Research Article

An Energy-Efficient Link Layer Protocol for Reliable Transmission over Wireless Networks

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In multihop wireless networks, hop-by-hop reliability is generally achieved through positive acknowledgments at the MAC layer. However, positive acknowledgments introduce significant energy inefficiencies on battery-constrained devices. This inefficiency becomes particularly significant on high error rate channels. We propose to reduce the energy consumption during retransmissions using a novel protocol that localizes bit-errors at the MAC layer. The proposed protocol, referred to as Selective Retransmission using Virtual Fragmentation (SRVF), requires simple modifications to the positive-ACK-based reliability mechanism but provides substantial improvements in energy efficiency. The main premise of the 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 develop stochastic models of the Simple Positive-ACK-based reliability, the previously-proposed Packet Length Optimization (PLO) protocol, and the SRVF protocol operating over an arbitrary-order Markov wireless channel. Our analytical models show that SRVF provides significant theoretical improvements in energy efficiency over existing protocols. We then use bit-error traces collected over different real networks to empirically compare the proposed and existing protocols. These experimental results further substantiate that SRVF provides considerably better energy efficiency than Simple Positive-ACK and Packet Length Optimization protocols.

1. Introduction

Many deployment scenarios of multihop wireless networks require high transmission reliability; for instance, wireless ad hoc and sensor networks are anticipated to be deployed in disaster recovery areas, battlefields, remote patients' homes, and so forth. While it is sometimes argued that high density of devices can potentially cater for reliability [1], due to energy depletion and lack of battery recharging facilities, even a dense network eventually becomes sparse. Therefore, protocol stack of a data-critical network should have in-built support for transmission reliability.

To cater for the battery constraints of wireless devices, it is important to provide reliable communication without significant energy depletion. Contemporary wireless standards (e.g., 802.15.4 [2], 802.11 [3], and 802.16 [4] standards) support a positive-ACK based retransmission scheme to provide reliable communication. This scheme, referred to as Simple Positive-ACK throughout the paper, has not been designed for energy efficiency. While there have been efforts to improve the energy efficiency of transmission reliability on wireless networks [5–17], most of the proposed protocols introduce a significant level of resource complexity to replace Simple Positive-ACK. Moreover, most of these protocols are not true hop-by-hop reliability protocols, although it has been acknowledged widely that hop-by-hop reliability is the key to overall network reliability [7–11]. Some of these protocols are designed for a particular communication model of a specific technology and hence cannot be classified as generic wireless ad hoc reliability protocol [9, 17].

In [13], Modiano proposed a true hop-by-hop reliability mechanism, which has better energy usage than standard Simple Positive-ACK protocol. This protocol, called Packet Length Optimization (PLO), adapts the length of transmitted

packets in accordance with the underlying channel conditions; large packets are transmitted during good channel conditions and vice versa.

In this paper, we propose minor modifications to the Simple Positive-ACK protocol to improve its energy efficiency. We note that all the data in a corrupted frame are not in error and therefore it is not necessary to retransmit the complete frame. We propose to localize 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).

To determine provable performance benefits of the proposed SRVF protocol, we develop stochastic models for Simple Positive-ACK, PLO, 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 a Kth-order Markov channel. Using these models, we show that SRVF requires significantly lesser energy for reliable transmission than Simple Positive-ACK and PLO protocols.

We verify our theoretical findings through trace-driven simulations of SRVF, PLO, and Simple Positive-ACK protocols. For experimental evaluation, we use a comprehensive corpus of bit-error traces collected over real-life WSN and WiFi networks at different data rates. (These traces are available at http://wisnet.seecs.edu.pk/downloads.php). Our trace-driven simulations show that SRVF provides significant improvement in average energy efficiency at all data rates. For 250 kbps WSN traces, SRVF has approximately 17% better energy usage than Simple Positive-ACK and 11% better energy usage than PLO. For 802.11 traces, we have recorded an average improvement of approximately 12% over Simple Positive-ACK and 14% improvement over PLO.

The rest of this paper is structured as follows. Section 2 describes proposed protocol in detail. Section 3 develops stochastic models for the protocols under study and provides the analytical comparison of these models. Section 4 elaborates empirical performance analysis based on trace driven simulations. Section 5 summarizes key conclusions of this paper.

2. Protocol Description

The most commonly used hop-by-hop reliability protocol is Simple Positive-ACK. In this protocol, frame is retransmitted completely in spite of the fact that only a small subset of data is in error. In this section, we propose a novel energy-efficiency protocol for hop-by-hop reliability, which is based on the premise that all data in a corrupted frame need not to be retransmitted. The proposed protocol is referred to as Selective Retransmission using Virtual Fragmentation (SRVF) protocol throughout this paper.

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 including the partial checksums in the headers on these virtual fragments, the sender transmits the MAC data frame. 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. SRVF messaging is described pictorially in Figure 1.

If any fragment checksum fails at the receiver, the receiver sends a fragment ACK frame that contains information about which fragments are in error. This information is in the form of a bitmap. One bit is reserved for each virtual fragment. 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 only retransmits those virtual fragments that have errors.

Stochastic models of energy efficiency of SRVF and other existing protocols understudy are developed in the next section.

3. Stochastic Modeling and Theoretical Performance of Reliable Protocols

In this section, we first describe the basic parameters and assumptions about the models being constructed. Then we develop analytical models for Simple Positive-ACK, PLO, and SRVF. Finally, we perform a comparative analysis of the energy efficiency of these models. In each of these models, we derive energy efficiency in terms of the total number of transmitted bits that are required to reliably transmit a MAC layer frame over a multihop network.

3.1. System Model, Assumptions and Notation. Let n_{data} and n_{hdr} represent the number of data and header bits in the MAC data frame; for example, in 802.15.4, $n_{hdr} = 104$ bits are used in the short addressing mode [18] and the minimum header size is 34 bytes in 802.11 networks. Similarly, let n_{ack} represent the number of bits in an acknowledgment (ACK) frame; for example, $n_{ack} = 40$ bits for 802.15.4 short addressing mode, while ACK size is 34 bytes in 802.11.

Number of retransmissions to achieve reliable communication on a wireless link is inherently dependent on the bit-error statistics of the underlying channel. Prior studies have shown that the MAC layer wireless channels generally exhibit high-order dependence structure in which each bit is dependent on multiple prior bits [19, 20]. Such a correlation structure is accurately captured by a high-order, say Kth-order, Markov channel model in which each received bit is dependent upon the previous K bits; the order K of the Markov channel model can vary for different MAC layer channels.

Let the output of the binary bit-error random process at a discrete time instance i be represented as $X[i] \in \{0, 1\}$, where $0 \Rightarrow$ an error-free bit. Then the states of a Kth order Markov channel model represent 2^K possible combinations of K consecutive bits as shown in Figure 2 for $K = 3$.
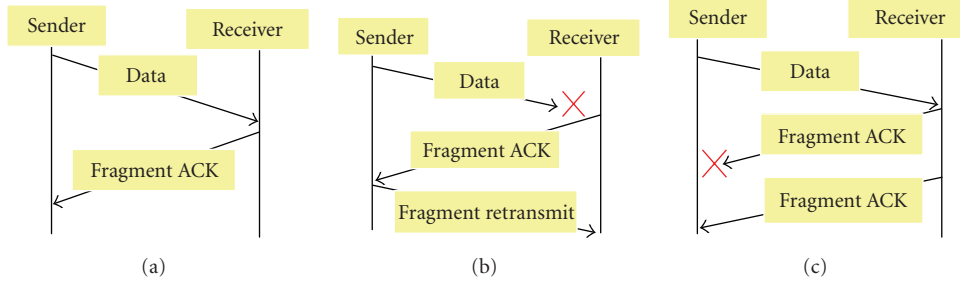
FIGURE 1: Typical protocol messaging for the SRVF protocol: (a) data and ACK Frames received correctly, (b) one or more fragments in error, and (c) ack in error.

Based on this notation, if the last received bit is error-free, then the current state of the Markov channel has a zero in the least significant bit (LSB) position, while for the last bit received with errors, the LSB is one (see Figure 2). Due to this structure, henceforth the error-free states of the Markov channel model are referred to as even states, while the corrupted state are referred as odd states.

Throughout this section, we assume that all hops of the network are independent Kth-order Markov channels, where K is a fixed arbitrary integer. Thus although the parameters of the channel on each hop might differ, we realistically assume that the order of the Markov channel model at each hop is fixed. From prior studies, we know that $K = 3$ for 802.15.4 residual channels [19] and $K = 10$ for 802.11 residual channels [21], and we perform all our analysis for a parameterized value of K so that the analysis is valid for Markov channels of arbitrary order. 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 of the channel model on the mth hop to the destination and the subscript i, j represents a transition from Markov state i to state j.

We quantify energy efficiency of a protocol as the number of bits that are required to reliably transmit one fixed-sized data frame of length L bits over an H-hop ad hoc network. As in the 802.11 and 802.15.4 standards, we assume that link layer reliability is provided on a hop-by-hop basis. To theoretically compare the energy efficiencies, we develop stochastic models of the three protocols under consideration. In case of a collision, all the protocols will have to retransmit the entire packet. Therefore, we ignore collision overhead in our analysis.

3.2. Simple Positive-ACK Protocol.

Simple Positive-ACK is the de-facto standard for hop-by-hop reliable transmission over multihop ad hoc networks. In this protocol, a MAC layer acknowledgment is sent for every correctly received frame. If a frame or its acknowledgment is lost en-route due to collisions or received with bit errors, the complete frame is retransmitted. The transmission is not considered successful until the successful reception of complete frame. Usually a retry threshold is associated for retransmission attempts; for example, the Default Retry Limit = 6 in 802.11
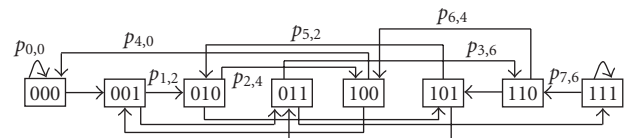

FIGURE 2: A 3-rd Order Markov Chain.

networks. Simple Positive-ACK is a mandatory part of the MAC protocol in 802.11 networks, whereas it is optional in 802.15.4 networks.

3.2.1. Probability of Frame Error for the Simple-ACK Protocol.

As a first step to analytically model retransmissions of a Simple-ACK protocol, we compute the probability of receiving an error-free frame of length L bits on a single-hop Kth-order Markov model. This probability is dependent on the present (even or odd) state of the model.

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.. Every state $i, 0 < i < 2^K$, of this model can transit to only two other states: either to state $(2i) \bmod 2^K$ (even state) or to state $(2i) \bmod 2^K$ (odd state). Since there are a total of 2^K states in a Kth-order Markov channel model, for ease of notation we do not repeat the $\bmod 2^K$ operation on state indices; henceforth all state indices are implicitly defined as $\bmod 2^K$.

Let Markov state $2i, 0 < i < 2^K$, be the current even state of the Kth-order Markov channel model. 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:

$$2i = 2^0(2i) \bmod 2^K \longrightarrow 2(2i) \bmod 2^K$$

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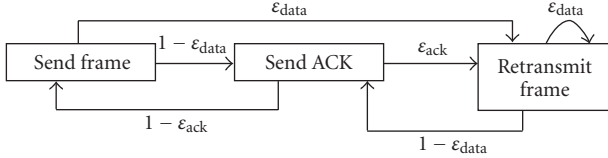
$$(1)$$

FIGURE 3: Markov model of Simple Positive-ACK.

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 $\pi_{2i}\prod_{j=0}^{K-2} p_{2^j(2i),2^{j+1}(2i)}(p_{0,0})^{L-(K-1)}$. This probability summed over all possible even Markov states yields $\sum_{i=0}^{2^{K-1}-1} \pi_{2i}\prod_{j=0}^{K-2} p_{2^j(2i),2^{j+1}(2i)}(p_{0,0})^{L-(K-1)}$.

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

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

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

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

$$\varepsilon_{\text{ack}} = 1 - (p_{0,0})^{n_{\text{ack}}-K}$$
$$\times \sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i}\prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1}\prod_{j=1}^{K} p_{2i+1,2^j(2i+1)} \right). \quad (3)$$

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 subsections.

3.2.2. Stochastic Model of Simple Positive-ACK. Simple Positive-ACK uses automatic repeat request (ARQ) with a retry threshold for retransmissions [18]. We use a Markov chain model to characterize the Simple Positive-ACK protocol. This model comprises of three states and is shown in Figure 3. Whenever a data frame needs to be transmitted, the process starts in the "Send Frame" state. Recall that $1-\varepsilon_{\text{data}}$ is the probability that a data frame is received without errors at the receiver, that is, 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 and 802.11 specifications, 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 data frame over a single hop using above model is

$$E\{1 - \text{hop bits for Simple Positive-ACK}\}$$
$$= (n_{\text{data}} + n_{\text{hdr}}) + E\{\text{transitions in "Retransmit Frame"}\}$$
$$\times (n_{\text{data}} + n_{\text{hdr}})$$
$$= \left(1 + \frac{1}{(p_{0,0})^{n_{\text{hdr}}+n_{\text{data}}-K}\mathfrak{A}} \right)(n_{\text{data}} + n_{\text{hdr}}), \quad (4)$$

where $\mathfrak{A}$ denotes

$$\sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i}\prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1}\prod_{j=1}^{K} p_{2i+1,2^j(2i+1)} \right). \quad (5)$$

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

$$E\{1 - \text{hop ACK bits for Simple Positive-ACK}\}$$
$$= \frac{n_{\text{ack}}}{(p_{0,0})^{n_{\text{ack}}-K}\mathfrak{A}}. \quad (6)$$

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 that are required to successfully transmit the data frame to the next hop as

$$E\{1 - \text{hop bits for Simple Positive-ACK}\}$$
$$= (n_{\text{data}} + n_{\text{hdr}})$$
$$\times \left(1 + \frac{1}{(p_{0,0})^{n_{\text{hdr}}+n_{\text{data}}-K}\mathfrak{A}} \right) + \frac{n_{\text{ack}}}{(p_{0,0})^{n_{\text{ack}}-K}\mathfrak{A}}. \quad (7)$$

Now assuming independent links on all H hops to destination yields

$$E\{H - \text{hop bits for Simple Positive-ACK}\}$$
$$= \prod_{m=1}^{H} \frac{\mathfrak{R}(n_{\text{data}} + n_{\text{hdr}}) + n_{\text{ack}}/\left(p_{0,0}^{(m)}\right)^{n_{\text{ack}}-K}}{\mathfrak{H}}, \quad (8)$$

where $\mathfrak{H}$ denotes

$$\sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i}^{(m)}\prod_{j=1}^{K} p_{2i,2^j(2i)}^{(m)} + \pi_{2i+1}^{(m)}\prod_{j=1}^{K} p_{2i+1,2^j(2i+1)}^{(m)} \right), \quad (9)$$

$\mathfrak{R}$ denotes

$$\left(1 + 1/\left(p_{0,0}^{(m)}\right)^{n_{\mathrm{hdr}}+n_{\mathrm{data}}-K}\right), \tag{10}$$

$\pi_i^{(m)}$ represents the steady-state probability of being in channel state i on the mth hop, and $p_{i,j}^{(m)}$ denotes the transition probability of going from state i to state j on the mth hop.

Equation (8) defines the expected number of bits that are required to communicate a data frame of n_{data} bits over an H-hop reliable channel. An obvious observation that can be made from (8) is that the number of transmitted bits and, consequently, the energy efficiency 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 is directly proportional to the probability of having errors on the channel. More importantly, note in (8) that the energy efficiency of Simple Positive-ACK 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 will be highlighted in the performance evaluation sections.

3.3. Packet Length Optimization.

Prior studies [13–15] have suggested packet length optimization approaches to increase the energy efficiency of reliable protocols. The basic idea in these approaches is to increase the packet size when channel conditions are good (i.e., in case of low BER) and decrease the packet size when the channel exhibits more error prone behavior. In [13], authors have adopted the idea of maintaining a retransmission history. Current channel conditions are inferred from this retransmission history. Under this approach, small number of retransmissions suggests good network conditions, whereas a large number of retransmissions indicate bad network conditions. We evaluate the protocol proposed in [13] as a representative of packet length optimization-based schemes. Throughout the paper, this protocol of [13] is generically referred to as the Packet Length Optimization (PLO) protocol.

3.3.1. Stochastic Model of Packet Length Optimization.

In this section, we extend the PLO model presented in [13] to cater for the more realistic Markovian channel model with arbitrary memory length. In [13], expected energy efficiency of PLO measured in terms of probability of number of retransmission is described as:

$$E\{1 - \text{hop Energy Efficiency}\}$$

$$= \int_{R=0}^{M} \frac{n_{\mathrm{data}}^{R}}{n_{\mathrm{data}}^{R} + n_{\mathrm{hdr}}} \cdot \Pr\{\text{Frame received correctly}\}$$

$$\cdot \Pr\{R \text{ retransmission in history window } M\}, \tag{11}$$

where n_{data}^{R} is the size of frame data for R retransmissions in a history window of size M. It should be emphasized that n_{data}^{R} is not the same for different values of R because the frame size varies based upon the number of retransmissions in current history.

Probability that a frame is received in error over a Markovian channel is already derived in (2). Probability of R retransmissions can hence be calculated easily using the following binomial probability density function:

$$\Pr\{R \text{ retransmissions} \mid \text{history window size } M\}$$

$$= \binom{M}{R}(\varepsilon_{\mathrm{data}})^{R}(1 - \varepsilon_{\mathrm{data}})^{M-R}. \tag{12}$$

Equations (2) and (12) are substituted in (11) and after some simplifying steps we obtain the following expression for the energy efficiency of PLO:

$$E\{1 - \text{hop Energy Efficiency}\}$$

$$= \int_{R=0}^{M} \frac{n_{\mathrm{data}}^{R}}{n_{\mathrm{data}}^{R} + n_{\mathrm{hdr}}} \cdot \binom{M}{R}\left(\varepsilon_{n_{\mathrm{data}}^{R}}\right)^{R}\left(1 - \varepsilon_{n_{\mathrm{data}}^{R}}\right)^{M-R+1}. \tag{13}$$

Assuming independence between each hop, (13) can be extended to H hops as

$$E\{H - \text{Hop Energy Efficiency}\}$$

$$= \prod_{m=1}^{H} \int_{R^{(m)}=0}^{M^{(m)}} \frac{n_{\mathrm{data}}^{R^{(m)}}}{n_{\mathrm{data}}^{R^{(m)}} + n_{\mathrm{hdr}}}$$

$$\cdot \binom{M^{(m)}}{R^{(m)}}\left(\varepsilon_{n_{\mathrm{data}}^{R^{(m)}}}\right)^{R^{(m)}}\left(1 - \varepsilon_{n_{\mathrm{data}}^{R^{(m)}}}\right)^{M^{(m)}-R^{(m)}+1}, \tag{14}$$

where superscript (m) denotes value of a particular parameter on the mth hop. For example, $M^{(m)}$ denotes the length of history window on mth hop.

Note that (13) describes energy efficiency averaged over all possible retransmissions. In low error rate conditions, probability of small number of retransmissions is high. Similarly probability that a frame is received correctly is also high. Moreover, because we use larger frame size for small number of retransmissions, the ratio of data bytes to actually transmitted bytes is also high. However, in case of high error rate channels, such as the 11 Mbps 802.11 networks, probability of large number of retransmissions is high. In this setting, we expect less energy efficiency from PLO, a fact that is substantiated later in this section using theoretical analysis and in the next section using empirical analysis.

3.4. Selective Retransmission Using Virtual Fragmentation (SRVF).

As described earlier, the basic premise of SRVF is to localize bit-errors by using virtual fragments. SRVF divides frames into virtual fragments and each virtual fragment is covered by a separate checksum. In this section, we develop a stochastic model of SRVF by operating over a Markov chain of arbitrary order.

3.4.1. Stochastic Model of SRVF. Let F denote the number of virtual fragments in a MAC data frame. For simplicity of analysis, we assume that all virtual fragments are of equal size $n_{\text{frag}} = (n_{\text{hdr}} + n_{\text{data}})/F$ bits. We also assume that $(n_{\text{hdr}} + n_{\text{data}})$ 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 the overhead of additional bits for this piggybacking is negligible. The size of the bitmap for correctly received and corrupted packets is dependent on the number of virtual fragments and stays same as long as number of virtual fragments is kept same. 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

$$
\varepsilon_{\text{frag}} = 1 - (p_{0,0})^{n_{\text{frag}}-K}
$$
$$
\times \sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i} \prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1} \prod_{j=1}^{K} p_{2i+1,2^j(2i+1)} \right),
\tag{15}
$$

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

$$
E\{\#\text{of corrupt fragments}\}
$$
$$
= F \times \varepsilon_{\text{frag}}
$$
$$
= F\left[1 - (p_{0,0})^{n_{\text{frag}}-K} \right.
$$
$$
\left. \times \sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i} \prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1} \prod_{j=1}^{K} p_{2i+1,2^j(2i+1)} \right) \right].
\tag{16}
$$

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

$$
\lambda = 1 - (p_{0,0})^{n_{\text{frag}}F\varepsilon_{\text{frag}}-K}
$$
$$
\times \sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i} \prod_{j=1}^{K} p_{2i,2^j(2i)} + \pi_{2i+1} \prod_{j=1}^{K} p_{2i+1,2^j(2i+1)} \right).
\tag{17}
$$

Here we emphasize that the expected number of retransmitted fragments, and consequently λ, will be monotonically decreasing functions of the number of retransmissions. However, 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.
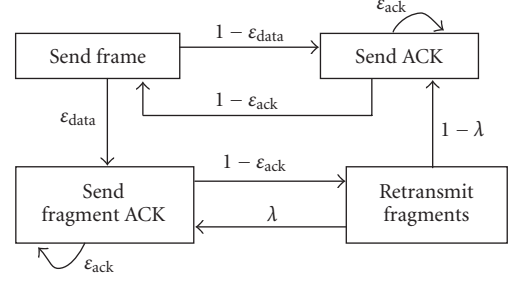

Figure 4: Markov model of SRVF.

Based on the parameters defined above, we propose a Markov chain model of SRVF shown in Figure 4. 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 Simple Positive-ACK 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

$$
E\{1 - \text{hop bits for SRVF}\}
$$
$$
= (n_{\text{data}} + n_{\text{hdr}}) + n_{\text{ack}}E\{\text{transitions in "SendACK"}\}
$$
$$
+ n_{\text{ack}}E\{\text{transitions in "Send Fragment ACK"}\}
$$
$$
+ \left(n_{\text{hdr}} + n_{\text{frag}}E\{\# \text{ of corrupt fragments}\} \right)
$$
$$
\times E\{\text{transitions in "Retransmit Fragments"}\}
$$
$$
= n_{\text{data}} + n_{\text{hdr}} + \frac{2n_{\text{ack}}}{(p_{0,0})^{n_{\text{ack}}-K}\mathfrak{A}} + \frac{n_{\text{frag}}F\varepsilon_{\text{frag}}}{(p_{0,0})^{n_{\text{frag}}F\varepsilon_{\text{frag}}-K}\mathfrak{A}},
\tag{18}
$$

Again invoking the assumption of independent hops, we obtain

$$
E\{H - \text{hop bits for SRVF}\}
$$
$$
= \prod_{m=1}^{H} \frac{n_{\text{data}} + n_{\text{hdr}} + 2n_{\text{ack}}/\left(p_{0,0}^m\right)^{n_{\text{ack}}-K} + \mathfrak{L}}{\mathfrak{I}},
\tag{19}
$$

where $\mathfrak{L}$ denotes

$$
\left(n_{\text{hdr}} + n_{\text{frag}}F\varepsilon_{\text{frag}}^m\right)/\left(p_{0,0}^m\right)^{n_{\text{frag}}F\varepsilon_{\text{frag}}^m-K},
\tag{20}
$$

$\mathfrak{I}$ denotes

$$
\sum_{i=0}^{2^{K-1}-1} \left(\pi_{2i}^m \prod_{j=1}^{K} p_{2i,2^j(2i)}^m + \pi_{2i+1}^m \prod_{j=1}^{K} p_{2i+1,2^j(2i+1)}^m \right),
\tag{21}
$$

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

3.5. Analytical Performance Evaluation. At this point, we have developed models for Simple Positive-ACK, PLO, and SRVF. For the performance evaluation of these models, realistic values of steady-state and transition probabilities are required. These values can be obtained from residual bit-error traces collected over operational networks. We have collected a comprehensive set of bit-error traces over WSN and WiFi networks. Steady-state and transition probabilities used to compare stochastic models of Simple Positive-ACK, PLO, and SRVF are derived from these traces. Detailed description of trace collection setup and properties of collected traces are elaborated in the next section on empirical analysis. In this section, we first define a criterion for performance comparison and then compare performance of each protocol analytically using this criterion.

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:

$$\text{energy efficiency}, \eta = \frac{n_{\text{data}}}{n_{\text{total}}}, \qquad (22)$$

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 an ad hoc network. Maximum value of η using (22) can be 1 (100% efficiency) only when communication overhead is zero (No Acknowledgments, Headers, and/or Retransmissions). An energy efficient protocol must exhibit higher values of η as compared to other protocols for the same number of data bytes to be transmitted.

To evaluate energy efficiency for 802.15.4, we use a data payload size of $n_{\text{data}} = 20$ bytes and header and ACK of $n_{\text{ack}} = n_{\text{hdr}} = 5$ bytes. For SRVF, the data payload of each frame is divided into four virtual fragments of 5 bytes each. For 802.11 evaluations, we use a data payload size of $n_{\text{data}} = 1000$ bytes and header and ACK of $n_{\text{ack}} = n_{\text{hdr}} = 34$ bytes. For SRVF, the data payload is divided into four virtual fragments of 250 bytes each. For Packet Length Optimization, we use packet sizes of $600, 800, 1000, 1200$, and 1400 bytes with a retransmission history window size 16. Throughout this section, we report results for reliable transmission over a single hop. Multihop results are similar and are skipped for brevity. For Packet Length Optimization, we use packet sizes of 15, 20 and 25 bytes with a retransmission history window size = 8.

For each trace, we first compute the transition and steady-state probabilities. These probabilities are then plugged into (7), (13), and (22) to ascertain realistic theoretical improvements in energy efficiency that can be provided by SRVF. Results shown in this paper are averaged over each setup due to brevity (details of setups are available in next section.)

The average theoretical improvements are given in Figure 5. SRVF improvement in Figure 5 refers to the
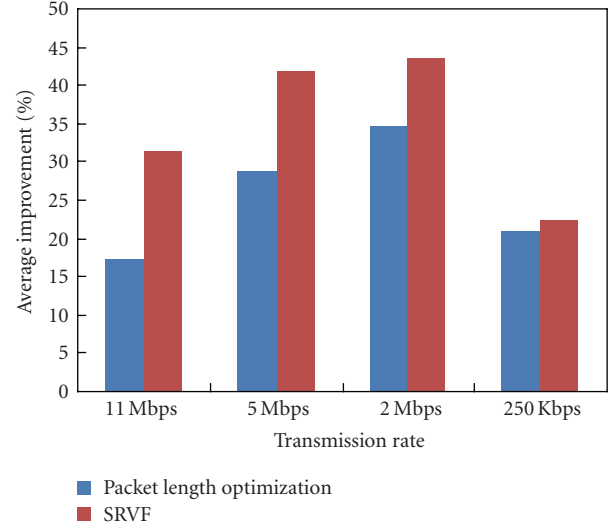

FIGURE 5: Average theoretical improvement in energy consumption over Simple Positive-ACK.

difference in the theoretical energy usage of SRVF and Simple Positive-ACK. Similarly, Packet Length Optimization improvement refers to the difference in the theoretical energy usage of Packet Length Optimization and Simple Positive-ACK.

It can be seen that SRVF has consistently better energy usage than Simple Positive-ACK. Packet Length Optimization is also better than Simple Positive-ACK in general. However, margin of improvement is high for SRVF as compared to PLO. The average improvement for SRVF over all data-rates is around 35% whereas for Packet Length Optimization average improvement is around 25%.

Absolute theoretical energy efficiency results are tabulated in Table 1. It can be seen that the lowest values are recorded for the highest data-rate (11 Mbps). Simple Positive-ACK yields very low energy efficiency value of 17%. PLO improves it significantly and doubles the energy efficiency (34%). SRVF improves it further and approximately triples the energy efficiency (48%) as compared to Simple Positive-ACK.

SRVF also reduces number of computations required to calculate CRC checksum. It is trivial to see that for a frame of length n bits and CRC polynomial degree d, non-SRVF-based protocols require $n.(d + 1)$ XOR operations and $n - (d + 1)$ Left Shift operations. In SRVF, frame with F fragments requires $(n \cdot (d + 1)/F)$ XOR operations and $n - (d + 1)$ Left Shift operations.

These results show that SRVF is theoretically better than both Simple Positive-ACK and PLO. These findings are substantiated further in the next section using trace driven simulations.

4. Empirical Performance Comparison of Reliable Protocols

We now use wireless traces collected over real networks to empirically evaluate protocols under study. The first part of

TABLE 1: Theoretical energy efficiency.

		Simple positive-ACK	Packet length optimization	SRVF
802.15.4	250 Kbps	22.81%	43.69%	45.24%
	11 Mbps	16.85%	34.16%	48.19%
802.11	5 Mbps	28.95%	57.70%	70.87%
	2 Mbps	32.81%	67.48%	76.38%

TABLE 2: Empirical energy efficiency.

		Simple positive-ACK	Packet length optimization	SRVF
802.15.4	250Kbps	42.45%	48.48%	59.46%
	11Mbps	57.64%	49.41%	79.26%
802.11	5Mbps	79.97%	81.67%	89.25%
	2Mbps	83.98%	85.97%	90.51%
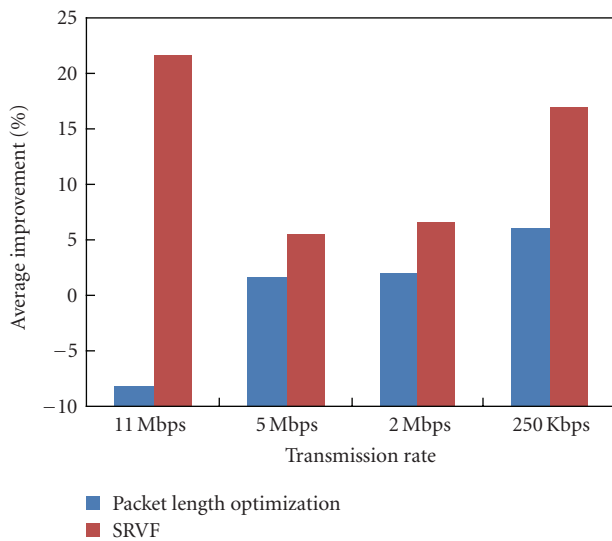
FIGURE 6: Average empirical improvement in energy consumption over Simple Positive-ACK.

FIGURE 7: Setup for 802.15.4 trace collection.

this section is dedicated to the description of trace collection setups and properties of the collected traces. The second part comprises of comparative analysis based on trace driven simulations.

4.1. Data Collection. We collected a comprehensive data set of 802.15.4 and 802.11 residual bit-error traces by making modifications to the wireless device drivers. (All traces are available at [22].)

We used Crossbow's Micaz motes and TinyOS to collect bit-error traces of wireless sensor networks. MAC layer configurations of TinyOS were modified to bypass checksum verification so that all frames were passed to upper layer regardless of errors in the frame. These traces were collected in four different locations/setups (shown in Figure 7). At least 6 traces per setup are collected and each trace consists of approximately 30 000 frames. Each setup is characterized based on distance and impairment between sender and the
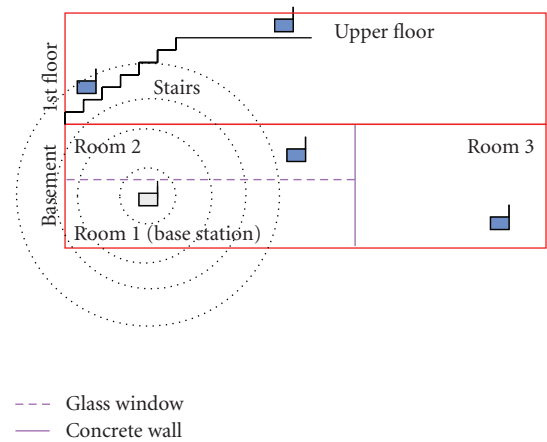
base station. These setups exhibited very low bit-error rate (BER) except location/setup named Room 3. This is due to longer distance and a concrete wall between Room 3 sender and the base-station. Average BER for Room 3 is 0.0133. All other setups exhibit BER below order of 10^{-3}. We are concerned only with high bit-error rates; therefore we restricted our analysis to only Room 3 setup. Further details of these traces are available in [19].

802.11 traces were collected using three different data rates (2, 5, and 11 Mbps) and three different settings representing home, office and university environments (shown in Figure 8). For each data rate at least 15 traces were collected. In each setup at least 5 traces per data rate were collected. Each trace was obtained by transmitting more than 100 000 frames. To capture bit-errors, receiver's MAC layer device drivers were modified to pass corrupted packet to upper layer. In addition to bit-errors, Signal to Silence Ratio (SSR) was also logged. Detailed description of these traces is available in [21].

4.2. Comparison of Experimental Energy Efficiency. To confirm our theoretical findings, we use trace driven simulations to empirically compare the energy efficiency of the protocols
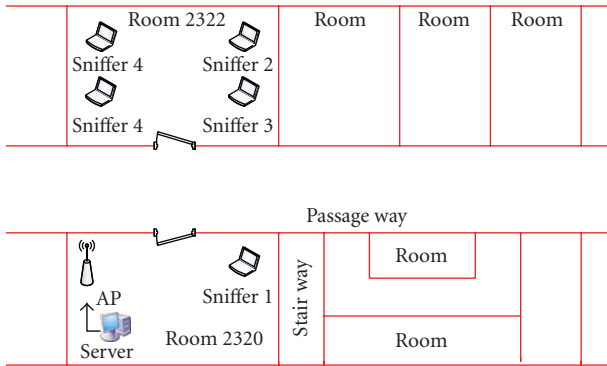
FIGURE 8: Experimental setups for 802.11 trace collections.

under consideration. For empirical analysis, two different traces are taken from the same setup. These traces represent sender and receiver channels, respectively. 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.

Table 2 shows the experimental average energy efficiency for each data rate. Each entry in the table is obtained by reliably transmitting more than 12.6 million bits for 802.15.4 traces. For 802.11, each entry is obtained by reliably transmitting more than 4.4 billion bits per data-rate.

Average energy efficiency improvement is shown in Figure 6. Similar to the theoretical findings, we observe that SRVF improves energy efficiency for all evaluated traces. PLO also improves the energy efficiency in case of 250 Kbps, 2 Mbps, and 5 Mbps data-rates. But the margin of improvement for PLO is significantly lesser than SRVF. Average improvement recorded by PLO is 0.37% whereas SRVF provides an average improvement of 13.6%.

In case of the 11 Mbps channel, PLO has actually a degraded performance and Simple Positive-ACK is better than PLO in this particular case. SRVF, for the same data-rate, has improved the efficiency by 21%. This has happened because PLO optimizes packet sized based on number of retransmissions in the current history. Simple BER statistics are not enough to analyze this factor and packet level statistics are required. It has been shown in [21] that mean packet error burst length for 11 Mbps traces is 4.16 packets. For traces other than 11 Mbps, mean packet error burst length is less than 2 packets. This explains the reason of failure of PLO because PLO adjusts the packet size based on the packet retransmission history. Given that 802.11 channels encounter large number of packet drops as compared to other traces, it is highly probable that most of the time PLO will transmit packets smaller than the optimal size and will degrade its energy efficiency.

Theoretical findings in the previous section have shown that the performance of SRVF increases with data rate and the performance of Packet Length Optimization decreases with increasing data rates. The empirical analysis also confirms these findings. Energy efficiency improvements by Packet Length Optimization are recorded to be 2%, 1.7% for

2 and 5 Mbps, respectively. For 11 Mbps, the performance of PLO is degraded by 8%. For similar settings, SRVF shows improvements of 6.5%, 9.2%, and 21.6%.

The comparative analysis of theoretical and experimental results reveals that experimental results are consistent with theoretical findings in terms of improvement over other protocols. The magnitude of energy efficiency improvement is however not same in theoretical and experimental evaluation. We argue that this minor inconsistency exists because theoretical results only quantify the expected value of energy improvement whereas during the experimental results we observed that traces collected under the same setup also largely exhibit varying behaviors. These variations are highlighted in the experimental results.

5. Conclusion

In this paper, we proposed an energy-efficient and reliable link layer transmission protocol called SRVF. Theoretical and simulation results showed that SRVF provides significantly better energy efficiency than the widely deployed Simple Positive-ACK protocol. SRVF was also compared with Packet Length Optimization, another popular protocol to improve energy usage of reliable protocols. We found that in most cases Packet Length Optimization improves over Simple Positive-ACK, but SRVF outperforms PLO by a significant margin.

Acknowledgments

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