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

Accuracy of Models

High

Low

Link layer

2-7 \% error

Full stack

0.25 \% error

Modeling Scope

High

Low

Our work

Zimmerling et al. [IPSN 12]

Buettner et al. [SenSys 06]

Polastre et al. [SenSys 04]

Challen et al. [MobiSys 10]

Langendoen & Meier [TOSN 10]

Park et al. [IPSN 10]

Bruneo et al. [PE 12]

Gelenbe et al. [TOSN 07]

Guenther et al. [UKPEW 12]
Outline

Validity of the Bernoulli assumption to ST vs LT

Modeling an ST-based multi-hop protocol

Model validation through real-world experiments
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 \( \{x_i\}_{i=1}^n \) of length \( n = 50,000 \):
   
   010011100111110011101010...

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

Traces for which the Bernoulli assumption does not hold (%)

Inter-packet interval (milliseconds)

- ST-Type 0 dBm
- ST-Type -15 dBm
- LT-Type 0 dBm
- LT-Type -15 dBm
Outline

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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

- \( \text{schedule received} \)
- \( \text{schedule missed} \)
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
Outline

Validity of the Bernoulli assumption to ST vs LT

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Model validation through real-world experiments
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

**average model error: 0.25%**

<table>
<thead>
<tr>
<th>Discarded schedule and data packets (%)</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Radio on-time per round (msec)

- reality: 0
- artificial: 20
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Application

LWB

Glossy

Radio Driver
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

<table>
<thead>
<tr>
<th>Type</th>
<th>Tx power</th>
<th>Total</th>
<th>Non-stationary</th>
<th>Weakly stationary</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-Type</td>
<td>0 dBm</td>
<td>9660</td>
<td>47</td>
<td>9613</td>
</tr>
<tr>
<td>ST-Type</td>
<td>-15 dBm</td>
<td>9660</td>
<td>256</td>
<td>9404</td>
</tr>
<tr>
<td>LT-Type</td>
<td>0 dBm</td>
<td>4189</td>
<td>1418</td>
<td>2771</td>
</tr>
<tr>
<td>LT-Type</td>
<td>-15 dBm</td>
<td>1777</td>
<td>588</td>
<td>1189</td>
</tr>
</tbody>
</table>
Validating Bernoulli

Let \( \{x_i\}_1^n \) 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