Poster Abstract: Synchronous Transmissions Enable Simple Yet Accurate Protocol Modeling

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ABSTRACT

Traditional low-power wireless protocols maintain *distributed network state* to cope with link dynamics. Modeling the protocol operation as a function of network state is difficult as the state is frequently updated in an uncoordinated fashion. Recent protocols use *synchronous transmissions (ST)*: multiple nodes send simultaneously towards the same receiver, as opposed to pairwise *link-based transmissions (LT)*. ST enable efficient multi-hop protocols with little network state.

We studied whether ST in Glossy enable simple yet accurate protocol modeling [10]. Based on extensive testbed experiments and statistical analyses, we found that: (*i*) unlike LT, packet receptions and losses with ST largely adhere to a sequence of independent and identically distributed (i.i.d.) Bernoulli trials; (*ii*) this property greatly simplifies accurately modeling ST-based protocols, as we demonstrated by obtaining model errors below 0.25% in energy for the Glossy-based Low-Power Wireless Bus (LWB).

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*wireless communication*

Keywords

Protocol modeling, synchronous transmissions, Glossy, Low-Power Wireless Bus, Bernoulli, wireless sensor networks

1. MOTIVATION AND KEY FINDINGS

To tame the unpredictability of low-power wireless links, traditional multi-hop protocols maintain substantial network state, such as link quality estimates [1]. The network state is distributed across the nodes for scalability reasons and constantly updated in an uncoordinated fashion against topology dynamics. This renders modeling the operation of these protocols as a function of network state extremely difficult.

Using *synchronous transmissions (ST)*, several nodes send simultaneously towards the same receiver. It has been shown that ST improve the one-hop communication reliability over link-based transmissions (LT) [5], thereby enabling efficient multi-hop protocols with little network state [6]. The open question is whether ST simplify accurate protocol modeling.

We have sought and found an answer to this question [10] based on one specific flavor of ST: Glossy network floods [7]. Several recent protocols build upon [6] or extend [4] Glossy. Our results from extensive testbed experiments and statistical time series analyses revealed the following key findings:

- Packet receptions and losses with ST largely adhere to a sequence of independent and identically distributed (i.i.d.) Bernoulli trials. The *Bernoulli assumption* is common but not always valid when modeling LT-based protocols [9].
- The validity of the Bernoulli assumption to ST allows for simpler and highly accurate protocol models. We demonstrated this by devising models of reliability and energy for the Glossy-based LWB [6]. For example, the model error in energy is within 0.25% from the real measurements, a figure never reported before in the related literature.

We detail our methodology and results in Sec. 2, and discusses the implications of our findings in Sec. 3.

2. METHODOLOGY AND RESULTS

Bernoulli assumption. Let a sequence of transmissions be a random event with success or failure as the only possible outcomes. The Bernoulli assumption stipulates that the receiver sees a sequence of i.i.d. Bernoulli trials. In practical terms, success means a packet is received with probability p, and failure means a packet is lost with probability $1 - p$.

We found that the Bernoulli assumption is highly valid to ST and significantly more valid to ST than to LT, based on the following methodology (see [10] for more details).

Methodology. We conducted two types of experiments for a total of 80 hours on the 139-node Indriya testbed [3]:

1) *ST-Type* experiments investigate how protocols perceive network-wide Glossy floods.
2) *LT-Type* experiments study how traditional protocols perceive single-hop independent broadcast transmissions.

We collected more than 1,200,000,000 events, grouped into packet reception traces of length $n = 50{,}000$. We represented each trace as a discrete-time binary time series $\{x_i\}_{i=1}^{n}$ where x_i is 1 if the i-th packet was received and 0 if it was lost. To avoid biases in the analysis, we checked for *weak stationarity*, a necessary condition for sound time series analyses [2], and removed about 10% of traces that violated this condition.

Next, we computed the *sample autocorrelation* $\hat{\rho}$ [2], which measures the linear dependence between the values of a time series as a function of the interval (lag) between them. Val-

SenSys'13, November 11–15, 2013, Roma, Italy.

ACM 978-1-4503-2027-6/13/11
http://dx.doi.org/10.1145/2517351.2517419.

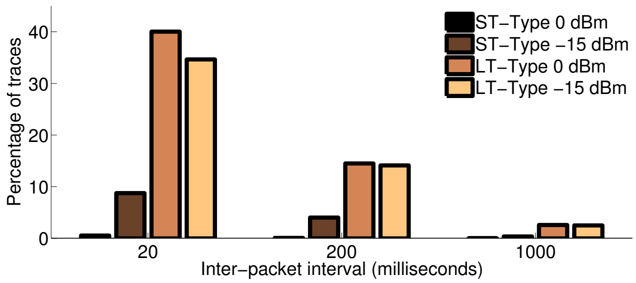

Figure 1: Percentage of weakly stationary traces for which the Bernoulli assumption does *not* hold.

ues of $\hat{\rho}$ range between -1 and 1. Negative ones indicate that as more packets are received (lost), the next packet is more likely to fail (succeed); the dual holds for positive values. If the samples in a time series are i.i.d. Bernoulli, values close to zero indicate independence among packet receptions at a given lag. It can be shown that, for many samples, a major portion of the sample autocorrelation values at lag 1 should fall within certain confidence bounds around zero [2]. Based on this, we constructed a statistical test to confirm or refute the Bernoulli assumption (henceforth BA) for a given trace.

Results. Fig. 1 plots the percentage of traces for which BA does *not* hold, for different inter-packet intervals (IPIs) and transmit powers. At 0 dBm, BA holds for more than 99% of the ST-Type traces irrespective of the IPI, whereas it holds only for 60% of the LT-Type traces at the smallest IPI. This shows that BA is significantly more valid to ST than to LT.

At -15 dBm, there are more ST-Type traces for which BA does not hold. At this low transmit power many nodes have only a few neighbors, which makes their reception behavior approach the one of LT. The percentage of traces for which BA does not hold decreases with longer IPIs, and becomes negligible at IPI = 1 s also for the LT-Type traces. This is in line with prior studies on LT [9], validating our methodology.

Modeling LWB. We leveraged the validity of BA to ST in Glossy for modeling end-to-end packet reliability and energy consumption in the Glossy-based LWB [6]. As for the latter, we note that the behavior of a LWB node is largely driven by a single event—the reception of schedule packets. Because BA holds, we can consider consecutive schedule receptions as independent, indicating their probability of success with a single parameter p_s. This allowed us to model the behavior of a LWB node as a discrete-time Markov chain (DTMC), shown in Fig. 2 to illustrate its minimality. Given the transition matrix of the DTMC and the radio on-time of every LWB state, which can be precisely estimated [10], we obtain the stationary distribution of the DTMC and hence the long-term expected radio on-time of an LWB node.

Fig. 3 shows that our model is highly accurate. The average relative model error is within 0.25% from measurements obtained during real executions on the FlockLab testbed [8]. In comparison, recent work on modeling LT-based multi-hop protocols reports errors in the range of 2–7% [11]—one order of magnitude larger than ours. We achieve this while modeling a complete low-power wireless stack, demonstrating that ST indeed enable simple yet accurate protocol modeling.

3. VALUE TO SENSOR NETWORKING

Models play an important role throughout the lifecycle of a protocol, from understanding to deployment and formal

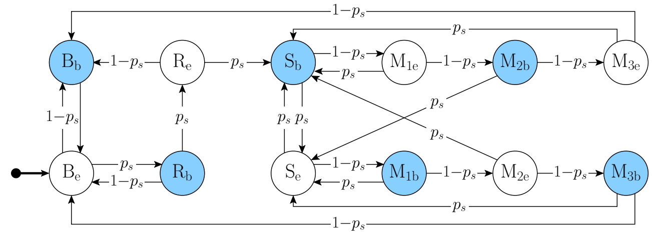

Figure 2: DTMC modeling the behavior of a LWB node receiving schedules with success probability p_s.

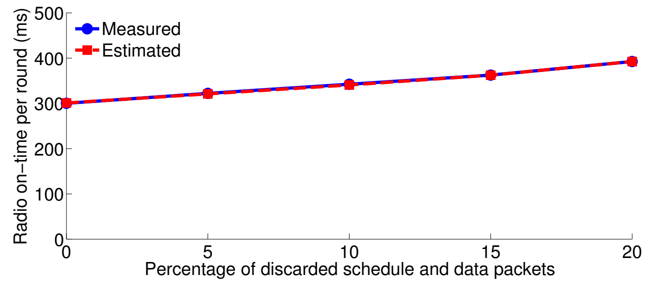

Figure 3: Radio on-time per round, estimated and measured. The model error is as low as 0.25%.

verification to runtime adaptation. The complexity of LT-based multi-hop protocols, however, renders accurate modeling extremely difficult. A new breed of protocols using ST is currently emerging. We found that ST not only improve on performance but also enable simpler and highly accurate protocol models. We maintain that our findings are of great value to the sensor network community, hopefully fostering further research into ST and new protocols exploiting them.

Acknowledgments. This work was supported by Nano-Tera, projects X-Sense and OpenSense, the Swedish Foundation for Strategic Research, and programme IDEAS-ERC, project EU-227977 SMScom.

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