier measurements $e^{-2\pi j f t/N}$

- x can be sparse in any domain
  - E.g. images are sparse in Wavelet and Fourier domains.
  - $\mathrm{x} = \Phi\, \mathrm{z}$ and z is sparse → can recover x from $\mathrm{y} = A\mathrm{x} = A\Phi\mathrm{z}$

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

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

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

Network can mix information using Collisions

Network Compressive Sensing Using Collisions

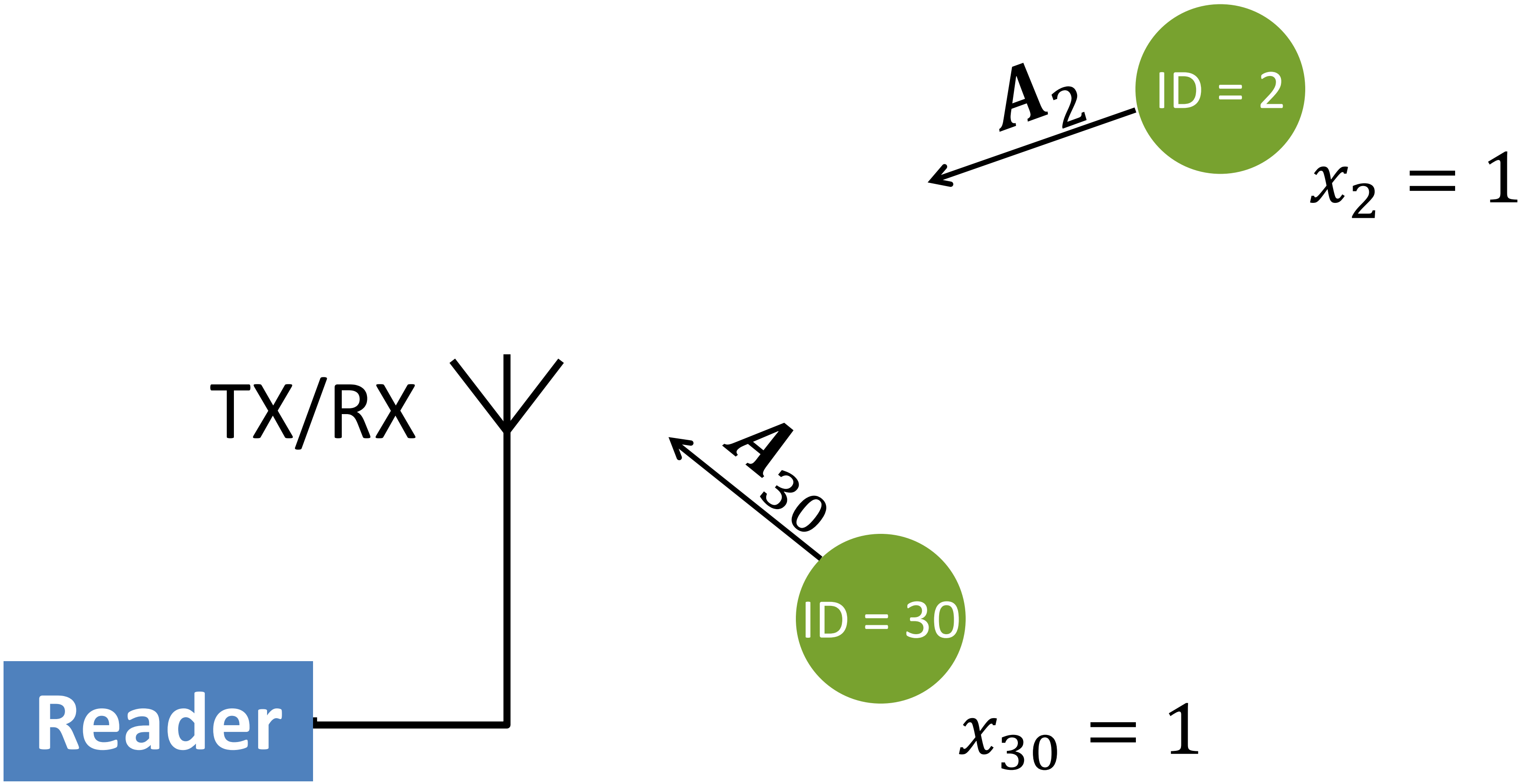
$$\begin{array}{ccccccc} & \boldsymbol{A}_1 & \boldsymbol{A}_2 & \boldsymbol{A}_3 & \boldsymbol{A}_4 & & \boldsymbol{A}_N \end{array}$$

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

Node with ID = i transmits 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:

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

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

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

Reader uses a compressive sensing decoder to recover $\mathbf{x}$ from $\boldsymbol{y}$

The reader receives a collision:

$$\boldsymbol{y} = \boldsymbol{A}_2 h_2 x_2 + \boldsymbol{A}_{30} h_{30} x_{30}$$

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{A}_2 & \cdots & \boldsymbol{A}_{30} & \cdots & \boldsymbol{A}_N \end{bmatrix} \times \begin{bmatrix} 0 \\ h_2 x_2 \\ \vdots \\ h_{30} x_{30} \\ \vdots \\ 0 \end{bmatrix}$$

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

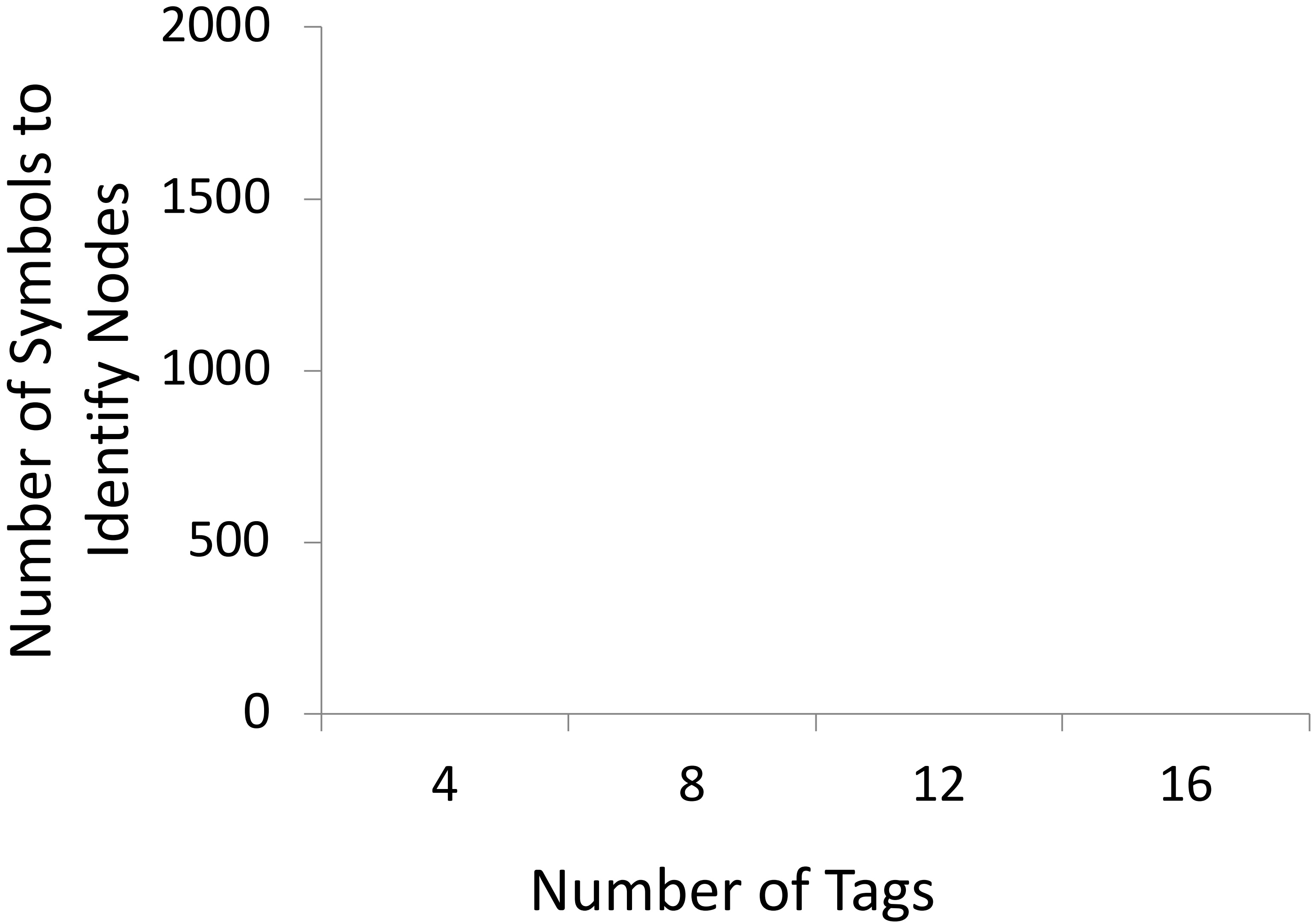
Allows you to estimate the channel from each tag

Node Identification

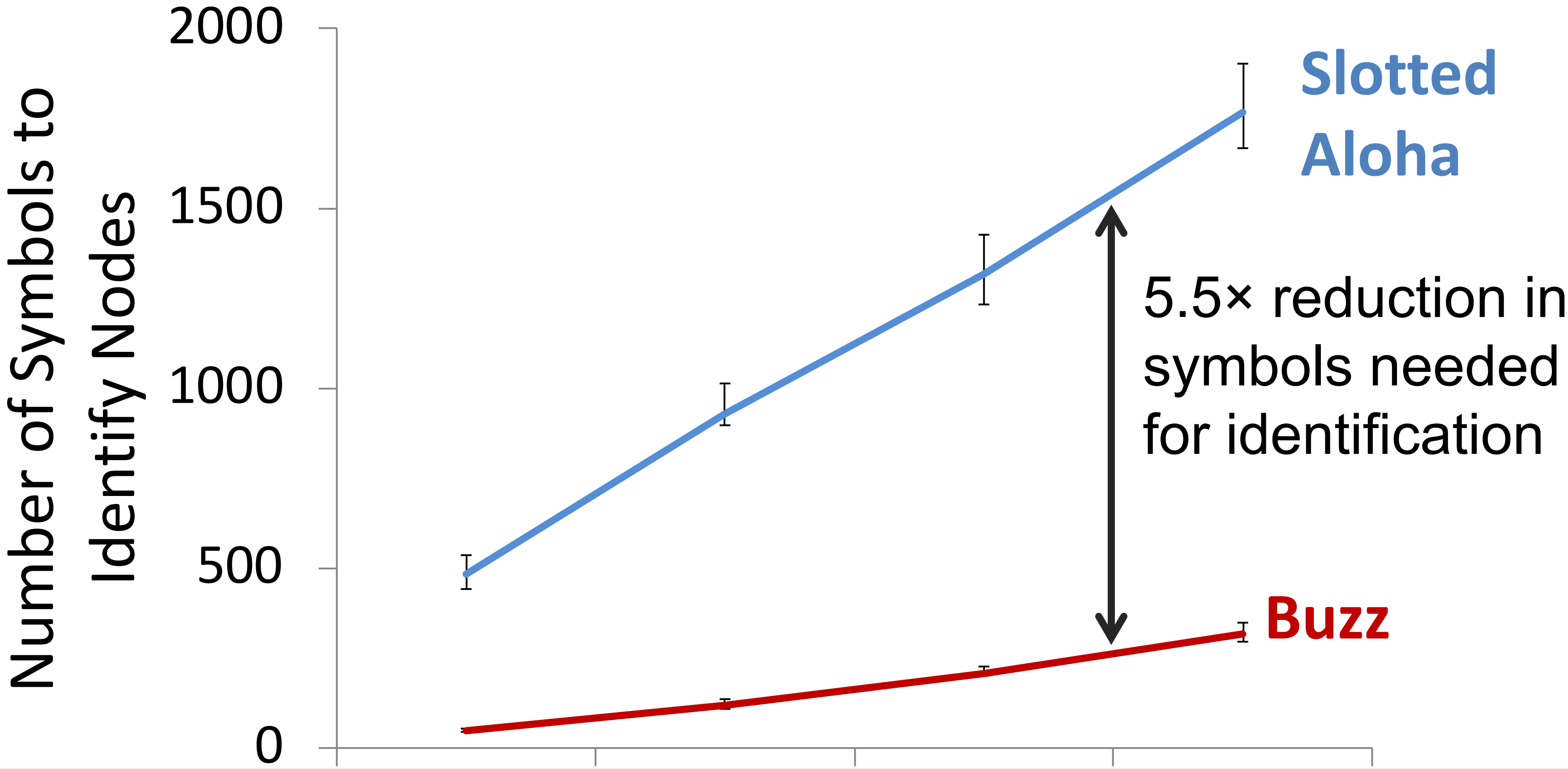
Compared Schemes

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

Node Identification



Node Identification



Network compressive sensing improves efficiency of node identification by 5.5×

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

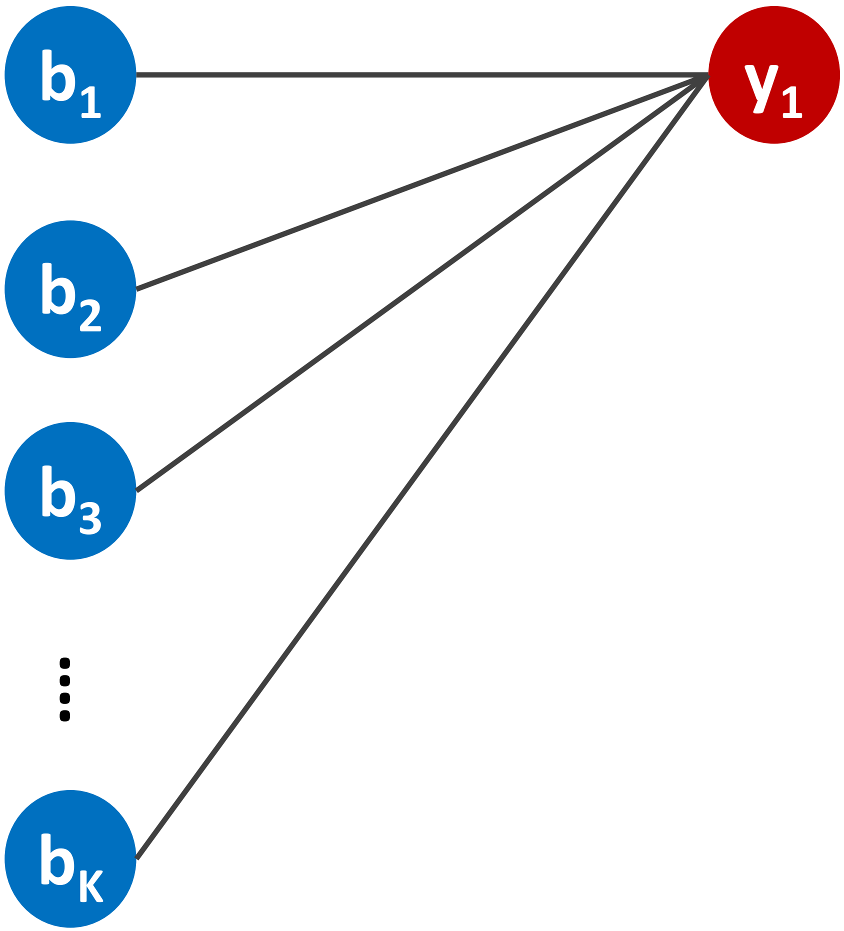
Network-Based Rate Adaptation

- 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

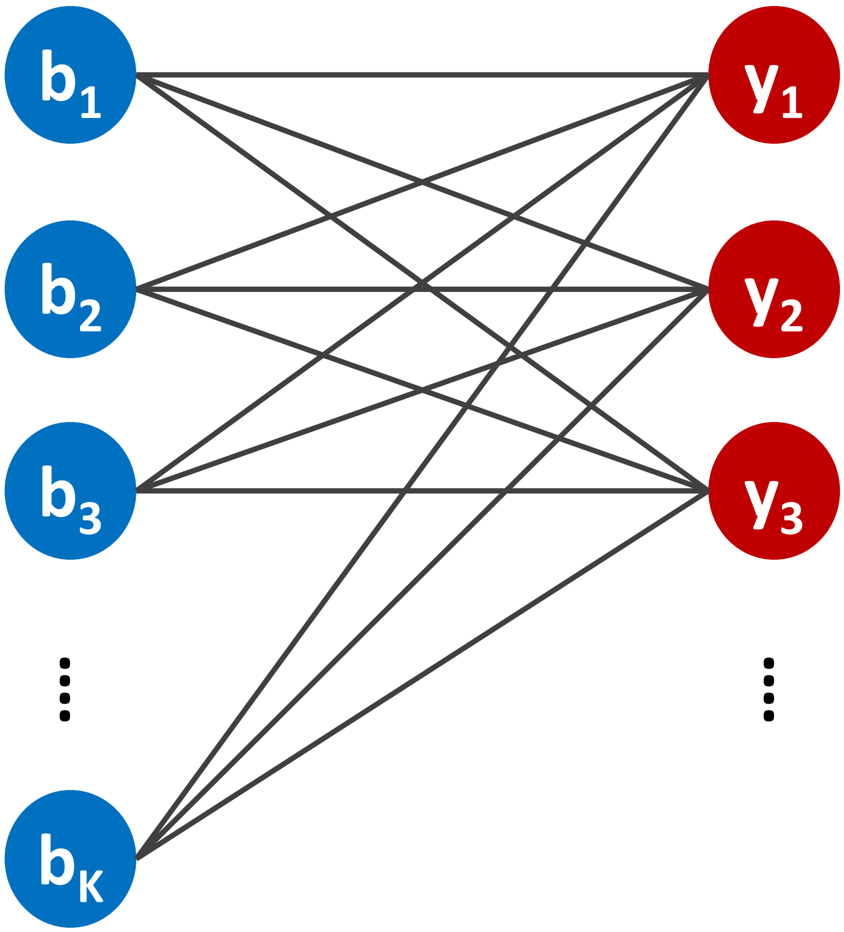
Collisions naturally act like a linear code



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

But simply colliding is not a good code

Repetition Code → Bad Code!

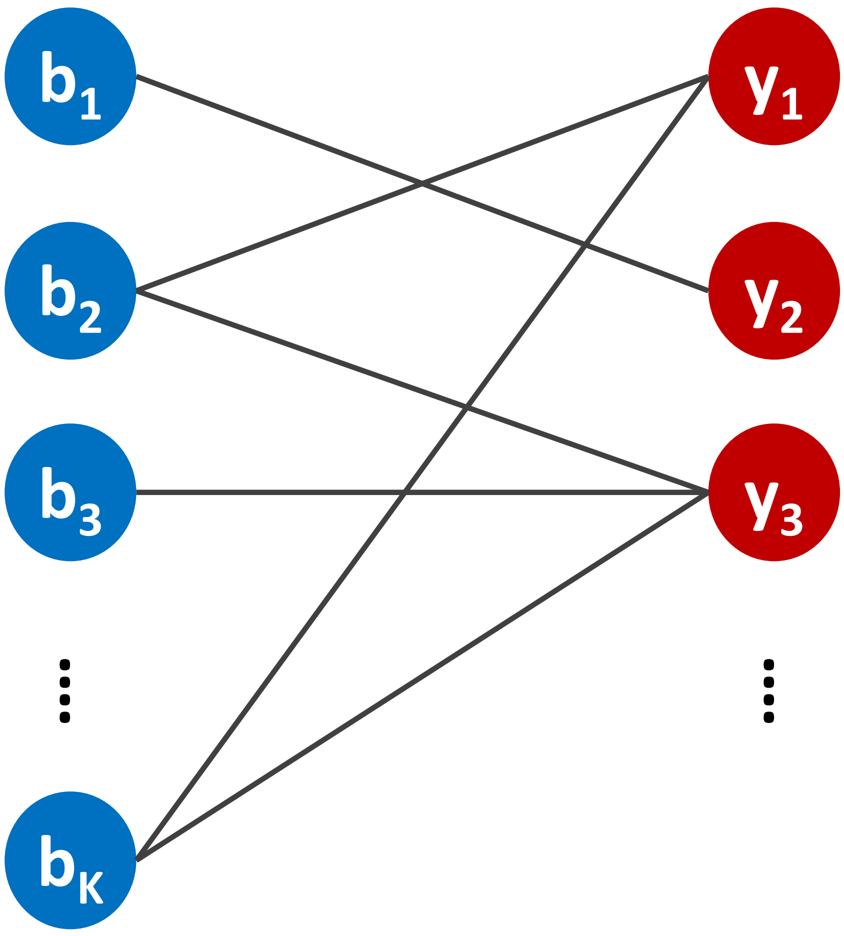


$y_1 = h_1 b_1 + h_2 b_2 + \ldots + h_K b_K$

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

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

Collisions as a Random Code



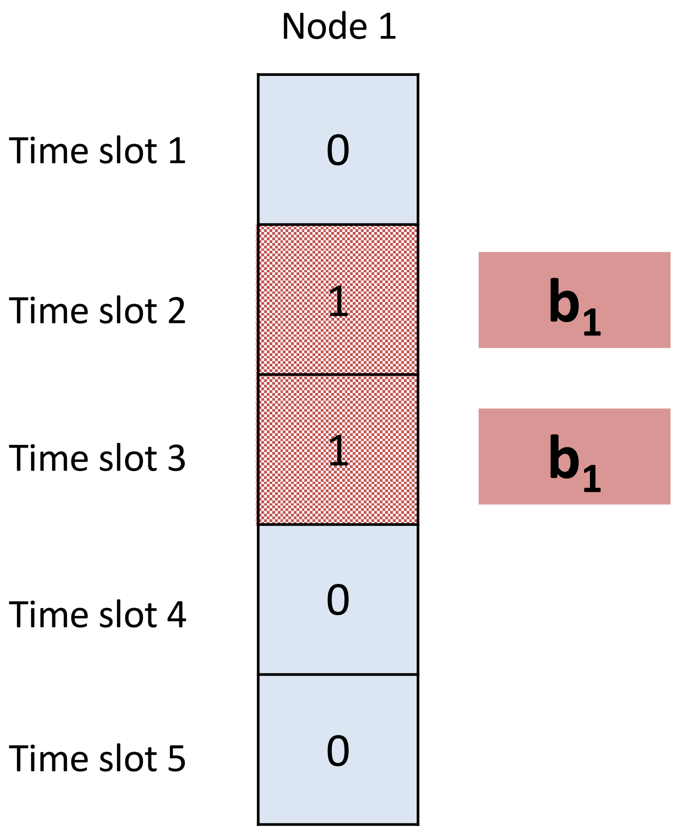
$y_1 = h_2\, b_2 + h_K\, b_K$

$y_2 = h_1\, b_1$

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

Collision as a Code

- Randomizing at each node
  - 1 => transmits message
  - 0 => remains silent



Collision as a Code

- Randomizing at each node
  - transmits message if 1, remains silent if 0

	Node 1	Node 2	Node 3	Node 4
Time slot 1	0	0	1	1
Time slot 2	1	0	1	0
Time slot 3	1	1	0	1
Time slot 4	0	1	1	0
Time slot 5	0	0	0	1

Collision as a Code

- Creating different linear combinations:

	Node 1	Node 2	Node 3	Node 4
Time slot 1	0	0	1	1
Time slot 2	1	0	1	0
Time slot 3	1	1	0	1
Time slot 4	0	1	1	0
Time slot 5	0	0	0	1

$y_1 = h_3\, b_3 + h_4\, b_4$

Collision as a Code

- Creating different linear combinations:

	Node 1	Node 2	Node 3	Node 4	
Time slot 1	0	0	1	1	$y_1 = h_3\, b_3 + h_4\, b_4$
Time slot 2	1	0	1	0	$y_2 = h_1\, b_1 + h_3\, b_3$
Time slot 3	1	1	0	1	
Time slot 4	0	1	1	0	
Time slot 5	0	0	0	1	

Collision as a Code

- Creating different linear combinations:

	Node 1	Node 2	Node 3	Node 4	
Time slot 1	0	0	1	1	$y_1 = h_3 b_3 + h_4 b_4$
Time slot 2	1	0	1	0	$y_2 = h_1 b_1 + h_3 b_3$
Time slot 3	1	1	0	1	$y_3 = h_1 b_1 + h_2 b_2 + h_4 b_4$
Time slot 4	0	1	1	0	$y_4 = h_2 b_2 + h_3 b_3$
Time slot 5	0	0	0	1	$y_5 = h_4 b_4$

Collision as a Code

- Creating different linear combinations:

Coding Matrix **D**

$$\mathbf{y} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \mathbf{H} \times \mathbf{b}$$

How to Decode?

- Received noisy symbols $\boldsymbol{y} = \boldsymbol{DHb} + \boldsymbol{n}$
- Possible solution: $\boldsymbol{b} = (\boldsymbol{DH})^{-1}\, \boldsymbol{y}$

$$\mathbf{y} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \end{bmatrix} \times \mathbf{H} \times \mathbf{b}$$

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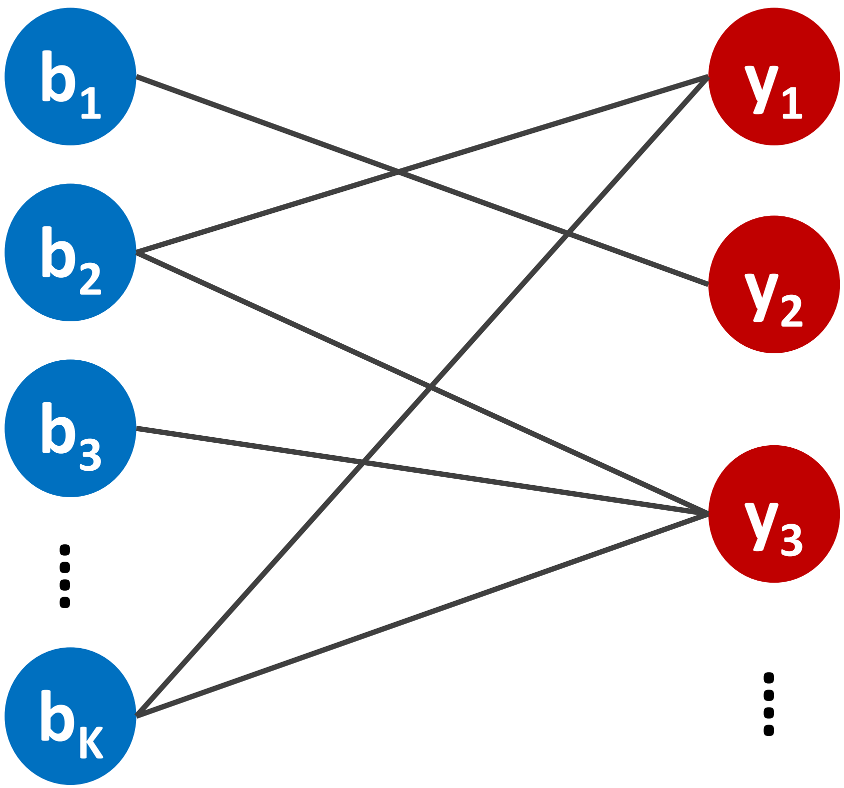
$$\mathbf{y} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \mathbf{H} \times \mathbf{b}$$

Too complex to invert $\boldsymbol{D}$ every time slot!

How Does the Reader Decode?

- Make code sparse → Leverage ideas from LDPC
- Each symbol is a collision of a small random subset of the nodes’ bits

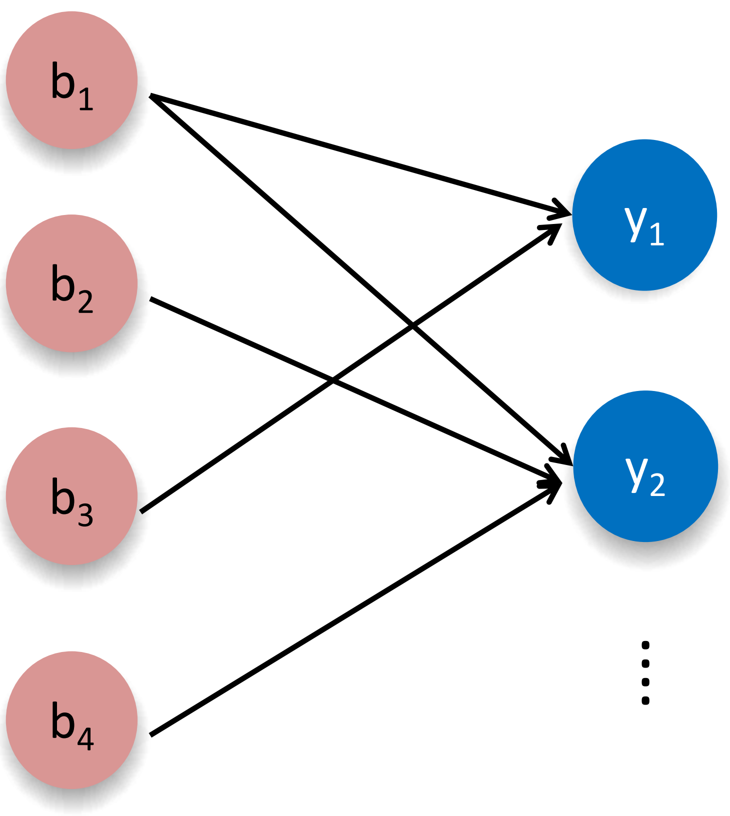


Belief Propagation enables the reader to decode quickly

- Received noisy symbols $\boldsymbol{y} = \boldsymbol{DHb} + \boldsymbol{n}$
- Find binary vector $\boldsymbol{b}$ that minimizes the deviation metric $E(\boldsymbol{b}) = \|\boldsymbol{DHb} - \boldsymbol{y}\|^2$
- Iterative Bit Flipping Decoder

Iterative Bit Flipping Example

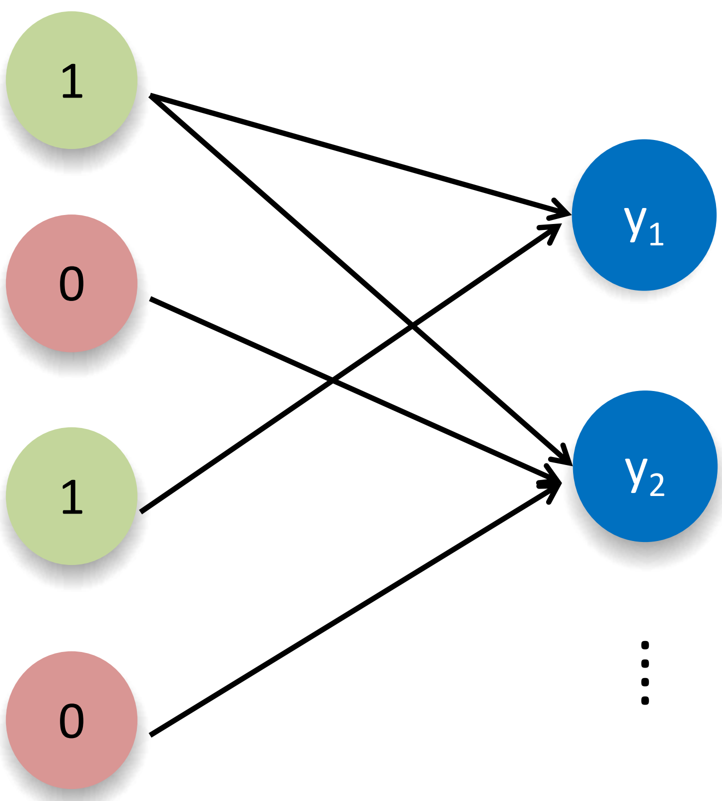
Example:



Iterative Bit Flipping Example

Example: Actual bits $\boldsymbol{b}$ = [1 0 1 0]

Channels $\boldsymbol{H}$ = [2 3 4 2]



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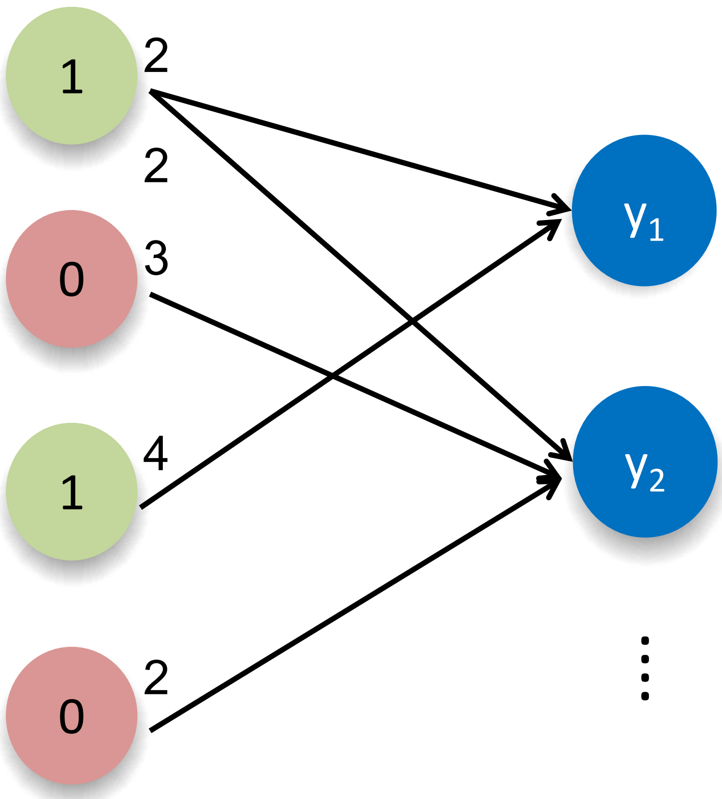
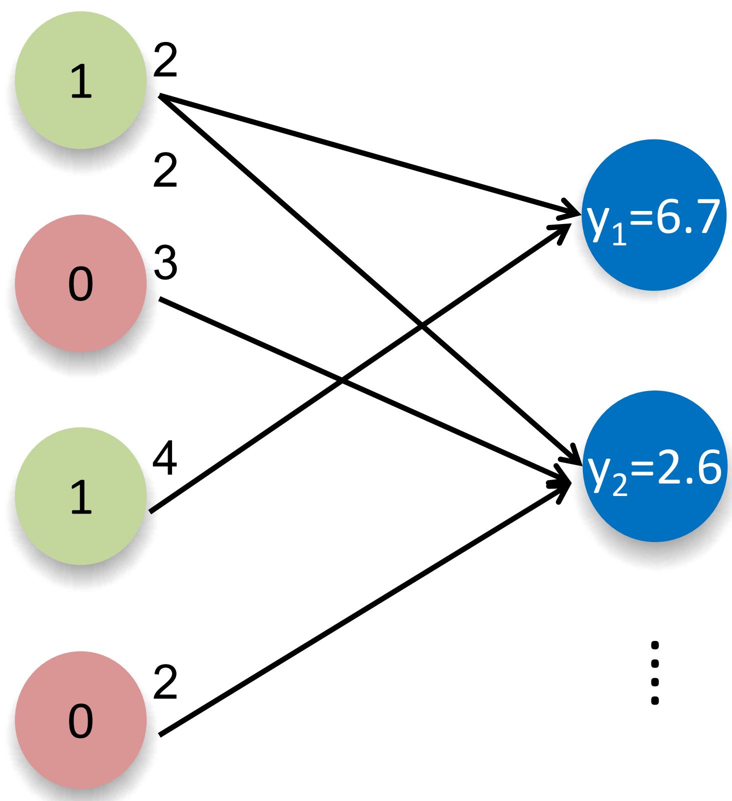


Iterative Bit Flipping Example

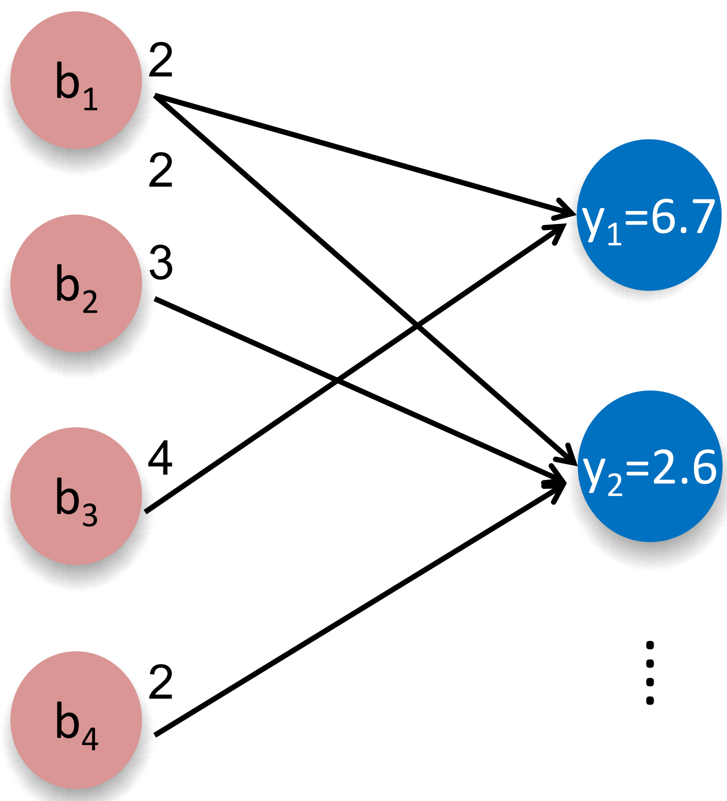
Example: Actual bits $\boldsymbol{b}$ = [1 0 1 0]

Channels $\boldsymbol{H}$ = [2 3 4 2]

Received noisy symbols $\boldsymbol{y}$ = [6.7 2.6]



Iterative Bit Flipping Decoder

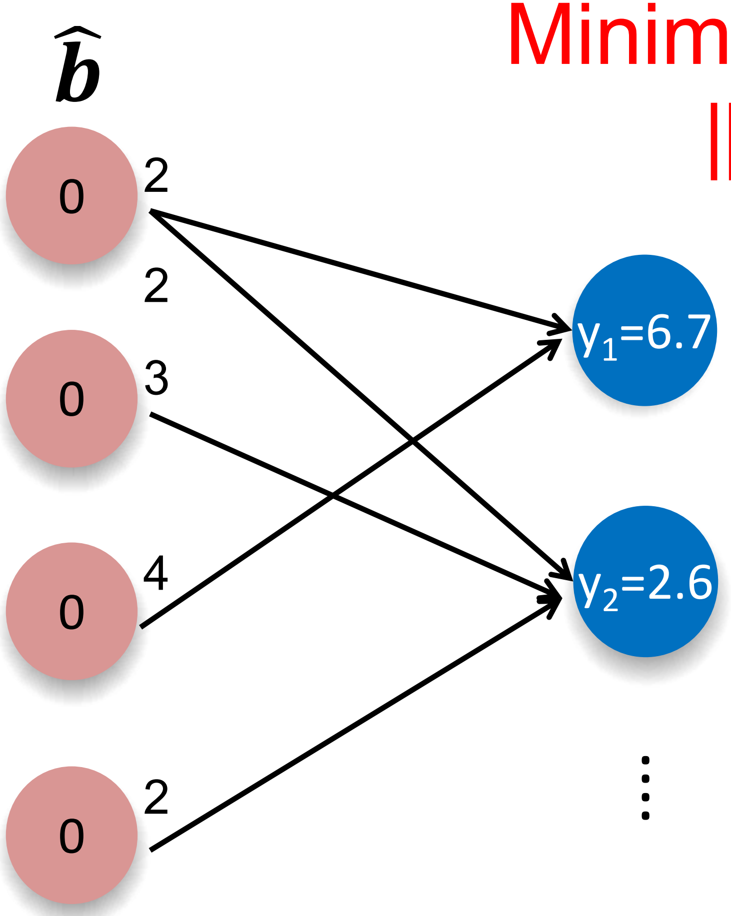


Iterative Bit Flipping Example

- Randomly initializing $\hat{\boldsymbol{b}}$

Minimize the $Error$

$\|\boldsymbol{y} - \hat{\boldsymbol{y}}\|^2$

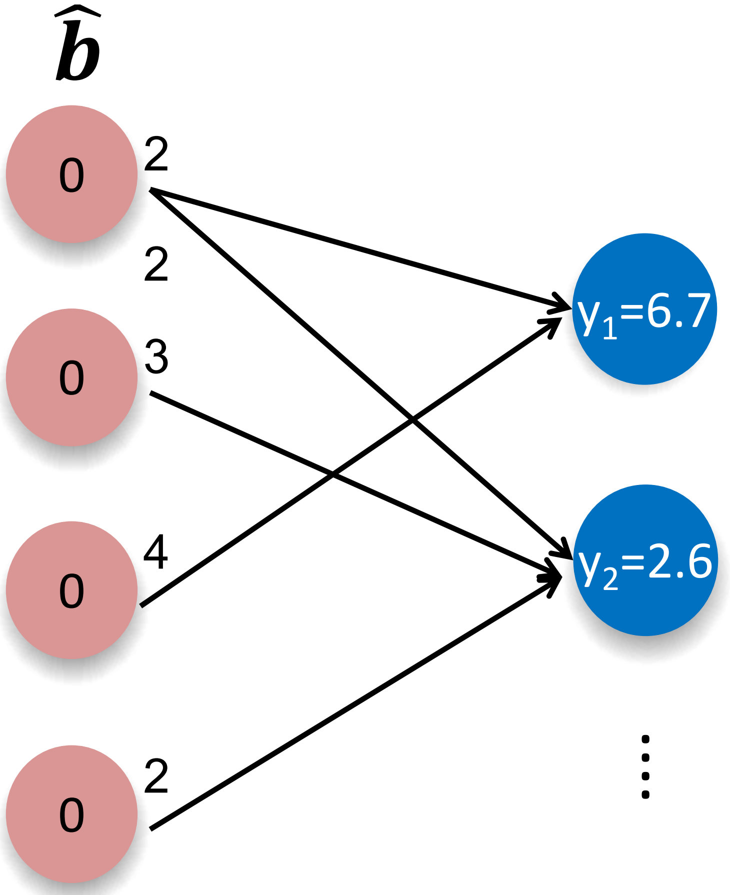


$\hat{y}_1 = 0$

$\hat{y}_2 = 0$

Iterative Bit Flipping Example

In what order should we flip the bits?



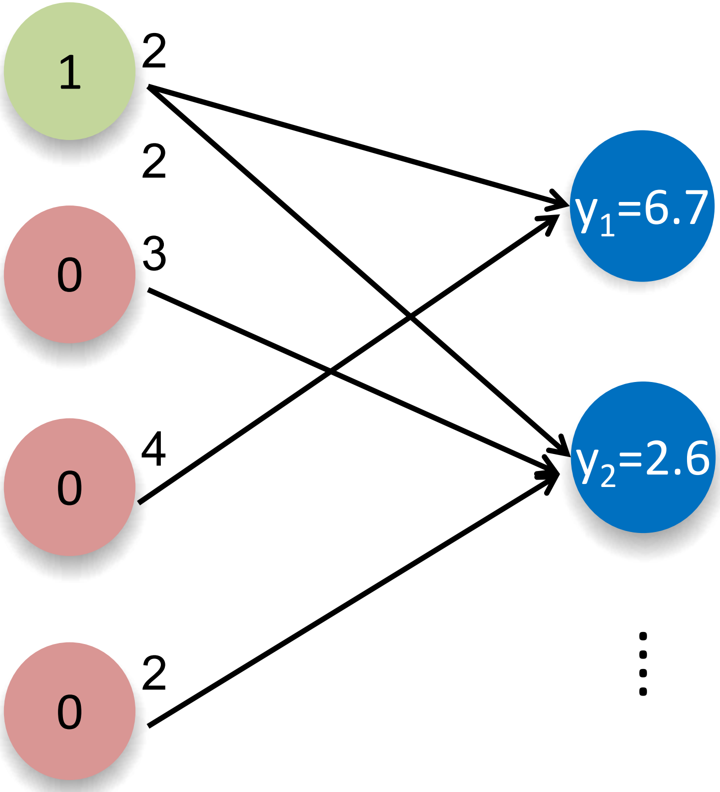
$\hat{y}_1 = 0$

$\hat{y}_2 = 0$

Iterative Bit Flipping Example

- If flipping bit 1

$\Delta Error$ **= -30**



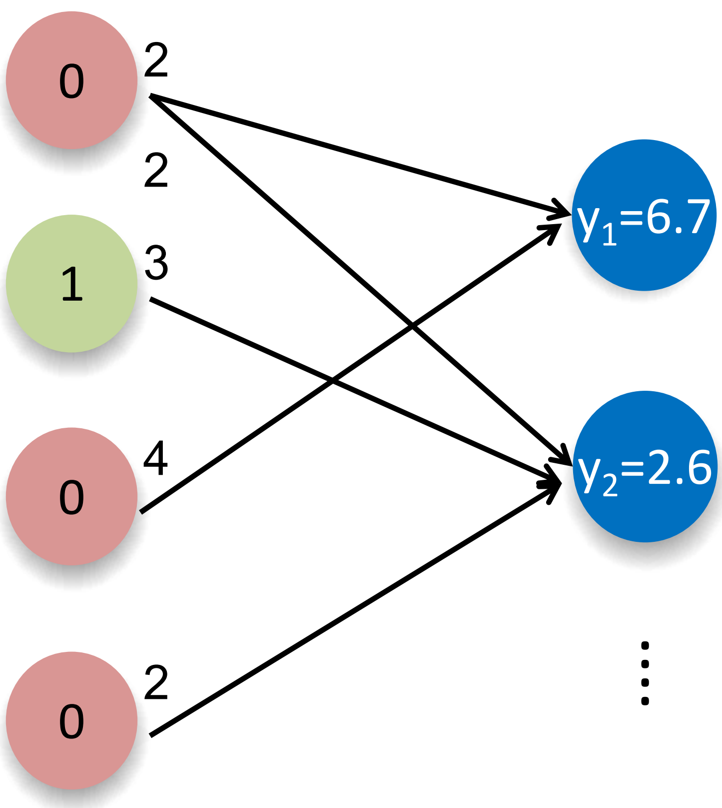
$\hat{y}_1 = 2$

$\hat{y}_2 = 2$

Iterative Bit Flipping Example

- If flipping bit 2

$\Delta Error$ **= -7**

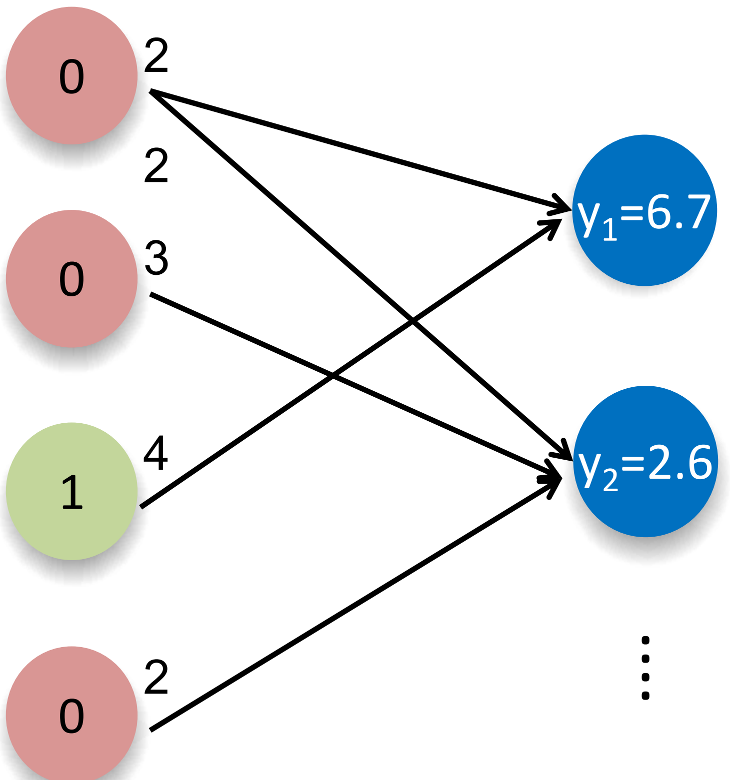


$\hat{y}_1 = 0$

$\hat{y}_2 = 3$

Iterative Bit Flipping Example

- If flipping bit 3



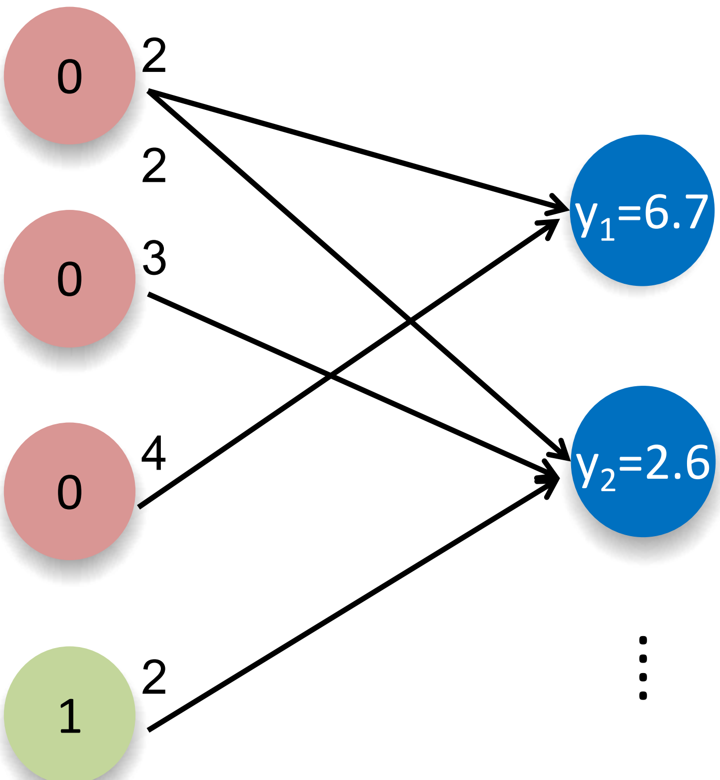
$\hat{y}_1 = 4$

$\hat{y}_2 = 0$

$\Delta Error$ **= -38**

Iterative Bit Flipping Example

- If flipping bit 4



$\hat{y}_1 = 0$

$\hat{y}_2 = 2$

$\Delta Error$ **= -7**

Iterative Bit Flipping Example

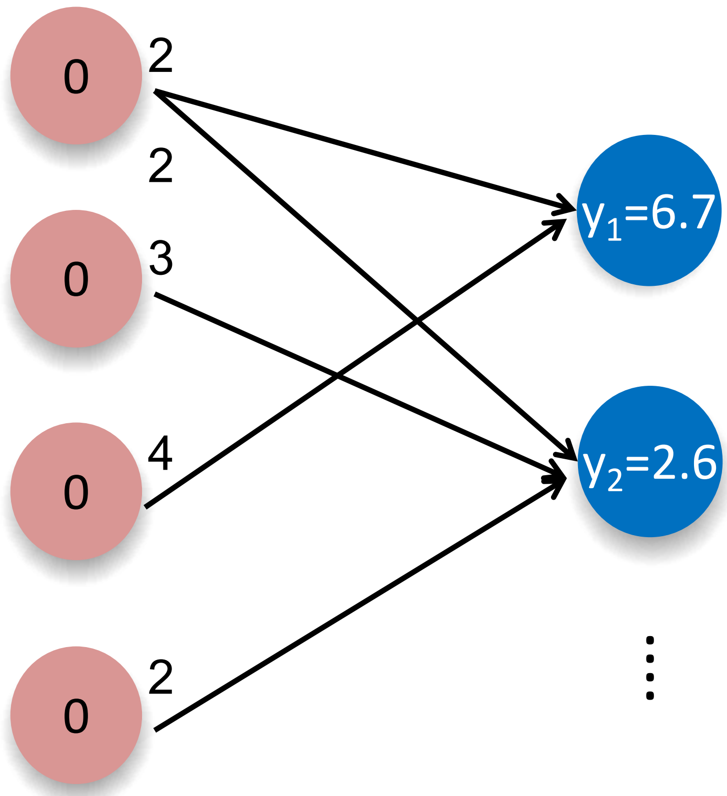
Flip bit that gives biggest reduction in Error

$\Delta Error$ = **-30**

$\Delta Error$ = **-7**

$\Delta Error$ = **-38**

$\Delta Error$ = **-7**



Iterative Bit Flipping Example

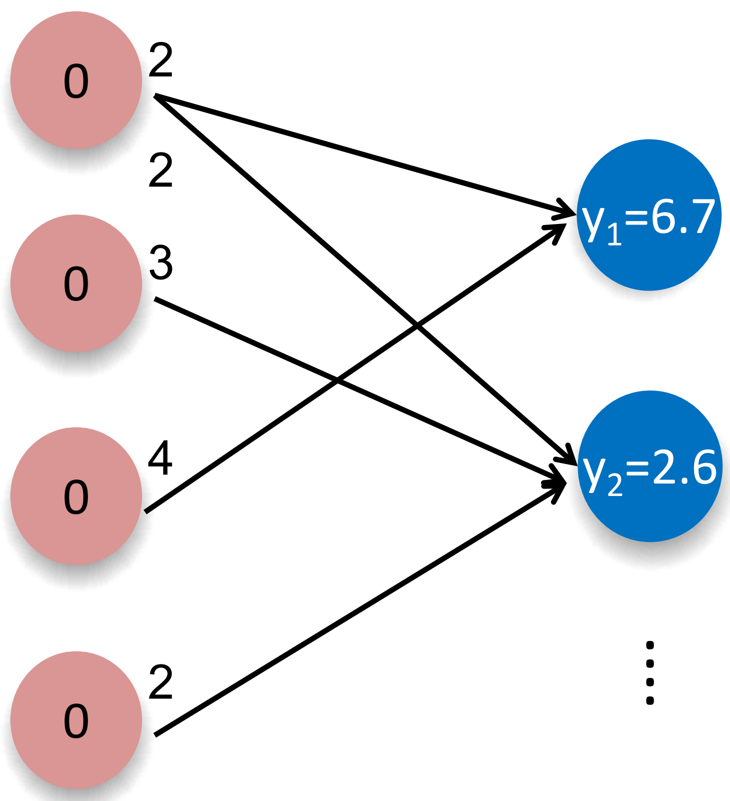
Flip bit that gives biggest reduction in Error

$\Delta Error$ = **-30**

$\Delta Error$ = **-7**

$\Delta Error$ = **-38**

$\Delta Error$ = **-7**



Iterative Bit Flipping Example

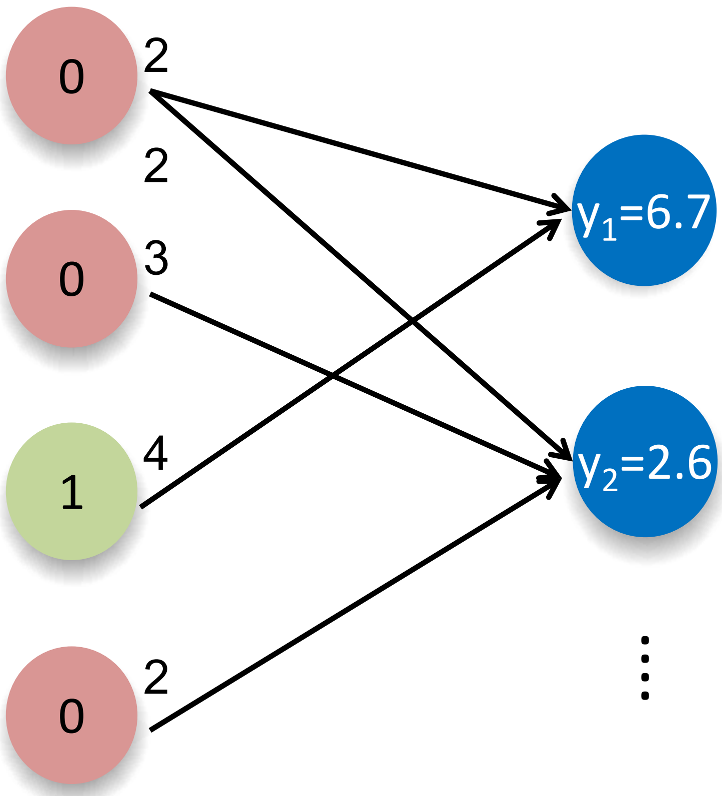
Flip bit that gives biggest reduction in Error

$\Delta Error$ = **-30**

$\Delta Error$ = **-7**

$\Delta Error$ = **-38**

$\Delta Error$ = **-7**



Iterative Bit Flipping Example

Flip bit that gives biggest reduction in Error

Minimize the $Error$

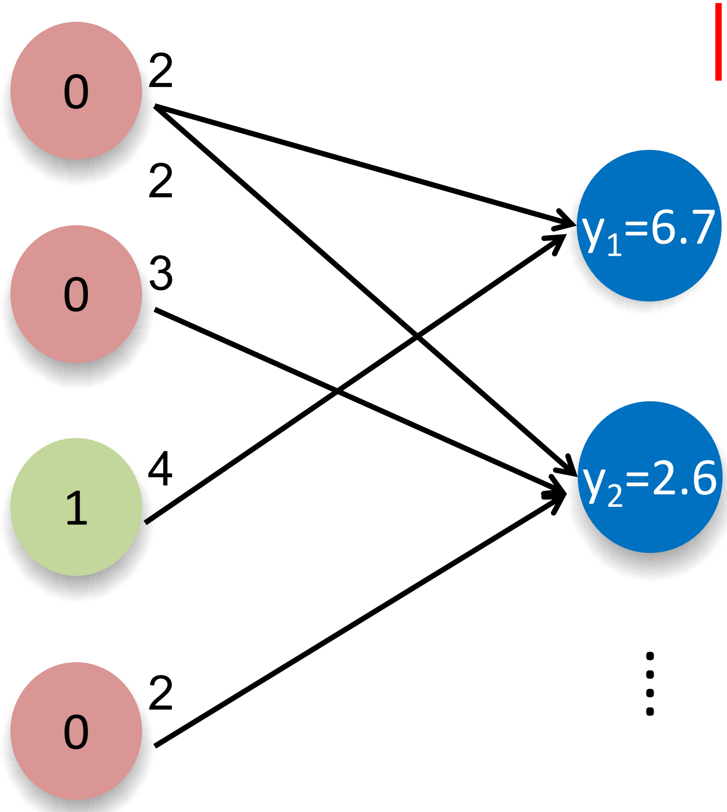
$\|\boldsymbol{y} - \hat{\boldsymbol{y}}\|^2$

$\Delta Error$ = **-30**

$\Delta Error$ = **-7**

$\Delta Error$ = **38**

$\Delta Error$ = **-7**



Iterative Bit Flipping Example

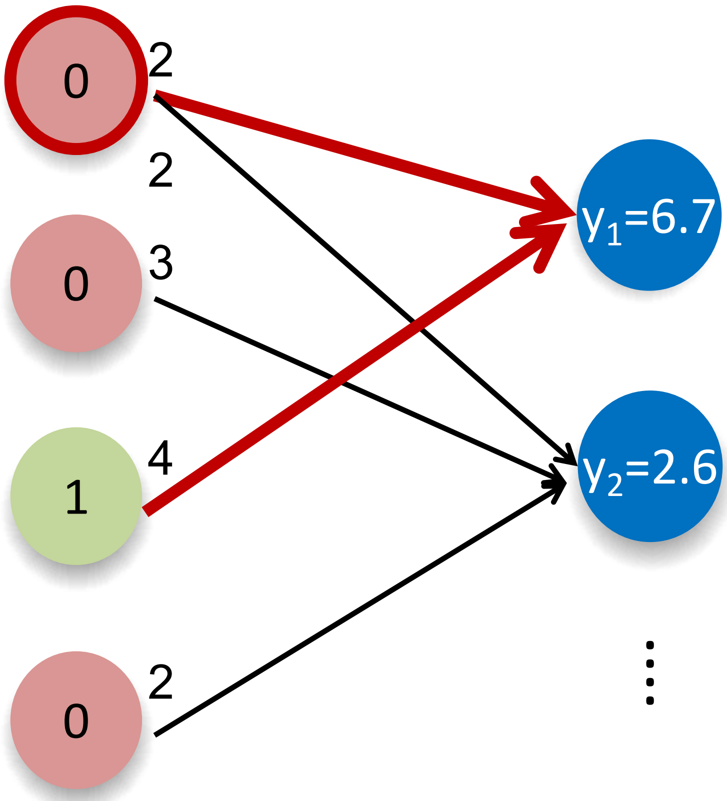
Update ΔE only for colliding nodes

$\Delta Error$ **= -30**

$\Delta Error$ **= -7**

$\Delta Error$ **= 38**

$\Delta Error$ **= -7**

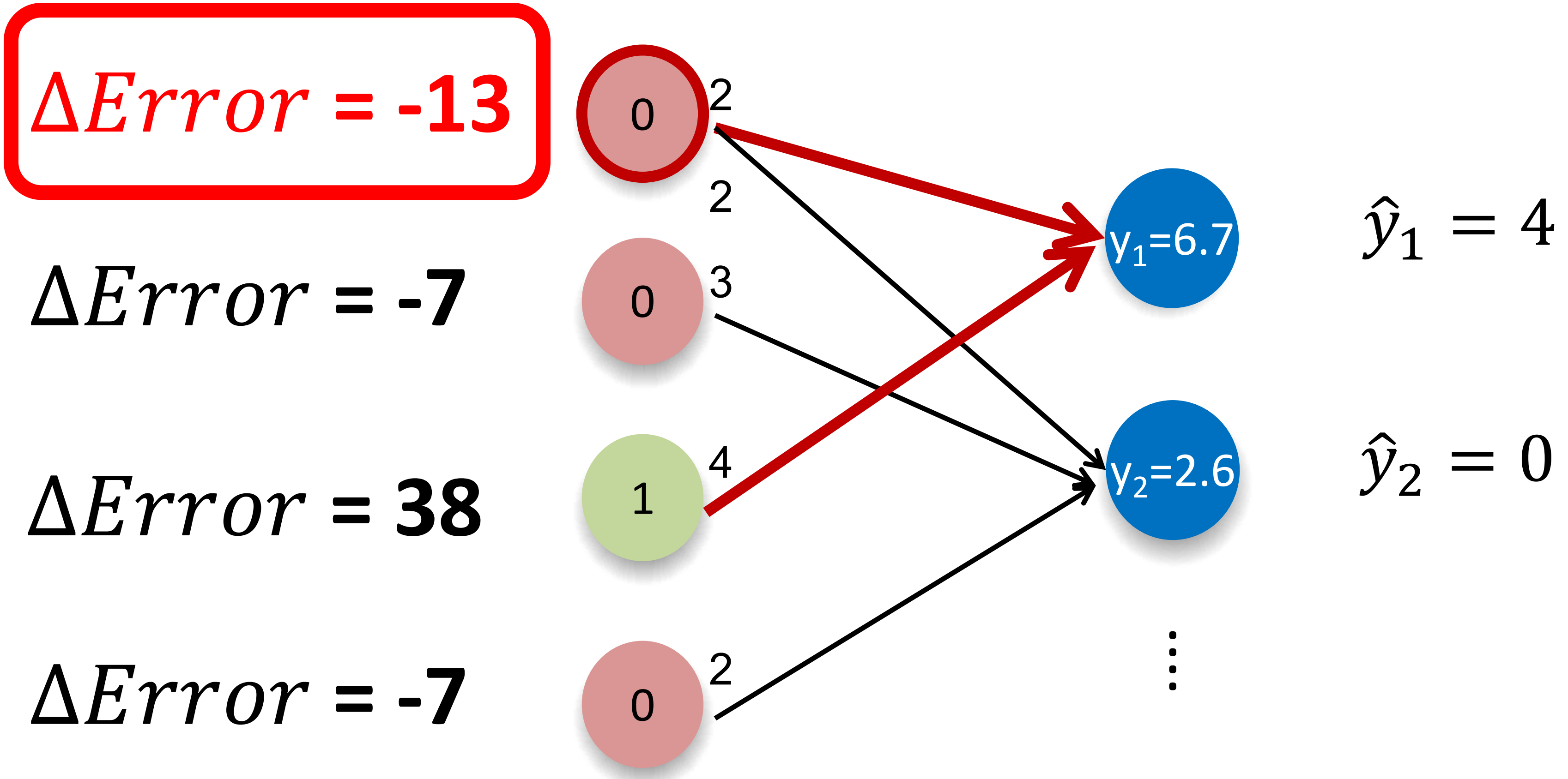


$\hat{y}_1 = 4$

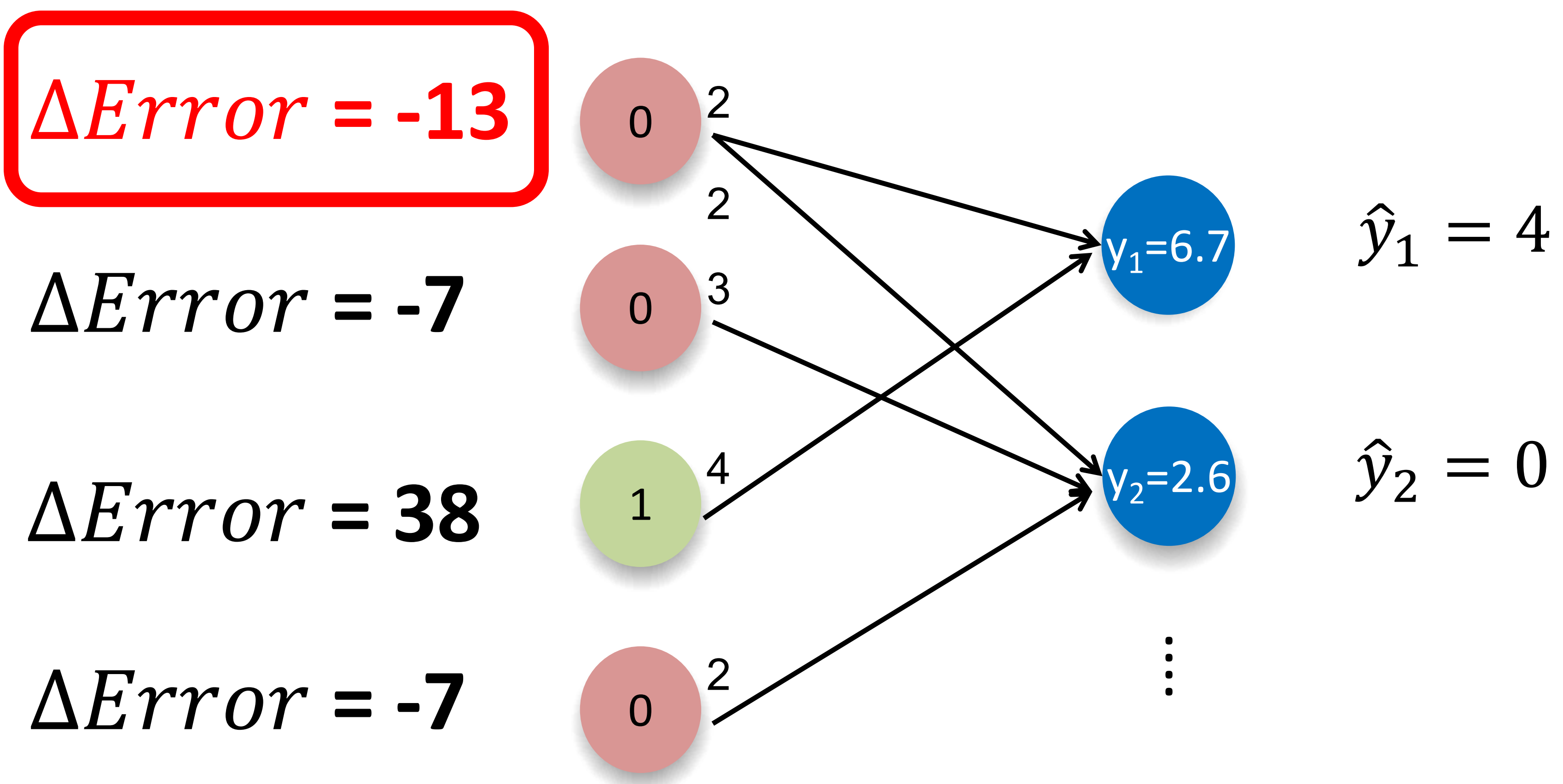
$\hat{y}_2 = 0$

Iterative Bit Flipping Example

Update ΔE only for colliding nodes



Iterative Bit Flipping Example



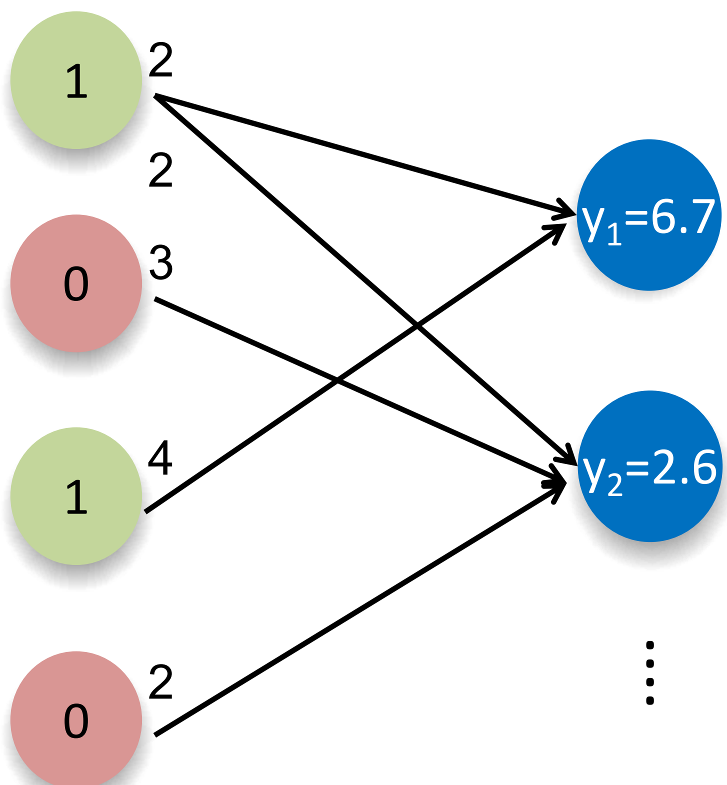
Iterative Bit Flipping Example

$\Delta Error$ **= 13**

$\Delta Error$ **= -7**

$\Delta Error$ **= 38**

$\Delta Error$ **= -7**

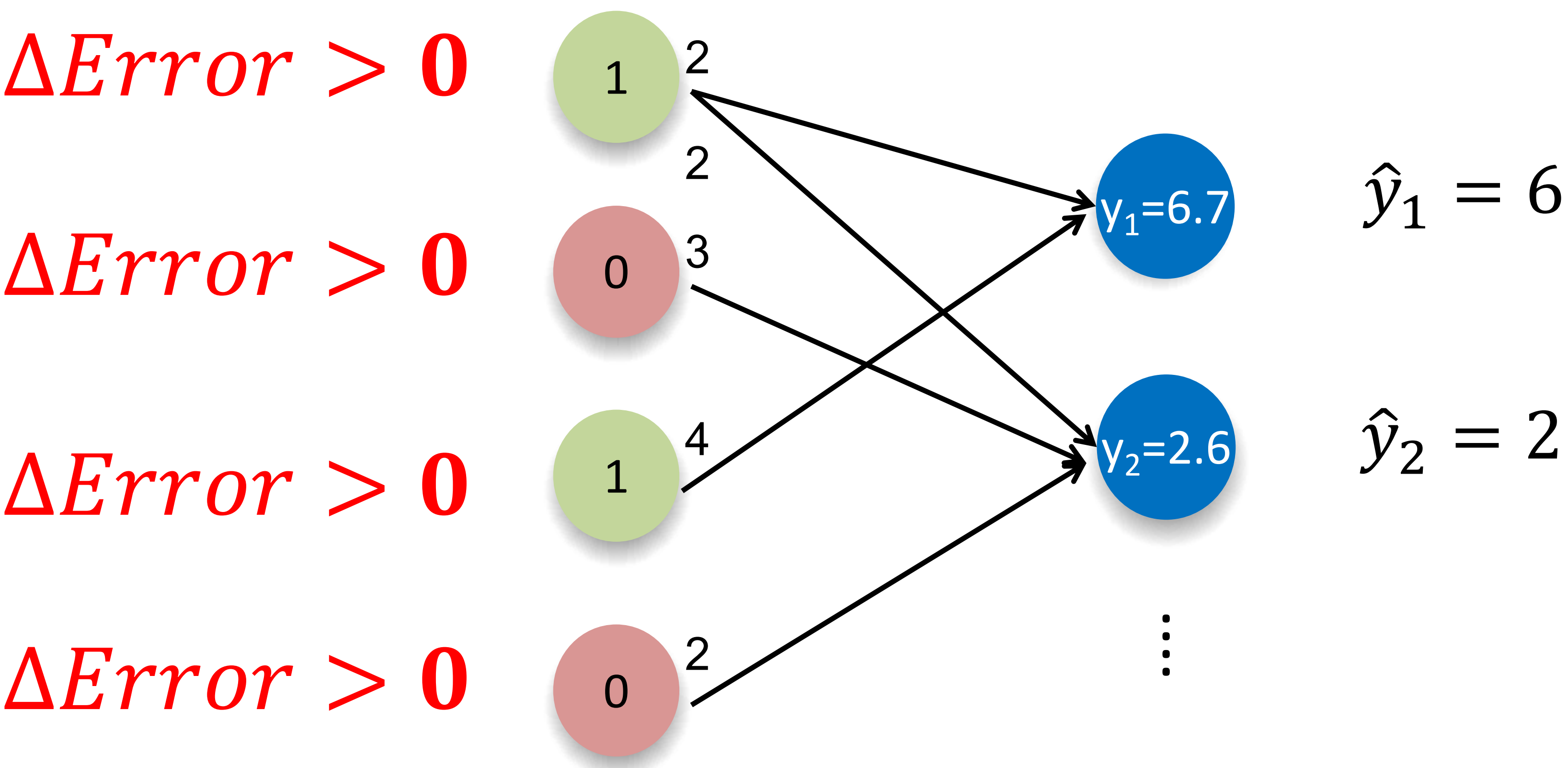


$\hat{y}_1 = 6$

$\hat{y}_2 = 2$

Iterative Bit Flipping Example

- No further reduction in $Error$ => Terminates
- $\hat{\boldsymbol{b}} = [\,1\;0\;1\;0] = \boldsymbol{b}$ (actual bits)

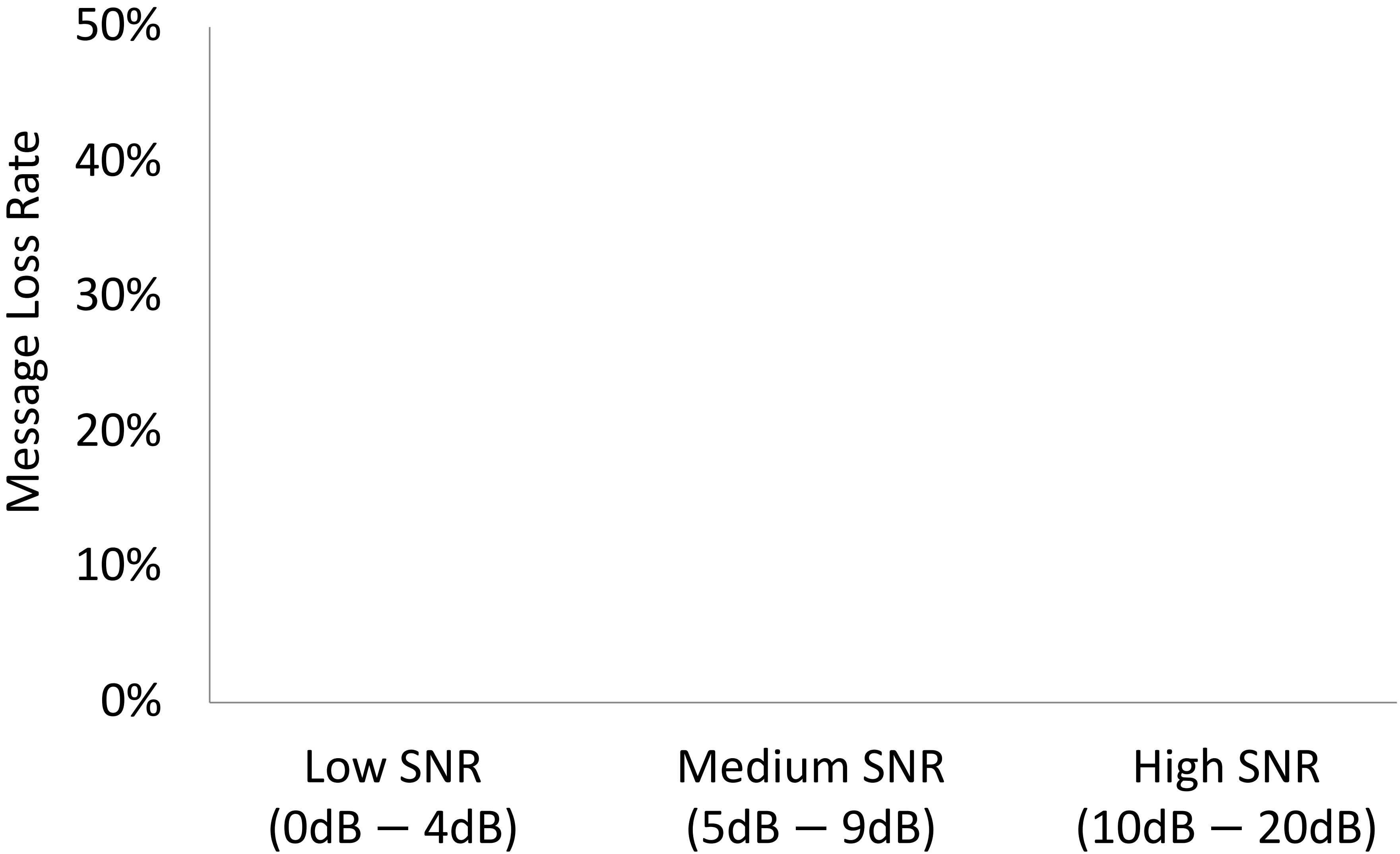


Evaluate Data Communication

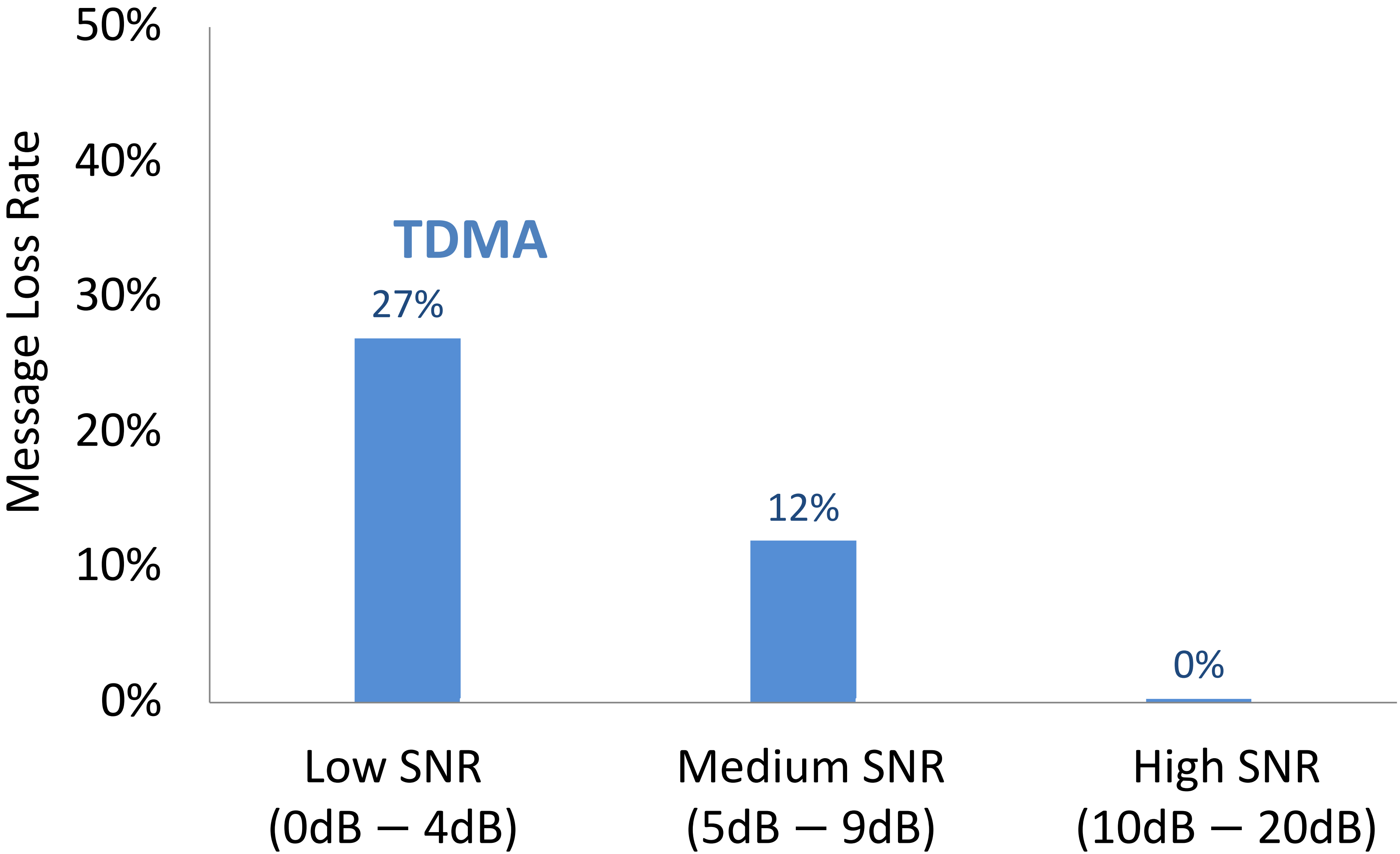
Compared schemes

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

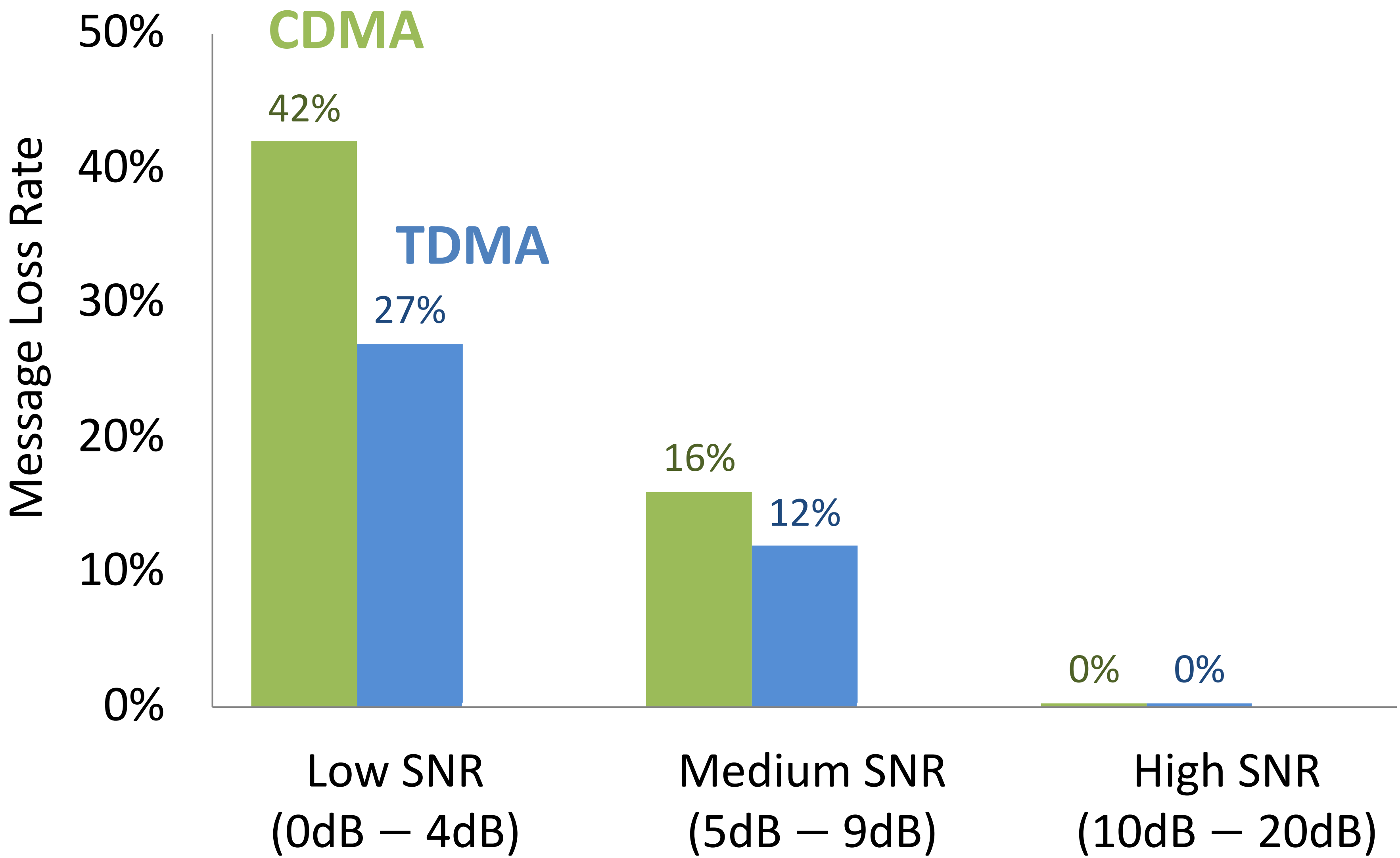
Reliability



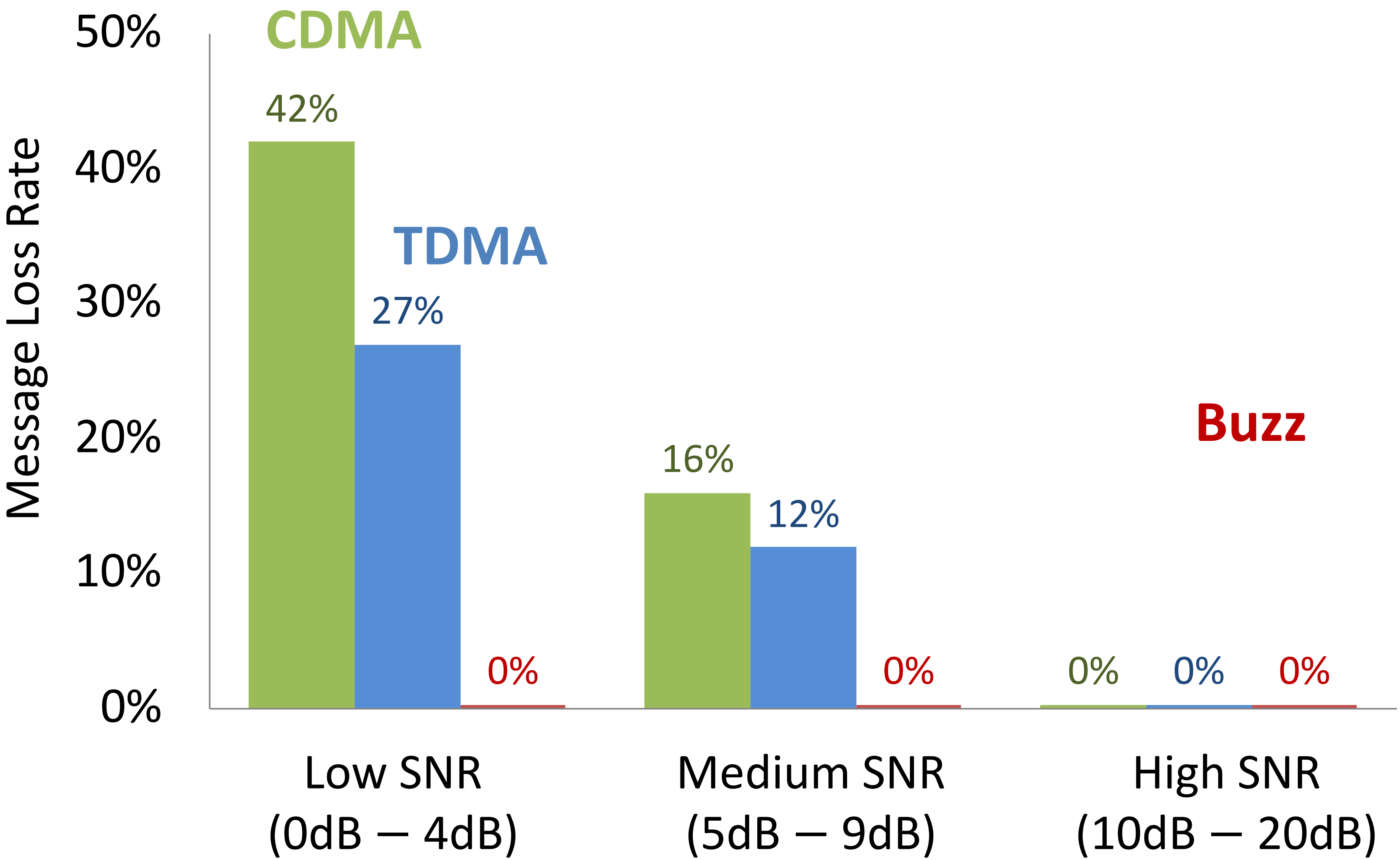
Reliability



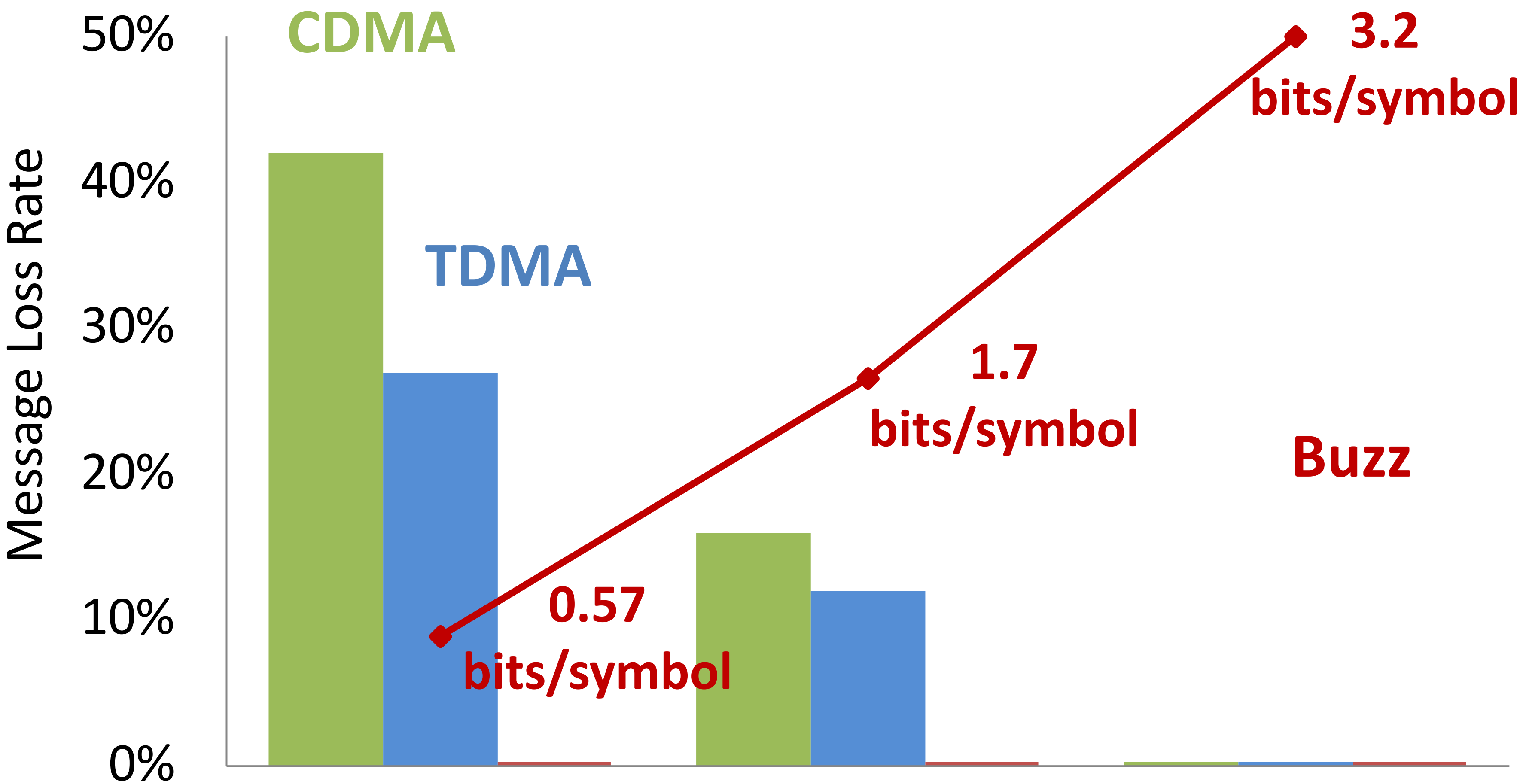
Reliability



Reliability



Reliability



Network as a node adapts bit rate to eliminate message loss

Evaluation Platforms

- RFID tag: passive stickers

Research Platforms

- RFID tag: computational RFIDs

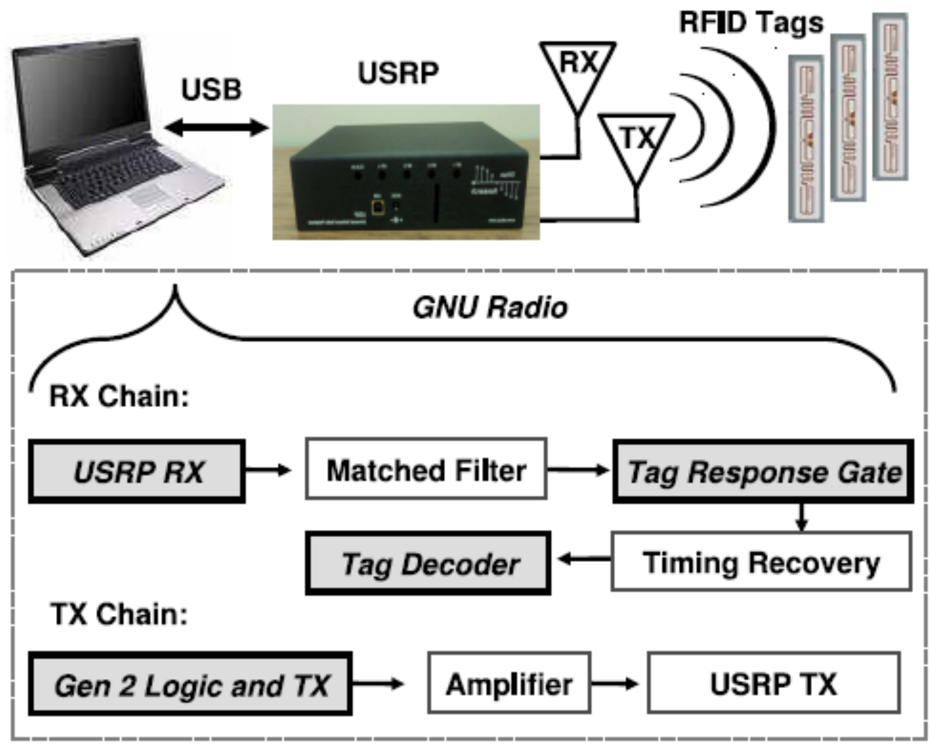
- MSP430 Microcontroller
  - 8KB RAM + 116KB Flash + 12 bit ADC/DAC
- Sensors:
  - Accelerometer + temperature + voltage + external sensors

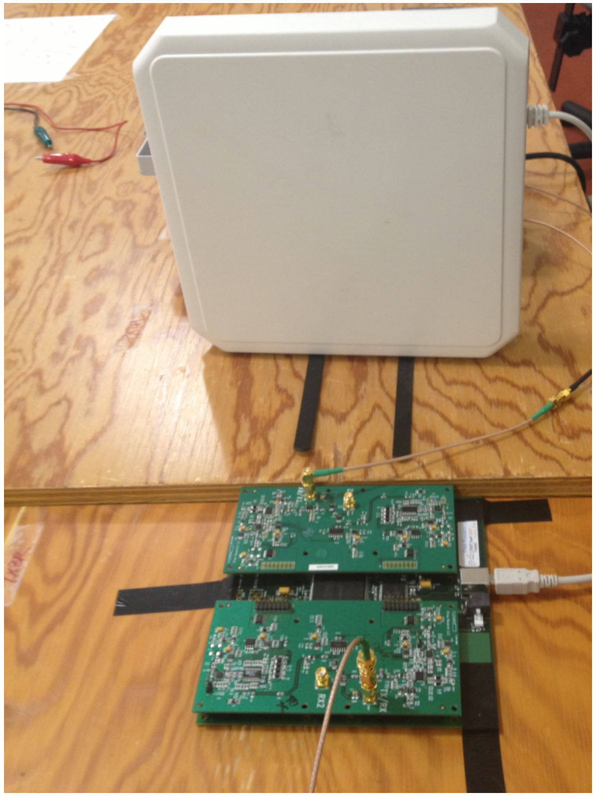
Research Platforms

- Reader: Think magic/Impinj

Research Platforms

- Reader: software radio based Gen-2 reader





Conclusion

- Many applications for low power networks.
- Nodes need to be very simple (low cost, low power) → cannot have advanced functionalities
- Need new research ideas that can enable advanced protocol.
- What would you do if I give you so many RFIDs?