Energy-efficient Rate Adaptive MAC Protocol (RA-MAC) for Long-lived Sensor Networks

Quanjun Chen
The University of New South Wales, Sydney, Australia,
Email: quanc@cse.unsw.edu.au

Wen Hu, Peter Corke
CSIRO ICT Centre, Australia,
E-mail: {wen.hu, peter.corke}@csiro.au

***Abstract*— This paper introduces an energy-efficient Rate Adaptive MAC (RA-MAC) protocol for long-lived Wireless Sensor Networks (WSN). Previous research shows that the dynamic and lossy nature of wireless communication is one of the major challenges to reliable data delivery in a WSN. RA-MAC achieves high link reliability in such situations by dynamically trading off radio bit rate for signal processing gain. This extra gain reduces the packet loss rate which results in lower energy expenditure by reducing the number of retransmissions. RA-MAC selects the optimal data rate based on channel conditions with the aim of minimizing energy consumption. We have implemented RA-MAC in TinyOS on an off-the-shelf sensor platform (TinyNode), and evaluated its performance by comparing RA-MAC with state-of-the-art WSN MAC protocol (SCP-MAC) by experiments[1].**

I. INTRODUCTION

Previous research shows that the dynamic and lossy nature of wireless communication is one of the major challenges to reliable data delivery in Wireless Sensor Networks (WSN). The traditional WSN approach is to use sophisticated Media Access Control (MAC) and routing protocols to compensate for poor link quality by using acknowledgments and retransmissions. However, these introduce extra traffic, increase energy consumption, and increase the size and complexity of the node's software.

There has been much less work focused on addressing the underlying link quality. Well known approaches include: adding relay nodes, using higher transmit power, applying frequency/antenna diversity or spread spectrum modulation techniques. All have difficulties or cost implications.

Coding and data bit rate are one of the remaining degrees of freedom in this problem. With suitable coding we could for example halve the data bit rate and achieve 3 dBm of extra signal processing gain. The resulting increased Signal to Noise Ratio (SNR) can move us from the lossy link zones to the good reception zones allowing error free transmissions without the need for multiple retransmissions.

Conventional Wireless Local Area Networks (WLAN) use rate adaptive MAC to optimise throughput, rather than overall transmission *energy cost*. To the best of our knowledge, RA-MAC is the *first rate-adaptive Media Access Control protocol for WSN* with the purpose of minimizing network energy consumption.

[1]Most of the work was done while Quanjun chen was an intern in CSIRO ICT Center, Australia.

II. RATE SELECTION MODEL

To reduce radio energy consumption, previous research shows that it is very important for the radio transceiver to be in sleep mode as much as possible. To wake a receiver from sleep mode, a sender sends a special signal (called a "tone") before transmitting a data packet. For a given link condition, expressed by Receiver Signal Strength Indicator (RSSI), and a data bit rate (R), the energy consumption to successfully transmit a data packet is

$$E(RSSI, R) = \frac{P_{tx}(t_o + \frac{f}{R}) + nP_{rx}(t_o + \frac{f}{R}) + \sigma}{PRR(RSSI, R)} \quad (1)$$

where t_o is the tone transmission duration, f is packet frame size in bits, and n the number of neighbors that overhear the packet, P_{tx} and P_{rx} are the power consumption for transmitting and receiving respectively. σ is the energy consumed to wake up the radio chip and to listen on the channel before transmitting. $PRR(RSSI, R)$ is the percentage of packets that can be successfully received at the receiver for a given $RSSI$ and R. The inverse proportion of $PRR(RSSI, R)$ is the number of retransmissions required to successfully deliver a packet.

The optimal bit rate $\widehat{R}$, given the link condition $RSSI$, is the one that minimizes the energy consumption

$$\widehat{R}(RSSI) = \underset{R}{\operatorname{argmin}} \quad E(RSSI, R) \quad (2)$$

III. RATE ADAPTIVE MAC (RA-MAC) ALGORITHM

The analytical results in Section II show that, in order to select the optimal data rates, the sender should monitor channel characteristics, which include $RSSI$ and the function $PRR(RSSI, R)$, continuously. Our proposed RA-MAC is designed to adapt transmission data rates to the channel characteristics dynamically for the purpose of minimizing transmission energy consumption.

When a sender sends a data packet, it first checks the delivery status of the last data transmission, which was transmitted at bit rate R_{last}. If the last packet was unsuccessful, the node decreases the bit rate level by 1 and transmits the data packet. Otherwise, the sender *predicts* the RSSI of the current packet transmission based on the moving average of recent RSSI samples, which have been piggybacked on the previous ACK packets. The sender then uses the predicted RSSI and the learned $PRR(RSSI, R)$ to select the current transmission bit rate R according to Eq. (2). Finally, the sender looks up the number of consecutive packets for which it has used the current R to transmit. If the number is larger than a certain threshold, the sender increases the current R by 1 and transmits the packet. Otherwise, the sender transmits the packet at the current R.

To adapt to changing channel condition more quickly, once the channel condition becomes bad (i.e., the last packet transmission fails), the sender decreases the data transmission rate R aggressively. Conversely as the channel improves (i.e., multiple successful recent packet transmissions), the sender increases the data transmission rate R in order to explore the performance function ($PRR(RSSI, R)$) at a higher bit rate.

The receiver collects current $RSSI$ and bit rate R after each received data packet. After the CRC verification process, the receiver updates the statistical performance function ($PRR(RSSI, R)$). If the packet is correctly received, the receiver sends an ACK packet which piggybacks the $RSSI$ and the learned performance ($PRR(RSSI, R)$) so that the sender can collect these performance values to guide its future packet transmissions.

IV. Implementation and Evaluation

We implemented RA-MAC in TinyOS on the TinyNode platform [1], which uses the XE1205 radio transceiver (from Semtech). This radio is highly programmable, and its physical data rates can be adjusted from 9.6kbps to 76kbps. By lowering transmission data rates, we can increase the transceiver's sensitivity (processing gain) and extend transmission ranges.

Fig. 1 shows the basic operations of RA-MAC in one duty cycle. Synchronized nodes poll the channel periodically. A sender firstly transmits a short tone to wake up a receiver before sending a one-byte data rate indicator to the receiver. Both tone signal and data rate indicator are transmitted at the base bit rate (i.e., 9.6 kbps). Now that the receiver is ready to receive at the specified data rate (i.e., 9.6, 20, 38 or 76kbps), the sender transmits the preamble and the data frame to the receiver at the specified data rate. Finally, the receiver transmits an ACK, together with RSSI and PRR, to the sender at the same data rate. To handle the clock drifts in the nodes, a synchronization packet is sent out every minute at the base transmission rate.

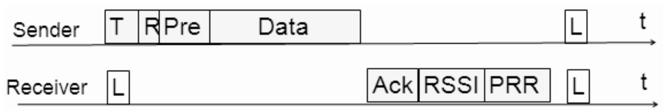
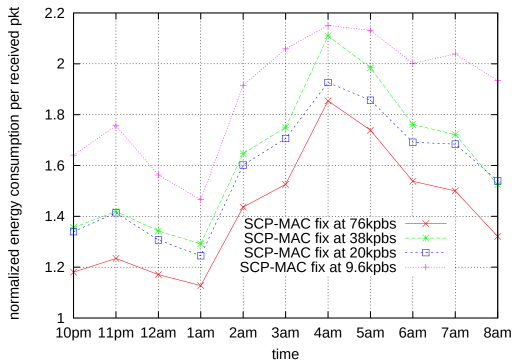
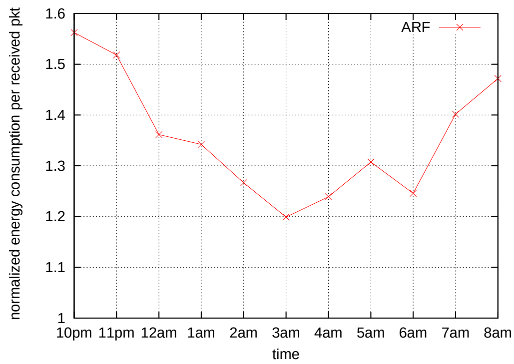


Fig. 1. The basic operations of RA-MAC. L: Polling. T: Tone. R: Data rate. Pre: preamble. Data: data frame. Ack: Acknowledgment bytes.

We ran the experiments on an *outdoor wireless link* (without line of sight, the distance between two nodes is approximately 30 meters) for multiple periods of 10 hours. We compare the performance of RA-MAC to that of SCP-MAC [2] with fixed bit rates. The evaluation metric is *Energy consumption per received packet*, which is total energy consumption divided by the number of packets received successfully. For ease of comparison, we normalize the energy consumption of different strategies with respect to RA-MAC.



(a) RA-MAC vs. SCP-MAC with fixed bit rates



(b) RA-MAC vs. ARF

Fig. 2. Normalized (against RA-MAC) energy consumption per received packet vs. time

Fig. 2(a) shows that RA-MAC reduces energy consumption significantly compared to SCP-MAC. For example, RA-MAC only consumes around 50% of the energy of SCP-MAC with various fixed bit rates, between 3am-4am. We also compared RA-MAC to Auto Rate Fallback (ARF), a popular used WLAN rate adaptive algorithm. Fig. 2(b) shows that RA-MAC outperforms ARF significantly.

V. Conclusion

We have introduced RA-MAC, which employs an adaptive approach to select the optimal data rates based on estimated link conditions to reduce network energy consumption. Our outdoor experiment evaluation showed that RA-MAC outperformed both WSN (SCP-MAC) and WLAN (ARF) MAC significantly.

References

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