ARQ with Implicit and Explicit ACKs in Sensor Networks

Z. Rosberg*, R. Liu*, A. Y. Dong*, L. D. Tuan*†, and S. Jha†

*CSIRO ICT Centre, Australia Email: {Zvi.Rosberg,Ren.Liu,Tuan.LeDinh}@csiro.au; alex.yifeidong@gmail.com
†School of Computer Science UNSW, Australia, Email: sanjay@cse.unsw.edu.au

***Abstract*—A common application of unattended sensor networks (WSN) is low data rate streaming from many scattered sensors to one or more sink nodes, where packet error rate per link vary within 1-70% and path length could be up to tens of hops. To cope with the stringent requirement of battery lifetime, a new notion of *statistically reliable* transport protocol is introduced and the energy-efficiency of a several variants of stop-and-wait hop-by-hop ARQ with explicit and implicit ACKs are proposed. The energy-efficiency of the protocols are precisely analyzed and compared numerically. The analysis reveals that implicit ACKs should be applied with caution so as to prevent an "avalanche" of implicit ACK transmissions. It is further shown that a simple combined implicit/explicit ACK resolves the "avalanche" problem. The mathematical analysis is verified by simulation using "TOSSIM" - a detailed simulator of the entire "TinyOS" system.**

I. Introduction

Many of valuable WSN applications are deployed in hostile/remote unattended locations without pre-existing infrastructure. In such harsh operational environments, a long sensor lifespan is almost mandatory. Typical packet error rates of WSN links vary within 1-70% [5] [6] [14] and path length from source to sink could be up to tens of hops. This work is motivated by our recent experience in deploying WSN at Burdekin, Australia, for water quality (water flows, water level, and salinity) monitoring [7] re-affirming these link quality and sensor lifespan problems. The driving application is a low data rate streaming from many scattered sensors to one or more sink nodes along a multi-hop path, which is then relayed for off-line processing.

Reliability requirement for data streaming applications is not absolute but rather statistical in its nature. That is, the reliability is determined by the quality of an ensemble of sensed data delivered at the sink rather than the reliability of each sensed data. Specifically, regardless of the sampling rate at the sensor source, during every time window, each sensed data from a random sample should be delivered to the sink node with a probability of at least β. Such reliability objective is referred to as *statistical reliability of level* β.

Using a statistical reliability objective when designing a reliable transport protocol is significant for WSN since it reduces the number of transmissions compared to absolute reliability. Consequently, sensors are more energy efficient and their lifespan is increased.

For reliable data transport, most sensors use send-and-wait (SW) hop-by-hop (HBH) ARQ with explicit acknowledgement (eACK), where the eACK is sent automatically by the MAC layer. Whereas eACKs are required for wired links, they are not required for wireless links along a multi-hop path, since a transmitter can "overhear" the forwarding transmission and interpret it as an implicit ACK (iACK).

The iACK mechanism bares an advantage for WSN since eACK transmissions can be saved. However, there is a potential issue with multi-hop paths. Consider a packet sent from node $i-1$ to node i and then forwarded by node i to node $i+1$. The forwarding transmission to $i+1$ is interpreted by node $i-1$ as an iACK. If $i+1$ receives the forwarding packet but $i-1$ fails to "overhear" the transmission, the latter will timeout and retransmit the packet to i. Node i, in turn, must iACK it by another forwarding transmission. Every such forwarding transmission made by node i, just to iACK node $i-1$, also triggers another unnecessary retransmission by node $i+1$ to iACK node i. The latter iACK cannot be avoided since node $i+1$ does not know if i has received his previous iACK. These unnecessary retransmissions continue all the way down to the sink, generating an "avalanche" effect.

This paper studies the energy efficiencies of SW HBH ARQ with eACK and compare it to two variants of iACK that prevent the "avalanche" affect. Related works are described Section II and the SW HBH ARQ with eACK and iACK variants are specified in Section III. The analysis and the energy-efficiency comparison are given in Sections IV. Analysis verification via the "TOSSIM" simulator is given in V and concluding remarks in Section VI.

II. Related Work

In [13], an absolute reliable transport 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 [12], the tradeoff between having reliability implemented at MAC, Transport and Application layers has been investigated. The proposed Reliable Multi-Segment Transport (RMST) combines MAC layer ARQ with transport layer NACK-based schemes to provide absolute reliability.

A statistically reliable transport protocol called *event-to-sink reliable transport (ESRT)* is presented in [2] for sensed data streaming applications not requiring absolute reliability. The reliability level of the protocol has been analyzed and simulated with NS2. The energy efficiency of ESRT analyzed in [11] has revealed that its energy efficiency deteriorates exponentially with the path length.

A comprehensive set of statistically reliable transport protocols were analyzed in [11], revealing that the selective repeat (SR) HBH ARQ is the most efficient protocol across the board. However, since SR ARQ requires a buffer size which could be too demanding for many sensors, SW HBH ARQ with eACK or iACK seems to be more appealing for most WSN.

III. Statistically Reliable ARQ Protocols

Classical ARQ protocols used for wired networks comprise three basic schemes: send-and-wait (SW), Go-Back-N (GBN) and selective repeat (SR) [3] [9] [10] [15]. With SW, the transmitter waits for an ACK or a timeout before its next transmission. With GBN and SR, the transmitter sends packets continuously. All three ARQ protocols can operate hop-by-hop or end-to-end. The analysis of [11] has revealed that energy-wise, hop-by-hop is better than end-to-end.

A. SW HBH ARQ with eACK

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

Since the reliability requirement is of some level $\beta < 1$, the number of retransmissions in each hop is bounded by some $N(\beta)$ derived below. Finding the least required $N(\beta)$ is important for energy saving.

Due to relatively high error rates of WSN links, SW HBH ARQ with eACK [12] is an attractive candidate. Accounting also the energy consumed by ACK transmissions, a SW HBH ARQ with iACK, as described below, seems to be even more attractive.

Note that unlike ESRT, where the number of transmissions increases exponentially with the path length [11], the number of transmissions of SW HBH ARQ with eACK increases linearly. Thus, SW HBH ARQ with eACK clearly outperforms ESRT for paths larger than some threshold.

B. SW HBH ARQ with iACK

Traditional SW HBH ACK uses explicit ACK messages which consumes energy which can be saved by using iACK in every node but the the last one. Clearly, the sink node is required to send an explicit ACK. Transmissions and retransmissions are as with SW HBH ARQ with eACK. Observe that if packet errors on the upstream and downstream adjacent links from node i are highly correlated, the energy saving with 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.

As explained in the introduction, a naive implementation of iACK (Pure-iACK) may cause a transmission “avalanche” affect. To combat the “avalanche”, two iACK variants (Oriented-iACK and Combined-ieACK) are proposed below.

Pure-iACK: All packets are sent in a broadcast mode and eACKs are completely avoided. Whenever node $0 < i < N$ receives a copy of a given packet from node $i-1$, it always forwards it to node $i+1$. This forwarding also servers as an iACK for node $i-1$. If an iACK for a given packet has not been received by node $i-1$ before a timeout occurs, it retransmits the packet. Clearly, node N sends eACKs rather than iACK.

A node does not use timeouts for retransmissions that have been previously iACK’ed. With iACK, such cases may occur when the node transmits just for iACK.

Note that if a transmission from node i is received by node $i+1$ it is received by node $i-1$ (perfect *spatial correlation*), then a packet is retransmitted only if both neighbors do require the retransmission. Since spatial correlation is not perfect, it may trigger the “avalanche” effect described above.

One way to prevent the “avalanche” effect is by using an orientation bit in the packets which signifies if it is an upstream ACK only.

Oriented-iACK: All packets are sent in a broadcast mode and eACKs are completely avoided. Unlike with pure iACK, an orientation bit is added to every packet. If the bit in a transmitted packet is zero, then the packet is both, an iACK and a forward packet; otherwise, it is just an iACK.

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.

Another way to prevent the “avalanche” effect is by combining eACKs with iACKs as described below.

Combined-ieACK: Upon the first reception of a specific packet in node i, the node forwards the packet which serves also as an iACK to node $i-1$. For all subsequent receptions of the same packet, the node sends an eACK.

Note that when a timeout occurs at node i, the packet is re-forwarded to node $i+1$. At the same time, it is also being interpreted by node $i-1$ as another iACK. Nevertheless, such interpretation is harmless since it does not result an avalanche.

One difference between Oriented-iACK and Combined-ieACK is that the former is implemented at the link layer, whereas the latter is implemented in both, the link and the MAC layers. With Combined-ieACK, after a packet is forwarded, the ACK responsibility is delegated from the link layer to the MAC layer. MAC layer ACK is more efficient since it is done automatically.

Another difference rises from the following scenario. Suppose that an iACK transmitted by node i is not received by both nodes, $i-1$ and $i+1$; and a retransmission from node $i-1$ arrives at node i before a timeout fires at i. With Combined-ieACK, node i sends an eACK; whereas with Oriented-iACK, it sends an iACK with orientation bit set to one. Although, the bit informs node $i+1$ that it is an iACK to node $i-1$, it can still use the packet if it had not received it yet. Such scenarios reduces the packet failure probability compared with Combined-ieACK.

IV. Multi-hop Statistical Reliability Analysis

For selecting a good generic transport protocol for WSN we analyze the energy efficiency of the protocols described in Subsection III-B. Consider a single path with $h+1$ sensors labeled $0, 1, \ldots, h$ and the corresponding h link hops $1, \ldots, h$, 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.

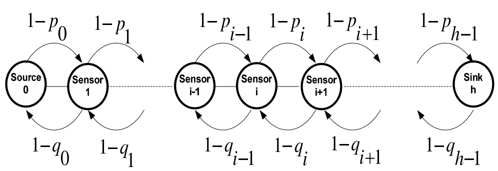

Fig. 1. A single route with transmission failure probabilities.

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

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 probabilities of the following reception event:

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

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.

As pointed out in [4], 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.

Unlike strict reliability used in [4] 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 transport protocols can be evaluated by the expected number packet transmissions.

A. Energy-efficiency of SW HBH ARQ Protocols

For each transport protocol, π, let $N_\pi^i(\beta)$ be the the minimum number of transmissions per sensed data required at every node i for guaranteeing a successfully delivery to the sink with probability β. Additionally, let $E_\pi(\beta)$ be the total expected number of transmissions (data and ACKs) per sensed data for guaranteeing a successfully delivery with probability β. First, we evaluate $N_\pi^i(\beta)$.

Proposition 1: For each one of the SW HBH ARQ protocol variants,

$$N_\pi^i(\beta) = N^i(\beta) = \left\lceil \frac{\log\left(1-\beta^{1/h}\right)}{\log(p_i)} \right\rceil \tag{1}$$

Proof: A sensed data transmitted by node i is received by node $i+1$ successfully with probability $\bar{p}_i$, regardless of the ACK mechanism and outcome. If an ACK is not received within a predetermined timeout, the sensed data is retransmitted. For any give maximum number of transmissions per sensed data, N^i, the sensed data is delivered to node $i+1$ successfully with probability $1-p_i^{N^i}$.

For uniform reliability along the hops, we require that each N^i satisfies $(1-p_i^{N^i}) \geq \beta^{1/h}$. It is simple to verify that the minimum N^i is resolved by (1). ■

Next, we evaluate $E_\pi(\beta)$ for SW HBH ARQ with eACK, labeled with $\pi = 1$.

Proposition 2: For the SW HBH ARQ with eACK protocol,

$$E_1(\beta) = \sum_{i=0}^{h-1} \frac{1-(1-\bar{p}_i\bar{q}_i)^{N^i(\beta)}}{\bar{p}_i\bar{q}_i}\left(1+\bar{p}_i\right). \tag{2}$$

Proof: Let X_1^i be the number of sensed data transmissions from node i to node $i+1$; and Y_1^i be the number of eACKs transmissions from node $i+1$ to node i, $0 \leq i \leq h-1$.

Note that X_1^i is a truncated geometrically distributed random variable (r.v.) with success probability of $\bar{p}_i\bar{q}_i$ taking values in $\{1, \ldots, N^i(\beta)\}$. Its expected value is given by:

$$\begin{aligned} E[X_1^i] &= N^i(\beta)\big(1-\bar{p}_i\bar{q}_i\big)^{N^i(\beta)-1} \\ &+ \textstyle\sum_{k=1}^{N^i(\beta)-1} k\big(\bar{p}_i\bar{q}_i\big)\big(1-\bar{p}_i\bar{q}_i\big)^{k-1} \\ &= \tfrac{1-\left(1-\bar{p}_i\bar{q}_i\right)^{N^i(\beta)}}{\bar{p}_i\bar{q}_i}. \end{aligned}$$

Since an ACK is sent for each packet that is successfully received at node i, we have:

$$E[Y_1^i] = \bar{p}_i E(X_1^i).$$

The expected value $E[X_1^i + Y_1^i]$ is given by

$$E[X_1^i + Y_1^i] = \frac{1-(1-\bar{p}_i\bar{q}_i)^{N^i(\beta)}}{\bar{p}_i\bar{q}_i}\left(1+\bar{p}_i\right). \tag{3}$$

Since $E_1(\beta) = \sum_{i=0}^{h-1} E[X_1^i + Y_1^i]$, the Proposition assertion follows from (3). ■

The next proposition shows that, energy-wise, Pure-iACK is inferior to Oriented-iACK.

Proposition 3: The energy efficiency of Pure-iACK, $E_2(\beta)$, and that of Oriented-iACK, $E_3(\beta)$, satisfy

$$E_2(\beta) \geq E_3(\beta). \quad (4)$$

Proof: Let X_2^i and X_3^i be the number of transmissions per sensed data made by node i using Pure-iACK and Oriented-iACK, respectively. For both protocols and $i < h$, let Y_i be the number of packet transmissions made by node i until node $i+1$ receives the packet and node i receives its respective iACK. Further, for $0 < i < h$, let Z_i be the number of packet transmissions made by node i until node $i-1$ receives an iACK with the Oriented-iACK protocol.

For the moment, suppose that the number of retransmissions is unbounded. Since with Pure-iACK, node i must send an iACK for every transmission received from $i-1$,

$$X_2^i = \max\{\tilde{X}_2^{i-1}, Y_i\}, \quad 0 < i < h, \quad (5)$$

where $\tilde{X}_2^{i-1}$ is the number of transmissions of a given packet from $i-1$ received by node i.

With Oriented-iACK, X_3^i is independent of X_3^{i-1}, and it is completely determined by the r.v.'s Z_i and Y_i. Specifically,

$$X_3^i = \max\{Z_i, Y_i\}, \quad 0 < i < h. \quad (6)$$

Since with both protocols, node $i-1$ must retransmits at least until it receives an iACK from node i, $\tilde{X}_2^{i-1} \overset{St}{\geq} Z_i$ (stochastically greater). Therefore, $X_2^i \overset{St}{\geq} X_3^i$ for $0 < i < h$.

For $i = 0, h$, both protocols act the same. Since $N^i(\beta)$ is independent of the protocol, $X_2^i \overset{St}{\geq} X_3^i$ also for the bounded retransmission case. Since stochastic dominance implies mean dominance, the proposition follows. ■

The energy efficiency of Oriented-iACK, $E_3(\beta)$, is derived in the following proposition.

Proposition 4: The energy efficiency of Oriented-iACK is given by

$$\begin{aligned} E_3(\beta) &= \frac{1-(1-\bar{p}_0\bar{q}_0)^{N^0(\beta)}}{\bar{p}_0\bar{q}_0} + \sum_{i=1}^{h-1} \frac{1-(1-\bar{p}_i\bar{q}_i r_i)^{N^i(\beta)}}{\bar{p}_i\bar{q}_i r_i} \\ &+ \frac{1-(1-\bar{p}_{h-1}\bar{q}_{h-1})^{N^{h-1}(\beta)}}{\bar{p}_{h-1}\bar{q}_{h-1}} \times \bar{p}_{h-1}. \end{aligned}$$

Proof: Note that a packet being forwarded by node i to node $i+1$ may not be overheard by node $i-1$; hence, triggering a retransmission by node $i-1$. Such events are accounted for by using the spatial dependency denoted above by r_i. Also recall that X_3^i denotes the number of transmissions per sensed data made by node i using Oriented-iACK.

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 $N^0(\beta)$. The probability of this event is $\bar{p}_0\bar{q}_0$, and by the truncated geometric distribution its expected value is given by

$$E[X_3^0] = \frac{1-(1-\bar{p}_0\bar{q}_0)^{N^0(\beta)}}{\bar{p}_0\bar{q}_0}. \quad (7)$$

For $0 < i < h$, the expected value of X_3^i is determined by (6). Assuming proper timeout setting, 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 transmission of node $i+1$ is 'overheard' by node i, but no more than $N^i(\beta)$.

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

$$E[X_3^i] = \frac{1-(1-\bar{p}_i\bar{q}_i r_i)^{N^i(\beta)}}{\bar{p}_i\bar{q}_i r_i}. \quad (8)$$

Note that since an orientation bit is used, node i does not retransmit when it receives packets from node $i-1$ marked as iACKs (with an orientation bit of one). The information required at node $i-1$ for such marking becomes available after it receives the iACK from node i.

As for the sink node, $i = h$, it needs to transmit an eACK. As with SW HBH ARQ with eACK, the expected number of these ACKs is given by

$$E[X_3^h] = \frac{1-(1-\bar{p}_{h-1}\bar{q}_{h-1})^{N^{h-1}(\beta)}}{\bar{p}_{h-1}\bar{q}_{h-1}} \times \bar{p}_{h-1}. \quad (9)$$

The proposition is now implied by combining (7)-(9). ■

Observe that for spatial dependency of $r_i = 1$, Pure-iACK saves all the eACKs used by SW HBH ARQ with eACK, except for the ACKs sent by the sink.

Finally, the energy efficiency of Combined-ieACK, $E_4(\beta)$, is readily available from the energy efficiency of SW HBH ARQ with eACK, $E_1(\beta)$.

Compared to SW HBH ARQ with eACK, Combined-ieACK saves one eACK in each node $i = 1, \ldots, h-1$. The number of sensed data transmissions with both protocols are the same. Therefore, the following proposition is implied.

Proposition 5: For the Combined-ieACK protocol,

$$E_4(\beta) = E_1(\beta) - (h-1). \quad (10)$$

B. Numerical Comparison

Figure 2 compares the energy efficiencies of the three protocols for realistic values of $\beta = 0.95$, $r_i = 0.7$, and for various error probabilities of $p_i = q_i = 0.01, 0.25, 0.50, 0.70$. The comparison is given for path length of $1, 2, \ldots, 8$.

It is observed that both, Oriented-iACK and Combined-ieACK, improve the eACK protocol with a slight advantage for Combined-ieACK. The improvement grows with the path length and becomes more substantial when link reliability increases. For example, if the path length is $h = 4$ hops, then the energy is decreased from 8 to 5 (37%), when $p = 0.01$; and from 21 to 18 (14%), when $p = 0.50$. For a path length of $h = 8$ hops, the energy is decreased from 16.5 to 9 (45%), when $p = 0.01$; and from 24 to 17 (29%), when $p = 0.25$.

V. Simulation Verification and Field Trial

To verify our analysis and its relevancy for TinyOS-based sensors, the protocols were implemented in "TOSSIM" - a detailed simulator of the entire "TinyOS" system [8].

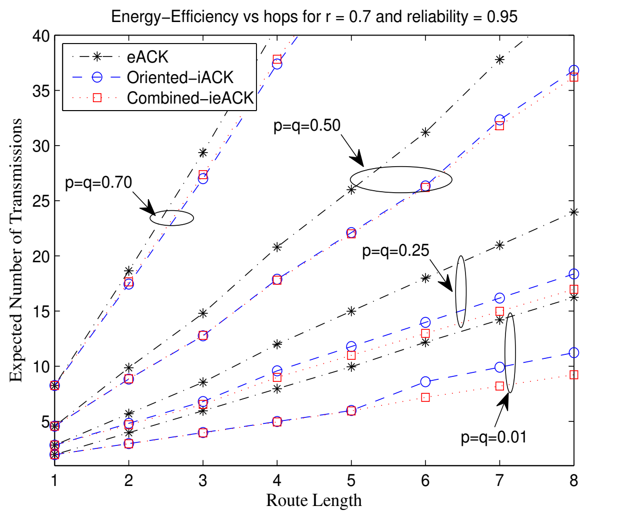

Fig. 2. Energy Efficiencies for $p = q = 0.05, 0.25, 0.50, 0.70$ and $r = 0.7$.

We simulated a linear network of 9 equally spaced nodes, where packet losses are due to shadow fading and link access contention. A message forwarding agent is also implemented for packet relay along the path. The simulation results along with the analytical results for $p_i = q_i = 0.01, 0.25, 0.50$ and $r_i = 0.7$ are shown in Figure 3.

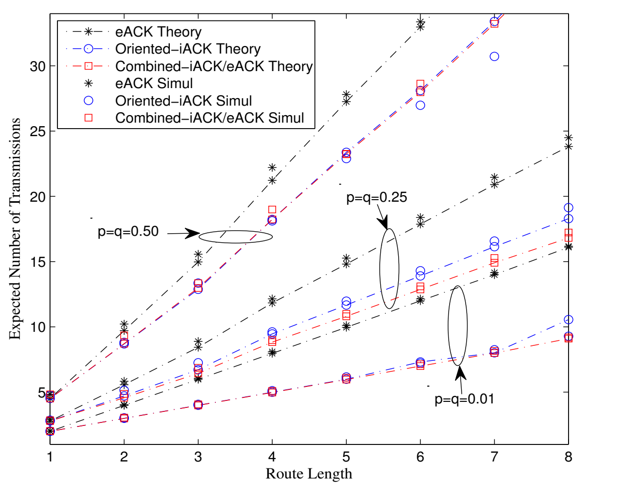

Fig. 3. Energy Efficiencies for $p = q = 0.01, 0.25, 0.50$ and $r = 0.7$.

It can be observed that our analytical predications match closely the TOSSIM simulation results. Note that there are marginal differences for a loss rate of 50% when the path length exceeds 5 hops. The debug log generated by TOSSIM, reveals that packet contention and racing condition in those cases become an issue due to excessive retransmissions. These practical issues are not considered in our theoretical analysis.

Field trials were also conducted using MICA2 motes, revealing that nonreciprocal links do occur and may cause a severe "avalanche" affect if Pure-iACK is used. The field trial also shows that Combined-ieACK and Oriented-iACK do prevent the "avalanche" affect. Due to space limitation, the field trial results will be reported elsewhere.

VI. Conclusion

We showed that for statistically reliable data streaming applications over multi-hop paths in WSN using Pure-iACK ARQ, an "avalanche" of undesirable retransmissions may occur. Two protocol enhancement were proposed, both were shown to prevent the "avalanche". The energy-efficiency of the protocols were precisely analyzed and compared numerically. The comparison shows that the simple Combined-ieACK is slightly better than Oriented-iACK and both are much better than eACK. The mathematical analysis is also verified by simulation using "TOSSIM" - a detailed simulator of the entire "TinyOS" system.

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