Statistical Reliability for Energy Efficient Data Streaming in Wireless Sensor Networks

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***Abstract*—A common application of wireless sensor networks (WSN) is streaming sensed data from multiple sensors to one or more sink nodes. Typical WSN deployments are in unattended hostile fields where link packet error rate may vary within 1-70% and path length could be up to tens of hops. Field experiments also reveal that channel error rate fluctuate within a short time scale. To cope with such harsh conditions, we propose a new notion of *statistically reliable* transport protocol is introduced; and the energy-efficiency of a comprehensive set of statistically reliable data delivery protocols are analyzed. Our analysis reveals that selective repeat hop-by-hop ARQ (SR) is the most efficient protocol across the board. However, for WSN where SR is infeasible due to buffer and processing constraints, a new adaptive hybrid protocol is proposed, which is the most energy-efficient protocol. The hybrid protocol starts with streaming a larger than required sensed data without recovery until some threshold hop; then it switches to implicit send-and-wait hop-by-hop ARQ. Detailed NS2 simulation and a field experiment confirm our theoretical findings.**

I. Introduction

Wireless sensor network (WSN) technology is rapidly advancing and many experimental and commercial WSNs have been already deployed in the recent years. Some of the reported pilot trials reveal that the *data yields* in real WSNs are far from being satisfactory, e.g., 50% at the Redwood network [15], 58% at the Great duck island [14] and 68% at the Volcano network [18]. These trials highlight the fact that data yield in WSN is a major concern requiring further investigation.

Data yield is addressed mainly by applying a reliable data delivery protocol based on ARQ. Generally with ARQ, a receiver sends acknowledgment packets (ACKs) for every successfully received packet and a transmitter retransmits the packet upon timeout. They are many variants of ARQ protocols, as well as other reliable data delivery protocols. These protocols differ by their data delivery reliability properties as well as by their energy efficiency.

To gain better insight into WSN reliable data delivery, we first propose a new definition for reliability as a common quality of service (QoS) measure for data delivery applications. Then, we compare between the energy-efficiency of most common protocols given they are all tuned to the same reliability level. Based on our gained insight, we also propose a new adaptive hybrid protocol, which is the most energy-efficient.

The motivation for our new definition of reliability is to include energy-efficiency into the reliability notion. This is consistent with the recent idea of balancing between reliability and energy expenditure [4] [6] that. Our recent experience in deploying WSN applications [7] [17] also indicates that occasional packet losses are tolerable. The reliability is actually determined by the quality of an ensemble of the sensed data delivered at the sink, rather than the reliability of each individual data sample.

Thus, requiring that each data packet is successfully delivered only with probability $\beta < 1$, rather than with probability one (absolute reliability), has the potential of saving transmissions and therefore energy. This reliability notion will be referred to as *statistical reliability* and is defined as follows.

> Statistical reliability with level β is a QoS level where during every predetermined time window, a predetermined size of random sensed data are delivered to the sink node from every source, each with a probability of at least β.

The relation between energy consumption and transmissions is well known. It follows from the fact that the number of transmissions are linearly correlated with the sensor wake-up time, which is in turn the major sensor energy consumer [9].

The significant of our statistical reliability notion for designing reliable transport protocols becomes apparent from our performance analysis in Section V. Our analysis shows that using the default implementation of ARQ in most sensor MAC layers, i.e., hop-by-hop send-and-wait ARQ (see e.g., B-MAC), the following energy saving is achieved when tuning the protocol for $\beta = 0.95$ rather than for absolute reliability. For a 5-hop route, there is an energy saving of 20%, when the packet error rate (PER) in each hop is 0.5; and 9% saving, when PER is 0.2.

Our main novel contributions are:

- A new QoS measure for WSN application reliability.
- A comprehensive rigorous analysis of the energy efficiency of most common data delivery protocols with statistical reliability.
- A new hybrid statistically reliable protocol combining between "hop-by-hop send-and-wait ARQ with implicit ACKs" and "ESRT" [4].

The rest of the paper is organized as follows. A brief survey of related works is given in Section II. A rigorous analysis of the energy efficiency of a comprehensive set of statistically reliable data delivery protocols is derived in section III and in the appendix. Our theoretical findings are confirmed by detailed discrete-event simulation results using NS2 and by a field experiment, both presented in Section IV. Then, the protocol performance are compared in Section V. Finally, a hybrid protocol, which is the most suitable transport protocol for a general WSN is presented in Section VI.

II. Related Work

In [16], an absolute reliable data delivery protocol called *PSFQ (pump slowly, fetch quickly)* has been proposed for reliable code distribution in WSN. PSFQ performs controlled pumping and intermediate nodes use hop-by-hop recovery ARQ based on negative acknowledgment (NACK).

In [13], the authors investigate the tradeoff between having reliability implemented at MAC, Transport and Application layers. The proposed Reliable Multi-Segment Transport (RMST) combines MAC layer ARQ with transport layer NACK-based schemes to provide guaranteed delivery. These works differs from ours in that they focus on absolute reliable data delivery. However, most sensor applications do not require 100% guaranteed data delivery. Moreover, such absolute reliability may incur significant overhead.

Event-to-sink reliable transport (ESRT) is presented in [4] for sensed data streaming applications not requiring absolute reliability. The reliability level of the protocol has been analyzed and simulated with NS2. In this paper, the energy efficiency of ESRT is analyzed as well. Our analysis reveals that its energy efficiency deteriorate exponentially with the path length. As a result, we propose a hybrid scheme combining ESRT and implicit hop-by-hop ARQ with significant improvement on energy efficiency.

Reliable communication mechanisms with the objective of minimizing energy efficiency were studied in [6]. EPB (Energy Per Bit) was introduced to characterize the energy efficiency, identify an optimal bound, and conclude that lazy loss detection (i.e., selective repeat) ARQ is the most energy efficient as an absolute reliable data delivery protocol. In our analysis, we adopted transmitted packet number as energy efficiency indicator (on packet level instead of bit level) in conjunction with statistical reliability instead of absolute reliability.

III. Multi-hop Statistical Reliability Analysis

A large variety of statistically reliable data delivery protocols are specified below. To improve the energy efficiency of WSN, these specified protocols, which are variants of conventional ones, adapt the maximum number of retransmissions to the channel error rate and the required statistical reliability β.

For selecting a good generic candidate for a WSN protocol stack we analyze the energy efficiency of these protocols. For the sake of modeling and analysis, consider a single path with $h+1$ sensors labeled $0, 1, \ldots, h$ and the corresponding h link hops from a sensor source to the sink node as depicted in Figure 1. To reflect real signal fading of wireless channels we allow nonreciprocal links between adjacent sensors as well as fading dependency between adjacent links.

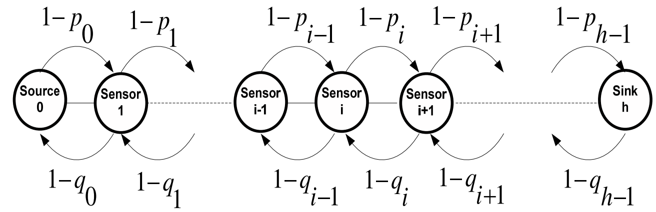

Fig. 1. A single route with transmission failure probabilities.

For every i, the probabilities that a transmission from node i to node $i+1$ and from node $i+1$ to node i are received successfully are denoted by $1-p_i$ and $1-q_i$, respectively. We assume that reception failures are *spatial dependent* but *time independent*. Spatial dependency means that the reception of a transmission from node $i \geq 1$ at node $i+1$ is correlated with the reception at node $i-1$. Specifically, for every transmission of node $i \geq 1$, let r_i denote the conditional probability of the following reception event:

$$r_i \stackrel{def}{=} Pr[\text{Success at node } i-1 | \text{Success at node } i+1].$$

Time independent means that a reception failure of a transmission from node i at time t is independent of a reception failure of another transmission from the same node at time $t_1 \neq t$. We also assume that transmitter power and topology are controlled so as to limit the transmission range within only one hop away.

For notational brevity, for every probability, p, $\bar{p}$ denotes $1-p$.

As pointed out in [6], link error rate probabilities are readily available for the transport layer from the *Link Quality Indicator (LQI)* defined by IEEE standard 802.15.4 [1] which are highly correlated. LQI is implemented on Chipcon CC2420 [2] and used on MicaZ and Telos sensors.

Unlike strict reliability used in [6] for code distribution application, this paper concerns with data streaming applications requiring only *statistical reliability*. Statistical reliability is less stringent than strict reliability and leads to more energy efficient transport protocols.

Energy efficiency of a transport protocol is determined mainly by the sensor "sleeping time" controlled from the MAC layer. Sleeping time is proportional to the sensor idle time, which is determined by the number of transmitted/received packets. Thus, energy efficiency of statistically reliable data delivery protocols can be evaluated by the expected number packet transmissions.

Given a transport protocol, π, its normalized energy efficiency, E_π, is defined as the expected number of transmissions (sensed and ACK packets) required for delivering one sensed data with probability β from source to sink.

A. Energy-efficiency of ESRT

With ESRT [4], a sufficiently large number of random sensed data are sampled within each time interval at a source sensors and transmitted toward the sink without any acknowledgment (ACK) or retransmissions. In [4], the sample size at the source is determined by an outer-loop protocol between the source and the sink nodes aimed at receiving a required mean sample size at the sink. In this paper, the source sample size is determined analytically as a function of β and the hop count between the source and destination.

Observe that at each hop, the sample size is reduced on the average by factor of $1-p$, where p is the link packet error rate. Thus, the sample size at the source sensor increases exponentially with the path length and so is the overall number of transmissions. As our analysis shows, for paths longer than some threshold, ESRT becomes energy-inefficient and the number of transmissions clogs the WSN. This phenomenon has been already pointed out in [4].

The ESRT protocol label is denoted by$\pi = 1$. With ESRT, retransmission is replaced with a much larger random sample size at the source used for backups. Let $N_1(\beta)$ be the minimum number of backups required for each sensed data for successful delivery with probability β.

Proposition 1: For the ESRT protocol, $N_1(\beta) = \left\lceil \frac{\log(1-\beta)}{\log\left(1-\prod_{i=0}^{h-1}\bar{p}_i\right)} \right\rceil$ and $E_1 = N_1(\beta)\left(1+\sum_{i=1}^{h-2}\prod_{k=0}^{i-1}\bar{p}_k\right)$, where $\lceil x \rceil$ is the smallest integer larger than or equals x.

Proof: See Appendix. ■

Observe that when β approaches one, $N_1(\beta)$ approaches infinity and so is E_1. The explanation is simple; for any finite $N_1(\beta)$, there is a positive probability that all $N_1(\beta)$ transmissions will fail.

B. Energy-efficiency of SW E2E ARQ

Classical ARQ protocols used for land-line networks comprise three basic schemes: send-and-wait (SW), Go-Back-N (GBN) and selective repeat (SR) [5] [8] [10] [21]. With SW, the transmitter waits for an ACK or a timeout before its next transmission. With GBN and SR, the transmitter sends packets continuously. However, to prevent buffer overflow at the receiving node, the number of unacknowledged transmissions is kept below a preset size of N packets. GBN and SR are implemented by a sliding window of size W, where W is determined by N and the round trip time (RTT) estimator. The objective is to keep a continuous stream of transmissions, hence utilizing channel capacity while maintaining lower packet delay.

All three ARQ protocols can operate hop-by-hop (HBH) or end-to-end (E2E). With respect to packet delay, E2E is better than HBH for small error rate, and worse for high error rate [16]. To the best of our knowledge, the relation between HBH and E2E with respect to energy-efficiency has not been studied.

The SW E2E ARQ protocol label is denoted by $\pi = 2$ and all temporal notations above are redefined. Let $N_2(\beta)$ be the minimum number of transmissions required for each sensed data for successful delivery with probability β.

Proposition 2: For the SW E2E protocol,

$$N_2(\beta) = \left\lceil \frac{\log(1-\beta)}{\log\left(1-\prod_{i=0}^{h-1}\bar{p}_i\right)} \right\rceil \quad \text{and}$$

$$E_2 = \frac{1-\left(1-\prod_{i=0}^{h-1}\bar{p}_i\bar{q}_i\right)^{N_2(\beta)}}{\prod_{i=0}^{h-1}\bar{p}_i\bar{q}_i}\Big[1+\sum_{i=0}^{h-2}\prod_{k=0}^{i}\bar{p}_k + \left(\prod_{k=0}^{h-1}\bar{p}_k\right)\left(1+\sum_{i=0}^{h-2}\prod_{k=0}^{i}\bar{q}_{h-1-k}\right)\Big].$$

Proof: See Appendix. ■

Note that $N_2(\beta)$ and $N_1(\beta)$ are equal and for the extreme case of $h = 1$, $E_2 = E_1$, as expected. Also, for $\beta \to 1$, $N_2(\beta) \to \infty$

C. The energy-efficiency of SW hop-by-hop ARQ

With SW HBH ACK ARQ, reliability is assured in every hop. If a transmitter receives an ACK from its subsequent node before the preset timeout occurs, it transmits a new packet; otherwise, it retransmits the preceding packet. A receiver transmits an ACK for every packet it receives successfully including for duplicates. It is worth noting that when a packet is received successfully for the first time, it is forwarded regardless of its ACK outcome. By convention, duplicates are not forwarded.

Since the reliability requirement is of some level β, the number of retransmissions in each hop is bounded by some $N(\beta)$ derived below. Using the minimum upper bound is important for energy saving.

Due to relatively high error rates of wireless links in WSN, SW HBH ACK ARQ [13] seems as an attractive candidate. However, considering the energy used for ACKs, an implicit SW HBH ACK (SW HBH iACK ARQ), described below, could be more efficient.

Unlike ESRT protocol, where the number of transmissions increases exponentially with the path length, the number of transmissions with HBH ACK increases linearly. Thus, SW HBH ACK is expected to outperform ESRT for paths shorter than some threshold. This threshold certainly depends on the link error rates. Indeed, in the ideal case with no errors, ESRT incurs no transmission overhead whereas SW HBH ACK does.

The SW HBH ARQ protocol label is denoted by $\pi = 3$. Let $N_3^i(\beta)$ be the minimum number of transmissions required at link hop i for each sensed data for successful delivery with probability β.

Proposition 3: For the SW HBH protocol,
$N_3^i(\beta) = \left\lceil \frac{\log\left(1-\beta^{1/h}\right)}{\log(p_i)} \right\rceil$ and
$E_3 = \sum_{i=0}^{h-1} \frac{1-(1-\bar{p}_i\bar{q}_i)^{N_3^i(\beta)}}{\bar{p}_i\bar{q}_i}(1+\bar{p}_i)$.

Proof: See Appendix. ■

D. The energy-efficiency of SW HBH iACK

Traditional SW HBH ACK use explicit ACK messages which consumes energy. Explicit ACKs are required for wired links; however, with wireless links, the transmitter can "overhear" the forwarding transmission and interpret it as an implicit ACK. Clearly, the sink node is required to send an explicit ACK. Transmissions and retransmissions are as with SW HBH ACK. This ARQ version, referred to as *SW HBH iACK*, has been proposed in [19].

If packet errors on the upstream and downstream links are highly correlated, the energy saving with SW HBH iACK is apparent since ACKs are almost free. Since the distance and the landscape between a node and its close neighbors are most likely similar, the reception qualities are expected to be highly correlated.

A potential issue arising out of our NS2 simulation is the retransmission timeout setting. Unlike explicit ACK sent immediately by the hardware, iACK timeout depends on the forward queues.

Another potential issue with iACK is an “avalanche” effect demonstrated in [12], where unnecessary retransmissions are generated all the way down to the sink due to miss-interpretation of a packet transmission role. One way to prevent the “avalanche” effect is by using an orientation bit in the packets which signifies if it is used as an upstream ACK only.

Specifically, all packet headers contain an orientation bit and sent in a broadcast mode and no explicit ACKs are sent. If the bit in a transmitted packet is zero, the packet serves as an implicit ACK and as a forward packet; otherwise, it serves just as an implicit ACK.

Clearly, each node i switches the bit to one (if iACK retransmissions are required) after it receives an iACK from node $i+1$. Note that node $i+1$ does not iACK such retransmissions, hence stopping the avalanche.

The SW HBH iACK protocol label is denoted by $\pi = 4$ and all temporal notations above are redefined. Let $N_4^i(\beta)$ be the minimum number of transmissions required at link hop i for each sensed data for successful delivery with probability β.

Proposition 4: For the SW HBH iACK protocol, $N_4^i(\beta) = N_3^i(\beta)$ and

$$\begin{aligned} E_4 &= \tfrac{1-(1-\bar{p}_0\bar{q}_0)^{N_4^0(\beta)}}{\bar{p}_0\bar{q}_0} + \textstyle\sum_{i=1}^{h-1} \tfrac{1-(1-\bar{p}_i\bar{q}_i r_i)^{N_4^i(\beta)}}{\bar{p}_i\bar{q}_i r_i} \\ &+ \tfrac{1-(1-\bar{p}_{h-1}\bar{q}_{h-1})^{N_4^{h-1}(\beta)}}{\bar{p}_{h-1}\bar{q}_{h-1}} \times \bar{p}_i. \end{aligned}$$

Proof: See Appendix. ∎

Observe that for spatial dependency of $r_i = 1$, SW HBH iACK saves all the ACKs of SW HBH ARQ except for the ACKs from the sink.

E. The energy-efficiency of E2E SR ARQ

SW ACK protocols have minimal buffer requirements, but their channel utilization and packet delay are not efficient. To improve the utilization and packet delay, continuous transmissions are used by GBN and SR. The improvement is at the expense of buffer size, which is not suitable for some sensors, e.g., MICA2 motes have only 4 KB [3].

To avoid unnecessary delays, it is common practice in wired networks to transmit an ACK (with GBN) or a negative ACK (NACK, with SR), upon every received packet. However, to save energy, the version proposed here send a single ACK/NACK for a batch of packets.

GBN and SR have an HBH and E2E versions. Due to buffer size limitations in sensors, E2E could be more attractive for some sensors since it would not stress the buffers at the relay sensors.

To track lost packets, both protocols use sequence numbers (SN) to label the sensed data packets. With SR ARQ, each transmitter transmits all available data constantly without waiting for a NACK. To prevent buffer overflow at the receiving nodes, a sliding window of size W described above is used. SR ARQ use NACKs rather than ACKs indicating which packets should be retransmitted. When a NACK arrives, the source retransmits only the NACK’ed packets.

In our version of SR ARQ, the receiver sends a single NACK packet for every batch of K newly received packets. That is, duplicate packets are not counted for NACK triggering. Each NACK packet comprises the list of SN requested by the receiver along with the highest SN received. Thus, NACKs are sent also if packets are not lost. Furthermore, from the highest SN received and the NACK’ed packets, the source can compute the receiver buffer occupancy and maintain a count of the unacknowledged packets.

Additionally, to save unnecessary retransmissions, the receiver maintains the number of NACKs sent for each packet and limits its number by some upper bound $N(\beta)$ derived below. Note that unlike with other protocols, the maximum number of retransmissions cannot be controlled by the source.

Timeout can be controlled either by the transmitter or by the receiver. When a timeout fires at the receiver, it retransmits its last NACK; when a timeout fires at the transmitter, it returns to its transmission state at the last received NACK.

Buffer occupancy of SR ARQ and GBN ARQ described below have been derived in [10] and [21]. Here, we derive its energy-efficiency.

The E2E SR ARQ protocol label is denoted by $\pi = 5$ and let K denote the batch size of each NACK. Although the protocol uses some sliding window of size W, the window size is irrelevant for deriving the minimum number of retransmissions, $N_5(\beta)$, since only failed packets are retransmitted.

Let $a = 1 - \prod_{i=0}^{h-1} \bar{p}_i$, $b = 1 - \prod_{i=0}^{h-1} \bar{q}_i$ and Define,

$$E[X_0] = \sum_{n=1}^{N_5(\beta)+1} a^{n-1} \sum_{k=n-1}^{N_5(\beta)} \binom{N_5(\beta)}{k} (1-b)^k b^{N_5(\beta)-k}$$

$$E[Y_h] = \sum_{n=1}^{N_5(\beta)} a^{n} \sum_{k=n-1}^{N_5(\beta)} \binom{N_5(\beta)}{k} (1-b)^k b^{N_5(\beta)-k}.$$

Proposition 5: For the E2E SR ARQ protocol, $N_5(\beta) = \left\lceil \frac{\log\left(1+(1-a)-\beta\right)}{\log\left(a(1-b)+b\right)} \right\rceil$ and

$$E_5 = E[X_0]\left(1 + \sum_{i=0}^{h-2}\prod_{k=0}^{i} \bar{p}_k\right) + E[Y_h]\left(1 + \sum_{i=1}^{h-1}\prod_{k=1}^{i} \bar{q}_{h-k}\right)/K.$$

Proof: The proof is given in [11]. ∎

F. The energy-efficiency of HBH SR ARQ

The HBH SR ARQ protocol label is denoted by $\pi = 6$. The expected number of transmissions for each hop with HBH SR ARQ, E_6^1, is a special case of E2E SR ARQ with $h = 1$. The total number of expected transmissions is $E_6 = hE_6^1$.

G. The energy-efficiency of E2E GBN ARQ

With GBN ARQ, each transmitter transmits continuously all available data using a sliding window of size W described above. To save energy, the receiver sends a single ACK packet for every batch of K packets received successfully. The ACK specifies the next expected SN packet implying that all packets with lower SNs have been received. Upon receiving an ACK, the transmitter backs to the expected packet and retransmits that packet and all the following packets.

Although a reliability level less than one may be required, GBN cannot limit the number of retransmissions due to its inherent structure. Thus, the protocol may transmit more packet than its reliability level requires.

Since the transmitter backs to the packet specified by the ACK, the receiver is not required to buffer packets received out of order. The transmitter, on the other hand, is required to buffer all un-ACK'd packets.

The E2E GBN ARQ protocol label is denoted by $\pi = 7$, the sliding window size is set to W and the batch size of each ACK is set to K. Note that when the batch ACK size $K > 1$, the relation between RTT and the ideal W should given in multiples of K packets since the receiver waits for K new packets before transmitting an ACK. Ideally, given RTT and K, the ideal W is the number of batches, each of which comprise K packets, that can be transmitted during RTT. Implied is that $W = n \times K$, for some positive integer n. Also recall that with E2E GBN ARQ. setting a maximum number of retransmissions per packet infeasible.

Proposition 6: For the E2E GBN ARQ protocol,

$$\begin{aligned} E_7 &= \frac{1}{\prod_{i=0}^{h-1} \bar{p}_i^W \bar{q}_i} \Big[1 + \sum_{i=0}^{h-2} \prod_{k=0}^{i} \bar{p}_k^W \\ &+ \frac{(\prod_{k=0}^{h-1} \bar{p}_k^W)}{K} \Big(1 + \sum_{i=0}^{h-2} \prod_{k=0}^{i} \bar{q}_{h-1-k} \Big) \Big] . \end{aligned}$$

Proof: The proof is given in [11]. ∎

H. The energy-efficiency of HBH GBN ARQ

The HBH GBN ARQ protocol label is denoted by $\pi = 8$.

The expected number of transmissions for each hop with HBH GBN ARQ, E_8^1, is a special case of E2E GBN ARQ with $h = 1$. The total number of expected transmissions is $E_8 = hE_8^1$.

IV. Simulation and Field Trial

A. NS2 simulation

To verify our analytical model and gain further insight into the problem, we conducted a detailed simulation in a sensor field of 73 nodes using ns2. These nodes are deployed in 9 concentric circles centred at the basestation. The nodes are positioned on the spokes originating from the basestation. The spokes are at 45 degrees from each other. We used the *destination-sequenced distance-vector (DSDV)* routing protocol and the two-ray ground propagation model with controlled packet loss rate in each hop. The radio interface in our simulation is 802.11 DCF MAC with RTS/CTS disabled for packets of size 40 bytes.

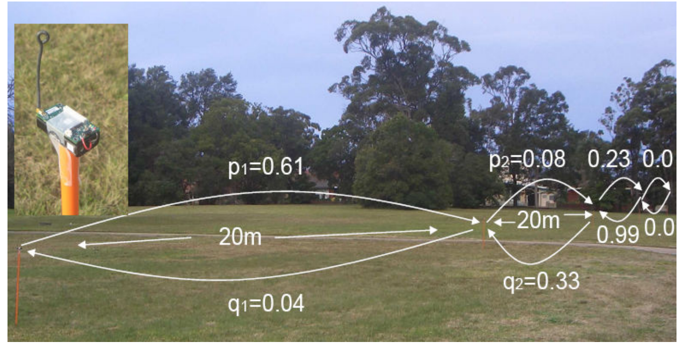

Fig. 2. Experiment Setup

Every node generates packets at rate 0.5 per second. The traffic is scheduled such that each spoke take turns to transmit eliminating interference. Note that such light traffic model is typical for WSN application. It reduces the effect of congestion and queueing, which is not included in our analytical model.

With this light load, collisions with channel error rates less than 20% is unlikely with 802.11 CSMA collision avoidance, even when RTS/CTS is disabled. For higher channel error rates, the actual channel packet loss has been estimated and the maximum number of transmission per packet with ARQ, $N_\pi(\beta)$, is set as function of the actual losses. For ARQ-related protocols, the retransmission timeout is set to be twice the CSMA backoff period.

Beside model verification, the NS2 simulation produces other performance measures such as *actual reliability, packet delay* and *"goodput"*. The expected number of transmissions in the NS2 simulation (with the 95% confidence intervals) for ESRT, SW HBH eARQ, SW HBH iACK, are depicted along with the analytical results in Figures 4-6. The average packet delays of these protocols along with the hybrid protocol defined below are depicted in Figures 7-9.

B. The Field Trial

Field trials were conducted outdoor in an open yard, with 5 MICA2 motes placed in a line 20 meters apart. The motes were elevated to 1 meter above ground, with transmission power set to 0dBm. We first measured the loss rate of each hop by programming each node to broadcast 3000 beacon packets to neighbors. The loss rate measured at each hop for each direction is shown in Figure 2.

Three sets of experiments were conducted.

- The first experiment is with ESRT. The results are shown in Figure 3 in red lines comparing the energy efficiency of the experiment and the analysis (Proposition 1). The

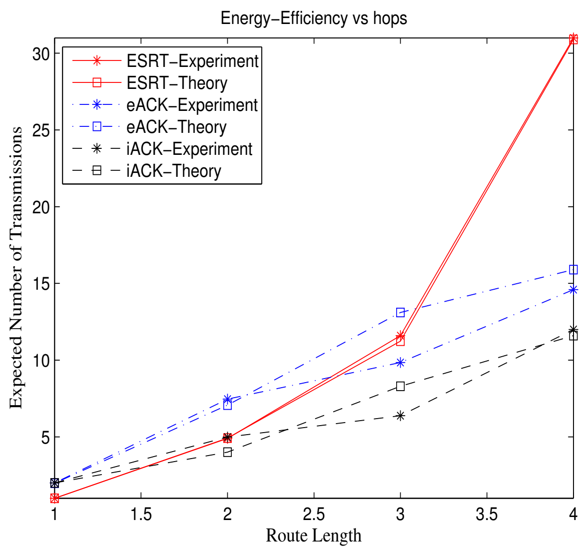

Fig. 3. Experiment Results

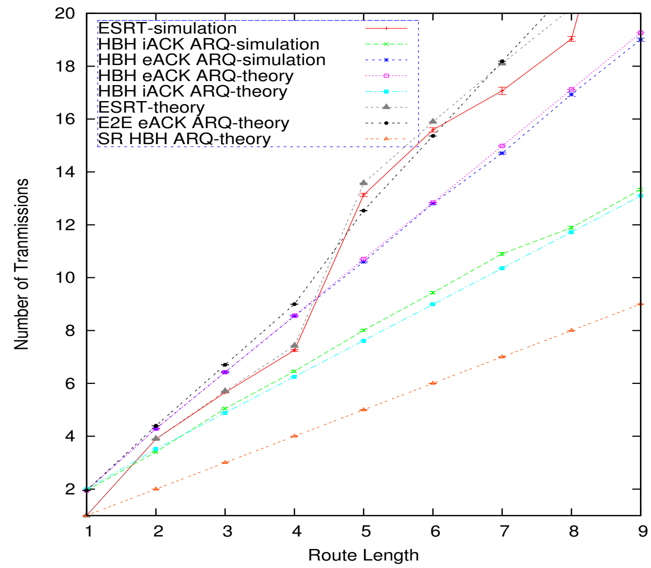

Fig. 4. Energy Efficiencies for $p = 0.05$.

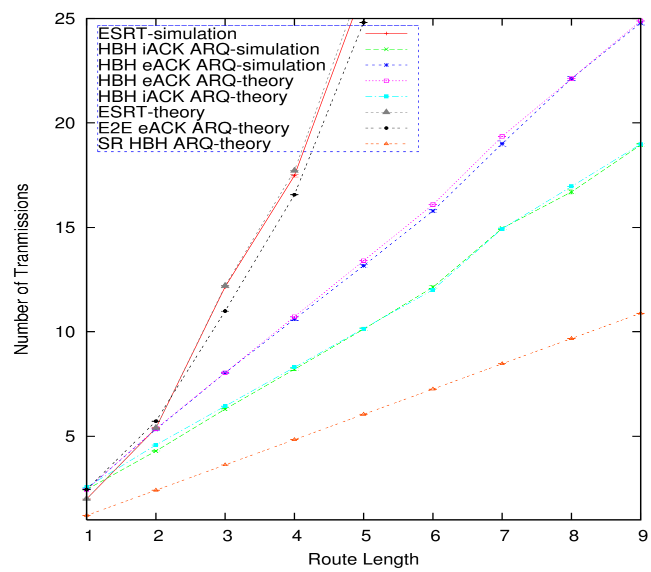

Fig. 5. Energy Efficiencies for $p = 0.20$.

actual realized loss rates were $\boldsymbol{p} = (0.69, 0.19, 0.36, 0.0)$ at respective hops.

- The second experiment is with SW HBH ARQ (eACK). The results are shown in Figure 3 in blue comparing the energy efficiency of the experiment and the analysis (Proposition 3). The actual realized loss rates were $\boldsymbol{p} = (0.41, 0.26, 0.34, 0.01)$ and $\boldsymbol{q} = (0.01, 0.5, 0.999, 0.02)$.
- The third experiment is SW HBH implicit ARQ (iACK). The results are shown in Figure 3 in black comparing the energy efficiency of the experiment and the analysis (Proposition 4). The actual realized loss rate at this experiment are $\boldsymbol{p} = (0.44, 0.07, 0.15, 0.00)$ and $\boldsymbol{q} = (0.03, 0.26, 1 - 10^{-6}, 0.00)$.

Due to reception variations in different experiments, it is impossible to compare all the protocols under the same conditions as we did in our simulations. We still find the resulting trends from these experiments follow theoretical predictions very closely. The differences for 3 hops with eACK and iACK are due to numerical stability in the computation for q_3 very close to one. From the experiments, ESRT is best for $1-2$ hops. For long paths, eACK has its merit, and iACK is the most efficient protocol.

V. Performance Evaluation

With respect to energy-efficiency, it is expected that SR ARQ is more efficient than GBN ARQ. This is indeed confirmed by the graphs generated by our analysis (not depicted here) showing that for realistic values of $\beta = 0.95$, $W = 12$ and $K = 4$, SR ARQ performs better for every hop count and p.

The graphs further show that both, SR HBH and E2E, are more efficient than any each of the GBN modes. Furthermore, for both ARQ, HBH is more efficient than E2E. When the error rates exceeds 10%, GBN explodes to astronomical figures.

Since SR HBH ARQ outperforms SR E2E ARQ and for both modes of GBN, the two latter protocols are not depicted in Figures 4-6. These Figures demonstrate clearly that SR HBH ARQ outperforms all other protocols across the board. For reliable links, i.e., $p_i = q_i \leq 0.01$, ESRT is equivalently efficient for path lengths smaller than some threshold. For $p_i = q_i = 0.01$, the threshold is 6 hops and for $p_i = q_i = 0.005$, the threshold is 11 (not shown in the figures).

Although the figures are depicted for statistical reliability of $\beta = 0.95$, $r_i = 0.7$, packet error rates $p_i = q_i = p$, where $p = 0.05, 0.20, 0.45$, ACK/NACK batch size of $K = 4$, and a sliding window size of $W = 12$, the relative merit of each protocol is similar for all practical set of parameters.

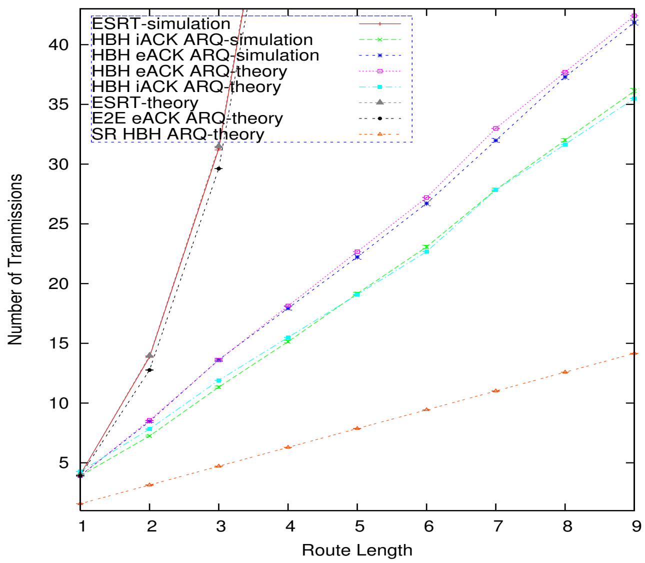

Fig. 6. Energy Efficiencies for $p = 0.45$.

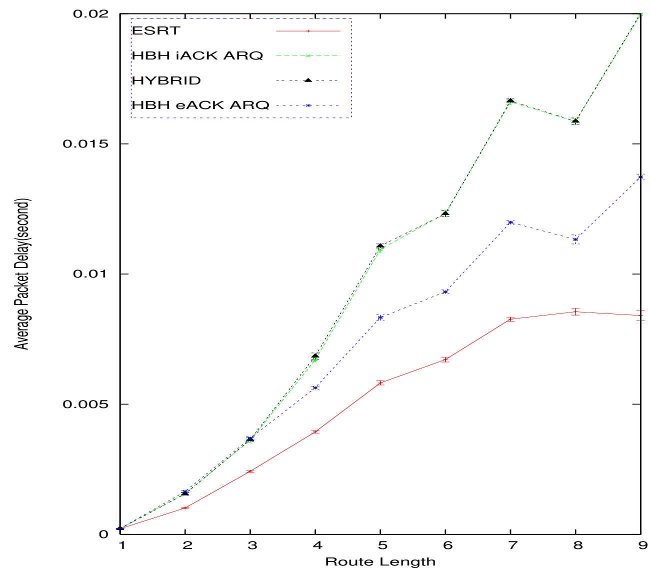

Fig. 7. Average packet delay for $p = 0.05$.

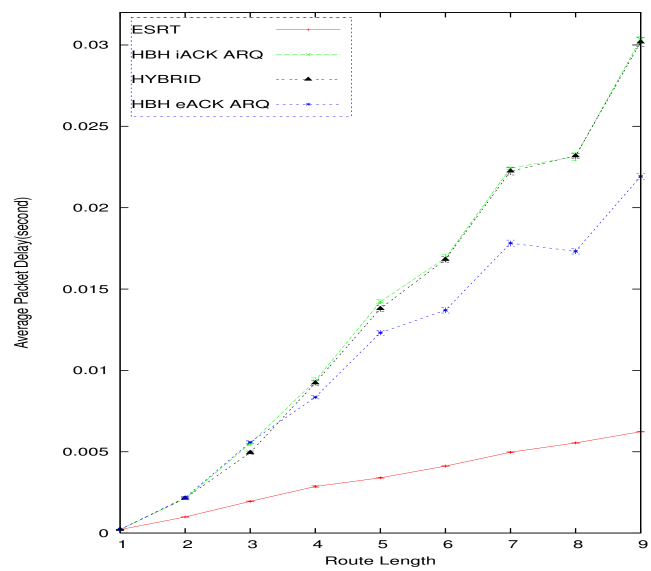

Fig. 8. Average packet delay for $p = 0.20$.

For some WSN, SR HBH ARQ may incur too high buffer and processing penalties. For such WSN, SW HBH iACK emerges as the most energy efficient protocol except for path lengths less than some threshold, where ESRT is better. The threshold depends on the link reliability. For $p_i = q_i = 0.01$, ESRT is better for path lengths less than or equals five; For $0.01 \leq p_i = q_i < 0.45$, ESRT is better for a single hop path; and for $p_i = q_i \geq 0.45$, ESRT is always worse. The dominance of ESRT for short paths when the links is very reliable is explained by the fact the required number of redundant sensed data can be predicted well and trades-off the overhead of the ACK at the sink node.

The simulated average packet delay with their 95% confidence interval using ESRT, SW HBH eARQ, SW HBH iACK, and the proposed Hybrid are depicted Figures 7-9 for $p_i = q_i = 0.05, 0.20, 0.45$.

The figures demonstrate the ESRT is best with respect the packet delay.

VI. An Optimal Hybrid Transport Protocol

When SR ARQ is not a feasible option, the performance comparison presented in Section V suggests that a hybrid protocol mixing ESRT and Implicit SW hop-by-hop can perform better than a pure protocol.

Our field trials show that network topology and link error rates vary in short time scale. Most routing protocols [20] have built-in mechanisms to measure the packet error rate. The proposed hybrid protocol adapts the maximum number of retransmissions in each hop based on the channel error estimations.

From Section V, the optimal hybrid protocol should mix between ESRT and iACK ARQ. From the nature of ESRT, it must start at the sensor source where data is sampled. Furthermore, Implicit SW are hop-by-hop and therefore their energy-efficiency is basically additive in the number of hops it is being used. (Some artifact in selecting the minimal number of retransmission may cause some deviation from linearity). Therefore, the optimal mixture of an hybrid protocol is to start with ESRT for the first H_{th} hops, which depends on the path length and link error rate. Then proceed with iACK ARQ until the sink.

Based on our numerical findings in Section V, the proposed hybrid protocol is given by the following pseudo code:

```
p = link_estimate(nexthop);
if (p < 0.01)
  H_th = 5;
else if (p < 0.45)
  H_th = 1;
else
```

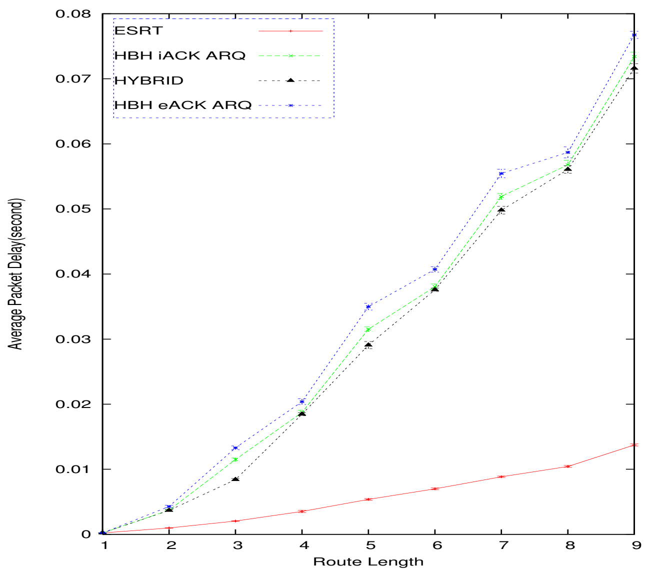

Fig. 9. Average packet delay for $p = 0.45$.

```
  H_th = 0;
hop = packet->hopcount;
N4_beta = 1; n_trans = 1;
if (hop > H_th)
  N4_beta = log(1-beta^(1/hop))/log(p);
while (n_trans < N4_beta) {
   send(nexthop, packet);
   n_trans++;
   timer(wait_for_iACK);
} // maximum retransmission reached
send(nexhop, packet);
// last transmission without ACK
```

APPENDIX

Proof of Proposition 1:

Suppose that each sensed data has N backups. By the time independency assumption, the number of sensed data successfully delivered across h link hops having failure probabilities of $\boldsymbol{p} = \{p_i\}$, $X_{h,\boldsymbol{p}}$, is binomially distributed with N and success probability of $\prod_{i=0}^{h-1} \bar{p}_i$. Thus,

$$\beta(N, \boldsymbol{p}) \stackrel{def}{=} P\left(X_{h,\boldsymbol{p}} \geq 1\right) = 1 - \left(1 - \prod_{i=0}^{h-1} \bar{p}_i\right)^N. \quad (1)$$

For statistical reliability at level β, $N_1(\beta)$ is the minimum integer satisfying $\beta(N, p) \geq \beta$, which implies the first part of the Proposition.

The energy efficiency, E_1, is determined by the convolution of successful transmissions along the h hops, given that $N_1(\beta)$ backups for each sensed data are transmitted from the source sensor.

Let $K(i)$ be the number of successful transmissions in link hop $i = 0, \ldots, h-1$. Clearly, $K(0) = N_1(\beta)$ and by the Bayesian rule

$$E[K(i)] = E\left[E[K(i)|K(i-1)]\right] = \bar{p}_{i-1} E[K(i-1)].$$

Then, by recursion

$$E[K(i)] = N_1(\beta) \prod_{k=0}^{i-1} \bar{p}_k, \ i = 1, \ldots, h-1.$$

The second part of the Proposition follows by noticing that the successful transmissions at hop i determines the number of transmissions at the next hop $i+1$.

■

Proof of Proposition 2:

A sensed data is received by the sink node successfully with probability $\prod_{i=0}^{h-1} \bar{p}_i$, regardless of the ACK outcome. If an ACK is not received at the source within a predetermined timeout, the sensed data is retransmitted. Given a maximum number of transmissions per sensed data, N, the sensed data is delivered successfully with probability $1 - \left(1 - \prod_{i=0}^{h-1} \bar{p}_i\right)^N$.

For statistical reliability at level β, the minimum N, $N_2(\beta)$, is given by the smallest integer satisfying

$$1 - \left(1 - \prod_{i=0}^{h-1} \bar{p}_i\right)^N \geq \beta, \quad (2)$$

which is resolved by $N_2(\beta)$ of the Proposition.

For evaluating E_2 note that unlike successful delivery, retransmissions of a sensed data is stopped only if it reaches the sink and its respective ACK reaches the source. This event occurs with probability $\prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i$. Otherwise, the source sensor retransmits the sensed data.

Let K_2 be the number of transmissions (sensed data and ACKs) using E2E ARQ with $N_2(\beta)$. Also, let X_i and Y_i be the number of transmissions of a single sensed data and an ACK made by and to node i along the route, respectively, $i = 0, \ldots, h$.

The expected number of transmissions per each measurement is given by

$$E_2 = E[K_2] = \sum_{i=0}^{h-1} \left(E[X_i] + E[Y_i]\right). \quad (3)$$

Note that X_0 is a truncated geometrically distributed r.v. with a success probability of $\prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i$ taking values in the set $\{1, \ldots, N_2(\beta)\}$. Its expected value is given by:

$$\begin{aligned} E[X_0] &= N_2(\beta)\left(1 - \textstyle\prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i\right)^{N_2(\beta)-1} \\ &\quad + \textstyle\sum_{k=1}^{N_2(\beta)-1} k\left(\prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i\right)\left(1 - \prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i\right)^{k-1} \\ &= \frac{1 - \left(1 - \prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i\right)^{N_2(\beta)}}{\prod_{i=0}^{h-1} \bar{p}_i \bar{q}_i}. \end{aligned} \quad (4)$$

The expected number of sensed data packets from any realization of X_0 successfully forwarded to node 1 is $\bar{p}_0$. Thus, $E[X_1] = \bar{p}_0 E[X_0]$. Similarly for every subsequent node along the forward route to the sink. At every subsequent hop i, the expected number of transmissions is reduced by a factor of $\bar{p}_{i-1}$. In the backward route of the ACK, a similar expected reduction occurs. The second part of the Proposition follows from (3) and (4).

■

Proof of Proposition 3:

The derivation of $N_3^i(\beta)$ is similar to the previous derivations, with the difference that here we further restrict the requirement for $N_3^i(\beta)$ to satisfy $(1-p_i^{N_3^i(\beta)}) \geq \beta^{1/h}$.

Each hop component of E_3 is derived as a special case of SW E2E ARQ with $h = 1$.

■

Proof of Proposition 4:

As with explicit SW HBH ARQ (HBH eACK ARQ), a sensed data is forwarded to the next hop if it has been successfully received regardless of the implicit ACK outcome. Therefor, $N_4^i(\beta) = N_3^i(\beta)$ for every i.

For E_4, note that a forward packet from node i successfully received by the next node $i+1$, may not be overheard by node i triggering a retransmission. Such events are accounted for by the spatial dependency defined above by $r_i = Pr[\text{success at } i-1|\text{success at } i+1] = Pr[\text{success at } i+1|\text{success at } i-1]$.

Let X_i be the number of transmissions made by node i, $0 \leq i \leq h$, for a single sensed data packet. For $i = 0$, the source node transmits until the sensed data and its forwarding transmission are both received at node $i = 1$ and $i = 0$, respectively, but no more than $N_4^i(\beta)$. The probability of this event is $\bar{p}_0\bar{q}_0$ and by the truncated geometric distribution its expected value is given by

$$E[X_0] = \frac{1-(1-\bar{p}_0\bar{q}_0)^{N_4^0(\beta)}}{\bar{p}_0\bar{q}_0}. \quad (5)$$

For $0 < i < h$, assuming proper setting of the timeouts, the transmitter node, i, transmits until the sensed data is successfully received by both, node $i-1$ and node $i+1$, as well as the forwarding by node $i+1$ is 'overheard' by node i, but no more than $N_4^i(\beta)$. The probability of this event is $\bar{p}_i\bar{q}_i r_i$ and by the truncated geometric distribution its expected value is given by

$$E[X_i] = \frac{1-(1-\bar{p}_i\bar{q}_i r_i)^{N_4^i(\beta)}}{\bar{p}_i\bar{q}_i r_i}. \quad (6)$$

The sink node, $i = h$, needs to transmit an explicit ACK. As with SW HBH ARQ, the expected number of these ACKs is

$$E[X_h] = \frac{1-(1-\bar{p}_{h-1}\bar{q}_{h-1})^{N_4^{h-1}(\beta)}}{\bar{p}_{h-1}\bar{q}_{h-1}} \times \bar{p}_i. \quad (7)$$

Combining (5)-(7) yields the second part of the Proposition.

■

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