SRVF: An Energy-Efficient Link Layer Protocol for Reliable Transmission over Wireless Sensor Networks[*]

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Abstract— **The 802.15.4 WSN standard provides optional reliability through positive acknowledgments. Since positive-ACKs are not designed for energy efficiency, there is significant room for improvement in the energy usage of reliable 802.15.4. In this paper, we propose a new reliable link layer protocol, referred to as the Selective Retransmission using Virtual Fragmentation (SRVF) protocol. SRVF requires simple modifications to reliable 802.15.4, but provides substantial improvements in energy efficiency. The main premise of the proposed protocol is to localize bit-errors by performing partial checksums on disjoint parts or virtual fragments of a packet. In case of error, only the corrupted virtual fragments are retransmitted. We analytically model reliable 802.15.4 and SRVF as Markov chains operating over an arbitrary-order Markov wireless channel, and show that SRVF provides significant theoretical improvements over reliable 802.15.4. We then use bit-error traces collected over a real sensor network testbed to experimentally evaluate the two reliable protocols. These experimental results show that SRVF has consistently and considerably better energy efficiency than the reliable 802.15.4.**

I. INTRODUCTION

The 802.15.4[1] wireless sensor networks standard supports an optional reliability scheme that relies on positive acknowledgements. However, this scheme has not been designed for energy efficiency. In this paper, we propose simple modifications to the 802.15.4 based on the observation that all the data in a corrupted frame is not in error, and therefore it is not necessary to retransmit the complete frame. We propose to localize the errors in a MAC frame by dividing the frame into disjoint parts, referred to as *virtual fragments*. On reception of a corrupted frame, only the virtual fragments in error are retransmitted. The proposed protocol is referred to as Selective Retransmission using Virtual Fragmentation (SRVF).

There have been efforts to model and improve the energy efficiency of transmission reliability on wireless sensor networks [3]−[11]. However, these schemes have significant level of complexity involved to replace reliable 802.15.4 and generally lack a mathematical model. SRVF is a simple hop by hop reliability protocol that relies on virtual fragment concept and does not assume availability of any additional hardware on sensor motes.

In this paper, we use a comprehensive dataset of bit-error traces collected using MicaZ motes[1]. We develop Markov chain models for reliable 802.15.4 and SRVF protocols. From these models, we derive expected values of the total number of bit transmissions that are required to reliably transmit a frame over the *K*-th order Markov channel. These models show that SRVF requires significantly lesser energy for reliable transmission than reliable 802.15.4. We verify our theoretical findings through trace-driven simulations of SRVF and reliable 802.15.4. These simulations show that an average of approximately 12% and up to 30% improvements in energy efficiency can be achieved using the proposed SRVF protocol.

II. DESCRIPTION AND ANALYTICAL MODELING OF RELIABLE 802.15.4 AND SRVF PROTOCOLS

In this section, we describe Selective Retransmissions using Virtual Fragmentation (SRVF) protocol. We quantify energy efficiency as the total number of transmitted bits. Therefore, in all following discussions the phrases “energy efficiency” and “number of bits” are used interchangeably.

A. Selective Retransmission using Virtual Fragmentation (SRVF)

SRVF is an ACK based protocol which operates as follows: Before transmitting a data frame, the sender logically divides the checksum field in the frame header into distinct equal-sized blocks. Each checksum block then covers a distinct logical block in the data or header part of the frame. These distinct data and header blocks are referred to as *virtual fragments*. After computing the partial checksums on these virtual fragments, the sender transmits the MAC data frame with the ACK bit set in the header. After receiving the packet, the receiver calculates the checksum for each virtual fragment separately. If the checksum is correct for every fragment, an ACK frame is sent to the sender indicating no error. If the ACK frame is received correctly at the sender, data frame transmission is considered successful.

If any *fragment checksum* fails at the receiver, the receiver sends a *fragment ACK frame* that contains information about which fragments are in error. A fragment ACK frame is not sent if all virtual fragments are in error. In that case, the sender times out and retransmits the entire frame. Otherwise, if the sender receives the fragment ACK without errors, it retransmits those virtual fragments that have errors. A pictorial description of a typical frame transmission using SRVF is given in Figure 1.

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[*] This work is supported by Nokia Research, China.

[1] These traces are available at http://www.wisnet.niit.edu.pk/data/

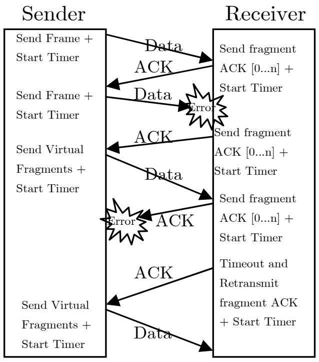

Figure 1: Typical protocol messaging for the SRVF protocol

B. Analytical Modeling of Energy Efficiency

We quantify energy efficiency of a protocol as the number of bits that are required to reliably transmit one fixed-sized data frame over an H -hop wireless sensor network. As in the 802.15.4 standard, we assume that reliability is provided on a hop-by-hop basis. To theoretically compare the energy efficiency, we develop analytical Markov chain models of both reliable 802.15.4 and SRVF protocols. In case of a collision both the protocols will have to retransmit the entire packet. Therefore, we ignore collision overhead in the analysis.

Let n_{data} and n_{hdr} represent the number of data and header bits in the MAC data frame. In 802.15.4, n_{hdr} = 104 bits are used in the short addressing mode [1]. Similarly, let n_{ack} represent the number of bits in an acknowledgment (ACK) frame; n_{ack} = 40 bits for 802.15.4 short addressing mode.

Throughout this section, we assume that all hops of the WSN are independent K -th order Markov channels, where K is a fixed arbitrary integer. Thus although the parameters of the channel on each hop might differ, the order of the Markov channel model at each hop is fixed. While we already know that $K = 3$ for 802.15.4 residual channels [14], we perform all our analysis for a parameterized value of K so that the analysis is valid for Markov channels of arbitrary order. Due to the hop-by-hop independent channel assumption, we can perform our analysis for a single hop and a product of the derived expressions will provide the final expression over H hops.

For the single-hop analysis, we do not use any superscript for the transition and steady-state probabilities. For the complete H -hop expression, π_i^m and $p_{i,j}^m$ are used to denote the steady-state and transition probabilities on the m -th hop to the destination.

1) Probability of Frame Error

We first compute the probability of receiving an error-free frame of length L bits on a single-hop K -th order Markov model. This probability is dependent on the present state of the model. If the last received bit is error-free then the state is referred to as an even state otherwise it is referred as an odd state.

Let us first focus on the scenario of being in an even state and receiving L consecutive good bits. Throughout this paper, we follow a realistic assumption that $L > K$, where K is the memory-length of the Markov process. There are a total of 2^K states in K-th order Markov model. These states are implicitly defined as $\bmod 2^K$ throughout the paper. Every state i , $0 \le i \le 2^K - 1$ of this model can transit to only two other states: i.e. to states $2i$ (even state) or $2i+1$ (odd state).

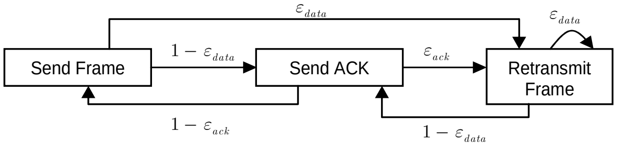

Figure 2: Markov model of Reliable 802.15.4

Let Markov state $2i$, $0 \le i \le 2^K - 1$, be the current even state of the K -th order Markov channel model. We choose state $2i$ as the starting state because of our assumption of starting in an even state. Thus the current state $2i$ can transit to either state $2(2i)$ or state $2(2i)+1$. Since we are only concerned with bursts of error-free bits, the probability of getting an error-free bit starting in state $2i$ is $p_{2i,2(2i)}$. Recall that if next bit is error free then next state is an even state. To get an error-free frame, we must stay in the even states for every remaining state transition which implies that after (at most) $K-1$ transitions, system will be in state 0 , giving the following state sequence:

$$2i = 2^0(2i) \to 2(2i) = 2^1(2i) \cdots \to \left(2^{k-1}(2i)\right) \bmod 2^K = 0.$$

From that state, to get the remaining error-free bits, the next $L-(K-1)$ transitions will be from state 0 to state 0 . To generalize the above discussion in terms of the parameters of the channel model, the probability of getting a burst of L good bits starting in state $2i$ is given by $\pi_{2i}\prod_{j=0}^{K-2} p_{2^j(2i),2^{j+1}(2i)}\left(p_{0,0}\right)^{L-(K-1)}$. This probability, summed over all possible even Markov states, yields $\sum_{i=0}^{2^{K-1}-1}\pi_{2i}\prod_{j=0}^{K-2} p_{2^j(2i),2^{j+1}(2i)}\left(p_{0,0}\right)^{L-(K-1)}$.

Based on the above discussion, the probability that a data frame will be corrupted by bit-errors during transmission is

$$\varepsilon_{data} = 1-\left(p_{0,0}\right)^{n_{hdr}+n_{data}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1}\prod_{j=1}^{K} p_{2i+1,2^j(2i+1)}\right). \tag{1}$$

The above expression gives the overall probability of getting one or more bit-errors in $n_{hdr} + n_{data}$ bits by summing over all possible state paths, starting in any state. Similarly, probability of receiving an error-free frame is $1-\varepsilon_{data}$.

Similarly, the probability that an ACK frame will be corrupted is

$$\varepsilon_{ack} = 1-\left(p_{0,0}\right)^{n_{ack}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1}\prod_{j=1}^{K} p_{2i+1,2^j(2i+1)}\right). \tag{2}$$

These probabilities of corrupted data and ACK frames are used to define state transition probabilities for the Markov protocol models that are developed in subsequent sections.

2) Analytical Model of Reliable 802.15.4

Reliable 802.15.4 is positive ACK based protocol which uses simple automatic repeat request (ARQ) with a retry threshold for retransmissions [1]. We use a Markov chain model to characterize the 802.15.4 protocol. This model comprises of three states and is shown in Figure 2. Whenever a data frame needs to be transmitted, the process starts in the "Send Frame" state. Recall that $1-\varepsilon_{data}$ is the probability that a data frame is received without errors at the receiver: i.e. the probability of exiting the "Send Frame" Markov state. Since there are only two possible next states from the "Send Frame" state, the probability of staying and leaving the "Send Frame" state is geometrically distributed.

Once a frame is received without errors at the receiver, the Markov chain process enters the "Send ACK" state. In accordance with 802.15.4 specification, if the ACK frame is received without errors at the sender then the process transits back to the "Send Frame" state for transmission of a new data frame. If either the data frame or the ACK frame is corrupted, the sender times out and retransmits the frame. This scenario is characterized by the "Retransmit Frame" state.The expected number of bits needed to reliably transmit one 802.15.4 data frame over a single hop using above model is

$$\begin{aligned}
&\mathrm{E}\{\text{1-hop data bits for reliable 802.15.4}\}\\
&=\left(n_{data}+n_{hdr}\right)+\\
&\mathrm{E}\{\text{transitions in "Retransmit Frame"}\}\times\left(n_{data}+n_{hdr}\right)\\
&=\left(1+\frac{1}{\left(p_{0,0}\right)^{n_{hdr}+n_{data}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)}\right)\left(n_{data}+n_{hdr}\right).
\end{aligned}\tag{3}$$

Similarly, the expected number of bits needed for successful transmission of the ACK frame corresponding to the above data frame is

$$\begin{aligned}
&\mathrm{E}\{\text{1-hop ACK bits for reliable 802.15.4}\}\\
&=\frac{n_{ack}}{\left(p_{0,0}\right)^{n_{ack}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)}.
\end{aligned}\tag{4}$$

The above expectation holds because the reverse probabilistic path to return to the "Send Frame" state must pass through the "Send ACK" state. This state structure and the assumption that the retransmissions are always less than the retry threshold give a geometric distribution on the "Send ACK" state.

Adding the data and ACK bits gives the expected number of total bits:

$$\begin{aligned}
&\mathrm{E}\{\text{1-hop bits for 802.15.4}\}\\
&=\left(n_{data}+n_{hdr}\right)\left(1+\frac{1}{\left(p_{0,0}\right)^{n_{hdr}+n_{data}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)}\right)\\
&+\frac{n_{ack}}{\left(p_{0,0}\right)^{n_{ack}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)}.
\end{aligned}\tag{5}$$

Now assuming independent links on all H hops to destination yields

$$\begin{aligned}
&\mathrm{E}\{H\text{-hop bits for 802.15.4}\}\\
&=\prod_{m=1}^{H}\frac{\left(1+\frac{1}{\left(p_{0,0}^{m}\right)^{n_{hdr}+n_{data}-K}}\right)\left(n_{data}+n_{hdr}\right)+\frac{n_{ack}}{\left(p_{0,0}^{m}\right)^{n_{ack}-K}}}{\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}^{m}\prod_{j=1}^{K}p_{2i,2^j(2i)}^{m}+\pi_{2i+1}^{m}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}^{m}\right)},
\end{aligned}\tag{6}$$

where π_i^m represents the steady-state probability of being in channel state i on the m-th hop, and $p_{i,j}^m$ denotes the transition probability of going from state i to state j on the m-th hop.

Equation (6) defines the expected number of bits that are required to communicate a data frame of n_{data} bits over an H-hop reliable 802.15.4 channel. An obvious observation that can be made from equation (6) is that the number of transmitted bits − and, consequently, the energy efficiency − of 802.15.4 is an inverse function of the probability of staying in the good state. In other words, and as can be argued intuitively, the energy efficiency of reliable 802.15.4 is directly proportional to the probability of having errors on the channel. More importantly, note in equation (6) that the energy efficiency of 802.15.4 is an increasing function of the number of bits that are used for data retransmission; n_{hdr}, n_{data} and n_{ack}. Unlike the channel parameters discussed above, sizes of MAC frames are controllable parameters that can be adapted to improve energy efficiency. Thus the SRVF protocol that reduces the size of the retransmitted frame should intuitively improve the energy efficiency of a reliable transmission. The extent of this improvement is highlighted in the performance comparison section.

3) Analytical Model of SRVF

Similar to the last section, we now develop a Markov chain model for the selective retransmission using virtual fragmentation (SRVF) protocol, proposed in this paper.

Let F denote the number of virtual fragments in a MAC data frame. We assume that all virtual fragments are of equal size $n_{frag}=\left(n_{hdr}+n_{data}\right)/F$ bits. We also assume that $\left(n_{hdr}+n_{data}\right)$ is a multiple of F, and therefore n_{frag} is an integer. This assumption can be easily satisfied in a real system by appending virtual zero bits to the data bits in the MAC frame. As mentioned in earlier discussions, fragment error information is piggybacked on the ACK frames. We assume that no additional bits are required for this piggybacking; i.e., the ACK frame's size stays the same as in the 802.15.4 standard. Since 802.15.4 data frames are relatively short (generally less than 100 bytes,) for reasonably-sized virtual fragments, the bitmap of correctly-received and corrupted packets should not be too large. Therefore, even if new bits have to be added to the ACK frames, the overhead of these bits would be negligible.

Based on our preceding discussion, the probability that a fragment is received with errors is

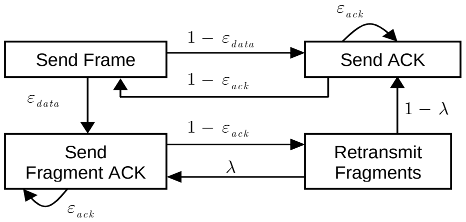

Figure 3: Markov model of Selective Retransmission using Virtual Fragmentation (SRVF)

$$\varepsilon_{frag}=1-\left(p_{0,0}\right)^{n_{frag}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right).$$

Then the probability that k out of the F fragments are corrupted is $\binom{F}{k}\left(\varepsilon_{frag}\right)^k\left(1-\varepsilon_{frag}\right)^{F-k}$, and the expected number of corrupt fragments at the receiver are

$$\begin{aligned}&\mathrm{E}\{\#\text{ of corrupt fragments}\}=F\times\varepsilon_{frag}\\&=F\left[1-\left(p_{0,0}\right)^{n_{frag}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)\right].\end{aligned}\tag{7}$$

Assuming that $K<n_{frag}\times F\times\varepsilon_{frag}$, the probability that the expected number of retransmitted fragments will encounter errors during a retransmission is

$$\lambda=1-\left(p_{0,0}\right)^{n_{frag}F\varepsilon_{frag}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right).$$

Here we emphasize that the expected number of retransmitted fragments, and consequently λ, will be monotonically decreasing functions of the number of retransmissions. However, for simplicity, we assume a fixed λ which implies that all of the virtual fragments corrupt in the first transmission are included in each retransmission. Thus the results provided by the present model will be worse than what would be observed in reality.

Based on the parameters defined above, we propose a Markov chain model of SRVF, which is shown in Figure 3. The SRVF model starts in the “Send Frame” state. If a data frame is received correctly, the Markov chain transits to the “Send ACK” state, which is reached only when all of the virtual fragments in a data frame have been received without errors. If some of the virtual fragments are corrupted, the process transits to the “Send Fragment ACK” state. The fragment ACK frame contains a bitmap of correctly-received and corrupted virtual fragments. The fragment ACK is retransmitted until it reaches the sender correctly. We assume that even in case of retransmissions, the fragment ACK frame will reach the sender before it times out. As with the 802.15.4 model, the distribution of next possible states in each Markov state is geometric.

The expected number of data bits required to reliably transmit a data frame using SRVF is

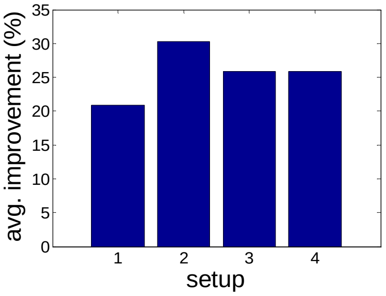

Figure 4: Theoretical improvements in energy efficiency provided by SRVF

$$\begin{aligned}&\mathrm{E}\{\text{1-hop bits for SRVF}\}\\&=\left(n_{data}+n_{hdr}\right)+n_{ack}\mathrm{E}\{\text{transitions in "Send ACK"}\}\\&+n_{ack}\mathrm{E}\{\text{transitions in "Send Fragment ACK"}\}\\&+\left(n_{hdr}+n_{frag}\mathrm{E}\{\#\text{ of corrupt fragments}\}\right)\times\\&\mathrm{E}\{\text{transitions in "Retransmit Fragments"}\}\\&=n_{data}+n_{hdr}+\frac{2n_{ack}}{\left(p_{0,0}\right)^{n_{ack}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)}\\&+\frac{n_{frag}F\varepsilon_{frag}}{\left(p_{0,0}\right)^{n_{frag}F\varepsilon_{frag}-K}\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}\prod_{j=1}^{K}p_{2i,2^j(2i)}+\pi_{2i+1}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}\right)}.\end{aligned}\tag{8}$$

Again invoking the assumption of independent hops, we obtain

$$\begin{aligned}&\mathrm{E}\{H\text{-hop bits for SRVF}\}\\&=\prod_{m=1}^{H}\frac{n_{data}+n_{hdr}+\left(\dfrac{2n_{ack}}{\left(p_{0,0}^{m}\right)^{n_{ack}-K}}+\dfrac{n_{hdr}+n_{frag}F\varepsilon_{frag}^{m}}{\left(p_{0,0}^{m}\right)^{n_{frag}F\varepsilon_{frag}^{m}-K}}\right)}{\sum_{i=0}^{2^{K-1}-1}\left(\pi_{2i}^{m}\prod_{j=1}^{K}p_{2i,2^j(2i)}^{m}+\pi_{2i+1}^{m}\prod_{j=1}^{K}p_{2i+1,2^j(2i+1)}^{m}\right)},\end{aligned}\tag{9}$$

where π_i^m and $p_{i,j}^m$ represent the steady-state and transition probabilities on the m-th hop, and ε_{frag}^m denotes the fragment error probability on the m-th hop.

III. PERFORMANCE COMPARISON OF RELIABLE 820.15.4 AND SRVF

We compute energy efficiency, E, as the ratio of the number of bytes in the original frame, n_{data}, and the total bytes, n_{total}, transmitted to reliably communicate the data frame:

$$\text{energy efficiency, } E=\frac{n_{data}}{n_{total}},\tag{10}$$

where n_{total} is an additive function of the number and size of data transmissions and the number and size of ACK transmissions that are required to reliably communicate a data frame over a WSN channel. Maximum value of E using equation (10) can be 1 (100% efficiency). This is possible only when communication overhead is zero (No Acknowledgments, Headers and Retransmissions). An energy efficient protocol must exhibit higher values of E as compared to other protocols for the same number of data bytes to be transmitted.

TABLE I
EXPERIMENTAL ENERGY-EFFICIENCIES OF RELIABLE 802.15.4 AND SRVF

SETUP	802.15.4	SRVF	Minimum Improvement	Maximum Improvement
Room 2	75.46%	78.53%	0.03%	4.38%
Room 3	43.25%	60.39%	11.52%	20.81%
Stairs	60.69%	72.54%	1.13%	26.39%
Up Floor	54.61%	69.40%	0.46%	29.19%

For all the results presented in this section, we use a data payload size of $n_{data} = 20$ bytes, header and ACK of $n_{ack} = n_{hdr} = 5$ bytes. For SRVF, the data payload of each frame is divided into four virtual fragments of 5 bytes each. Throughout this section, we report results for reliable transmission over a single hop. Multihop results are similar and are skipped for brevity.

C. *Comparison of Theoretical Energy Efficiency*

In this section, we compare theoretical energy efficiencies by computing the transition and steady-state probabilities from the collected traces. For each setup, we average the transition and steady-state probabilities over all the traces collected for that setup. These averaged probabilities are then plugged into equation (6) and (9) to get realistic and achievable theoretical improvement in energy efficiency.

The average theoretical improvements are given in Figure 4. (Here, improvement refers to the difference in the theoretical energy usage of SRVF and reliable 802.15.4.) It can be seen that SRVF has consistently better energy usage than reliable 802.15.4. The minimum improvement is around 20% for the Room 2 setup. This is intuitive because this setup has the least bit-error rate. However, for high error-rate channels, SRVF provides an average improvement of approximately 25% over 802.15.4.

D. *Comparison of Experimental Energy Efficiency*

We used Crossbow's Micaz motes and TinyOS to collect bit-error traces. Traces were collected in four different setups [14]. For each simulation, two different traces are taken from the same setup. These traces respectively represent sender and receiver channels. Total number of transmitted frames per simulation is bound by number of frames in the traces. In the simulations, we assume that sender timeout is significantly longer than receiver timeout. This is not an unreasonable assumption on channels with low bit error rate, such as the ones currently under consideration.

Table I shows the average energy efficiency for each setup. Each entry in the table is obtained by reliably transmitting more than 12.6 million bits per setup. Overall energy efficiency improvement averaged over all setups is 11.67%. We observe that SRVF improves energy efficiency for all evaluated traces. In the case of Room2 setup, the improvements are not as impressive as in other setups. This is due to the low error rates observed in this setup. However, the performance of SRVF is consistently and considerably better than reliable 802.15.4. Out of 20 different simulations (at least four simulations per setup), an improvement of more than 20% was observed four times, with a maximum improvement of approximately 30%.

Comparison of Figure 4 and Table I reveals that experimental results show lesser improvement than theoretical results. We argue that this performance drop is because the theoretical results only quantify the expected value of energy improvement. However, during the experimental results we observed that traces collected under the same setup can also largely exhibit varying behaviors. These variations are highlighted in the experimental results; for instance, see Table I the large variation in the minimum and maximum improvements in the Upper Floor setup shown in Table I. Since the analysis only quantifies the expected energy usage, these variations are not adequately catered for in the theoretical results. To substantiate this argument, we are currently deriving expressions for variance of energy efficiency under SRVF and 802.15.4.

IV. CONCLUSION

In this paper, we proposed an energy-efficient and reliable link layer transmission scheme called SRVF. Theoretical and simulation results showed that SRVF has significantly better energy efficiency than reliable 802.15.4.

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