Reliable and Efficient Backscatter Communication

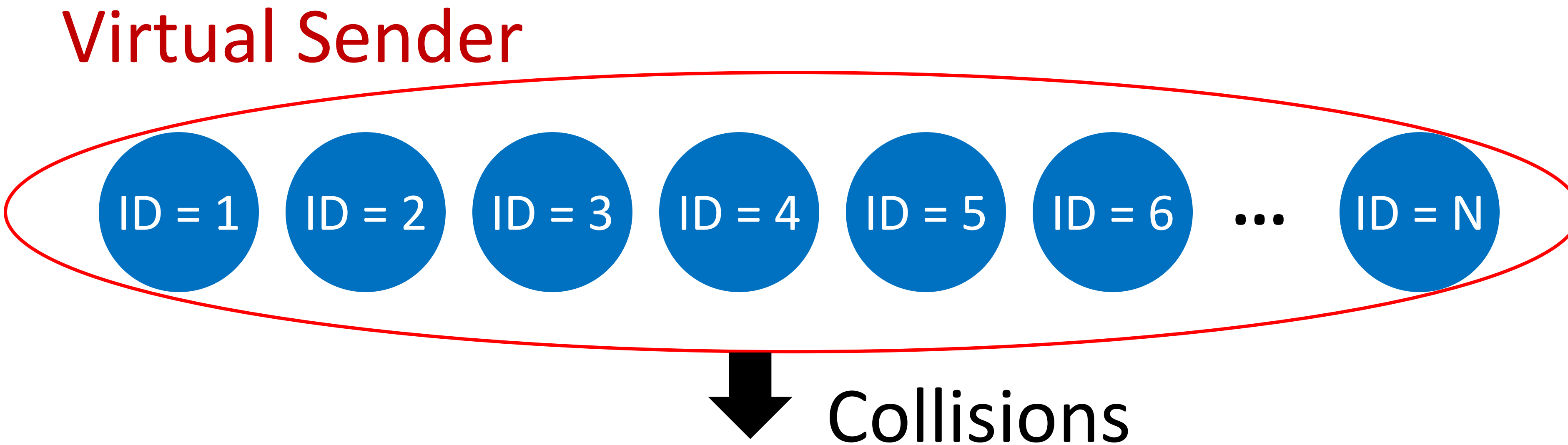
6.829, Lecture 10

Massachusetts Institute of Technology

Problems Addressed in Buzz

- RFID nodes cannot hear each other → collisions and inefficiency
- RFIDs do not adapt their bit rate to the channel
  - If the channel is good they do not increase the rate to transmit more bits
  - If the channel is bad, they do not decrease the rate
    - If the channel is really bad, they cannot decrease the bit rate below one bit per symbol

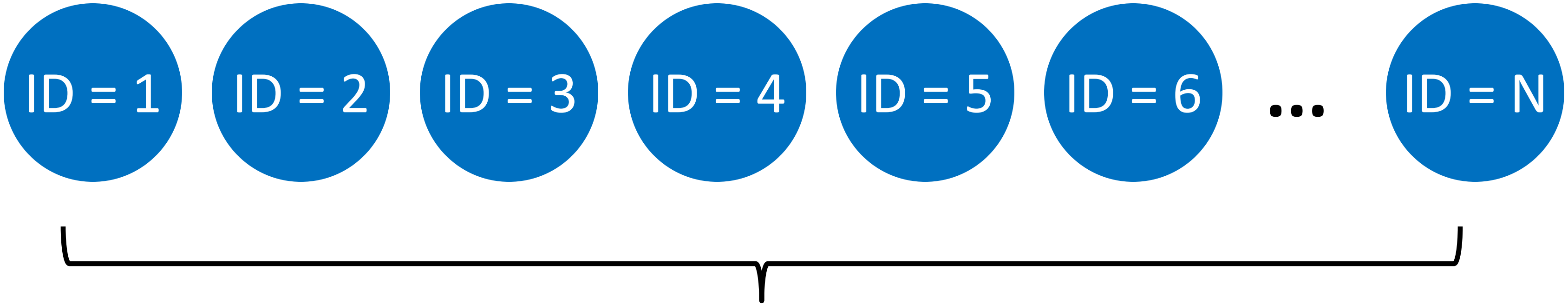
Network As a Node



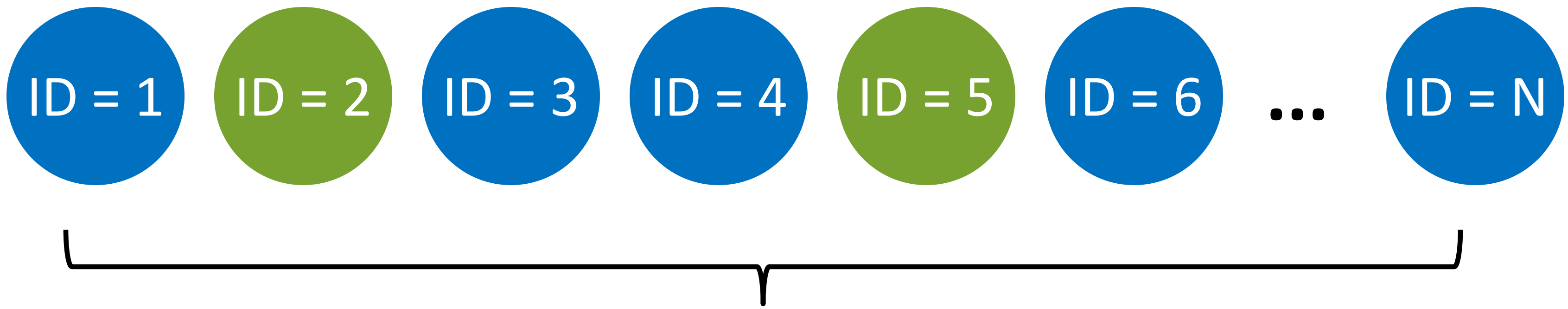
Collision becomes a code across the virtual sender's bits

- Deals with collision by decoding collision-code
- Adapts the rate by making collision-code rateless (i.e., if channel is good decode from fewer collisions)

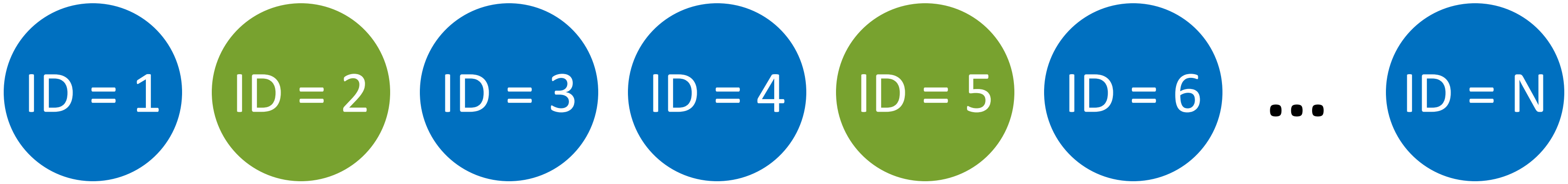
How can network-as-a-node help decode collisions?



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

vector $\mathbf{x}$

0	1	0	0	1	0	…	0

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 x and send it

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 $e^{-2\pi jft/N}$
- 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 $\boldsymbol{y}$

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

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

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

Network can mix information using Collisions

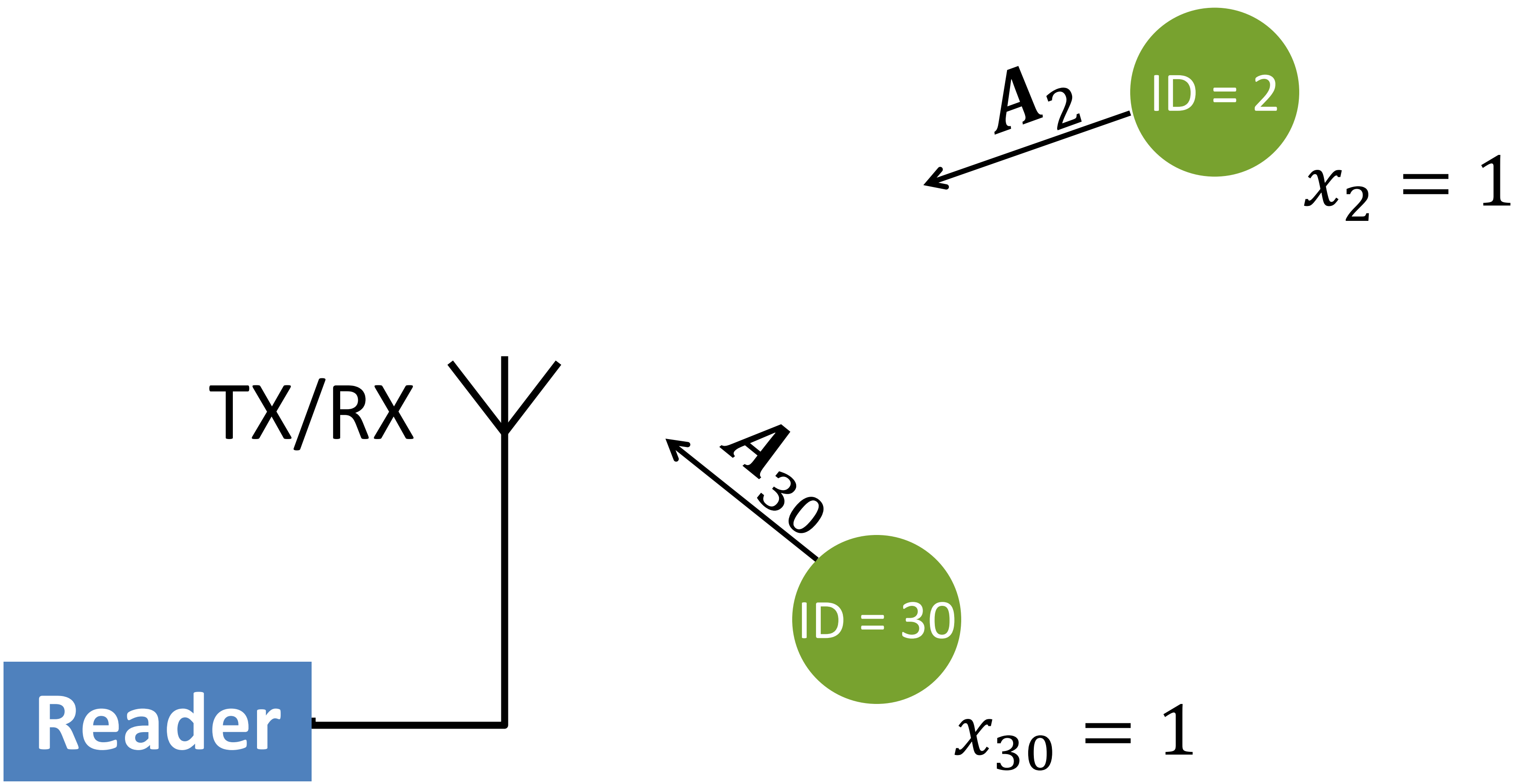
Network Compressive Sensing Using Collisions

$$\begin{array}{c} \\ \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \end{array} = \begin{array}{c} \begin{array}{cccccc} \boldsymbol{A}_1 & \boldsymbol{A}_2 & \boldsymbol{A}_3 & \boldsymbol{A}_4 & & \boldsymbol{A}_N \end{array} \\ \begin{bmatrix} 0 & 1 & 1 & 1 & & 0 \\ 0 & 0 & 1 & 0 & \cdots & 1 \\ 1 & 1 & 1 & 0 & & 1 \end{bmatrix} \end{array} \times \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix}$$

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 $\boldsymbol{y}$

In reality there are channels

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

Can network-as-a-node help adapt the bit rate?

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

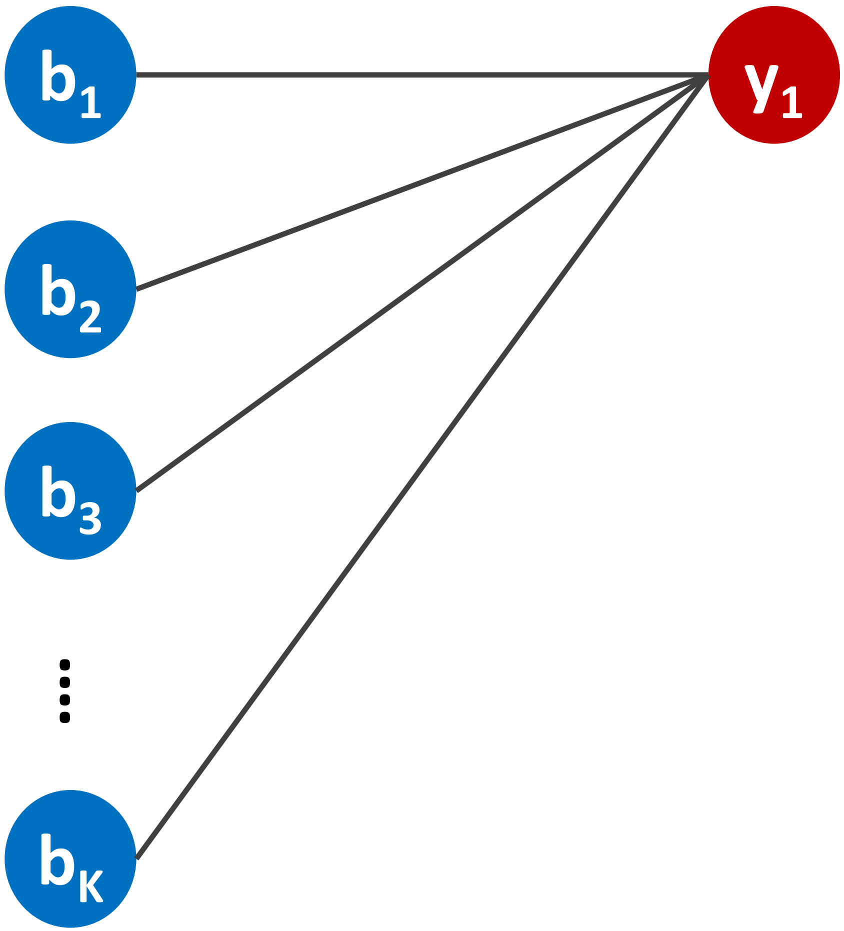
Network-Based Rate Adaptation

- 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

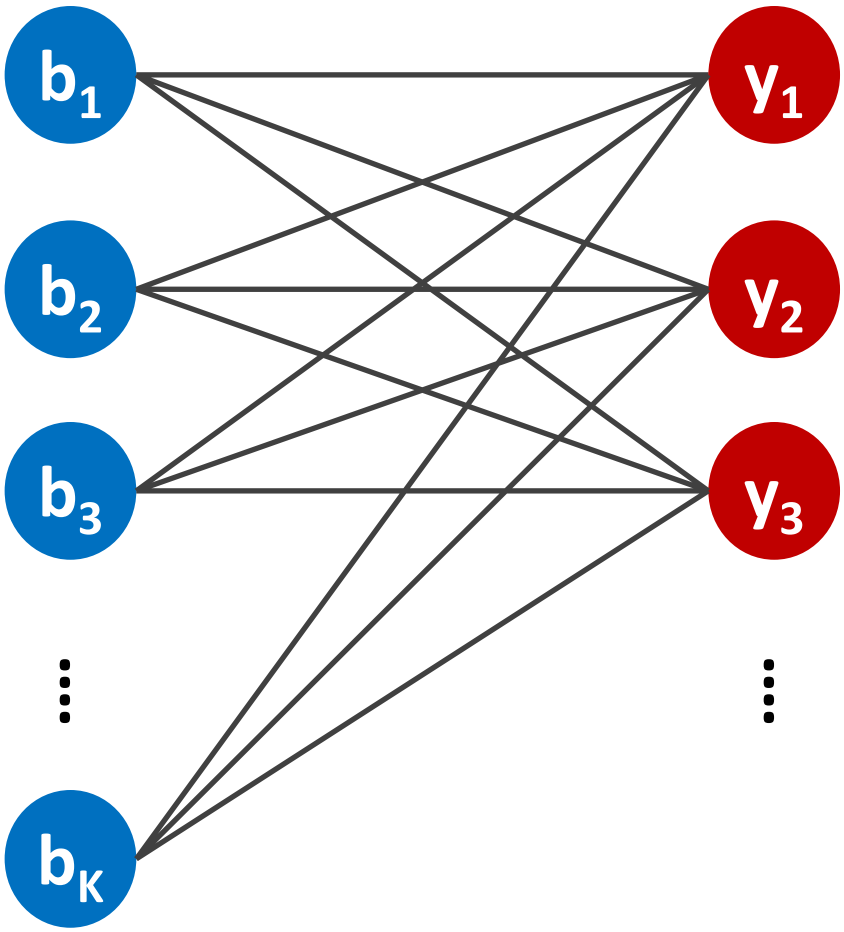
Collisions naturally act like a linear code



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

But simply colliding is not a good code

Repetition Code → Bad Code!



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

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

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

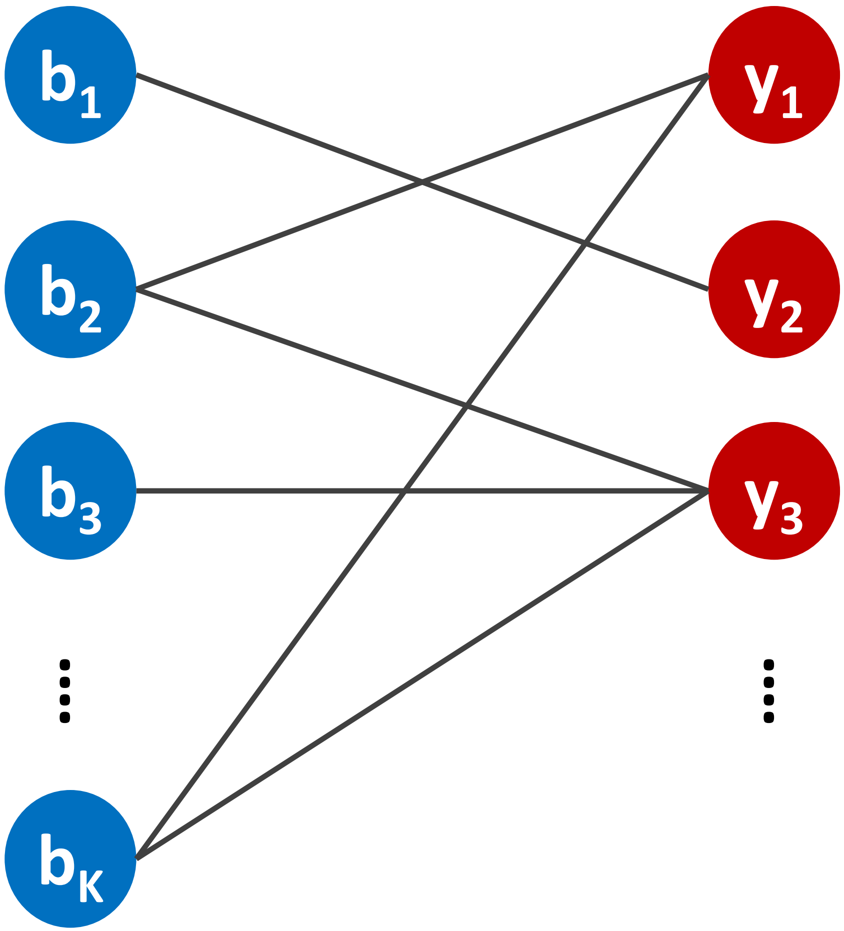
A good code for RFIDs

- ✓ 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"



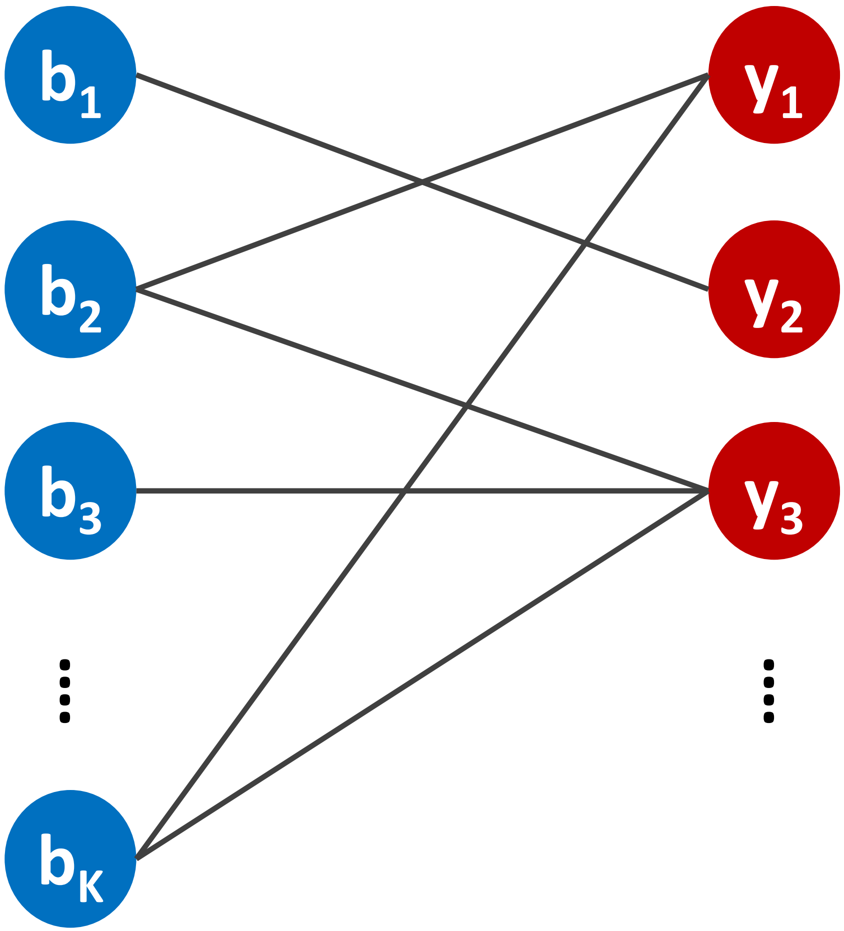
$y_1 = h_2\, b_2 + h_K\, b_K$

$y_2 = h_1\, b_1$

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

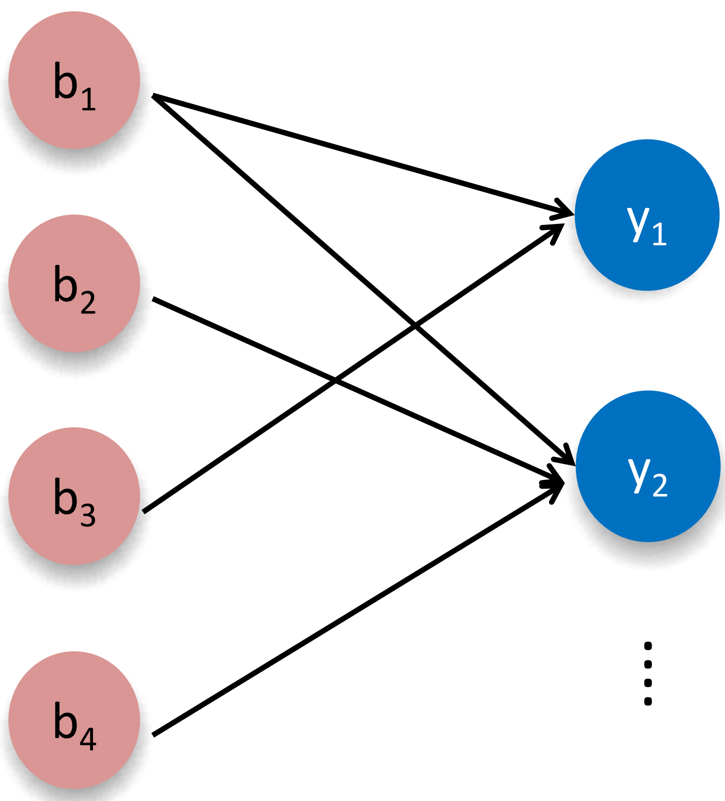
How Does the Reader Decode?

Sparse Code → Iterative Bit Flipping Decoder



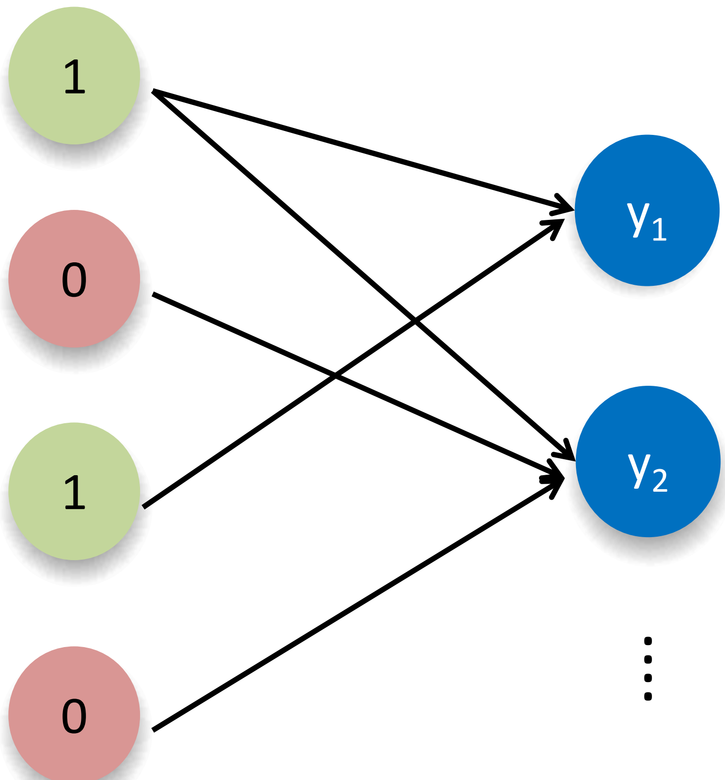
Iterative Bit Flipping Decoder

Example:



Iterative Bit Flipping Decoder

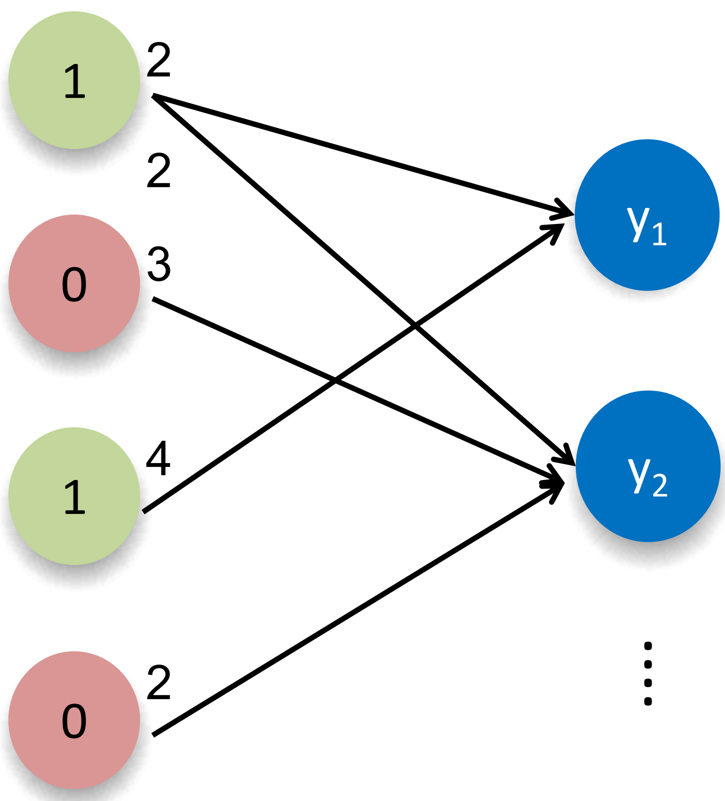
Example: Actual bits $\boldsymbol{b}$ = [1 0 1 0]



Iterative Bit Flipping Decoder

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

Channels $\boldsymbol{DH}$= [2 3 4 2; 2 0 0 0]

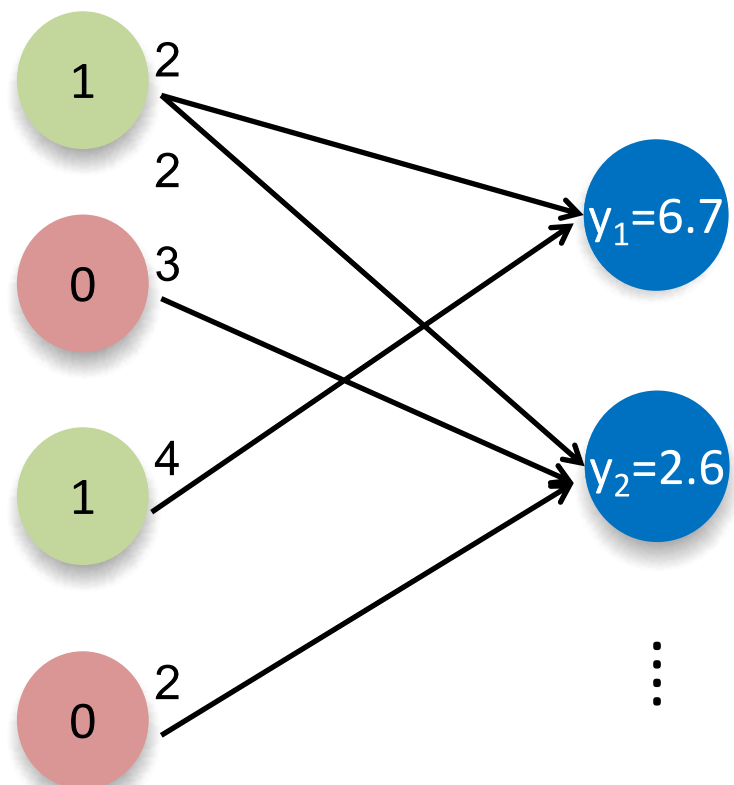


Iterative Bit Flipping Decoder

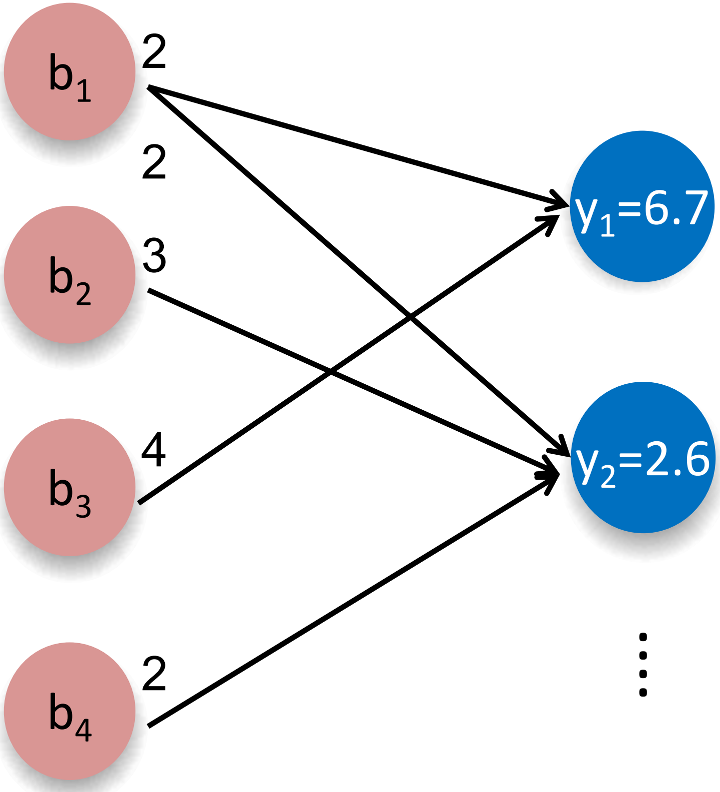
Example: Actual bits $\boldsymbol{b}$ = [1 0 1 0]

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

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

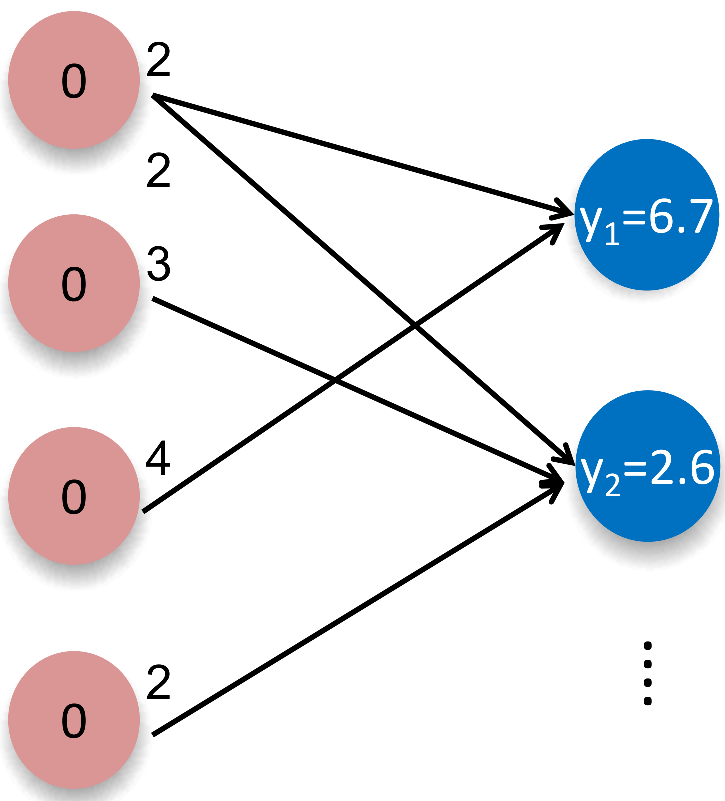


Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$



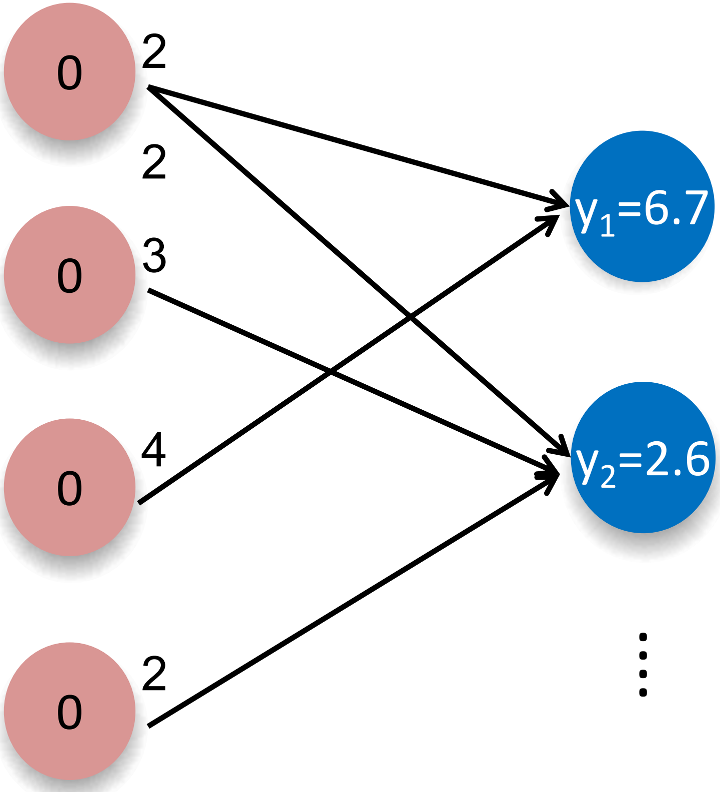
Minimizing $E(\widehat{b}) = \|DH\widehat{b} - y\|^2$

- Randomly initializing $\widehat{\boldsymbol{b}} = [\mathbf{0\ 0\ 0\ 0}]$



Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

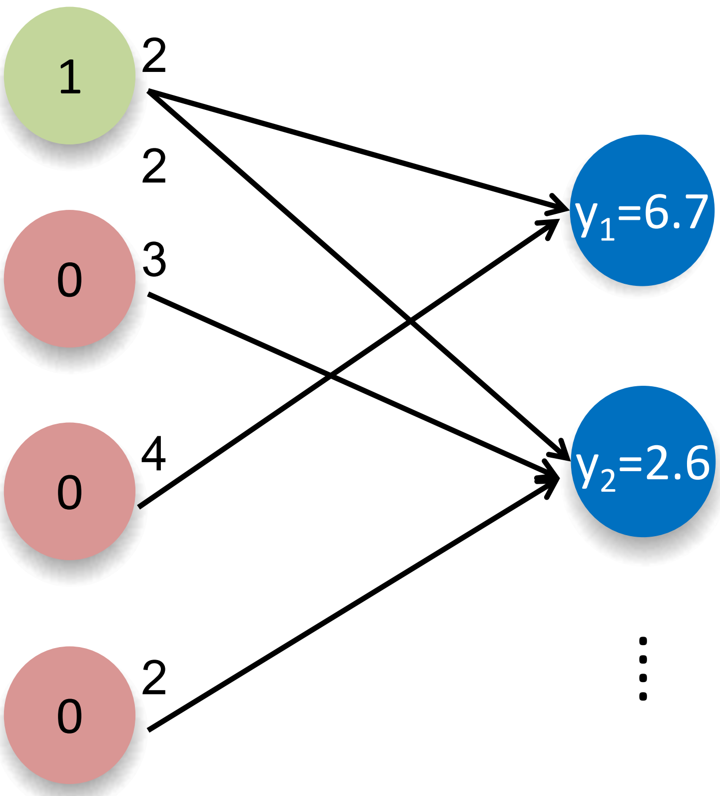
- Currently $E \approx 52$



Minimizing $E(\widehat{b}) = \|DH\widehat{b} - y\|^2$

- Currently $E \approx 52$

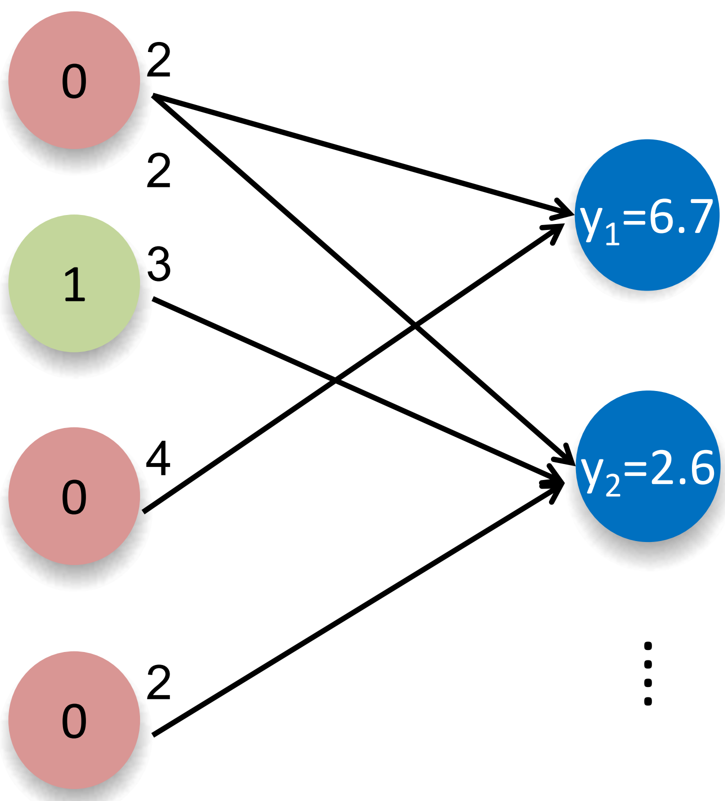
ΔE = 29.2



Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

- Currently $E \approx 52$

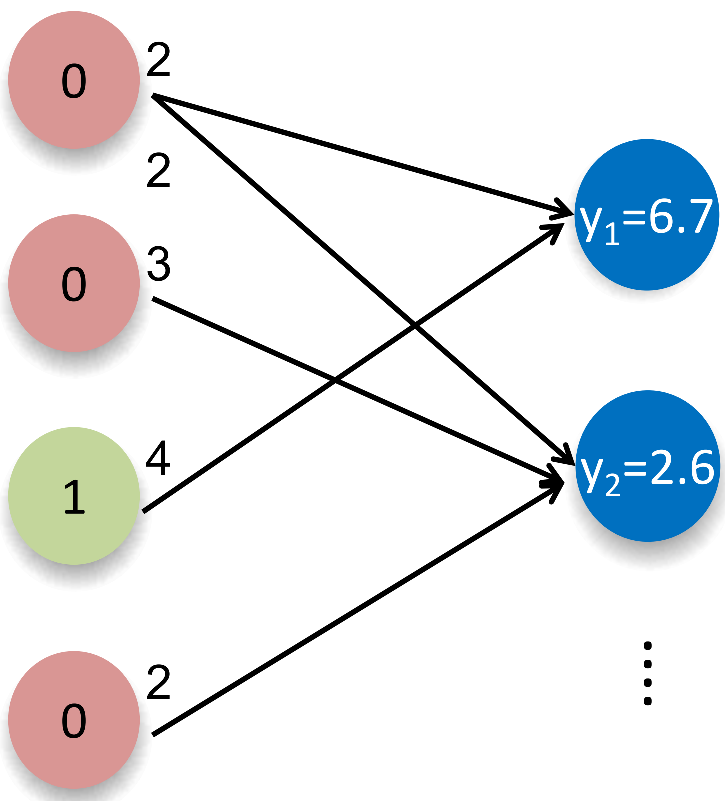
ΔE = 6.6



Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

- Currently $E \approx 52$

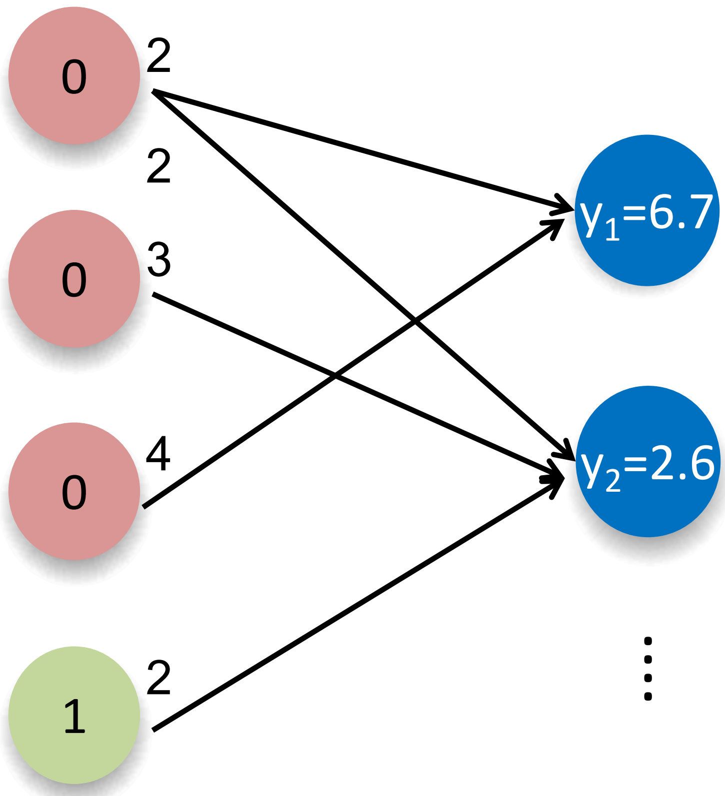
ΔE = 37.6



Minimizing $E(\widehat{b}) = \|DH\widehat{b} - y\|^2$

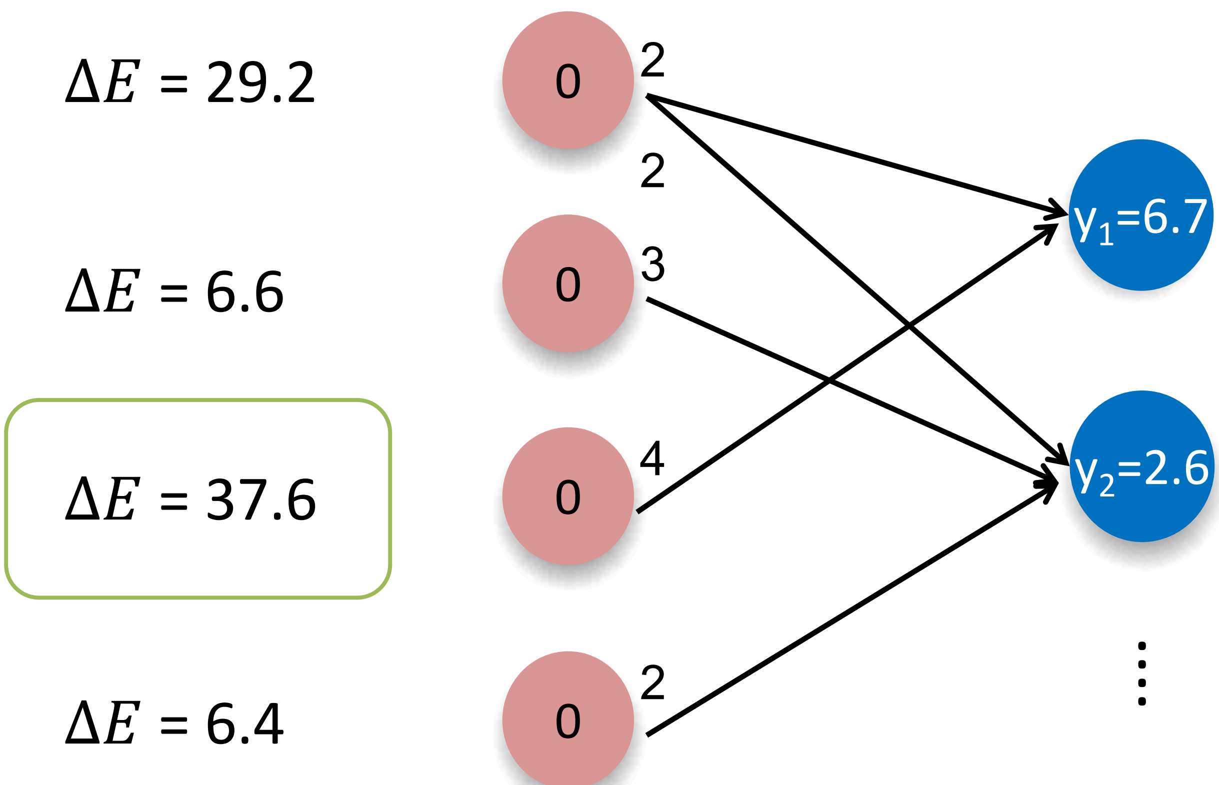
- Currently $E \approx 52$

ΔE = 6.4



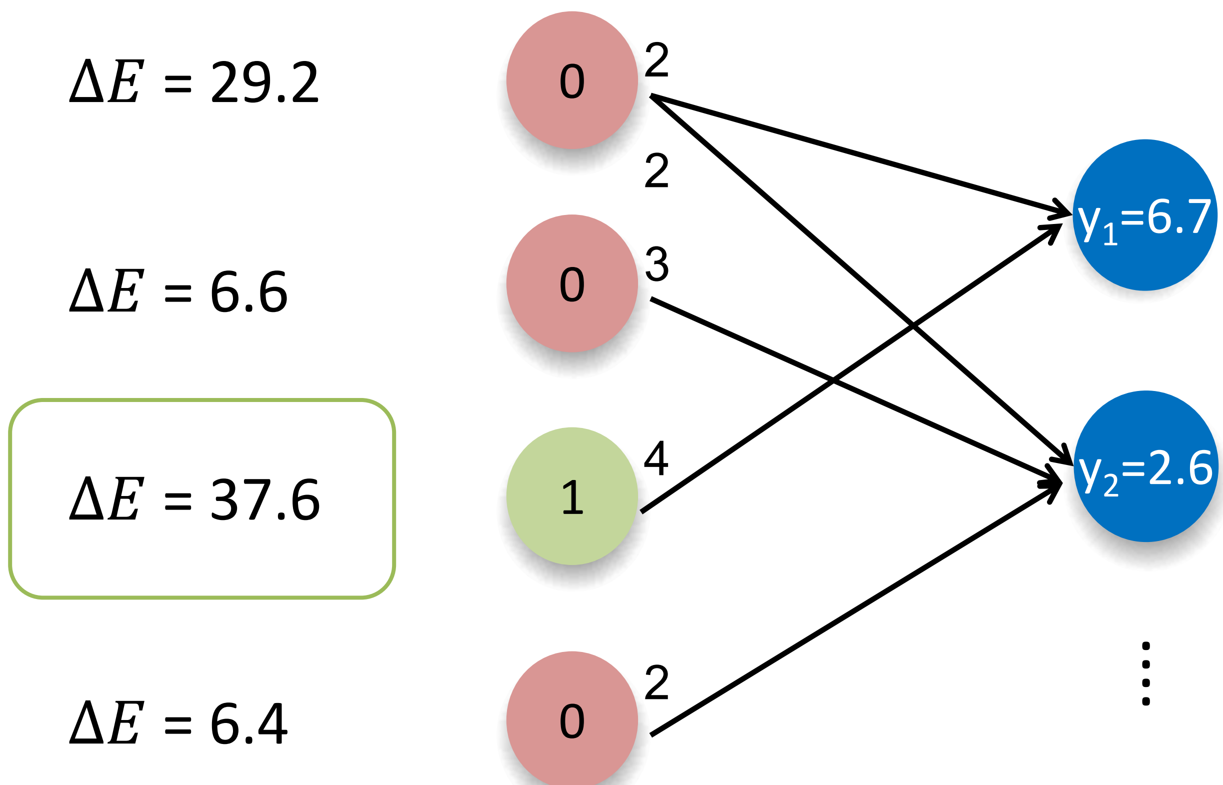
Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

- Currently $E \approx 52$



Minimizing $E(\widehat{b}) = \|DH\widehat{b} - y\|^2$

- Currently $E \approx 14$



Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

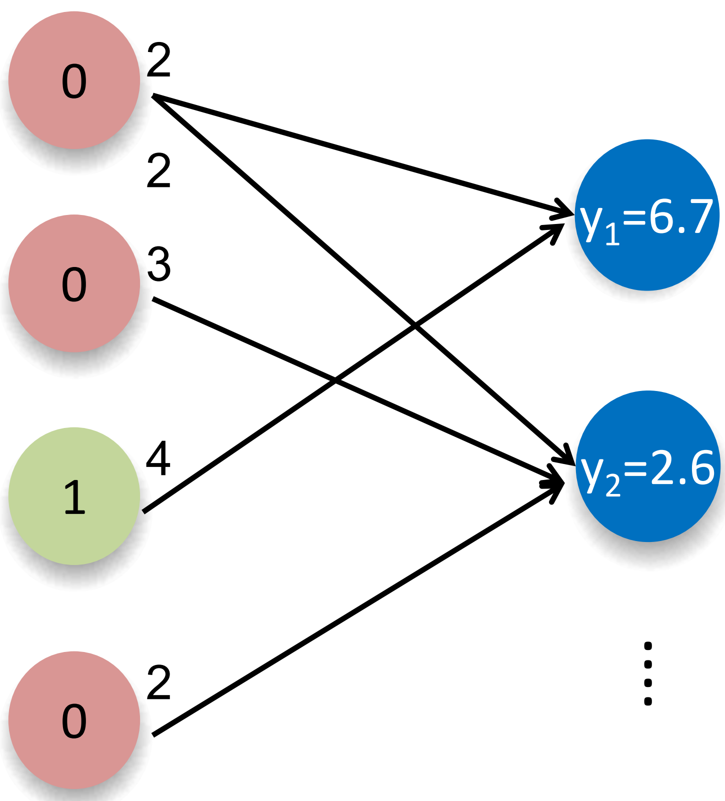
- Currently $E \approx 14$

ΔE = 29.2

ΔE = 6.6

$\boxed{\Delta E = -37.6}$

ΔE = 6.4



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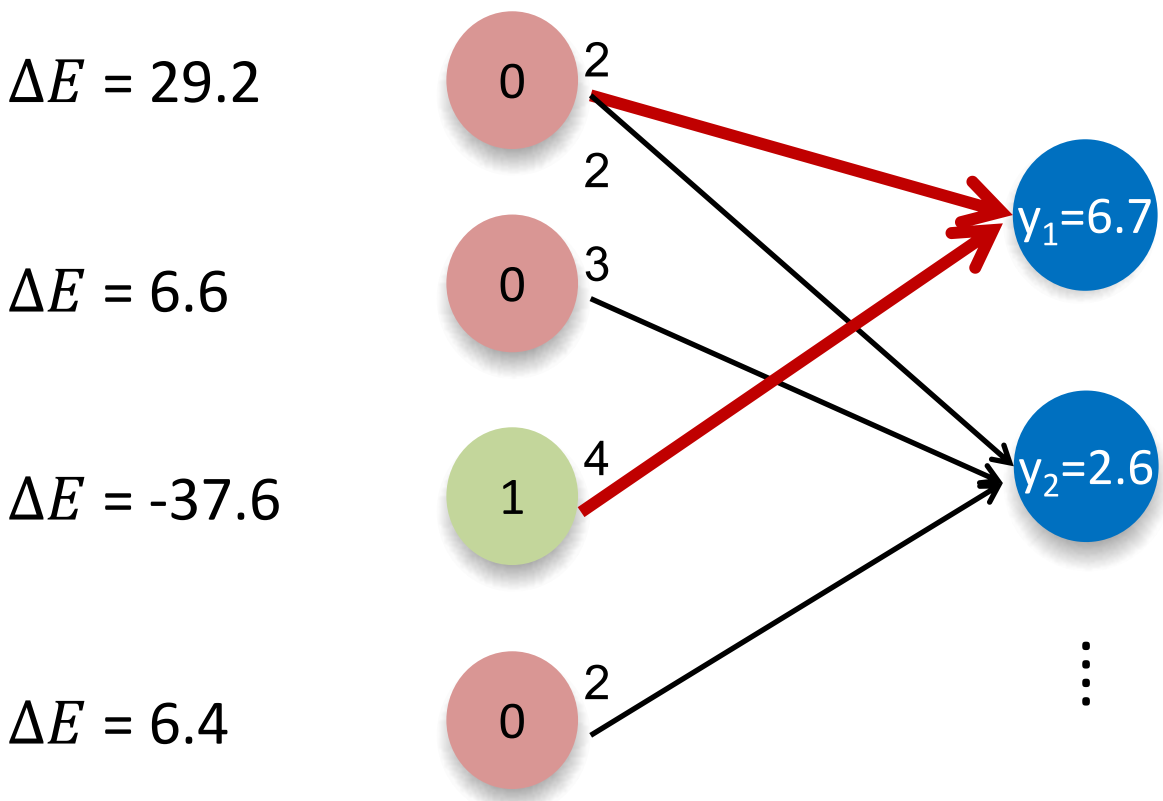
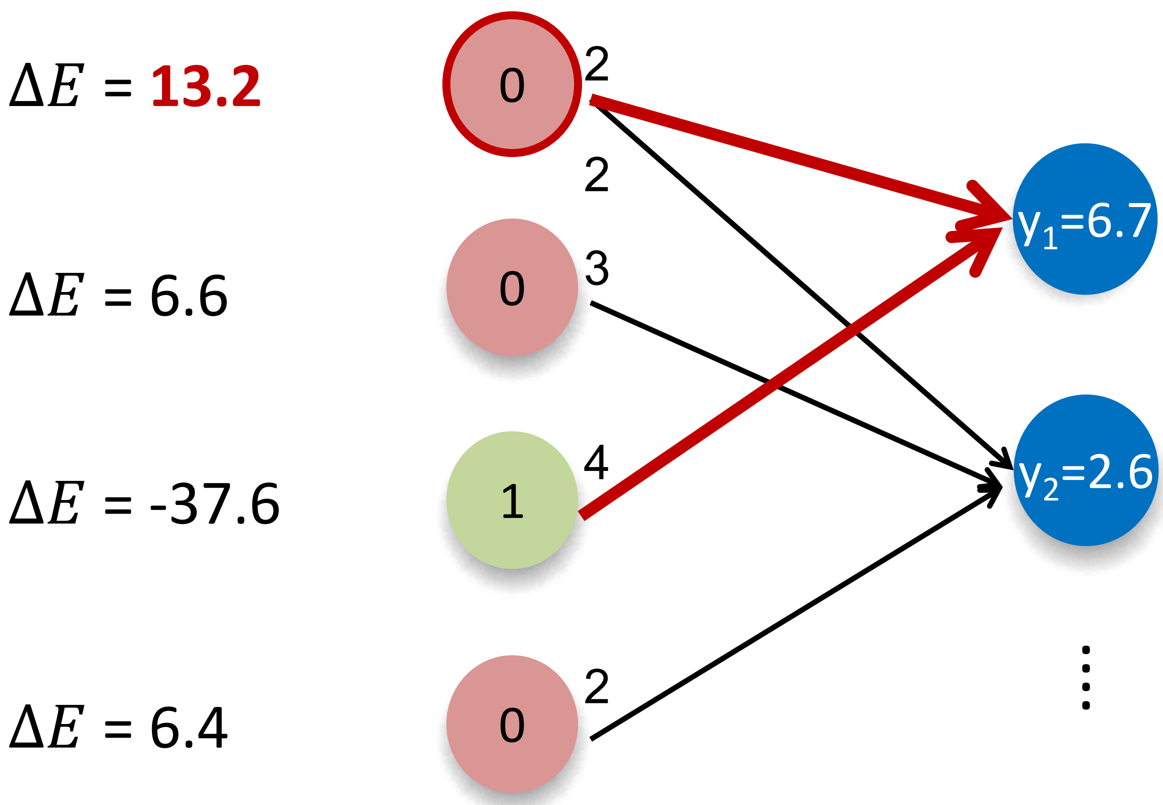


Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

- Currently $E \approx 14$



Minimizing $E(\widehat{b}) = \|DH\widehat{b} - y\|^2$

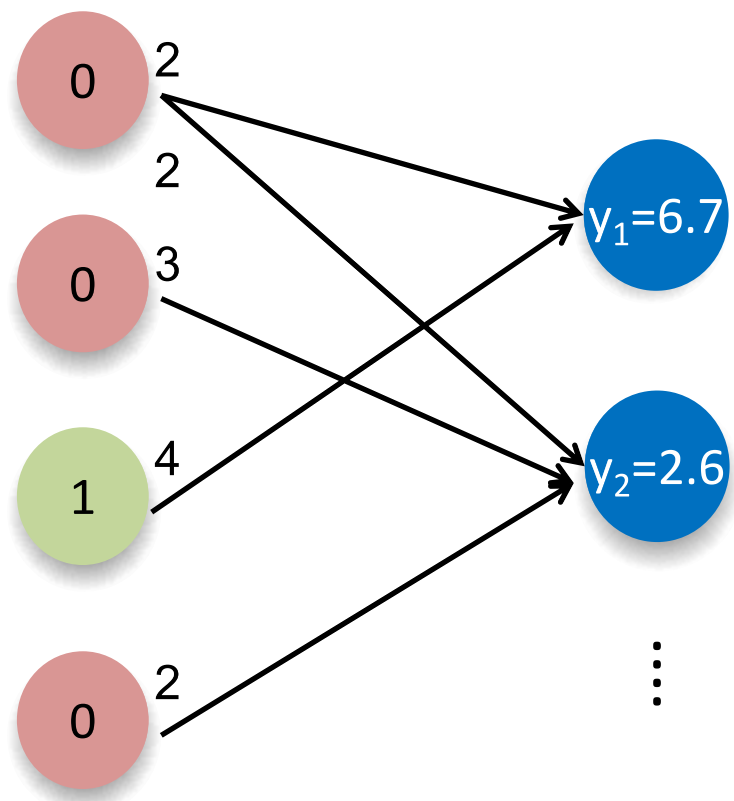
- Currently $E \approx 14$

ΔE = 13.2

ΔE = 6.6

ΔE = -37.6

ΔE = 6.4



Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

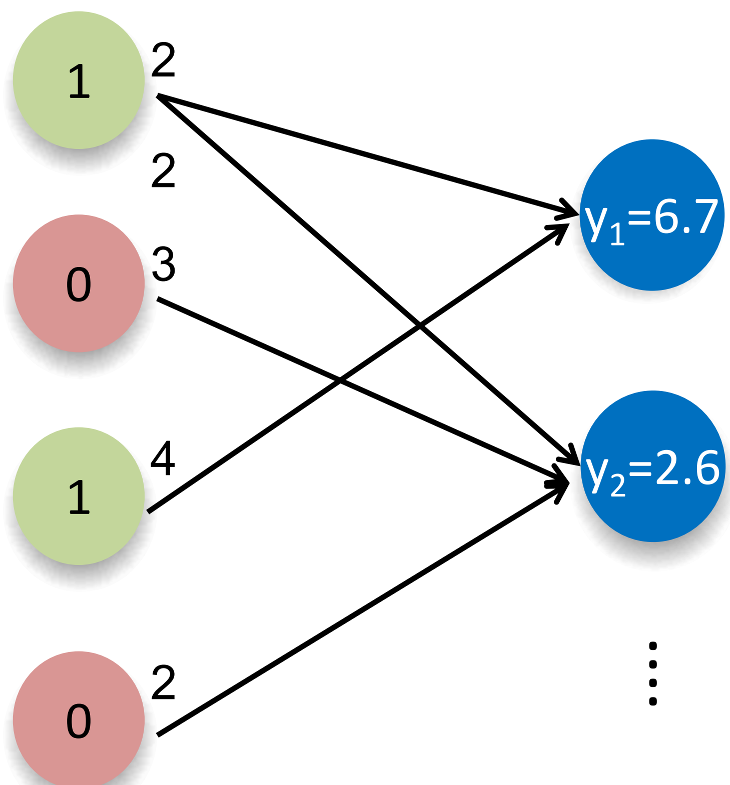
- Currently $E \approx 0.85$

$\boxed{\Delta E = 13.2}$

$\Delta E = 6.6$

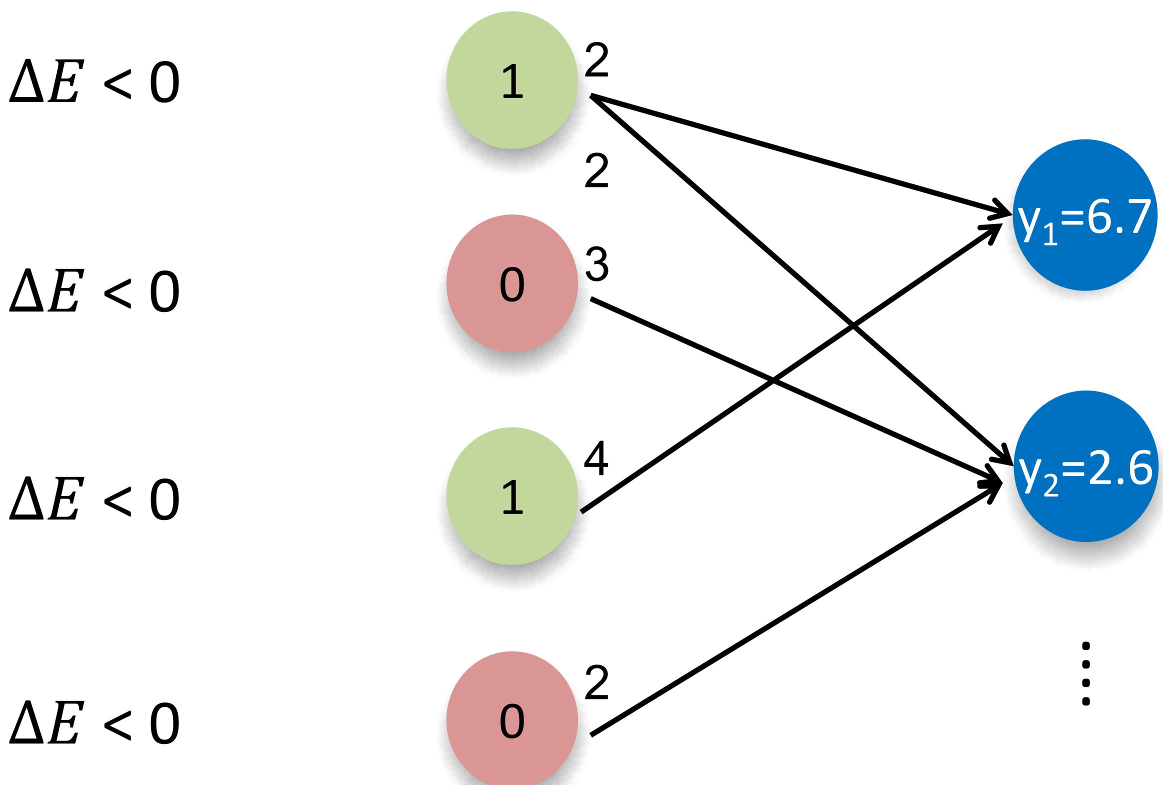
$\Delta E = -37.6$

$\Delta E = 6.4$



Minimizing $E(\hat{b}) = \|DH\hat{b} - y\|^2$

- Currently $E \approx 0.85$



Minimizing $E(\widehat{b}) = \left\| DH\widehat{b} - y \right\|^2$

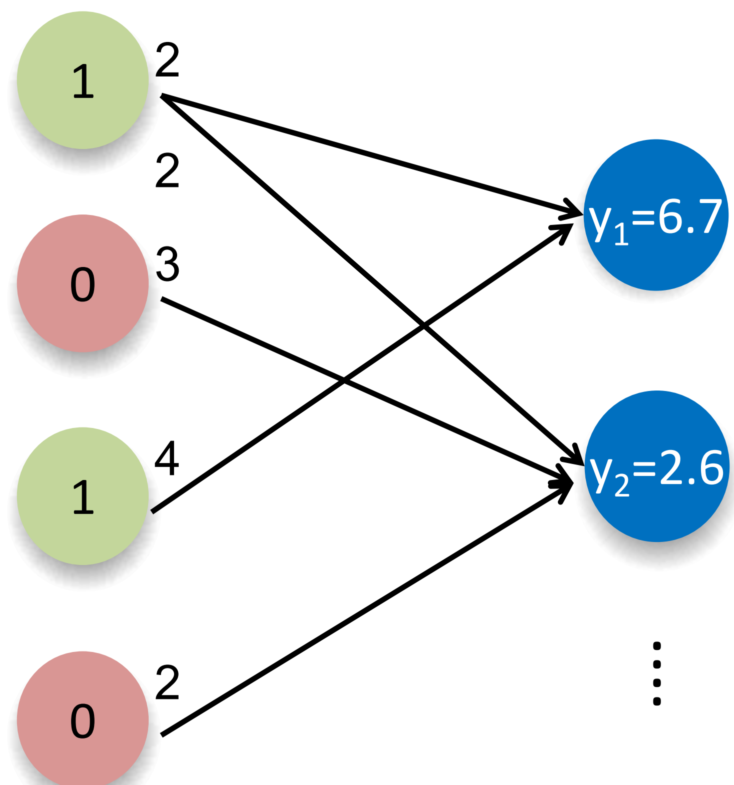
- Currently $E \approx 0.85$
- No further reduction in E => Terminates
- $\widehat{\boldsymbol{b}} = [\,1\ 0\ 1\ 0] = \boldsymbol{b}$ (actual bits)

$\Delta E < 0$

$\Delta E < 0$

$\Delta E < 0$

$\Delta E < 0$



Evaluation

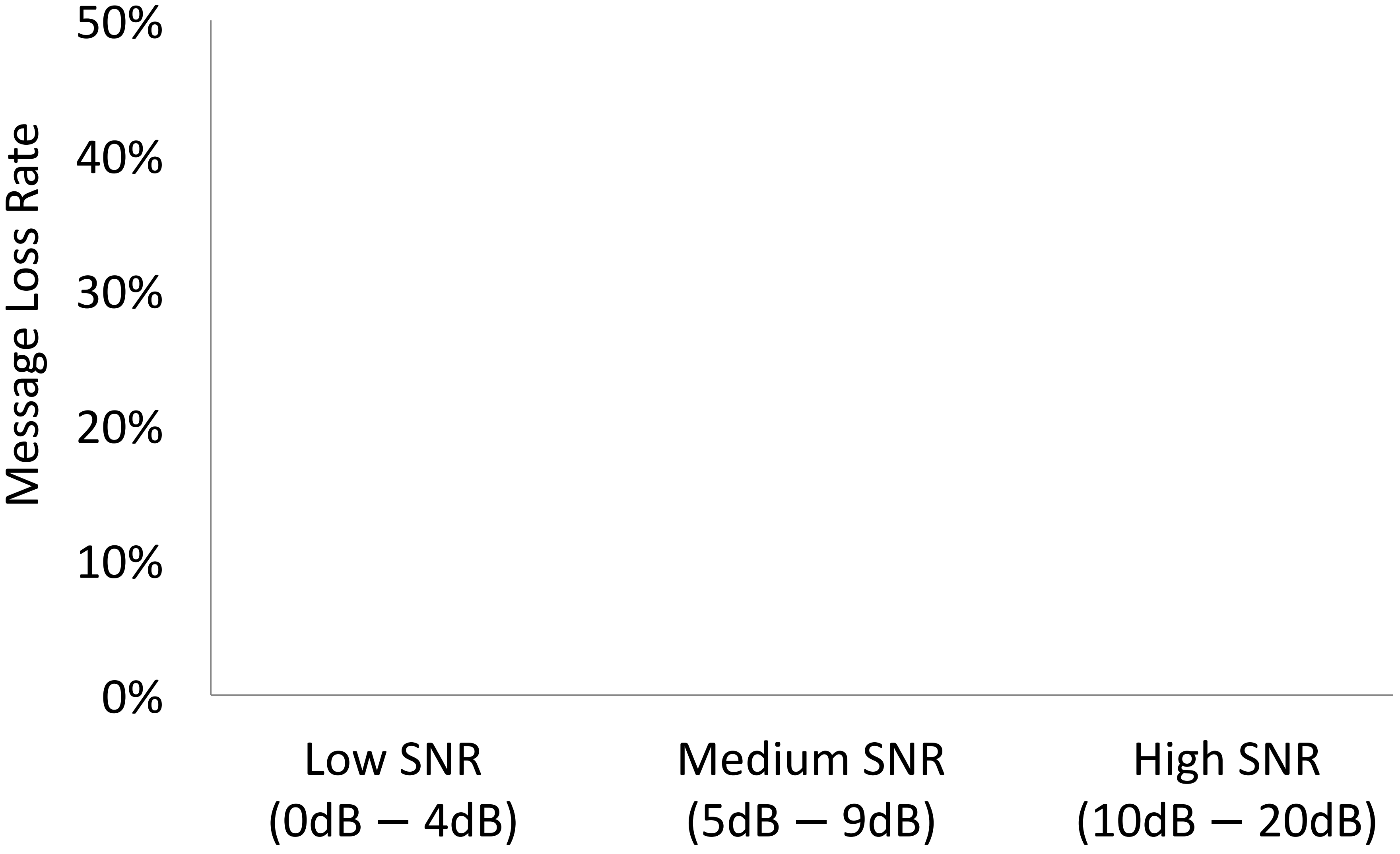
- Reader implementation on GNURadio USRP
- 16 UMass Moo programmable RFIDs

Evaluate Data Communication

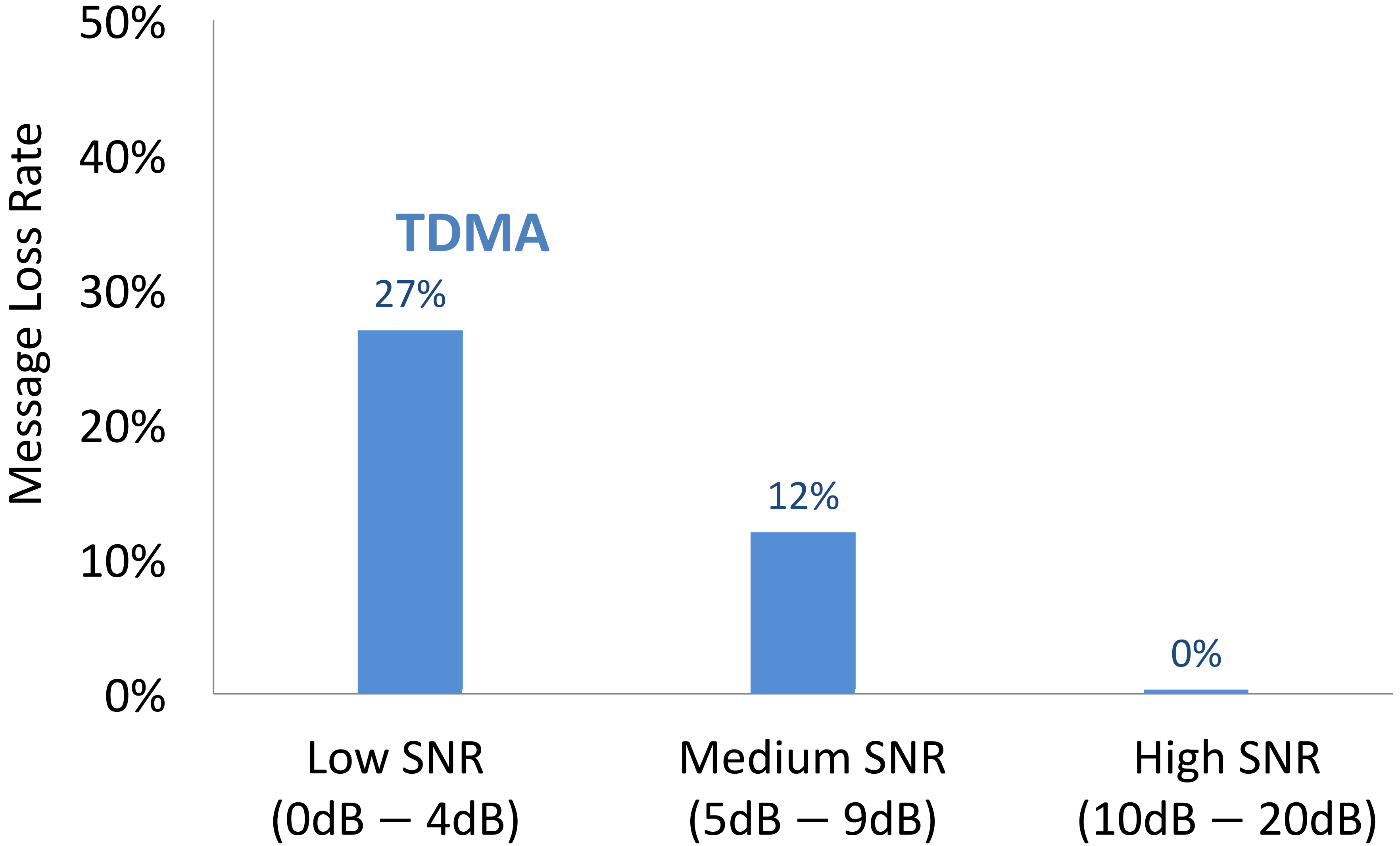
Compared schemes

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

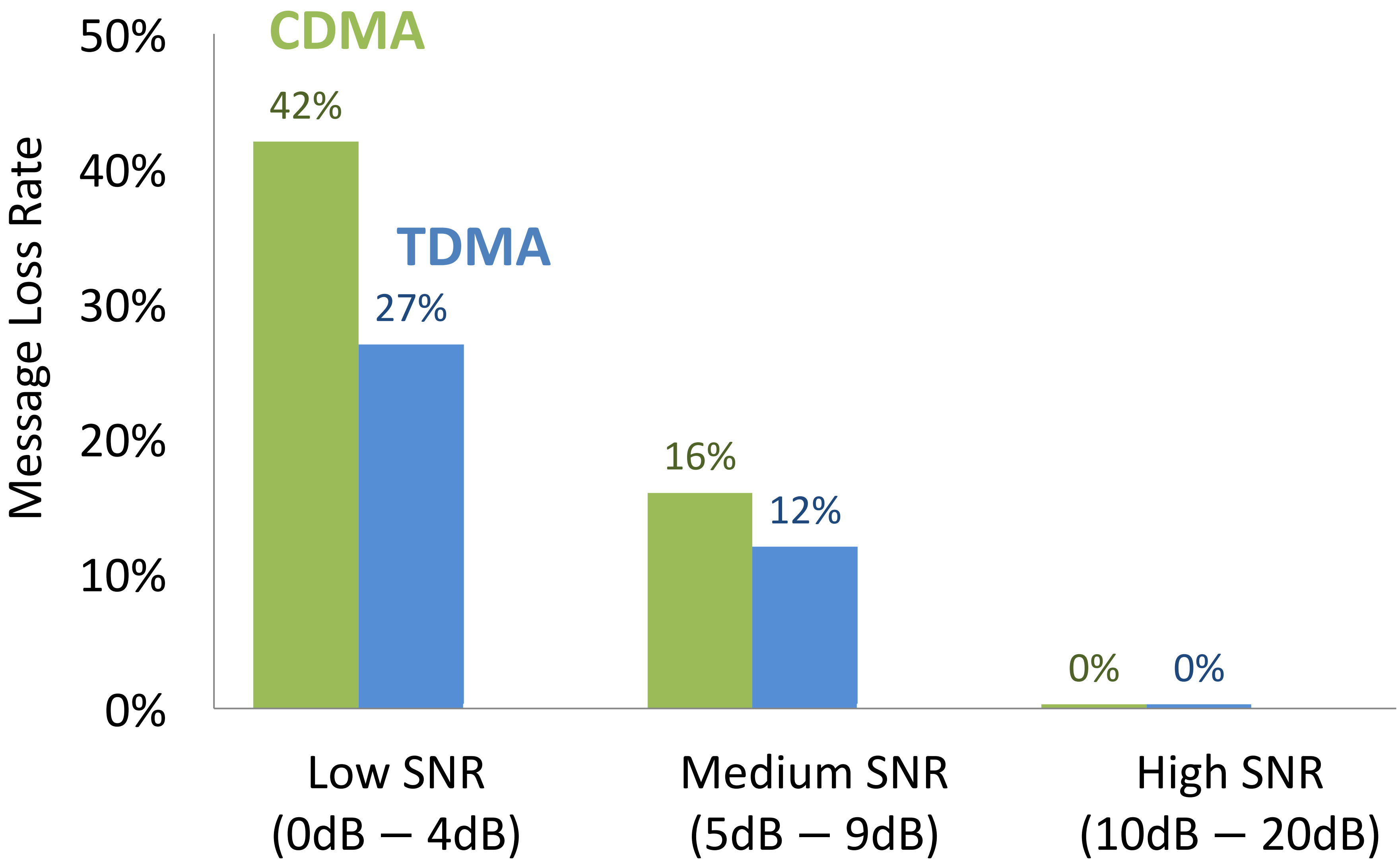
Reliability



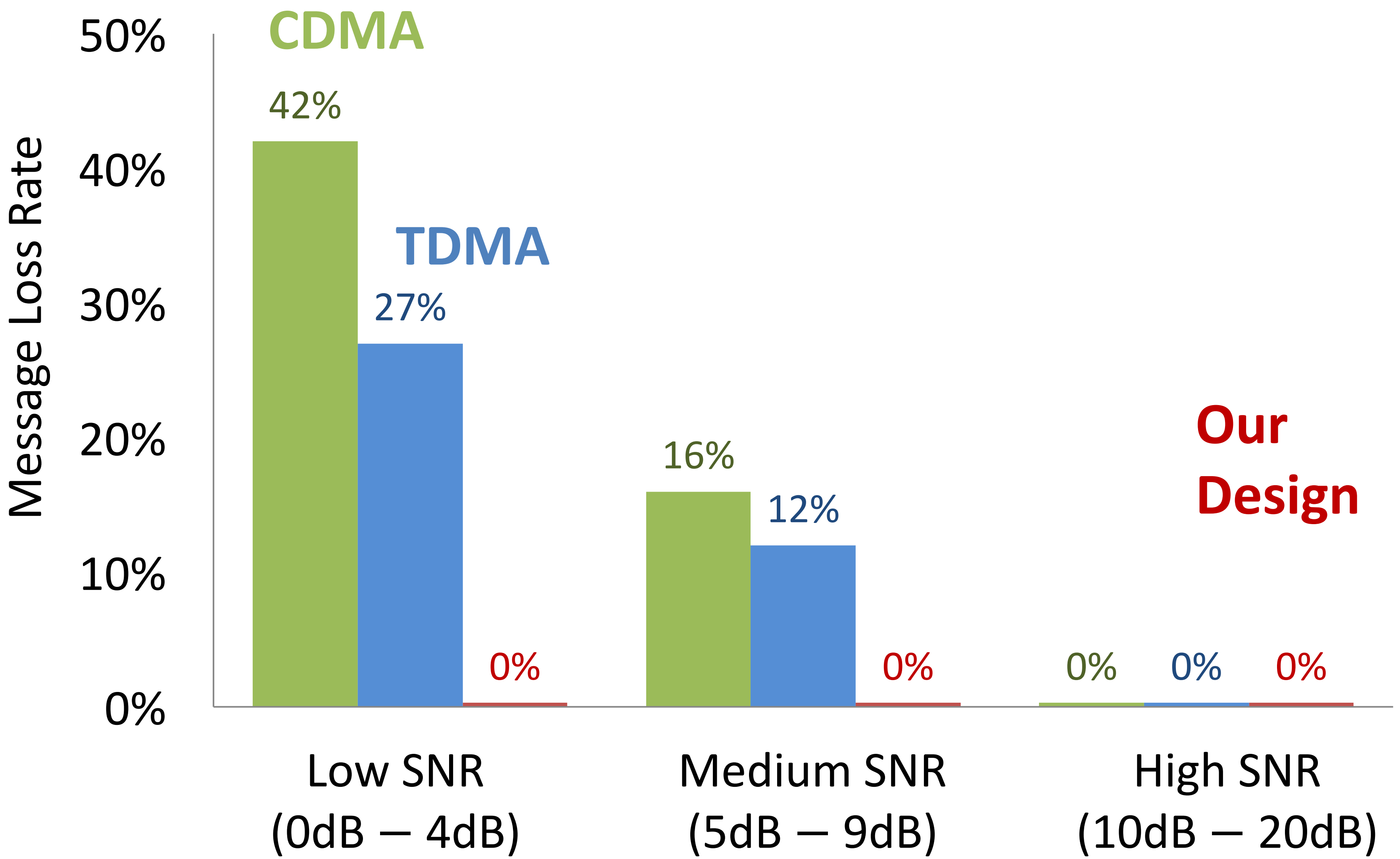
Reliability



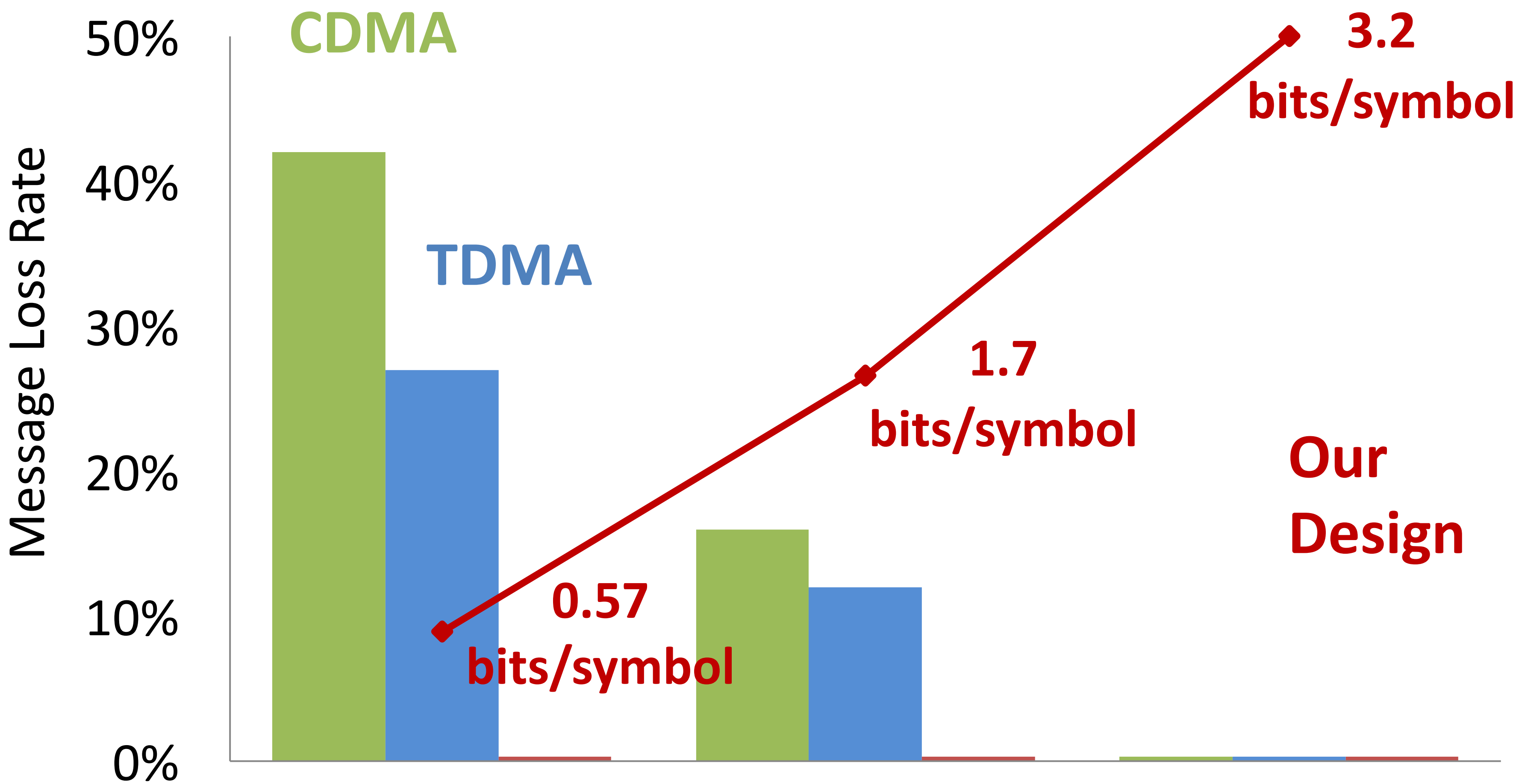
Reliability



Reliability



Reliability & Rate Adaptation



Network as a node adapts bit rate to eliminate message loss