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Embracing Uncertainty

Intelligent Tera-scale Networks of Miniaturized Battery-less Radios

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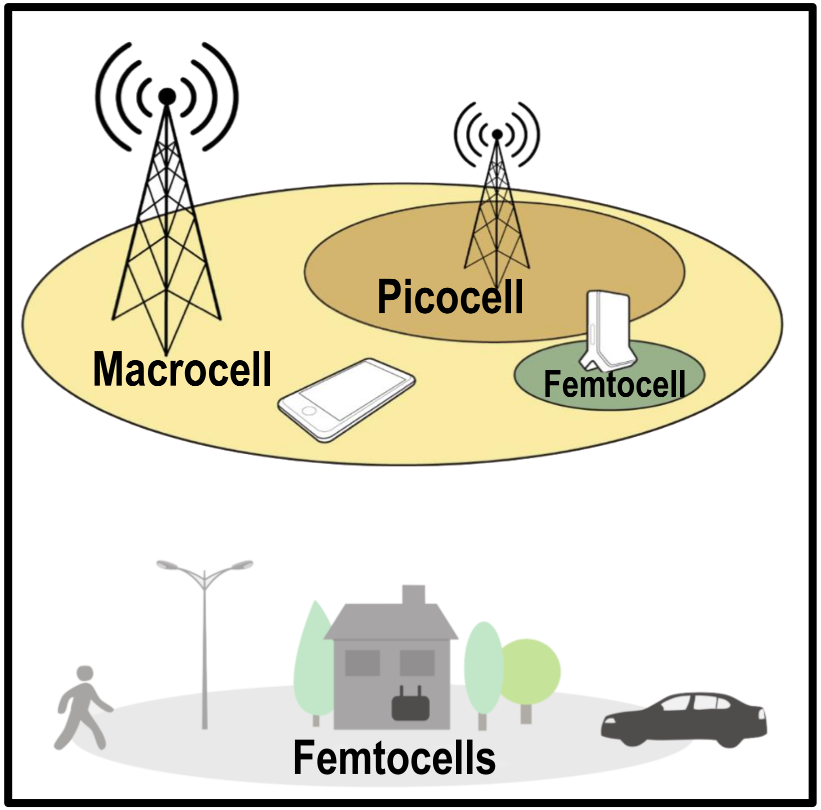
Stanford University

Today's Giga-scale Internet

Cellular Networks



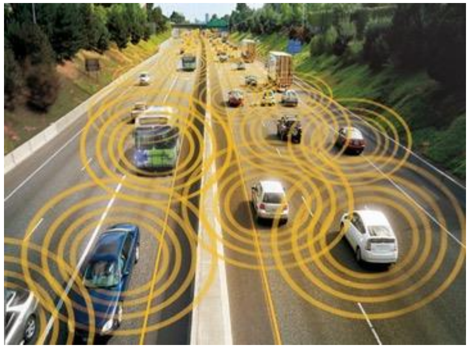
~ 6.7 Billion Subscribers
~ 6 Million Macro Cells
> 6 Million Small Cells in 2012

Wireless LAN

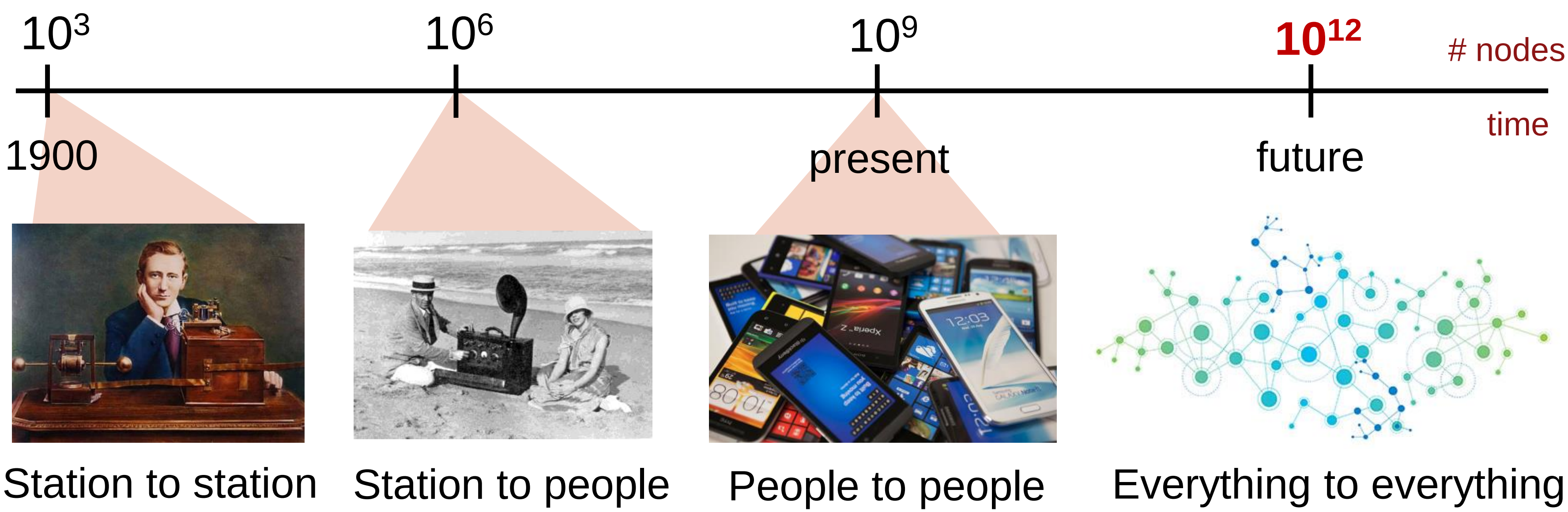
~ 65% of households in the U.S. have WiFi
~ 161 Million Access Points shipped in 2013
> 10 Billion WiFi devices shipped to date

An increasingly interconnected world

?



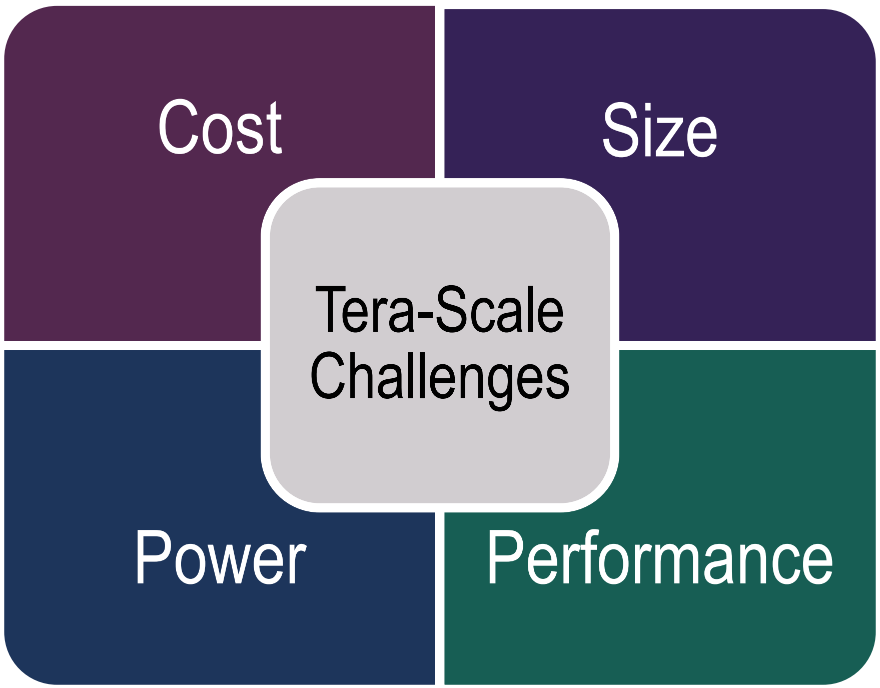
A century of wireless revolutions



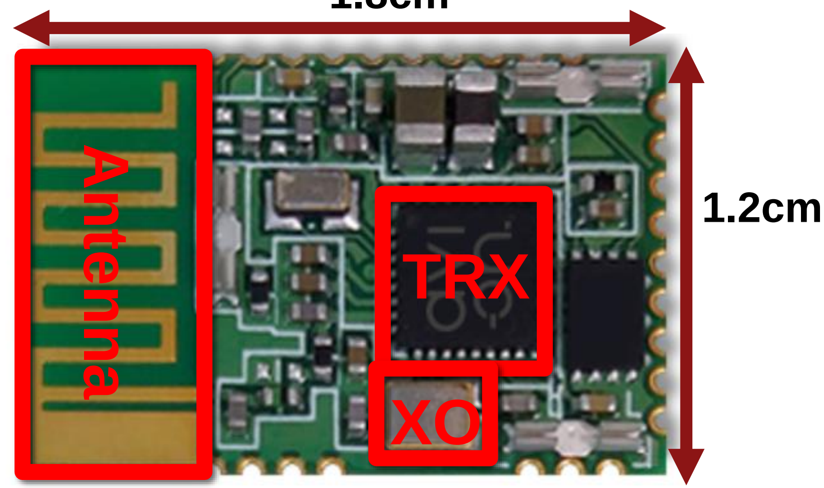
[SystemX Alliance]

- **1,000x leap for each cycle**
- **Paradigm shifts in**
  - **systems, algorithms, technology, and applications**

Challenges of tera-scale networks



Today's "Small" Radio



- Large footprint
- Off-chip components
- Battery-powered
- High cost

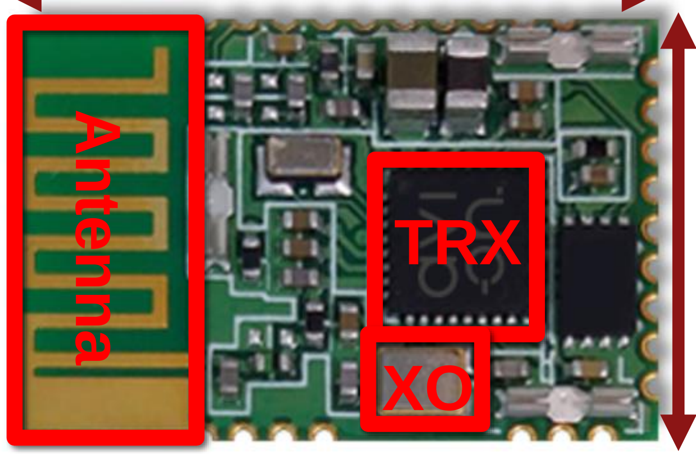
[AviOn]

Today's radios *cannot* address tera-scale requirements

Our approach: embracing uncertainty

- **Single-chip solution** to radically reduce cost and size of wireless nodes
  - No battery
  - No crystal resonator
  - No external antennas or capacitors
  - No tight coordination or synchronization between wireless nodes

1.8cm



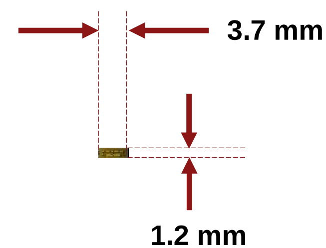
1.2cm

[AviOn]

[*Tabesh-Dolatsha-Arbabian-Niknejad 2015*]

single-chip radio

300x smaller



- 24 GHz RX wireless power and data
- 50cm communication range
- 60 GHz TX data with >12 Mbps datarate

Embracing *energy, clock, and medium access* uncertainty

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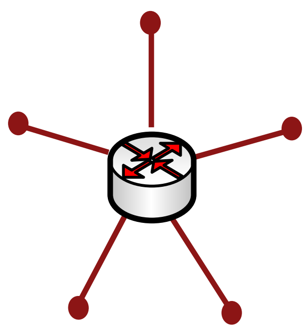
Talk outline

point-to-point

- Unreliable clocks & timing
- Unreliable energy sources
- Heavily duty cycled

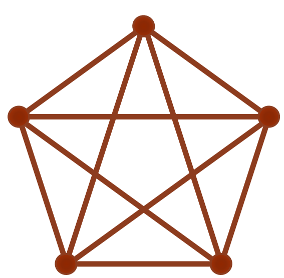
Part 1



star network

- Massive multiple access
- Minimal to no coordination
- One way communication

Part 2



mesh network

- Mesh networks
- On-sensor intelligence
- Privacy

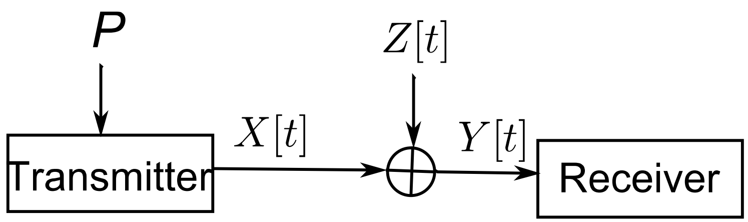
Part 3

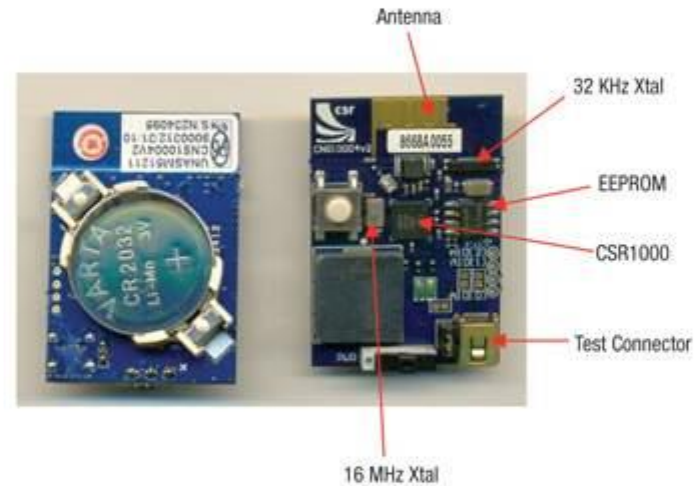
Part 1: Embracing energy & time uncertainty

point-to-point

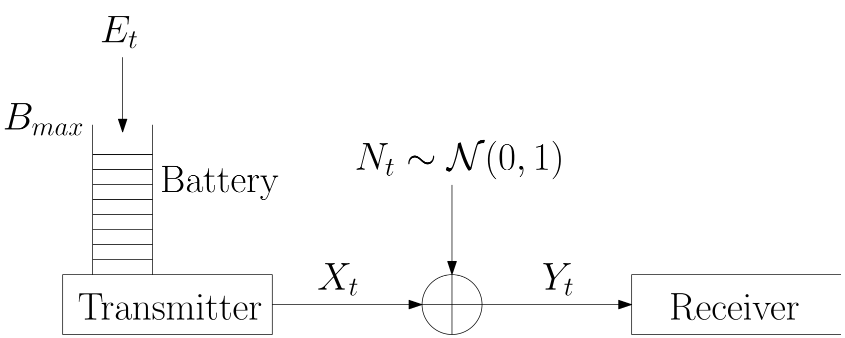
- Unreliable clocks & timing
- Unreliable energy sources
- Heavily duty cycled

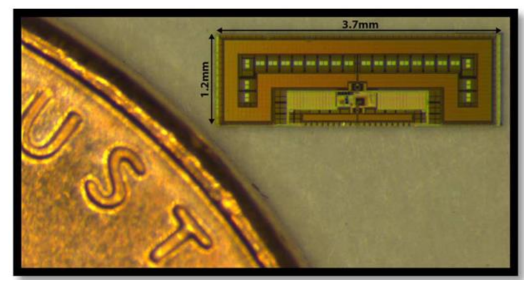
Embracing energy uncertainty





$$C = W \log\left(1 + \frac{P}{N_0 W}\right)$$





$$|X_t|^2 \leq B_t$$

$$B_{t+1} = \min(B_t - |X_t|^2 + E_{t+1}, B_{max})$$

$$C \approx \frac{1}{2}\log(1 + \mathbb{E}[\min(E_t, B_{max})])$$

[***Shaviv-Nguyen-Özgür 2015***]

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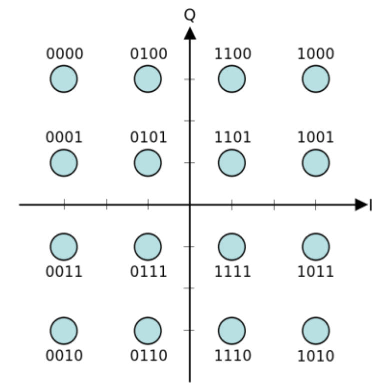
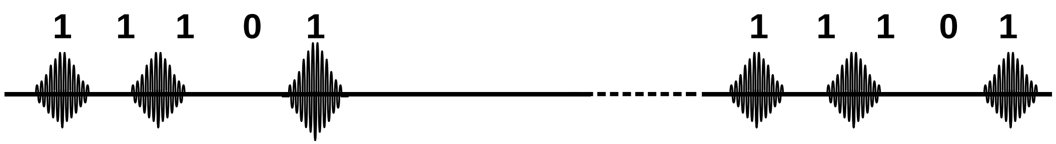
Ultra-low energy signaling schemes

Signaling schemes:

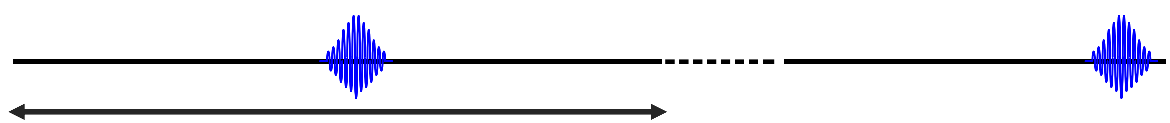
- Coherent communication?
- What about pulse amplitude modulation?
- What about on-off keying (OOK)?
- Pulse position modulation (PPM)



cannot encode information in phase or magnitude



possible if you can have a large on-chip capacitor

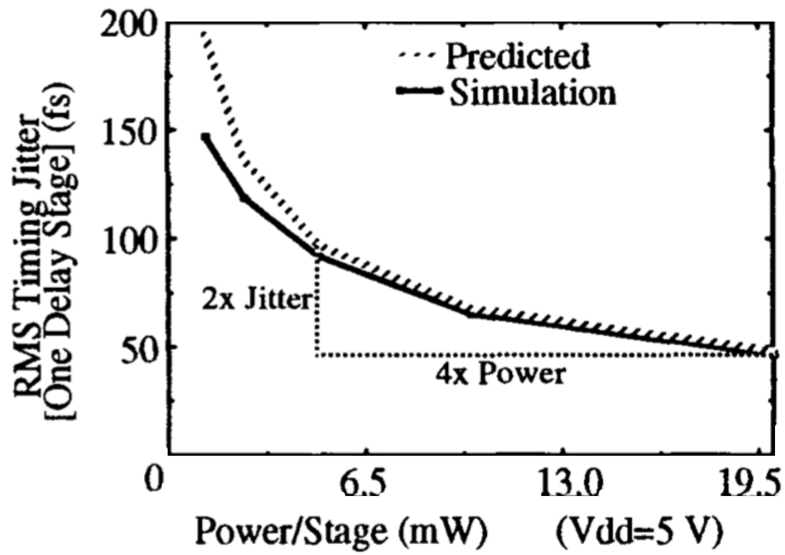


place pulse in 1 out of M positions

Ultra-low energy signaling requires accurate on-chip clocks

Accurate on-chip clocks are power hungry

Timing Jitter in CMOS Ring Oscillators

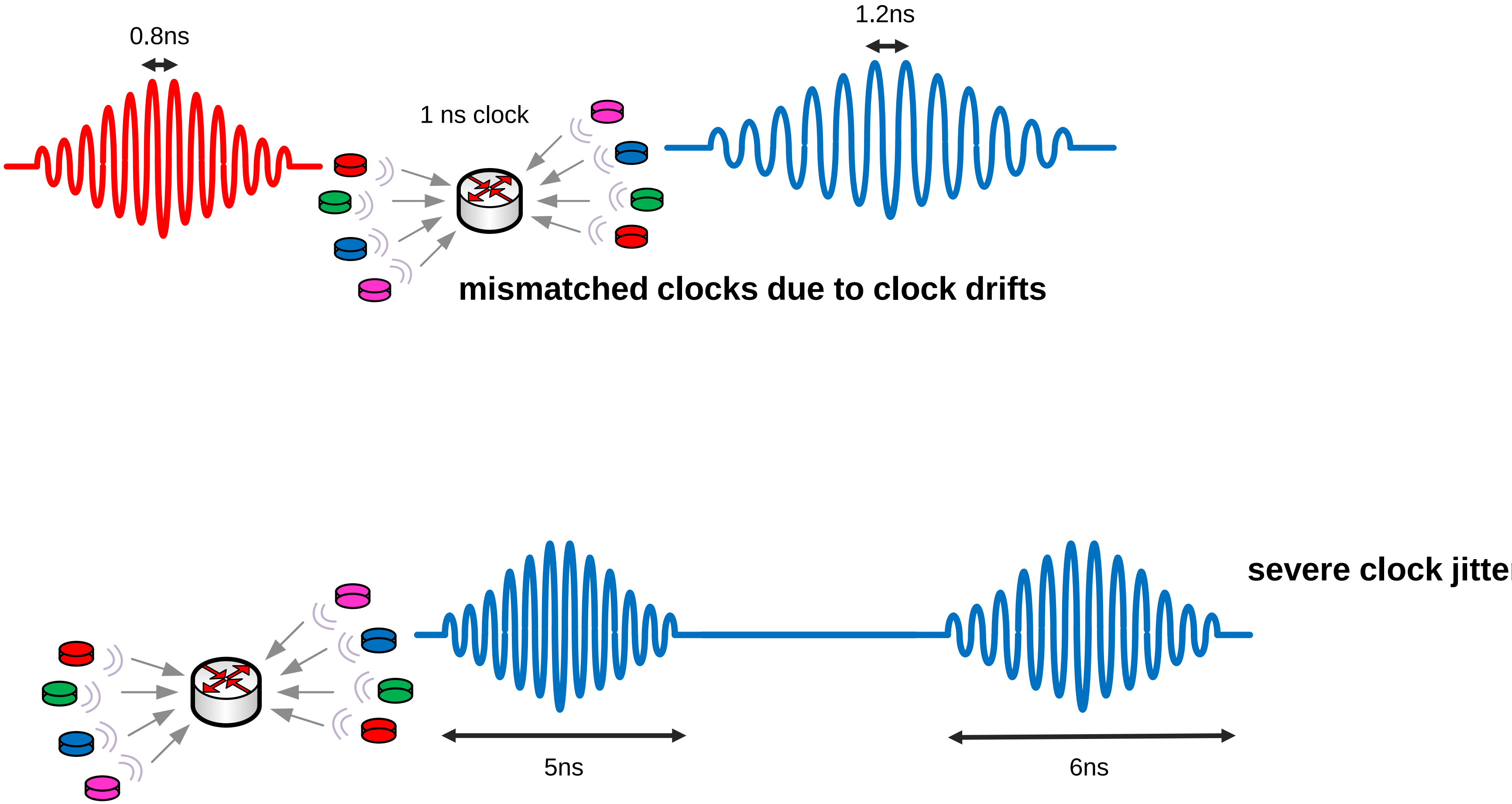


$$Jitter \propto \frac{1}{\sqrt{Power}}$$

Paul Gray, ISCAS '94

Next-generation devices will need to embrace clock uncertainty

Embracing clock and timing uncertainty



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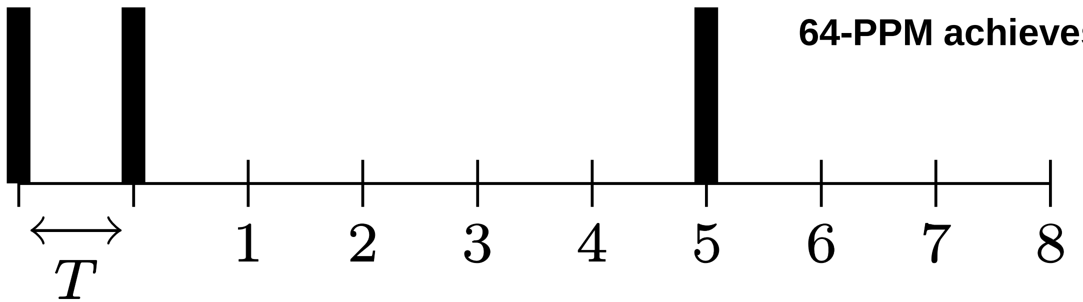
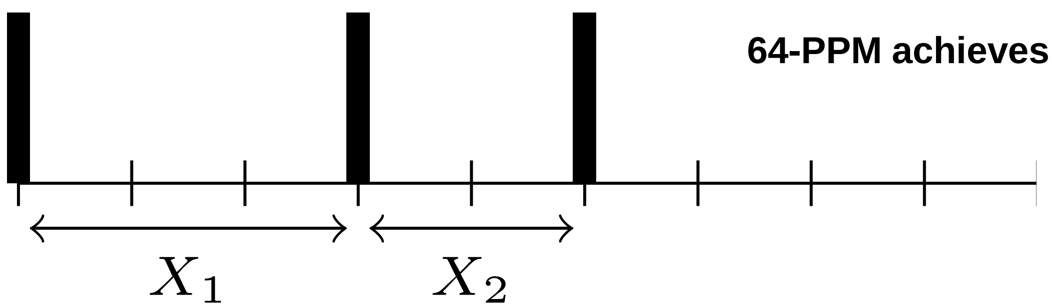
Fighting clock drift via clever coding tricks



64-PPM achieves 6 bits per frame using 3 pulses

The first two pulses are used to send the clock information to the receiver, and the third pulse conveys information via its position in one of 64 bins.



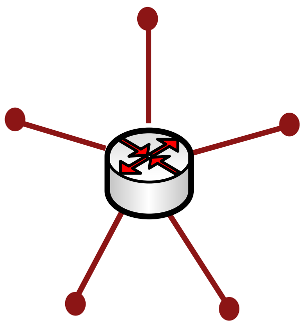
64-PPM achieves 10.35 bits per frame using 3 pulses

$$\frac{Y_1}{Y_2} = \frac{TX_1}{TX_2} = \frac{X_1}{X_2}$$

Information is conveyed using three locations. The pulses can be placed in any combination of bins as long as the ratios of the differences between locations are unique.

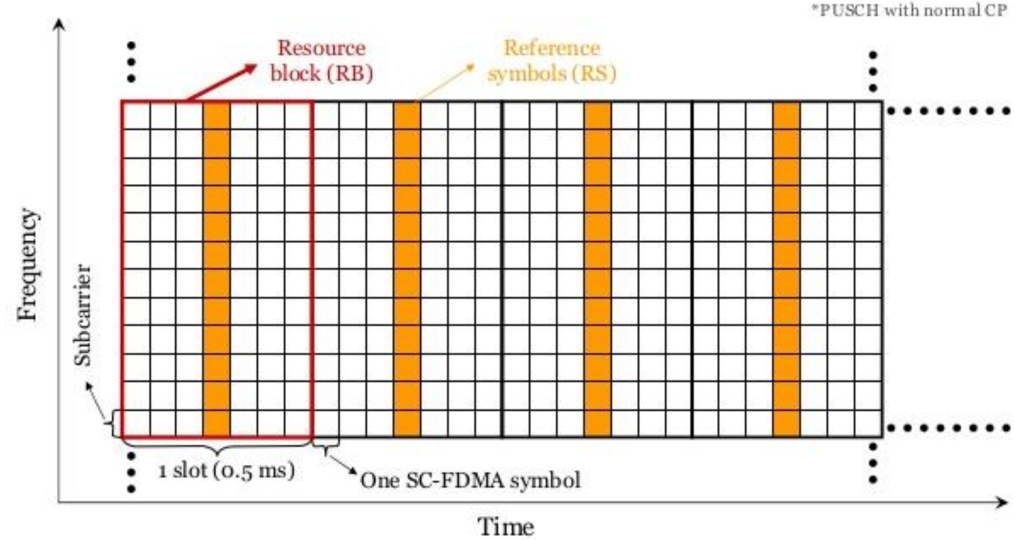
[*Shaviv-Özgür-Arbabian to be submitted*]

Part 2: Embracing medium access uncertainty



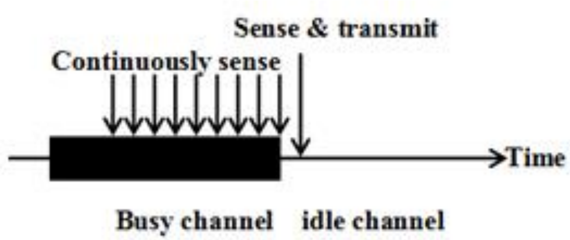
- Massive multiple access
- Minimal to no coordination
- One way communication

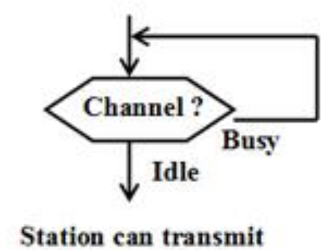
Existing multiple access schemes



Frequency and time resources are tightly allocated across active devices

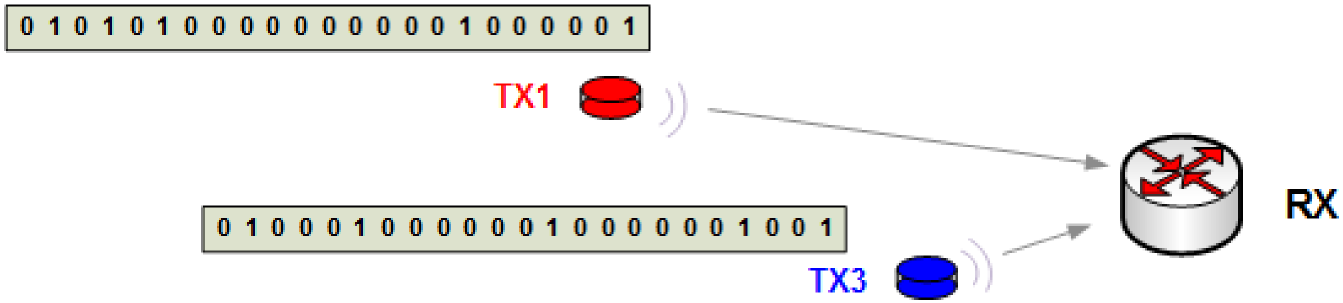
CSMA





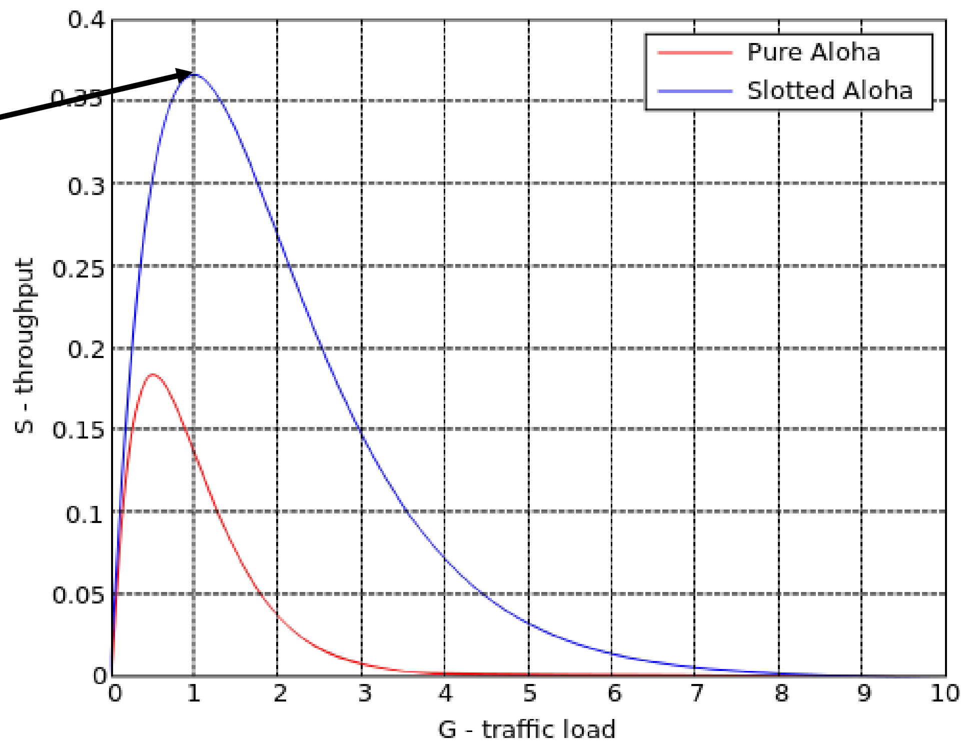
Spectrum is continuously sensed to determine whether or not the channel is busy

What about ALOHA?



both packets are lost due to collision!

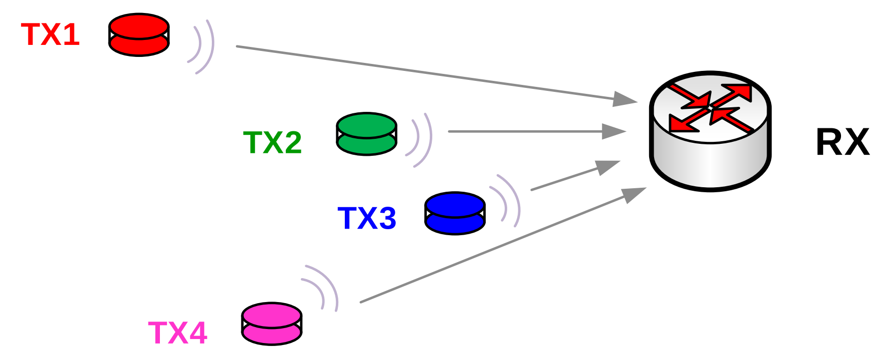
collision rate ~ 67%



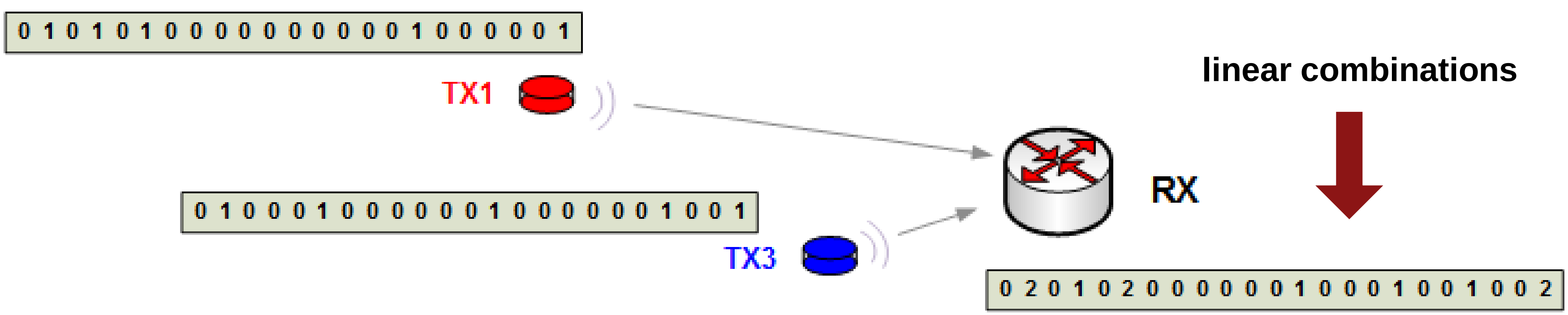
Colliding packets need to be retransmitted – this requires feedback!

Embracing packet collisions

CDMA

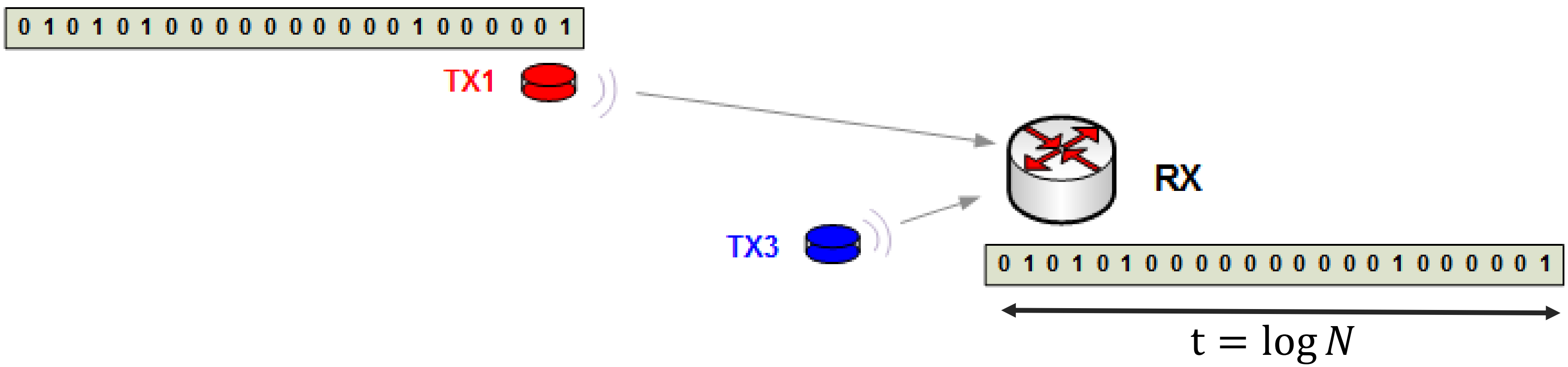


CDMA overcomes the near-far problem via sophisticated power control algorithms

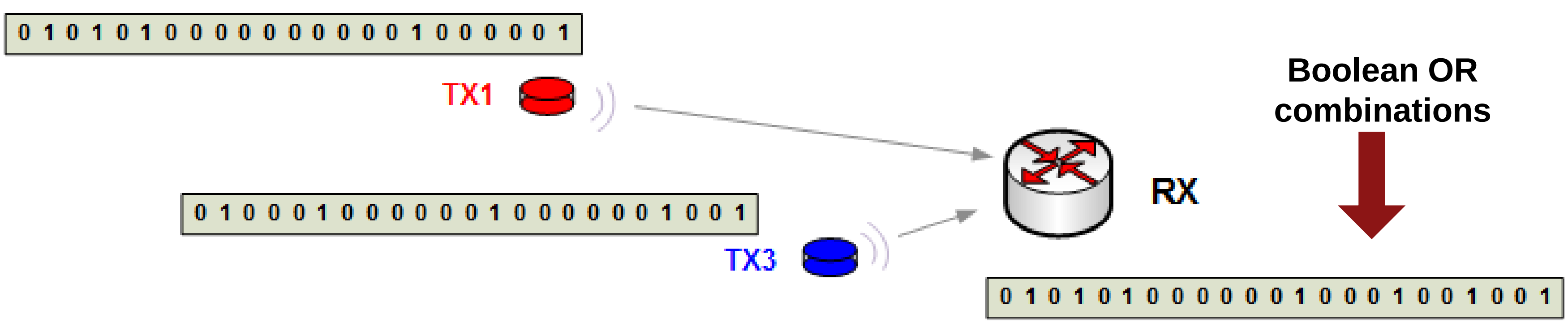


Cannot happen in our setting – because power control is very expensive!

A closer look at packet collisions



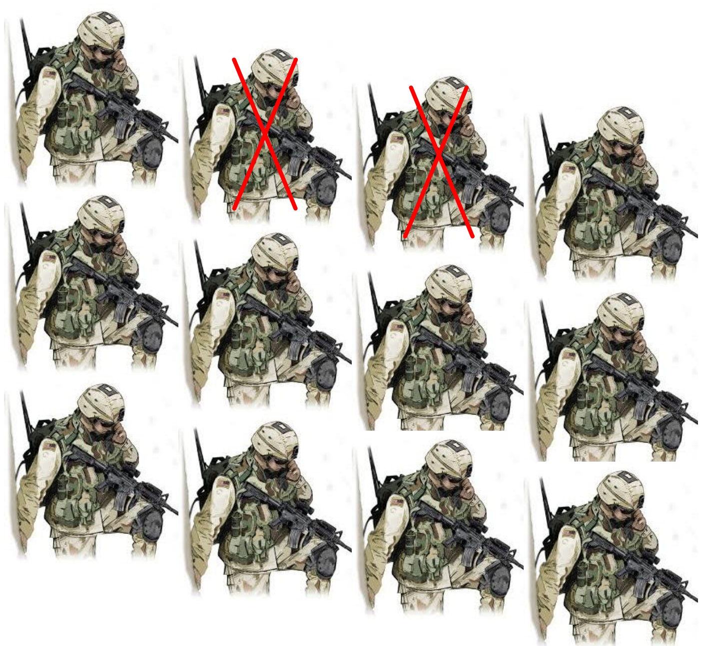
$\log N$ bits needed to send N messages



$t > \log N$ bits needed to send up to d out of N messages

Group testing

- N items (soldiers): $M_1, \ldots, M_N$
- d defective (infected): $\mathcal{G} = \{M_{i_1}, \ldots, M_{i_d}\}$
- Figure out the defective group: $\mathcal{G}$
- Naive method: test each item (**cost: N tests**)
- Group items together and apply t tests



Item Number

Test Number

	1	2	3	...	N	Y
1	1	0	0		0	1
2	0	1	1		0	1
3	1	1	0		1	1
4	0	0	0		0	0
..	0	1	0		1	1
.	1	0	1		1	1
	0	0	0		0	0
	0	1	0		0	1
	1	0	0		1	1
	0	1	1		0	1
	0	0	1		1	0
	0	0	0		0	0
	1	0	0		1	1
	1	1	0		0	1
	0	0	1		1	0
t	0	1	0		1	1
	1	0	1		0	1

Defectives (items 1 and 2) **Test Outcomes** (Y)

Group testing results

Item Number

Test Number

	1	2	3	. . .	N	Y
1	1	0	0		0	1
2	0	1	1		0	1
3	1	1	0		1	1
4	0	0	0		0	0
..	0	1	0		1	1
.	1	0	1		1	1
	0	0	0		0	0
	0	1	0		0	1
	1	0	0		1	1
	0	1	1		0	1
	0	0	1		1	0
	0	0	0		0	0
	1	0	0		1	1
	1	1	0		0	1
	0	0	1		1	0
t	0	1	0		1	1
	1	0	1		0	1

Defectives

Test Outcomes

Best upper bound: $t = O\left(d^2 \log N\right)$

Best lower bound: $t = \Omega\left(\frac{d^2 \log N}{\log d}\right)$

Collision resolving codes via group testing

Group testing code

	1	2	3	. . .	N
1	1	0	0		0
2	0	1	1		0
3	1	1	0		1
4	0	0	0		0
.	0	1	0		1
.	1	0	1		1
.	0	0	0		0
	0	1	0		0
	1	0	0		1
	0	1	1		0
	0	0	1		1
	0	0	0		0
	1	0	0		1
	1	1	0		0
	0	0	1		1
t	0	1	0		1
	1	0	1		0

TX1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1

Boolean OR +

TX2 0 1 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 1

=

R 0 1 0 1 0 1 0 0 0 0 0 0 1 0 0 0 1 0 0 1 0 0 1

colliding packets

Given R, determine TX1 and TX2!

Group testing codes do not place any restrictions on the weights of the codewords!

Low energy collision resolving codes

	1	2	3	. . .	N
1 2	1 0	0 1	0 1		0 0
3 4	1 0	1 0	0 0		1 0
. . .	0 1 0	1 0 0	0 1 0		1 1 0
	0 1	1 0	0 0		0 1
	0 0	1 0	1 1		0 1
	0 1	0 0	0 0		0 1
	1 0	1 0	0 1		0 1
t	0 1	1 0	0 1		1 0

Group testing code

	1	2	3	. . .	N
1 2	1 0	0 1	0 0		0 0
3 4	1 0	0 0	0 0		1 0
. . .	0 0 0	0 1 0	0 1 0		0 0 0
	0 0	0 0	0 0		0 0
	0 0	1 0	1 0		0 1
	0 0	0 0	0 0		0 1
	0 0	0 0	0 0		0 0
t	0 1	0 0	0 1		0 0

Sparse group testing code

Low energy collision resolving codes

	1	2	3	. . .	N
1 2	1 0	0 1	0 0		0 0
3 4	1 0	0 0	0 0		1 0
. . .	0 0 0	0 1 0	0 1 0		0 0 0
	0 0	0 0	0 0		0 0
	0 0	1 0	1 0		0 1
	0 0	0 0	0 0		0 1
	0 0	0 0	0 0		0 0
t	0 1	0 0	0 1		0 0

Sparse group testing code

Novel group testing code with 3 pulses only

Achievable: $t = (d+1)\sqrt{N}$

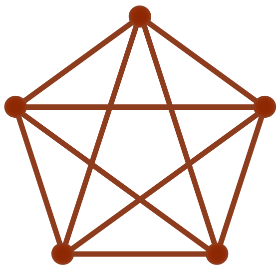
Best lower bound: $t \geq \frac{d}{\sqrt{3}}\sqrt{N}$

using $d+1$ pulses only

Reed Solomon codes are optimal!

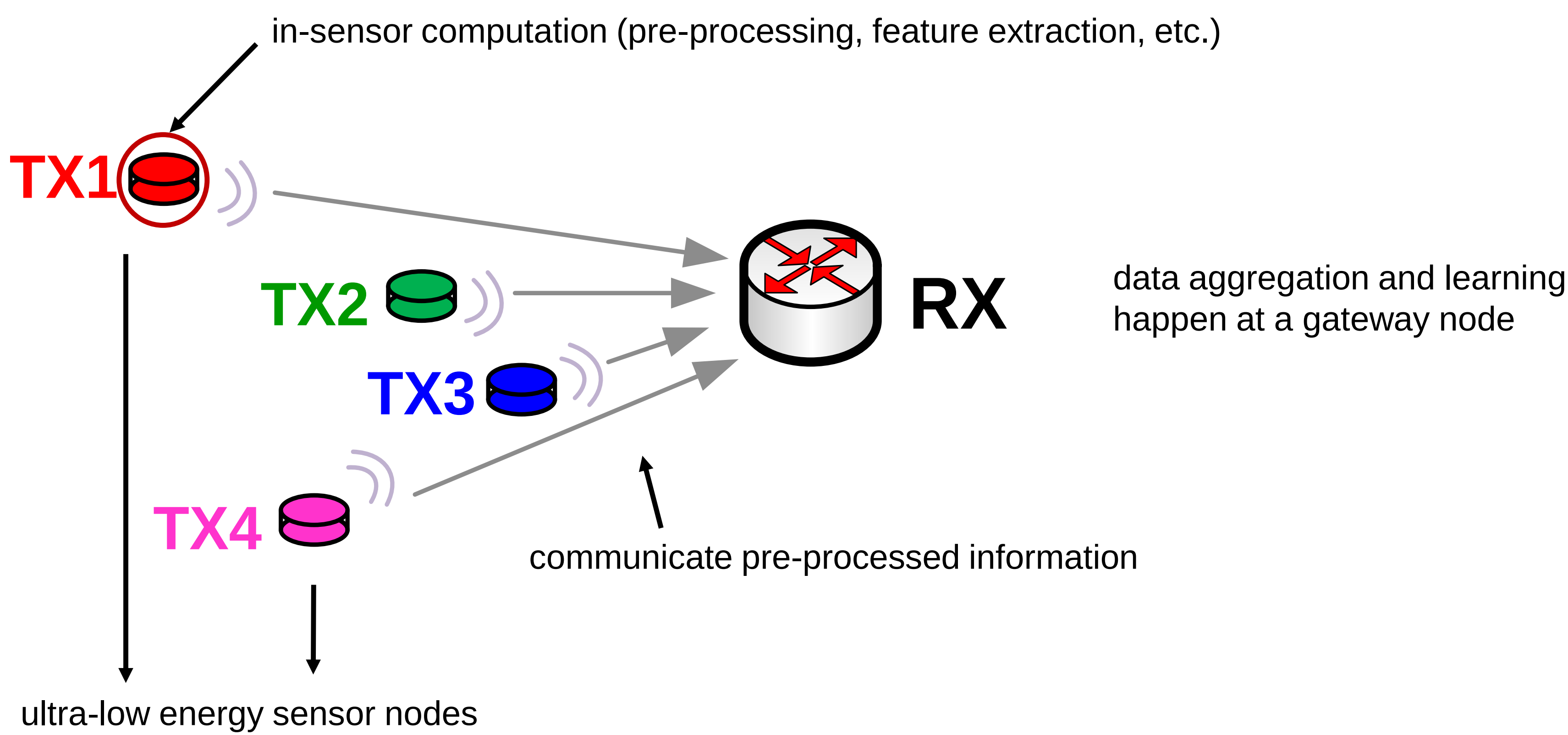
[*Inan-Kairouz-*Özgür *to be submitted*]

Part 3: Embracing computational uncertainty



- Mesh networks
- On-sensor intelligence
- Privacy

On-sensor intelligence

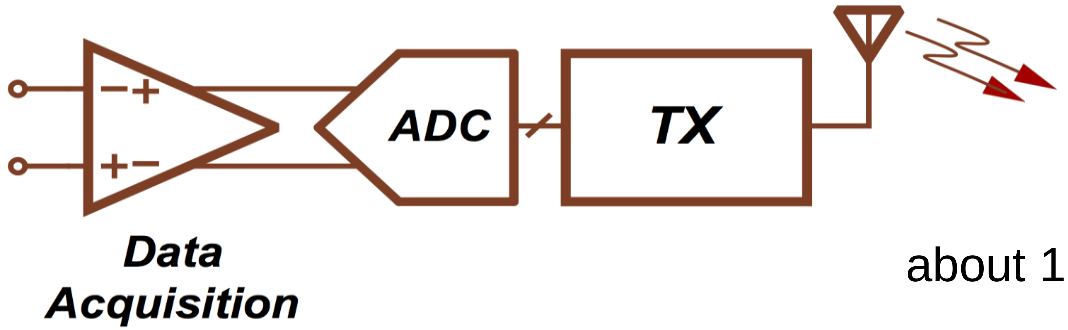


Key Questions:

1. How to tradeoff computation vs. communication
2. How to achieve impressive energy gains
3. How to privatize the sensors' data

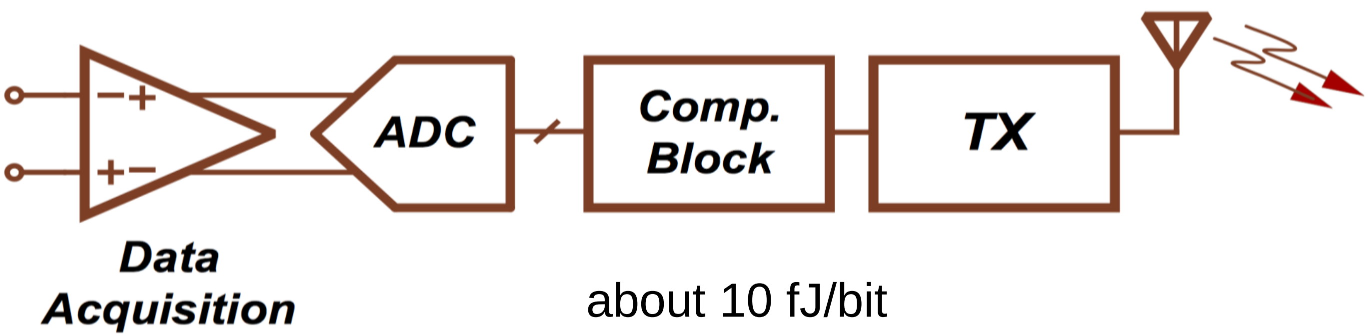
Computation vs communication

Sense → Communicate:



about 10 nJ/bit

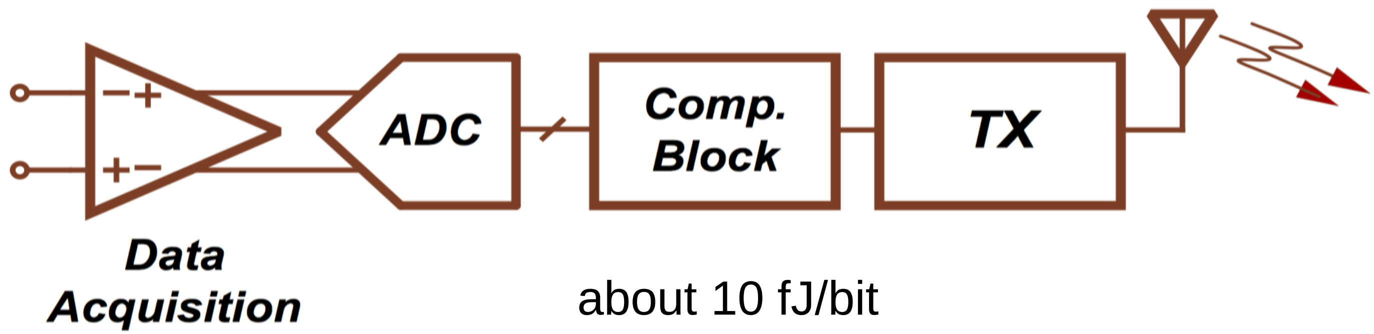
Sense → Compute → Communicate:



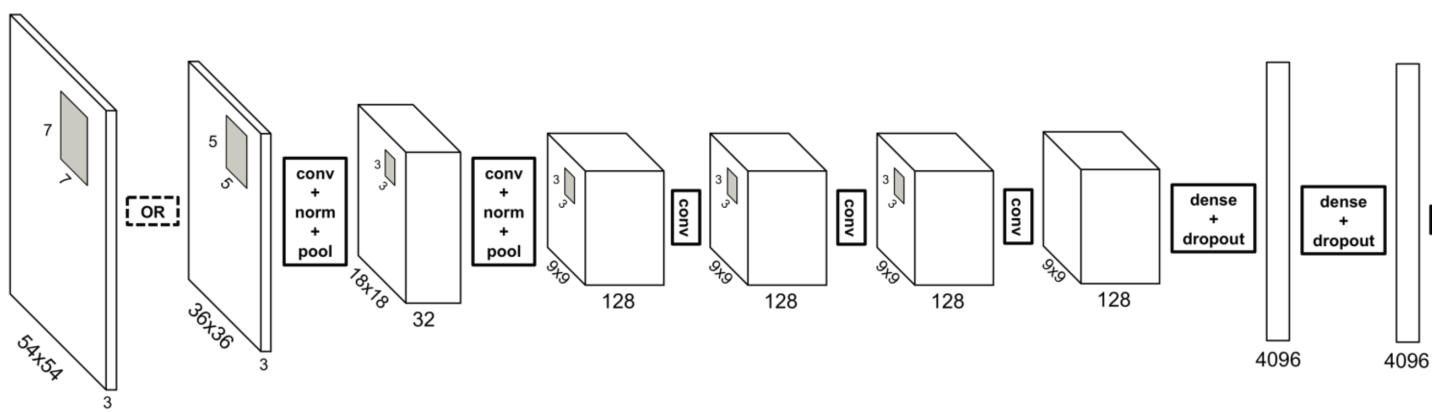
about 10 fJ/bit

Shall we just compute locally?

Sense → Compute → Communicate:

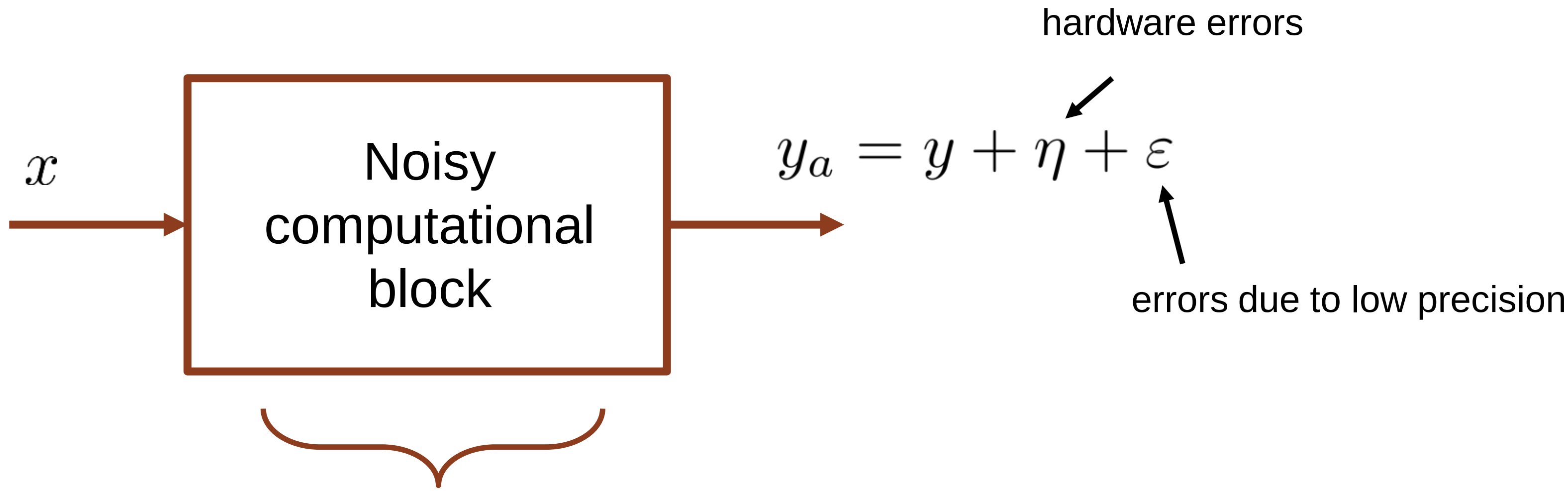


about 10 fJ/bit

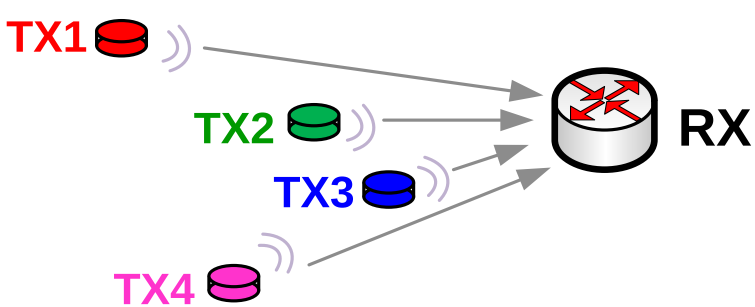


Need to examine the computation vs. communication tradeoff closely

Bringing intelligence + privacy to sensors

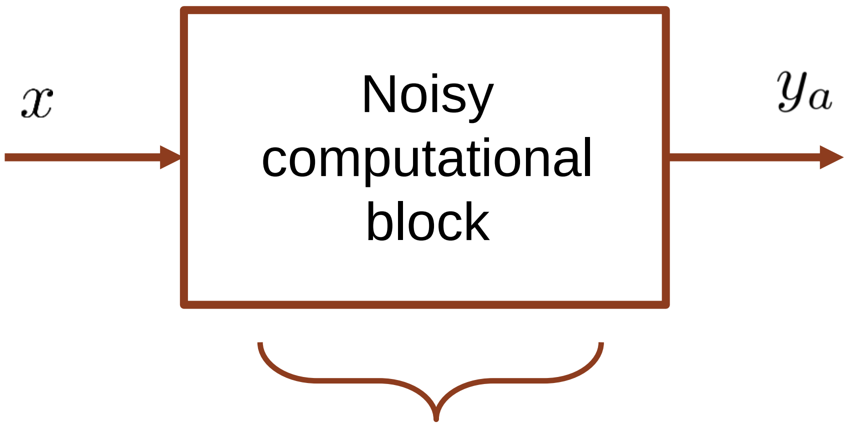


harnessing **low precision computations + stochastic fabric** to provide tremendous energy savings



noise gets “averaged out” when data is aggregated and ML models are learned

Bringing intelligence + privacy to sensors

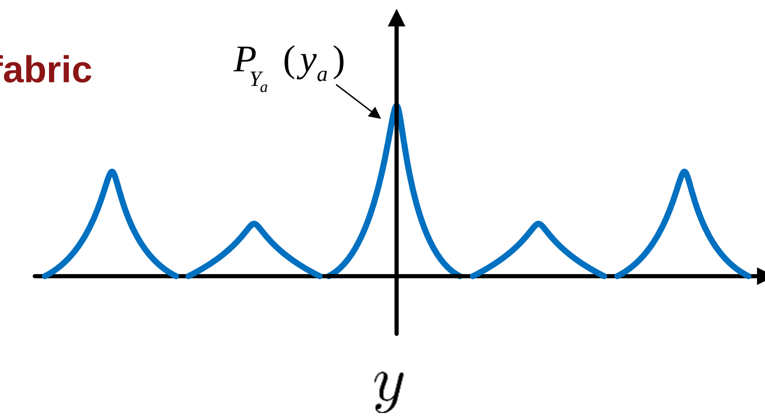


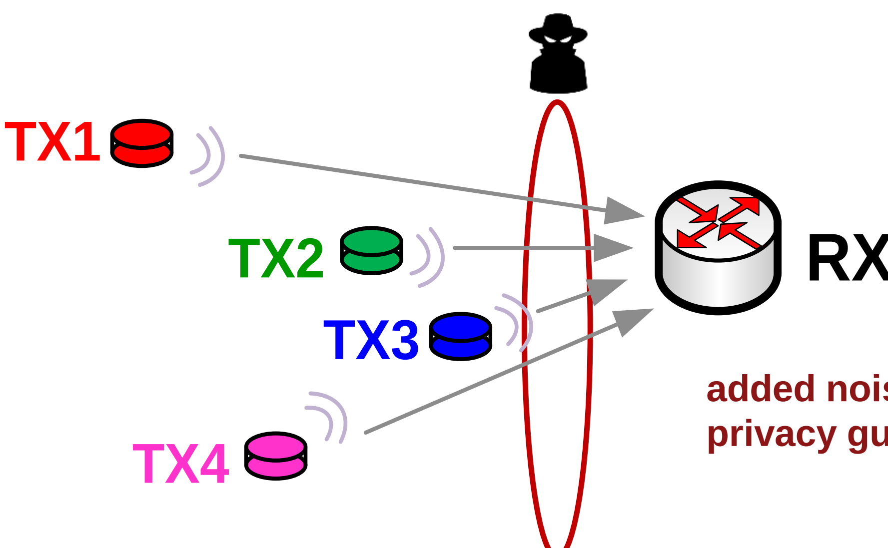
hardware errors

$$y_a = y + \eta + \varepsilon$$

errors due to low precision

harnessing **low precision computations + stochastic fabric** to provide tremendous energy savings



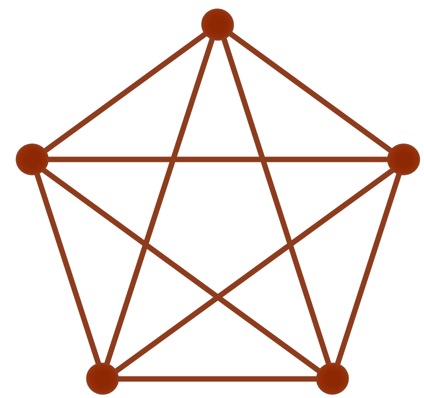


added noise provides strong privacy guarantees!

From star to mesh networks

Current implementation:
Star topology

Mesh topology



Mesh topology enables *long range coverage and high density deployment*

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Challenges of mesh networks

- Remove central node
- Bidirectional symmetric communication

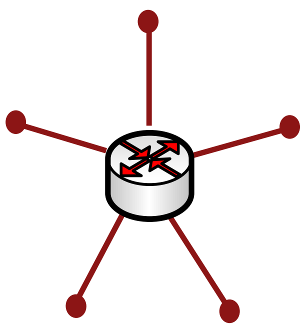
Challenges

1) Powering the nodes
2) Synchronizing the nodes
3) Lack of capable receiver
4) Routing data through the network

Thank you – please stop by our posters!

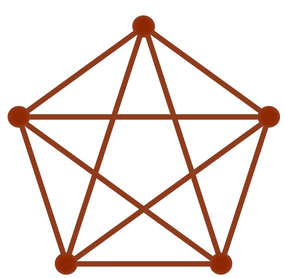
point-to-point

Embracing clock and timing uncertainty



star network

Embracing medium access uncertainty



mesh network

Embracing computational uncertainty