On Modeling Low-Power Wireless Protocols Based On Synchronous Packet Transmissions

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Motivation

Accurate mathematical models of low-power wireless protocols are important

- » Understanding (e.g., trade-offs, parameters)
- » Verification
- » System design (e.g., node placement, power sources)
- » Prediction and adaptation at runtime

But traditional **link-based** multi-hop protocols are intricate and difficult to model (e.g., ZigBee)

Motivation

Highly dynamic network topology due to:

» Volatile low-power wireless links

» Node mobility, failures

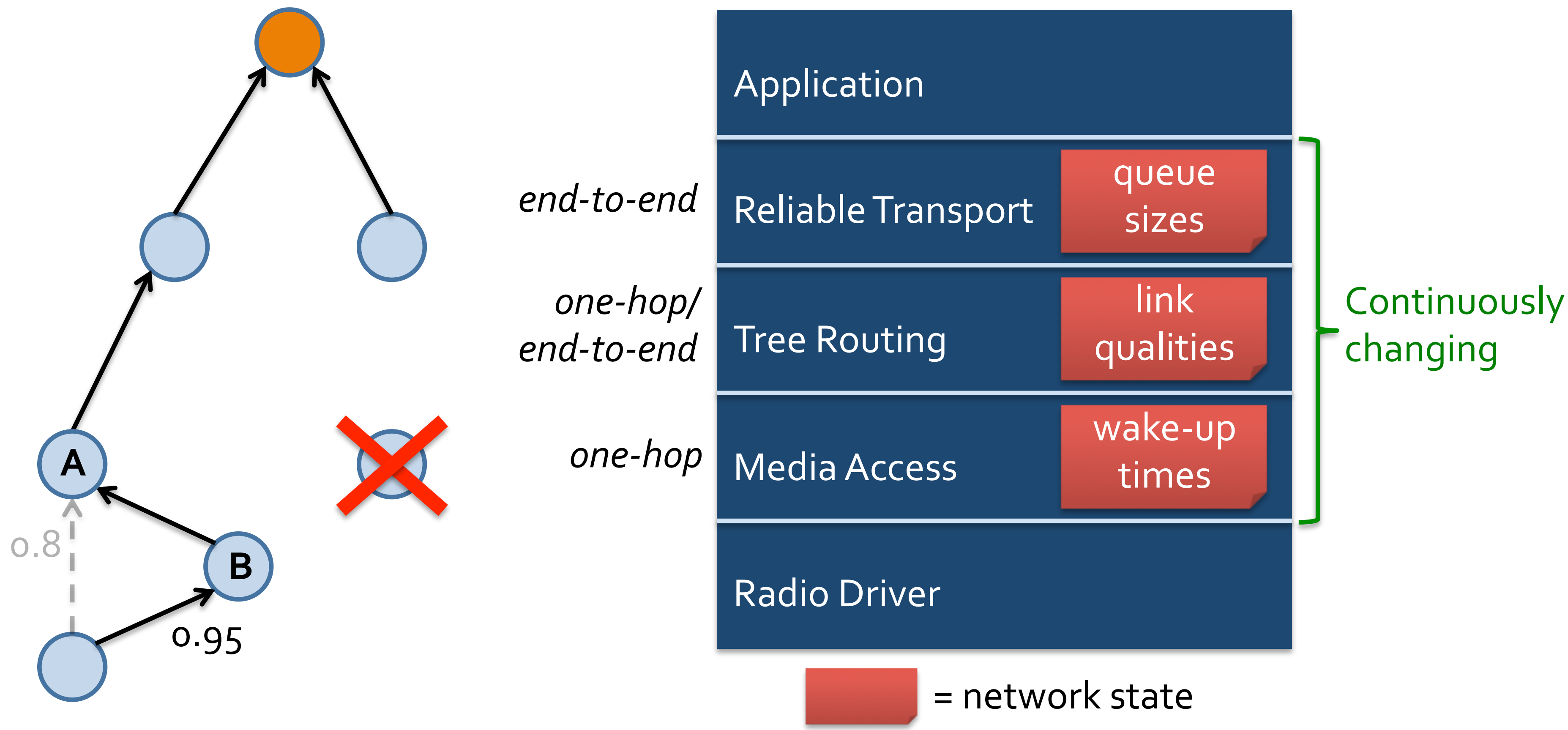
Traditional protocols maintain substantial **network state** that governs their operation (e.g., link qualities)

» Distributed across nodes

» Concurrent, uncontrolled updates

Modeling often stops at the link layer, where interactions are *single-hop* ➔ insufficient!

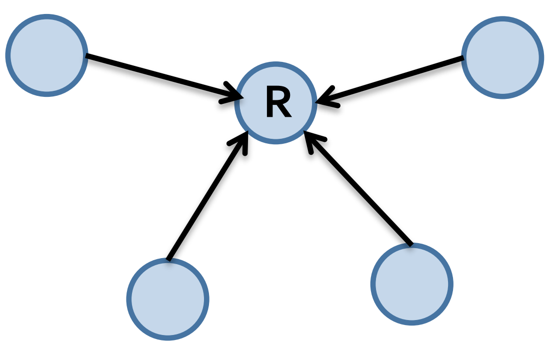
Example: End-to-End Delivery

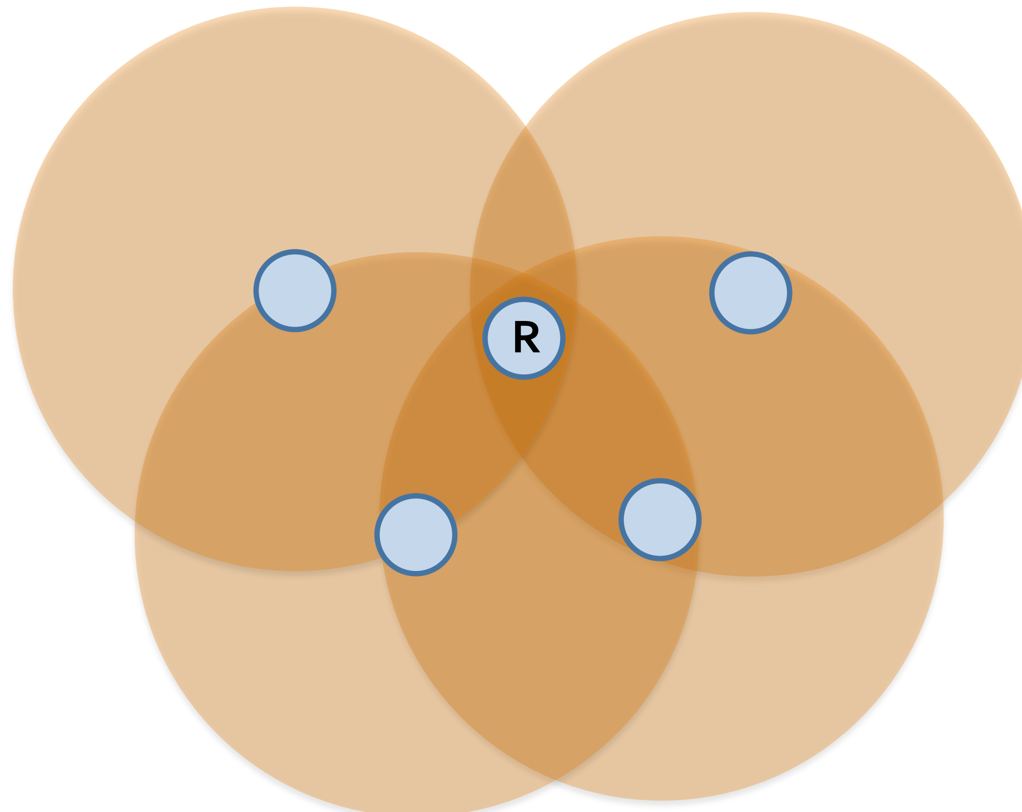


Protocols abstract the *unreliable* wireless channel as **point-to-point links ➔** major reason for complexity

Synchronous Transmissions (ST)

Multiple nodes send simultaneously to the same receiver, as opposed to pairwise *link-based transmissions (LT)*





Synchronous Transmissions (ST)

Enabled by IEEE 802.15.4 physical-layer phenomena:

- » *Power (and delay) capture* ➔ different/identical packets
- » *Constructive baseband interference* ➔ identical packets

Several recent protocols exploit ST for various purposes:

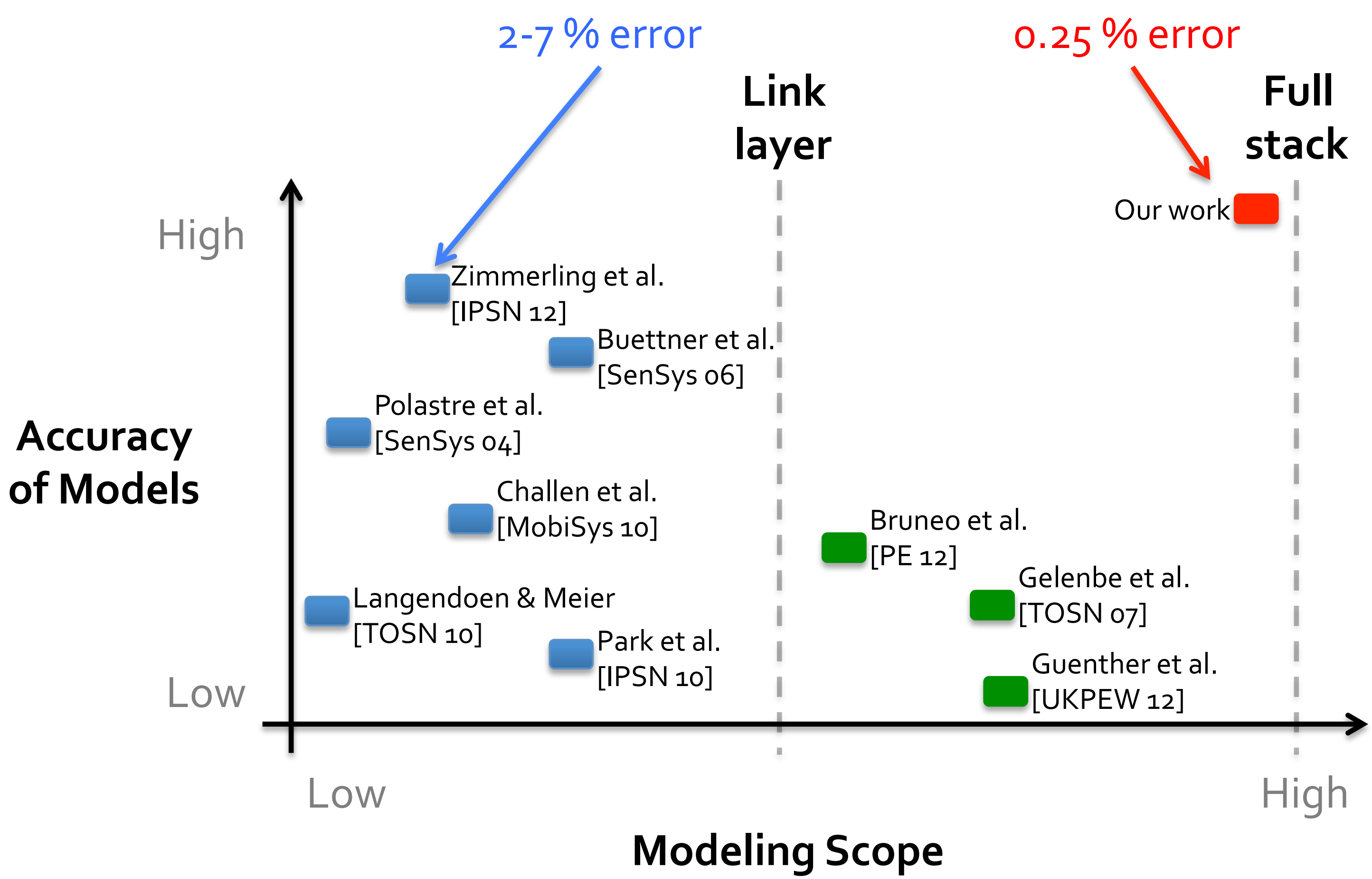
- » A-MAC [SenSys 10]: contention resolution
- » Glossy [IPSN 11]: network flooding
- » Splash [NSDI 13]: code updates
- » CAOS [SenSys 13]: all-to-all communication

ST enable efficient and reliable multi-hop protocols with *very little network state*

Open Question

Do ST also enable **simple** yet **accurate** modeling?

Modeling Trade-Off Space



Outline

Validity of the Bernoulli assumption to ST vs LT

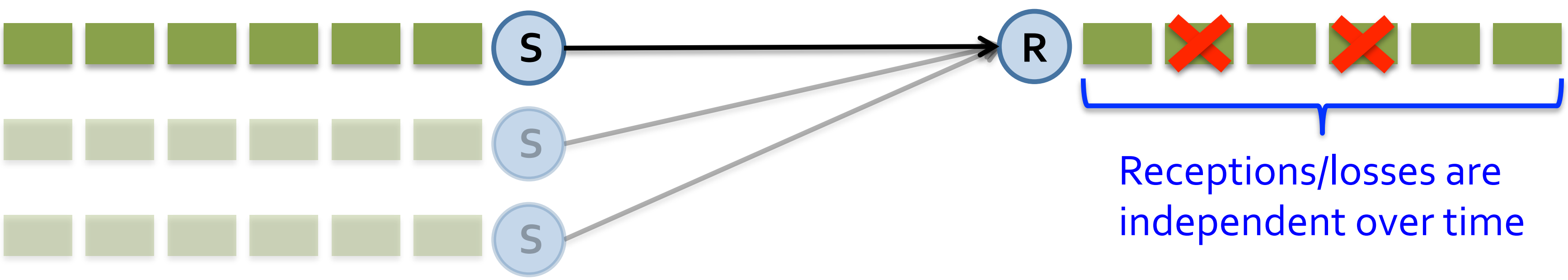
Modeling an ST-based multi-hop protocol

Model validation through real-world experiments

Bernoulli Assumption

Intended receiver of a sequence of packets observes a sequence of **i.i.d. Bernoulli trials**

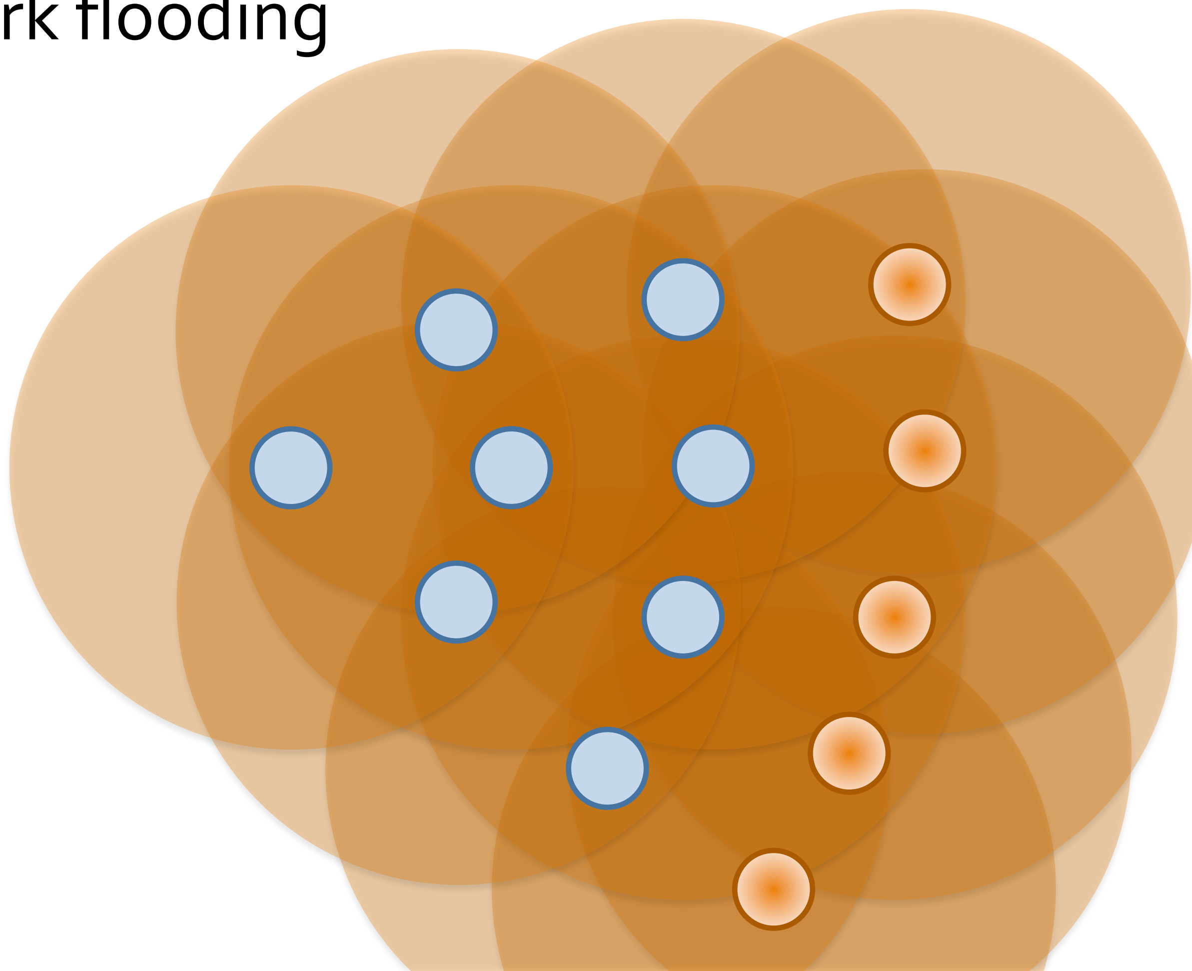
- » *Success* (packet received) with probability p
- » *Failure* (packet lost) with probability $1 - p$



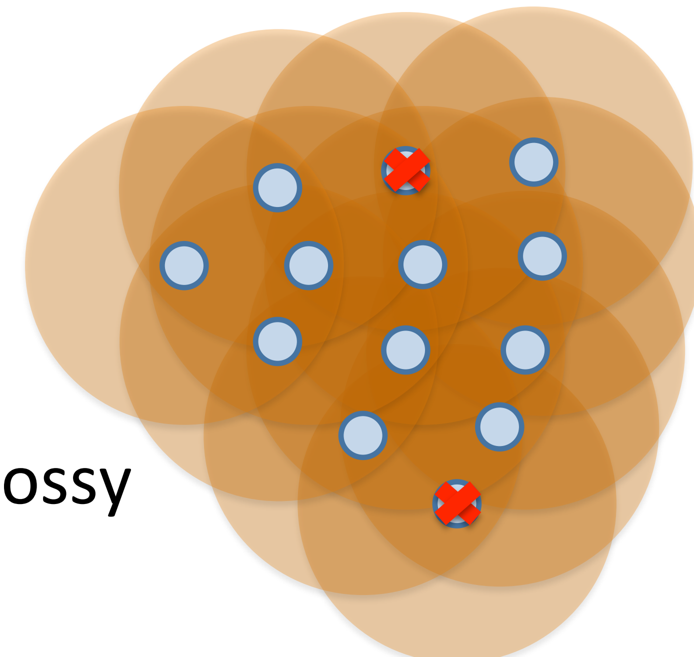
Empirical studies showed that this assumption is not always valid to LT (esp. when packets are close in time)

Methodology

Glossy [IPSN 11] leverages ST for efficient and reliable network flooding



Methodology

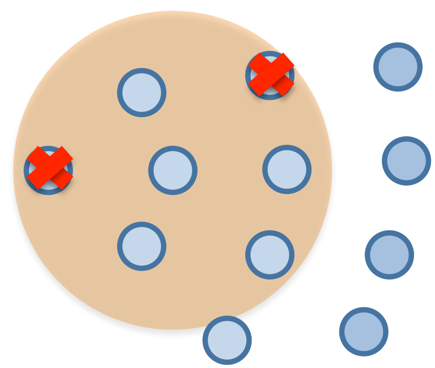


139-node testbed at NUS

20-byte packets at 20 ms IPI

ST-Type: how protocols perceive Glossy

- » 70 equally distributed nodes
- » 50,000 Glossy floods each
- » Remaining 138 nodes log



LT-Type: how protocols perceive LT

- » All 139 nodes
- » 50,000 broadcasts each
- » Nodes within radio range log

Collected >1,200,000,000 packet reception events

Trace Analysis

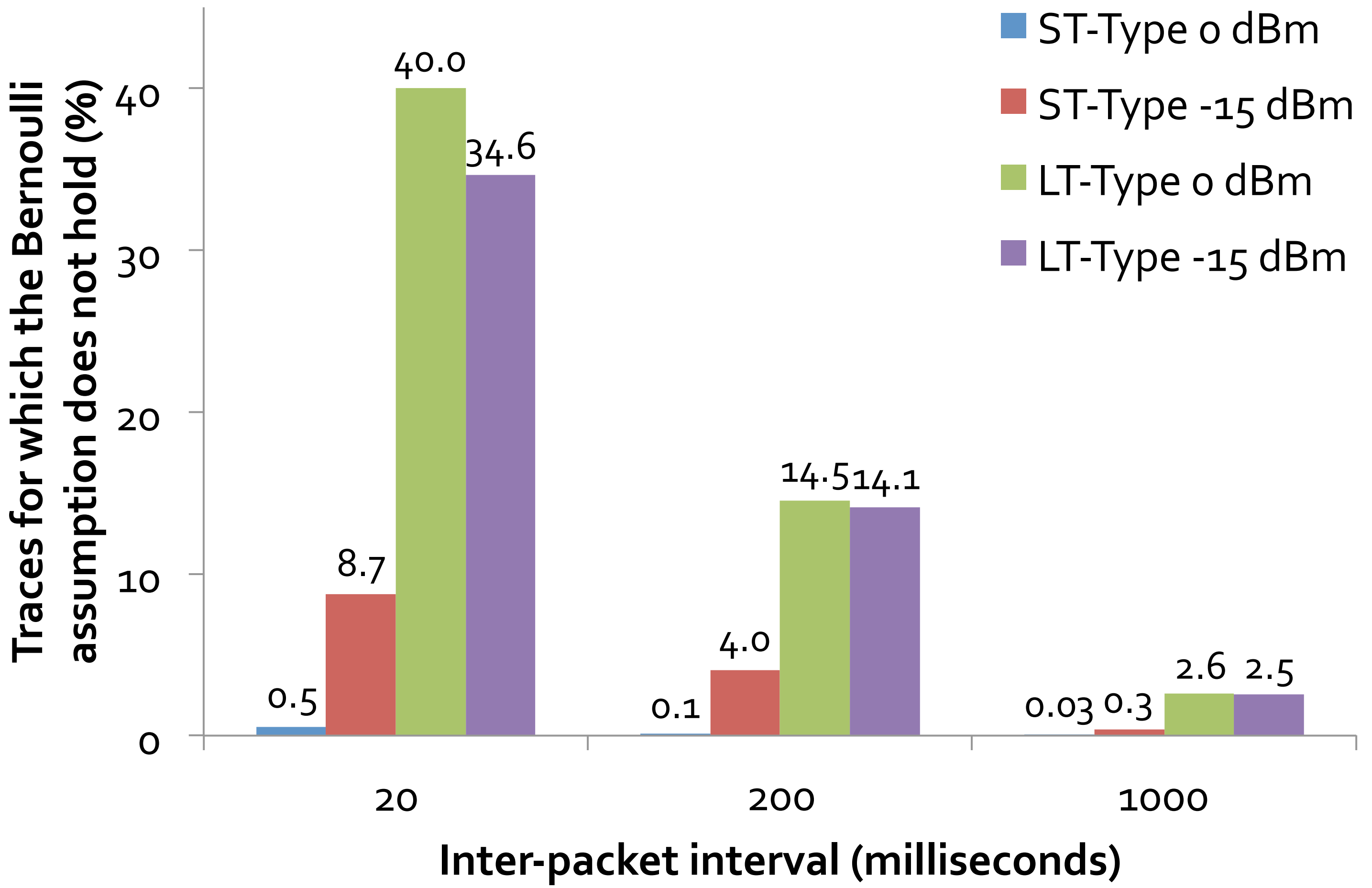
1) Represent every trace as a *discrete-time binary time series* $\{x_i\}^n$ of length n = 50,000:

   `0100111001111100111010 10...`

2) Keep only *weakly stationary* time series, using two empirical tests for non-constant mean/variance

3) Check the validity of the Bernoulli assumption, using a statistical test based on the *sample autocorrelation*

Bernoulli Results



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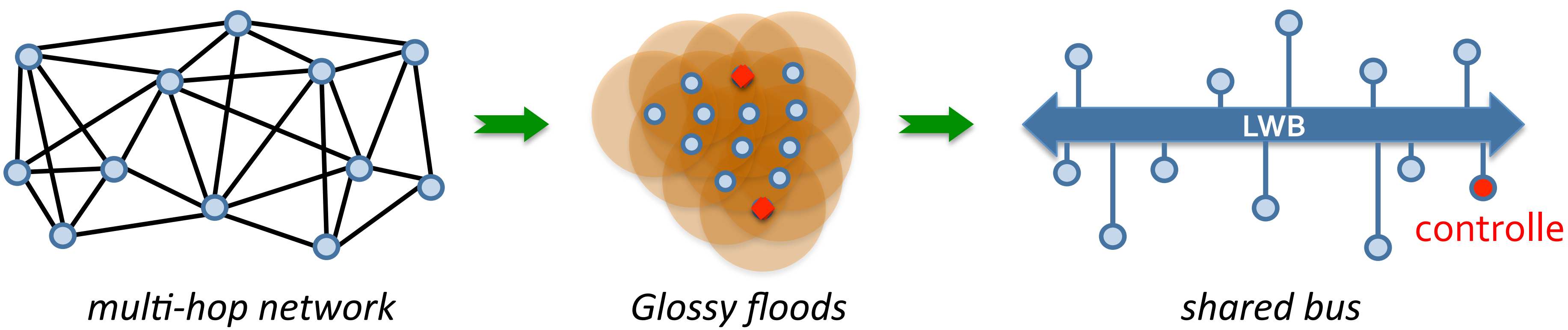
Low-Power Wireless Bus (LWB)

LWB [SenSys 12] uses **only ST** for communication

» Turns a multi-hop network into a "virtual" single-hop network, similar to a *shared bus*

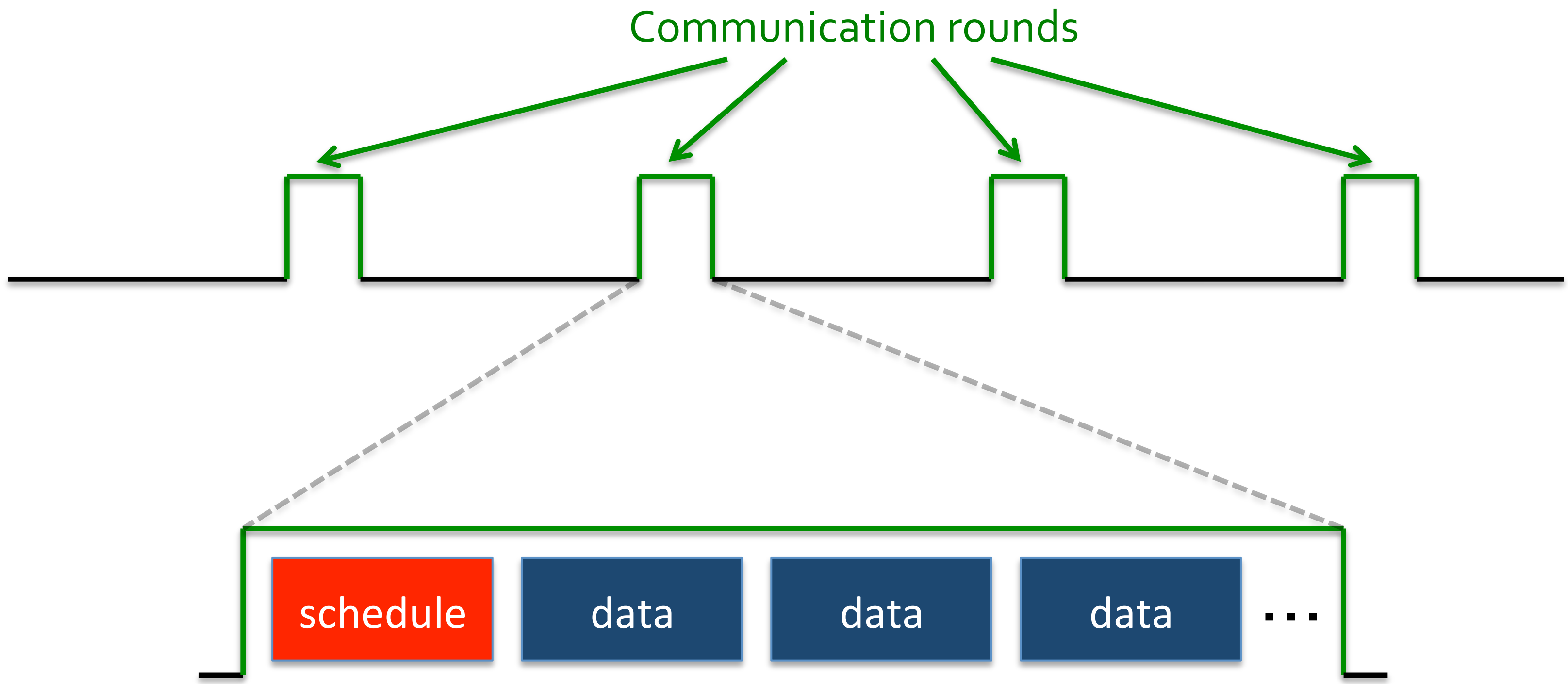


Centralized scheduling

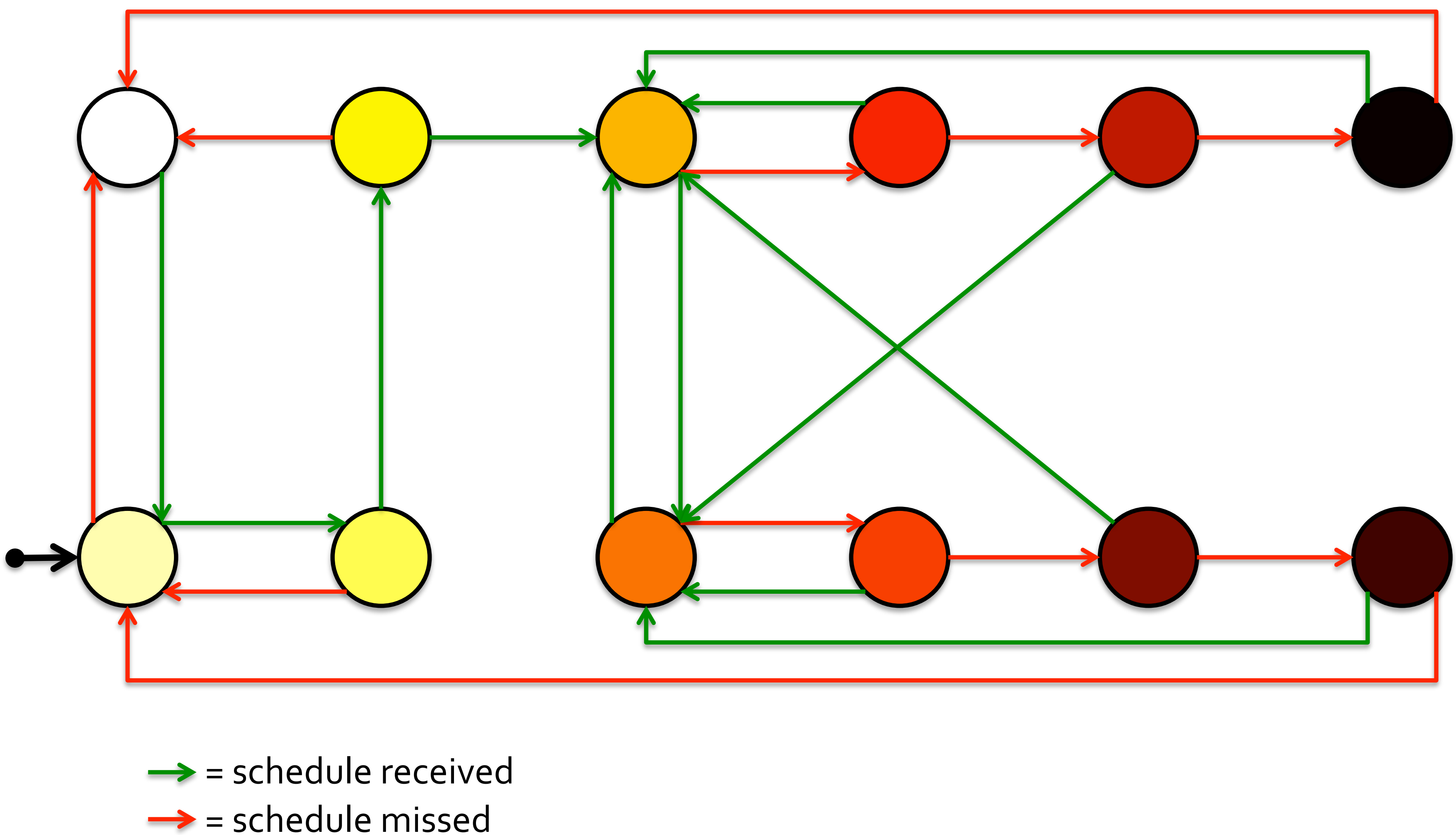
» A *controller* node orchestrates all communication

Schedule-Driven Operation

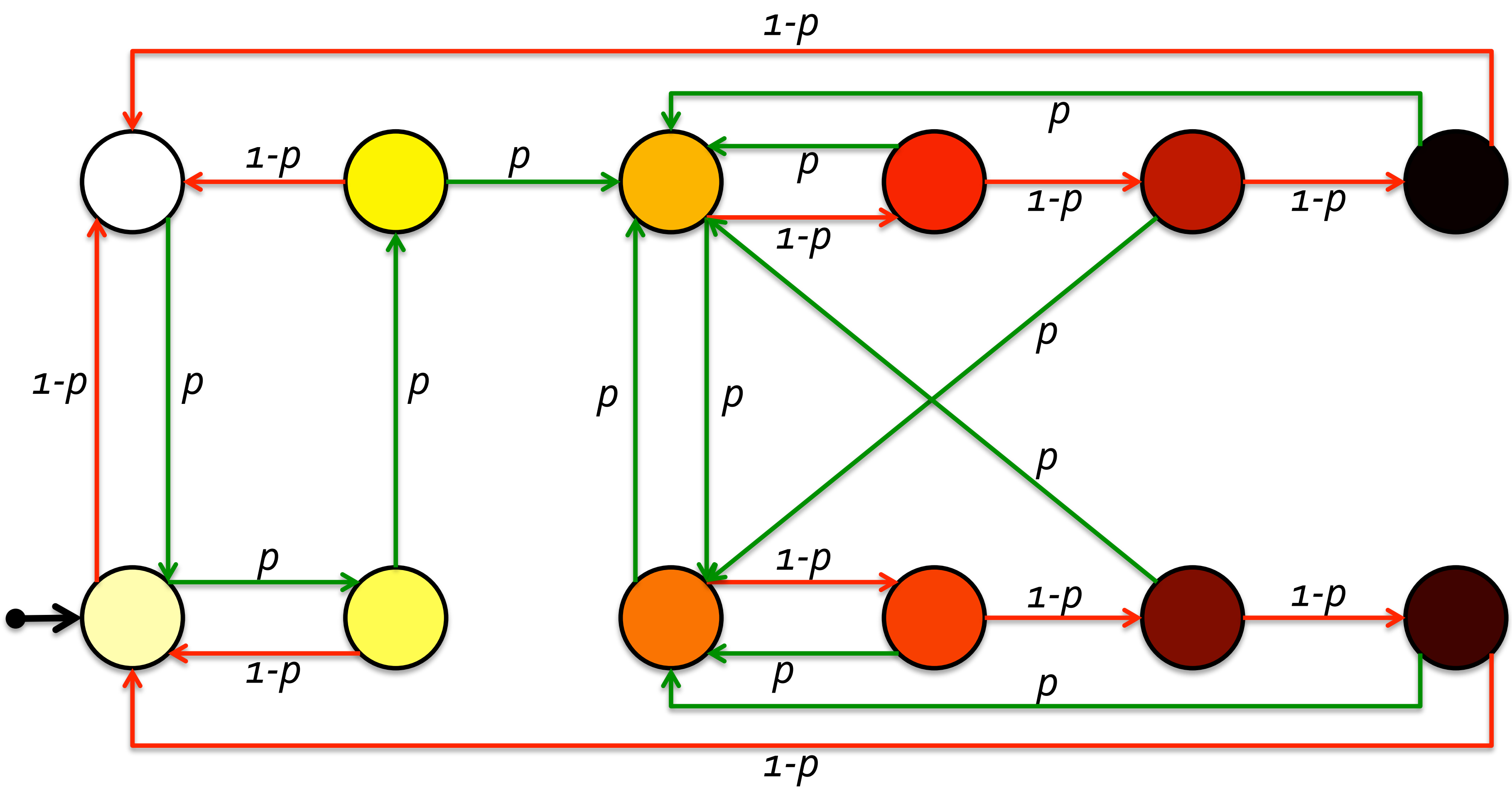
A *single* event – the reception of schedules from the controller – drives the operation of all LWB nodes



Finite-State Machine



Discrete-Time Markov Chain

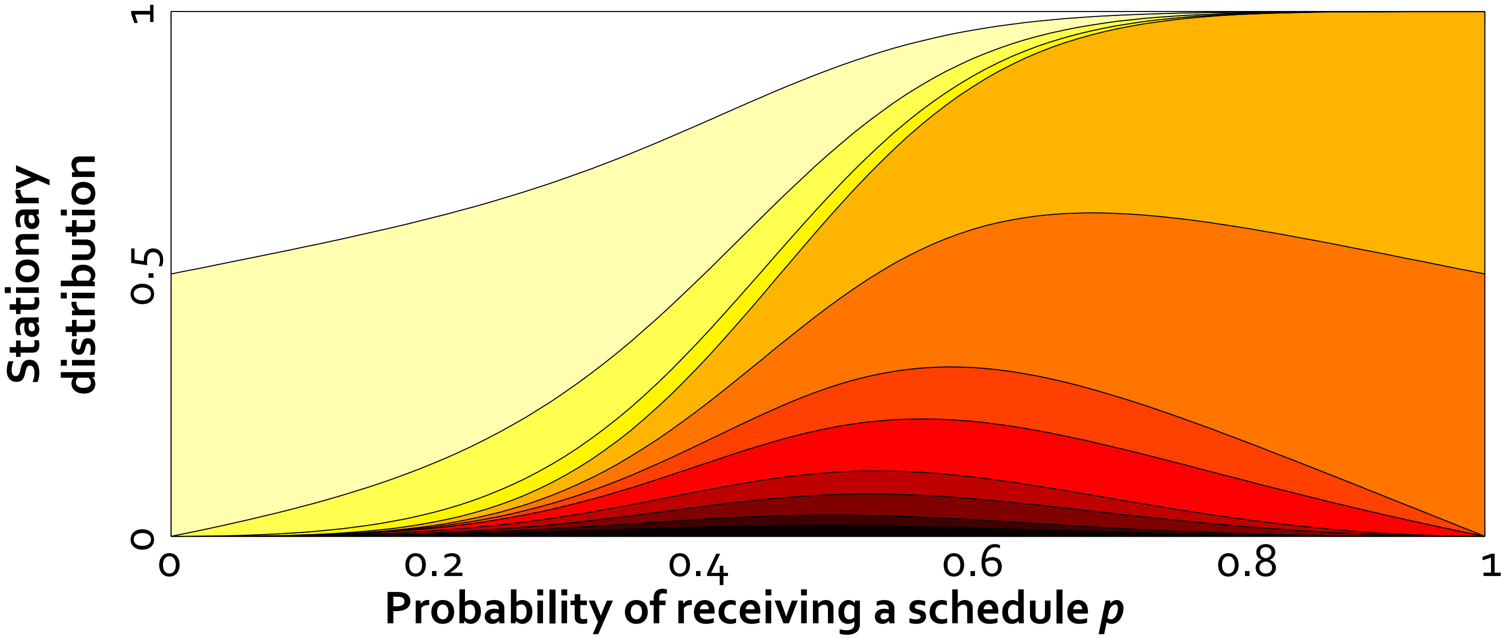


 = schedule received, with probability *p*

 = schedule missed, with probability *1-p*

Energy Model

Stationary distribution of the DTMC gives the frequency of visits to each state in the long run for a given *p*



Combined with the well-defined cost of each state, we get the long-term expected energy cost of a LWB node

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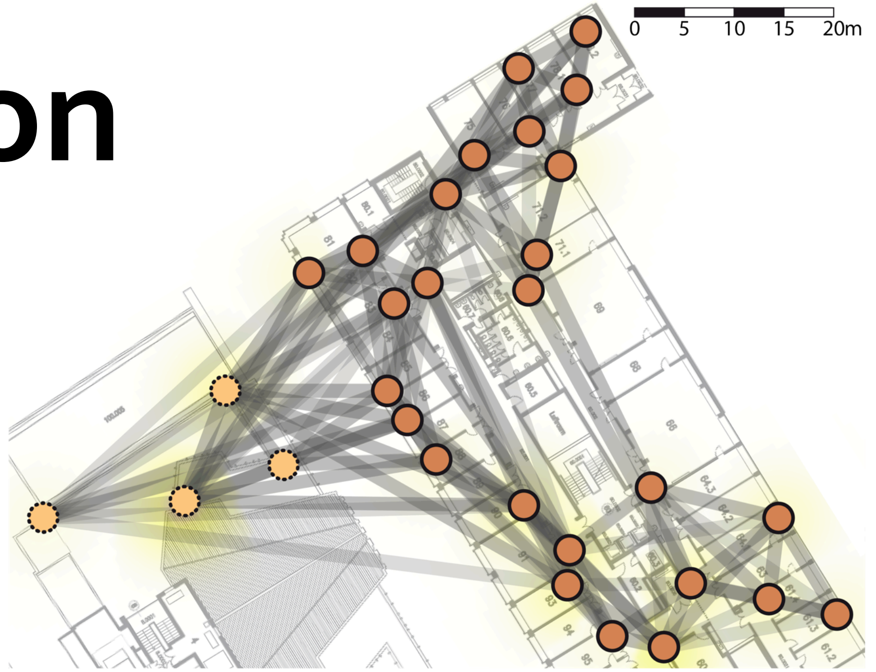
Model Validation



30-node testbed at ETH Zurich

15-byte payload at 6 sec IPI

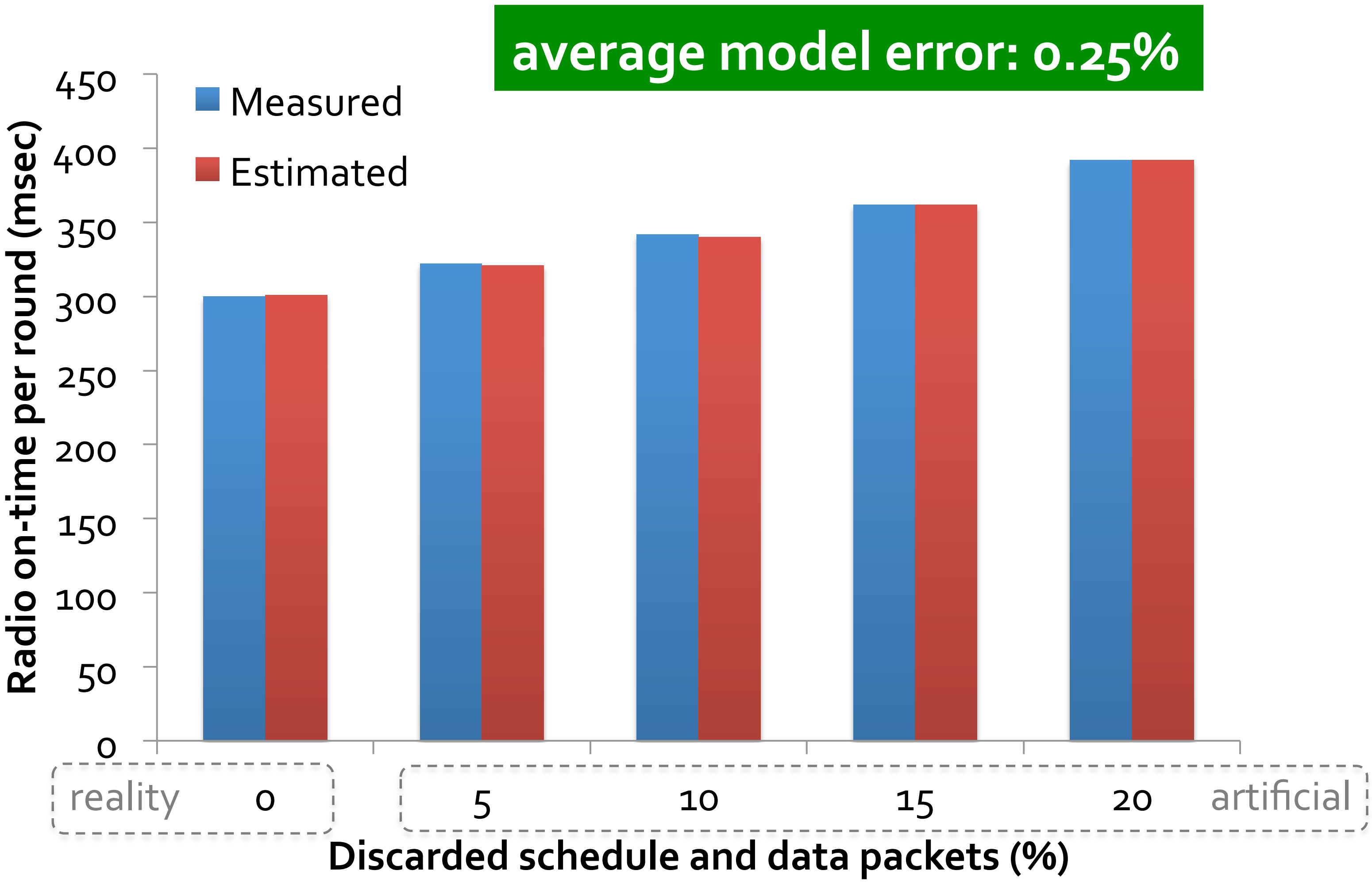
Tx power: 0 dBm (max)

Estimate several model parameters at runtime, such as:

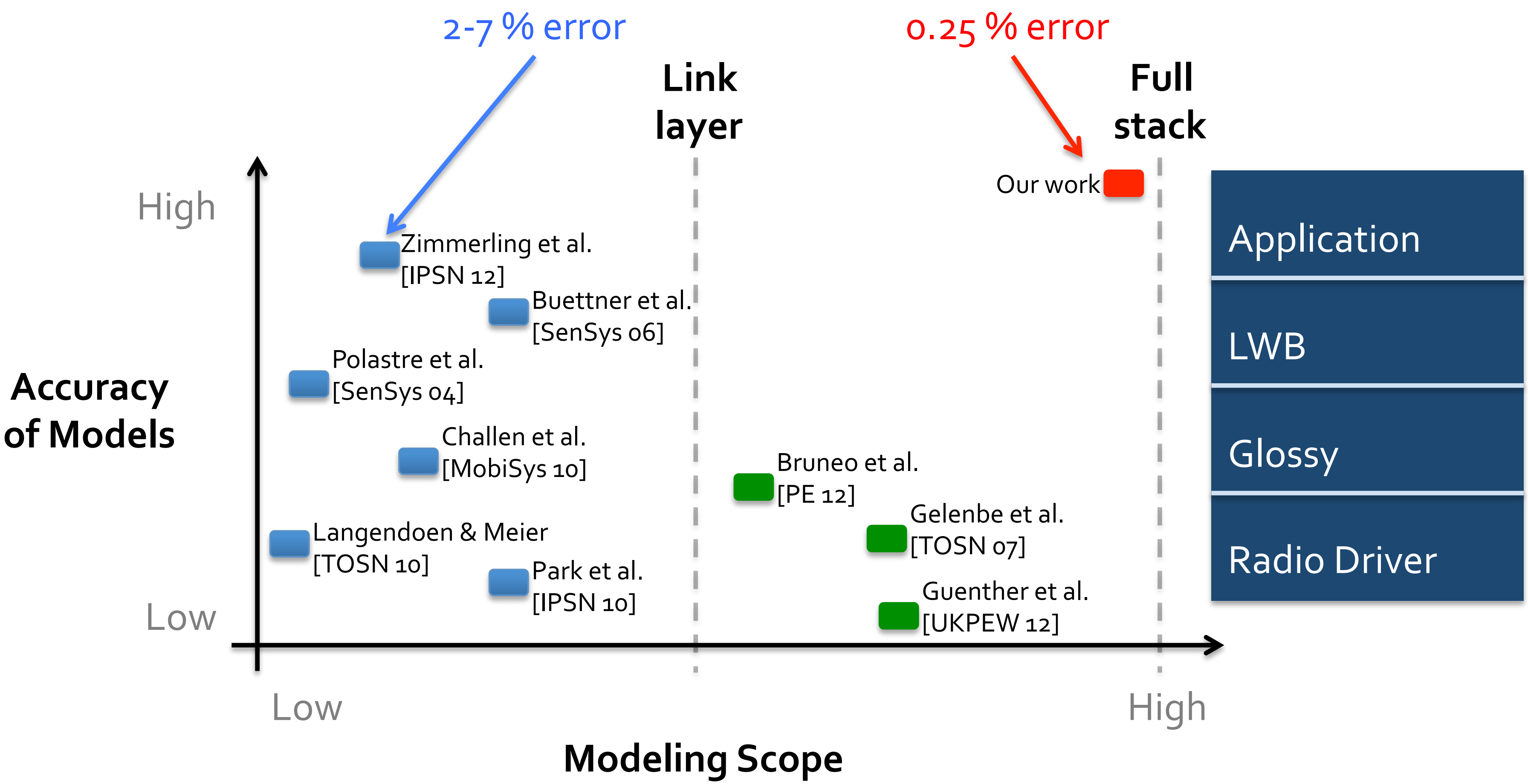
$$p = \frac{\text{number of received schedules}}{\text{number of expected schedules}}$$

Measure energy consumption using established software-based methods

Energy Validation Results



Modeling Trade-Off Space



Conclusions

The Bernoulli assumption is highly valid to ST but often illegitimate to LT

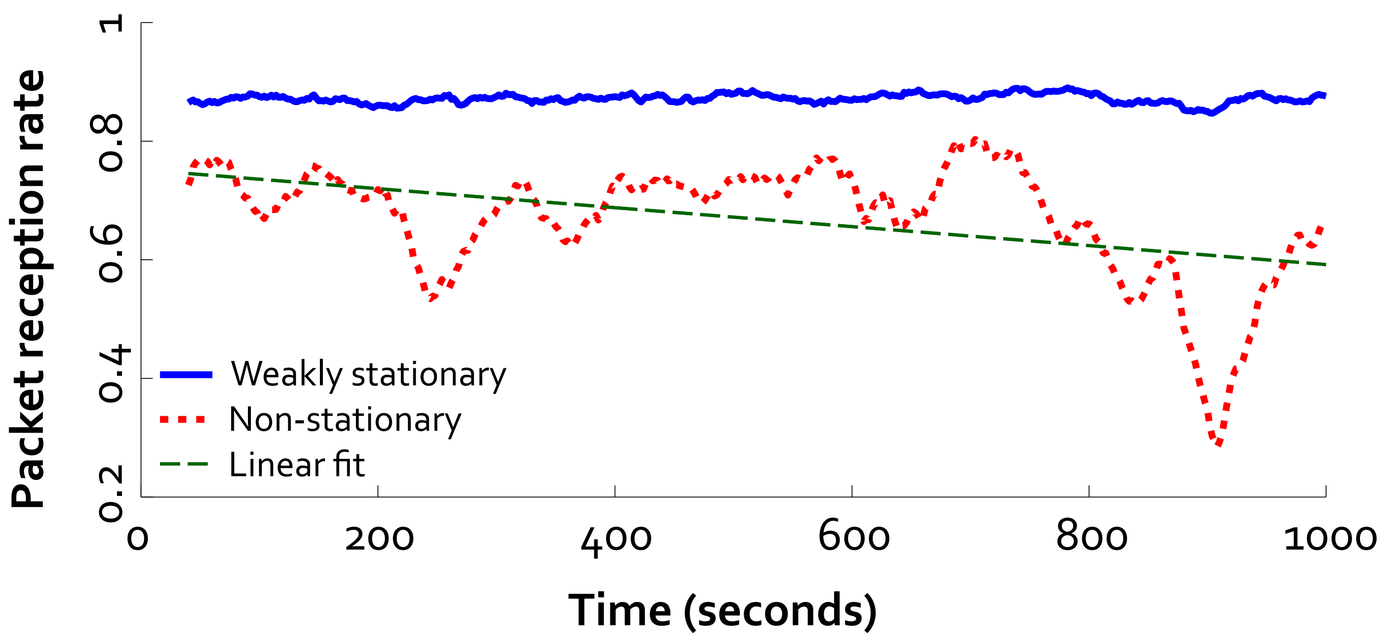
ST enable simple yet accurate modeling of a *complete* state-of-the-art low-power wireless networking stack

Test for Weak Stationarity

Formal tests (e.g., KPSS, ADF) often fail in practice

Empirically declare a trace as non-stationary if

- » PRR changes by 0.015 or more over the entire trace, or
- » PRR drops/rises by >0.05 within 40 seconds (2,000 packets)



Trace Statistics

Type	Tx power	Total	Non-stationary	Weakly stationary
ST-Type	0 dBm	9660	47	9613
ST-Type	-15 dBm	9660	256	9404
LT-Type	0 dBm	4189	1418	2771
LT-Type	-15 dBm	1777	588	1189

Validating Bernoulli

Let $\{x_i\}^n$ a realization of an i.i.d. sequence $\{X_i\}^\infty$ of random variables with finite variance

» For large n, about 95% of the sample autocorrelation values should lie within the confidence bounds $\pm 1.96/n^{1/2}$

» We consider the Bernoulli assumption valid for a given trace if the above holds already at lag 1