Overcoming Radio Link Asymmetry in Wireless Sensor Networks

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Abstract— **We derive two new energy efficient reliable data transport protocols for overcoming the negative impact of asymmetric radio links in wireless sensor networks. The energy efficiency of these algorithms is explicitly derived using our theoretical model, and validated by results obtained from simulations and field trials. The analytical, simulation and field trials demonstrate that our proposed protocols perform well in networks with asymmetric links and can save energy of up to 27% compared to conventional ARQ schemes.**

Keywords: Wireless Sensor networks, radio asymmetry, energy efficiency, reliability, implicit ARQ

I. INTRODUCTION

Link layer ARQ (automatic repeat request) protocols are widely used for reliable data delivery in wirelesss sensor networks (WSN). Two noticeable ARQ variants have been investigated in [10] and [11]. The authors of [10] study the performance of their proposed RMST protocol (reliable data streaming transport) in WSN which combines MAC layer ARQ with transport layer ARQ based on negative acknowledgment (NACK). The authors of [11] proposed another variant of ARQ called PSFQ (pump slowly fetch quickly) that "pumps" data to the destination along with hop-by-hop recovery based on NACK.

Since energy saving is one of the main concerns of WSN, it has been proposed in e.g., [5], [12] and [13] to avoid explicit acknowledgment (ACK) packets by utilizing the overhearing phenomenon of radio broadcast channels. That is, detecting the acknowledgments from the forwarding transmissions. This ACK mechanism, called implicit ACK, has a potential of energy saving. However, as our analysis below shows, implicit ACK could be problematic when the radio links are asymmetric.

Asymmetric links in real WSN cannot be ignored. Indeed, measurement studies [1]-[6] of WSN have revealed interesting statistical properties of low power wireless links in real environment. The authors of [1]-[4] study irregularities of radio communications and the authors of [5] and [6] study spatial and temporal properties of low power wireless link as well as their implications on multi-hop paths. These studies have highlighted the irregularity and asymmetry of radio links in wireless communications. The current consensus is that link asymmetry is caused by the variations of mote transmission power [1] [4]. Our field trials, described in Section II, indicate that link asymmetry stems also from frequency mismatch between neighbouring motes.

Although implicit ACK has been already used in [5], [12] and [13], the effect of asymmetric links has been overlooked. In this study, we demonstrate that radio asymmetry is non-negligible in real WSN and has a devastating impact on energy consumption of reliable data delivery with implicit ACKs.

We propose two novel variants of ARQ, ieARQ (ARQ with implicit and explicit ACKs) and E-ieARQ (enhanced ieARQ), to exploit the potential of energy saving of implicit ACK along with the severe impact of asymmetric links. Both protocols overcome the negative impact of asymmetric links and can save up to 27% energy compared to conventional ARQ.

The ieARQ protocol combines implicit and explicit ACKs and the E-ieARQ enhances ieARQ to further save energy by avoiding some of the explicit ACKs. The ideas for both protocols were inspired by a detailed flow diagram of the implicit ACK behaviour verified by a finite state machine (see Section III). The energy efficiency of the algorithms are analytically evaluated in Section IV and verified by simulations and field trials in Section V.

II. LINK ASYMMETRY IN FIELD TRIALS

We conducted field trials outdoors in the open yard at CSIRO Marsfield by placing five MICA2 [15] motes in a line 20 meters apart and one meter above ground as shown in Figure 1. The transmission power used was 0dBm.

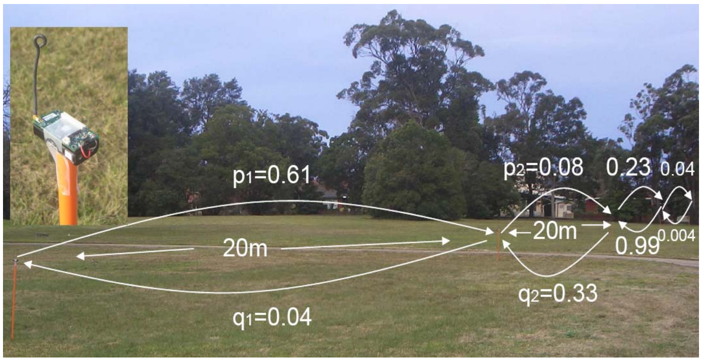

Figure 1: Field trial test-bed

To measure the loss rate at each hop, each mote broadcast 1000 beacon packets to its nearest neighbours. The loss rates measured at each hop and for each direction are shown in Figure 1. As can be seen, the loss variation is extremely high and the loss rates are not reciprocal. We confirmed that the loss rate of each device was not position dependent by swapping the device locations around. We also confirmed that there was no interference in the frequency band.

Table 1 shows the received signal strength indication (RSSI) and the packet error rate. It demonstrates that there is a high correlation between RSSI and loss rate indicating that RSSI is a good measure of link quality [9].

Hop	RSSI	Loss%		Hop	RSSI	Loss%
$0\rightarrow1$	-64.9	44.8		$0\leftarrow1$	-60.4	4.7
$1\rightarrow2$	-62.4	2.6		$1\leftarrow2$	-64.0	21.2
$2\rightarrow3$	-63.5	12.3		$2\leftarrow3$	-68.3	98.7
$3\rightarrow4$	-56.4	3.9		$3\leftarrow4$	-52.3	0.4

Table 1: Measurements on each hop

It is interesting to note that a large variation is manifested not only in the transmitted power, but also in the operational frequencies of the five motes. This is illustrated by Figure 2 showing the measured spectrum, including the effects of antenna performance. Note that in some cases the spectrum is shifted so much that the bands only partially overlap. Clearly, this is another major contributor to link asymmetry.

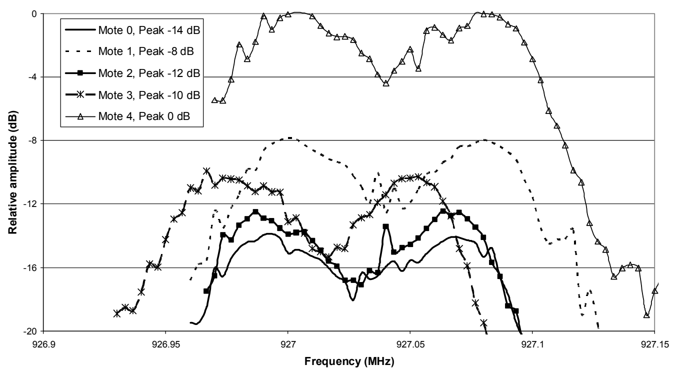

Figure 2: Frequency band and relative power of each mote

For example, Mote 0 has the lowest power, and hop $0\rightarrow1$ has a high error rate. Mote 1 has a higher transmit power, and both hop $1\rightarrow0$ and hop $1\rightarrow2$ have low error rates. The difference between the performance of hop $1\rightarrow0$ and hop $1\rightarrow2$ would be due to the difference in the receivers of motes 0 and 2. For hop $3\rightarrow2$, even though mote 3 transmission power is not the lowest, its frequency mismatch resulted the worst link in our test-bed (98.7% loss). Hop $3\rightarrow4$ would be affected by the frequency mismatch, but the lower antenna losses in mote 4 neutralized this effect, and gave significantly better reception than mote 2.

In the next section we propose new reliable data delivery protocols that overcome the negative effects of link asymmetry.

III. ENHANCED IMPLICIT/EXPLICIT ACK

For reliable data delivery, asymmetric links can result in a severe "*avalanche effect*", described below, which is disastrous for energy-constrained sensor nodes. We now discuss this effect when using the standard implicit ACK protocol, and then propose two new enhancements.

A. Implicit ARQ (iARQ) and its problems

Implicit acknowledgments obtained by overhearing have been adopted in ad hoc and sensor networks. Whenever a node forwards a message to its downstream node on behalf of its upstream node, this forwarded message can also be received by the upstream node, thereby serving as an implicit ACK. If it is not received before the timeout fires, the upstream node will retransmit the same message.

Figure 3 illustrates the "*avalanche effect*" of implicit ACK. It starts by a transmission of node-0 received by node-1, which then forwards it to node-2. The forwarded packet is received by node-2, but not by node-0. That is, the implicit ACK for node-0 fails. This event occurs with high probability in asymmetric links. At this event, node-0 must retransmit the data packet. Consequently, node-1 receives duplicate packets from node-0. In the case of implicit ARQ protocol, node-1 must retransmit the packet for the sake of acknowledgement only. Otherwise, node-0 will keep retransmitting its packet. The downstream node-2, on the other hand, must also retransmit the packet since it assumes that node-1 had not received its implicit ACK. This continues all the way down to the sink node, hence an "avalanche effect". Essentially, every time an implicit ACK fails to arrive at node-0, a duplicate packet is generated and forwarded down to the sink node.

Since asymmetric links are more likely to create one way losses, they result in more avalanches than symmetric links. The unnecessary duplicate transmissions due to the avalanche effect not only increase network congestion, but also deplete energy from the sensor nodes. This effect was observed in our test-bed of Figure 1.

B. Mixed implicit / explicit ARQ (ieARQ)

The above observations motivate the design of a mixed implicit/explicit ARQ. With this protocol, an explicit ACK is transmitted by any node that receives a duplicate that has been already implicitly ACKed.

As illustrated in Figure 4, when node-1 receives a duplicate packet, it sends an explicit ACK to the upstream node-0 rather than a retransmission to node-2. Since an explicit ACK is directed to the upstream node-0, the downstream node-2 is not mislead to retransmit. Hence, stops the avalanche effect.

It is worth noting that when both the data and the implicit ACK are lost (Figure 5), the retransmitted packet will reach node-1 while it is on "*Timer wait*" state. An explicit ACK generated at this event will come very close to the next retransmitted data, which also could be used as an implicit ACK.

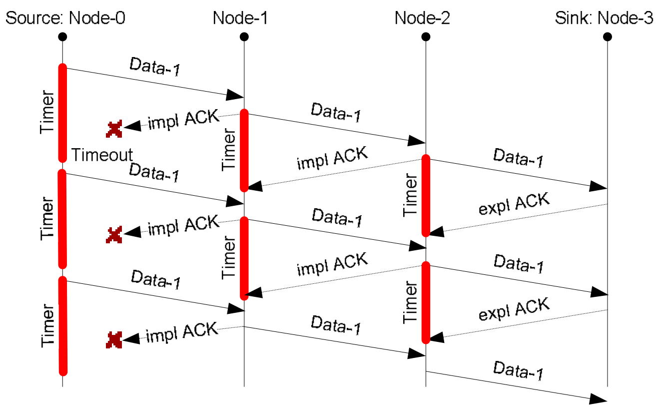

Figure 3: Avalanche effect due to asymmetric link.

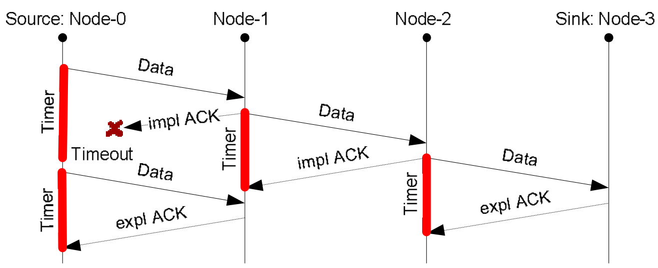

Figure 4: Implicit / explicit ARQ operation

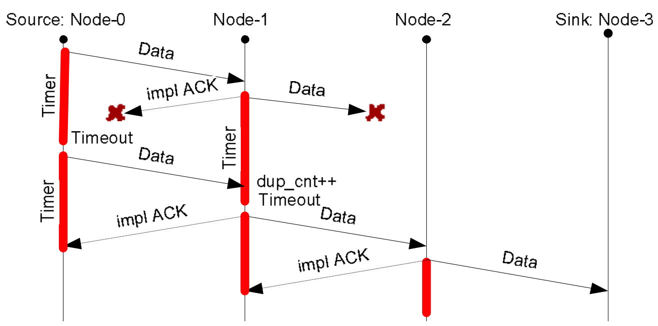

Figure 5: Enhanced implicit / explicit ARQ operation

Since node-1 is likely to retransmit the packet (which is also an implicit ACK) in a short while after the timeout fires, the explicit ACK could be "saved". However, if the implicit ACK from node-2 is just delayed and node-1 holds it's explicit ACK, node-0 will never receive an ACK and will continue with its unnecessary retransmissions.

C. *An enhanced implicit / explicit ARQ (E-ieARQ)*

A valid way of saving the explicit ACK described above is to hold the ACK while in "*Timer wait*" state and record the packet reception in the `dup_cnt` counter shown in Figure 5. If a timeout occurs, node-1 will retransmit the data and no more explicit acknowledgement will be needed. However, if the timer wait is terminated by an implicit ACK, node-1 will transmit an explicit ACK to node-0 to acknowledge the duplicate data received during the timer wait period.

The protocol of the E-ieARQ is specified by the finite state machine diagram of Figure 5. Whenever an intermediate node (in "Idle" state) receives a data packet from an upstream node, it will forward the packet and enter the "Timer Wait" state by starting a timer `[state transition 2]`. While in of "Timer Wait" state, if a retransmitted packet is received, E-ieARQ holds off the immediate ACK `[state transition 4]` and increments the duplicate reception counter, `dup_cnt`. If the timer terminates due to an ACK from a downstream node, the node needs to remember this duplicate data (`dup_cnt > 0`) and to send an explicit ACK `[state transition 5]` before falling back into "Idle" state. If a timeout occurs, the data packet is retransmitted via broadcast serving as an implicit ACK as well `[state transition 3]`. At this event, one ACK transmission is saved without losing reliability.

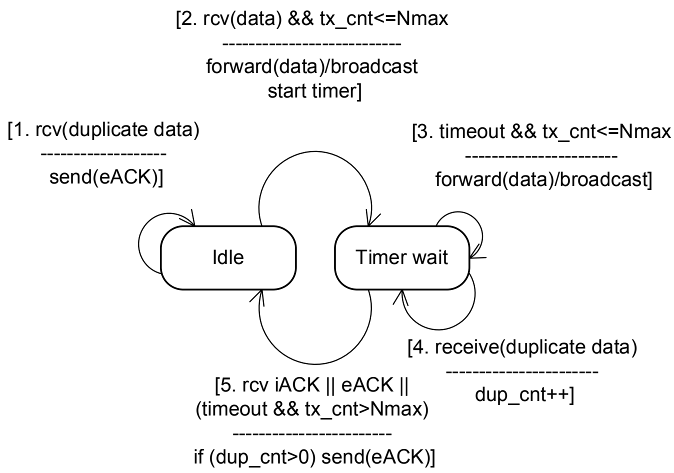

Figure 6: Enhanced-ieARQ algorithm.

IV. Performance Analysis

The energy efficiency of explicit ARQ, ieARQ and E-ieARQ are analysed in terms of *the expected number of transmissions* per packet successfully delivered from source to sink. This number includes both data packet and acknowledgement packet transmissions [1]. This notion of energy efficiency measure is commonly used in the literature, e.g., [14].

Consider a network path of $h+1$ nodes (labeled $0,1,\ldots,h$) comprising h hops. In a hop i, the loss probabilities for a transmission from node i to node $i+1$ and from node $i+1$ to node i are denoted by p_i and q_i, respectively.

[1] We don't distinguish data packet and acknowledgement packet in our analysis. In WSN applications, data packets are generally of small sizes, e.g. TinyOS limits maximum data payload to 29 bytes. After taking into consideration the radio turn around time, preambles, and headers, the difference between data packet and acknowledgement becomes insignificant.

Proposition 1: The expected number of transmissions required for a successful delivery of a single packet with explicit ARQ is given by

$$N_{ARQ} = \frac{1}{(1-p_0)(1-q_0)} + \sum_{i=1}^{h-1} \frac{2-p_i}{(1-p_i)(1-q_i)} + \frac{1}{(1-q_h)} \quad (1)$$

Proof: For each node $i \in [0,1,...,h-1]$, the expected number of forward data transmissions for each successful delivery across hop i is $\frac{1}{(1-p_i)(1-q_i)}$. (The sink node, *h*, does not forward data.)

For each node $i \in [1,2,...,h]$, the expected number of ACKs is $\frac{1}{(1-q_i)}$. (The source node, *0*, does not acknowledge.)

Equation (1) follows by summing up all expected number of transmission over all hops. ∎

Proposition 2: The expected number of transmissions required for a successful delivery of a single packet with ieARQ is given by

$$N_{ieARQ} = N_{ARQ} - (h-1) \quad (2)$$

Proof: For each node $i \in [1,...,h-1]$, one transmission is saved due to the implicit ACK mechanism compared to implicit ARQ, immediately implying (2). ∎

Proposition 3: The expected number of transmissions required for a successful delivery of a single packet with E-ieARQ is given by

$$N_{E-ieARQ} = \frac{1}{(1-p_0)(1-q_0)} + \sum_{i=1}^{h-1} \frac{4-2p_i-p_iq_i}{2(1-p_i)(1-q_i)} + \frac{1}{(1-q_h)} \quad (3)$$

Proof: For an intermediate node $i \in [1,...,h-1]$, the probability that both, the forward data and the implicit ACK are not received is p_iq_i. The scenario described in Section III.C can occur when node *i-1* retransmit before node *i*. Since the retransmission interval is governed by a fixed timeout period followed by a CSMA random back-off period, the probability that node *i-1* will retransmit before node *i* is *0.5*.

When this event occurs, the E-ieARQ saves ACK transmission, giving an average energy saving of $\frac{p_iq_i}{2}$ at hop *i* compared to *ieARQ*. Since the packet is expected to be transmitted $\frac{1}{(1-p_i)(1-q_i)}$ times, the overall expected savings is $\frac{p_iq_i}{2(1-p_i)(1-q_i)}$. Thus,

$$N_{E-ieARQ} = N_{ieARQ} - \sum_{i=1}^{h-1} \frac{p_iq_i}{2(1-p_i)(1-q_i)}$$ ∎

Comparing equations (1), (2) and (3), we have

$$N_{ARQ} \geq N_{ieARQ} \geq N_{E-ieARQ} \quad (4)$$

That is, ieARQ is more efficient than explicit ARQ and E-ieARQ outperforms both.

V. Simulation and Field Trials

A. *Simulation*

Simulation experiments were conducted with TOSSIM [8] on a sensor network comprising 73 motes. GenericComm is used for message passing. The motes were deployed in 9 concentric circles centered at the sink positioned on the spokes originating from the sink. The spokes are placed 45° from each other, and the distances between the circles are variable. This deployment avoids congestion close to the sink. Shadowing propagation model is used to calculate the loss probability between neighboring nodes, giving a range of loss probabilities between 0 and 0.5. A message forwarding agent is implemented to relay packets from each node hop-by-hop along the spoke to the sink. The variants of ARQ protocols (generally denoted by xARQ) discussed above are implemented in this forwarding agent.

The simulation and the theoretical results shown in Figure 7 indicate good matching for explicit ARQ, ieARQ and E-ieARQ protocols when the loss probability is less than 30%. For a loss of 50% or higher (not shown the figure), the theoretical estimates are more conservative than the simulation results. This is explained by the collisions occurring in practice and ignored by our model. These collisions are negligible for losses less than 30% but meaningful for losses larger than 50%.

Under reasonable conditions (a loss range within 0-30%), ieARQ and E-ieARQ offer the best performance. Under heavy loss conditions of 50%, E-ieARQ offers extra energy savings of up to 27% compared to standard ARQ.

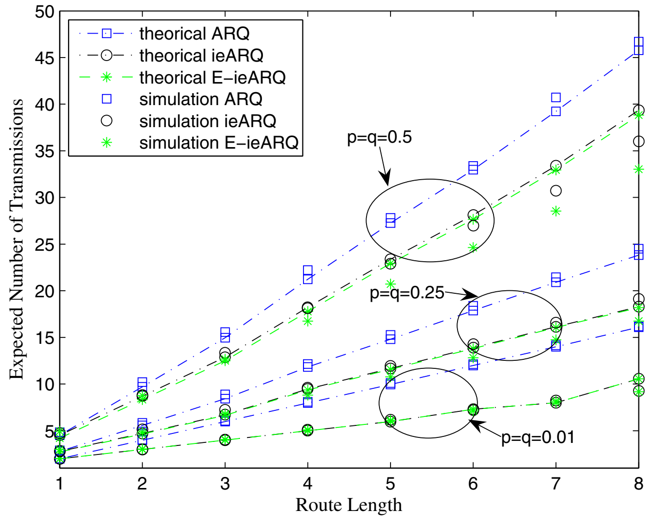

Figure 7: Simulation results of xARQ algorithms

B. *Field trial*

Field trials were conducted in our test-bed described in section II. This is an example of a practical sensor network with asymmetric links and loss probabilities shown in Figure 1. Three experiments were conducted for each scheme, each time sending 1000 packets. The final results were taken as the average of the three experiments. The field trial results of Figure 8 show that asymmetric links can diminish the benefit of implicit ACK. It is still better than explicit ACK for a path length of three; and worse for a path length of four. For path lengths of one and two, they are equivalent. Observe that ieARQ performs better than explicit for path lengths up to three, and similarly for a path length of four. Note also that E-ieARQ gives the best performance over all conditions. The savings in this field trial is up to 27% as well.

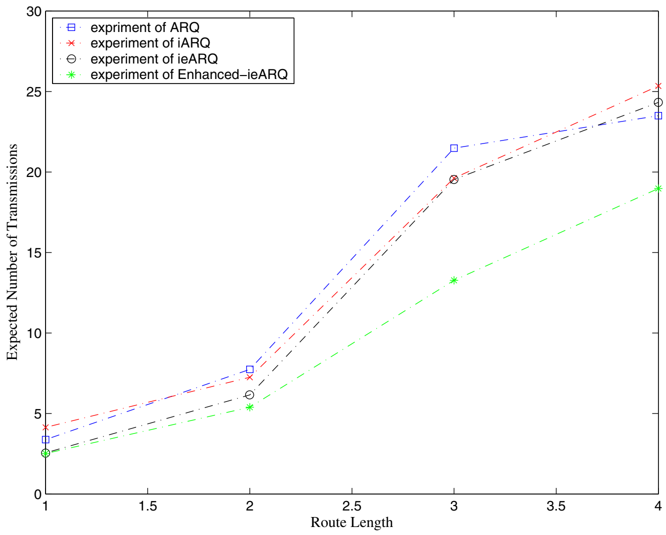

Figure 8: Field trial results of xARQ algorithms

VI. CONCLUSION

This work was motivated by our field trials showing extreme radio link asymmetry. Further measurements and detailed analysis shows that asymmetry is not only caused by variations in mote transmission powers but also by transceiver frequency mismatch. Our detailed analysis revealed that asymmetric links have a negative impact on reliable data delivery with implicit ARQ.

We proposed ieARQ and E-ieARQ protocols to combat the asymmetric links and the "*avalanche effect*". These reliable transport algorithms are designed using finite state machine and analyzed using our theoretical model. Simulations and further field trials show that the proposed algorithms perform well in network with asymmetric links, and the Enhanced algorithm (E-ieARQ) performs best in all conditions. The E-ieARQ was designed to further save transmissions compared to ieARQ. Our analysis, simulations, and field trials support the claims.

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