A MAC Protocol For Real-Time Sensing Applications Using Asymmetric Transceivers

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***Abstract*—We consider a class of single hop wireless sensor networks in which the sensor nodes collect data periodically and transmit it to a sink. To reduce the complexity, cost and energy consumption of the nodes we propose the use of an asymmetric transceiver model in which the sensor nodes can transmit to the sink using standard physical layer modulation schemes that support relatively high data rates but can receive from the sink using basic modulation schemes that can only support very low data rates. The use of the transceiver module in each sensor node is thus limited to receiving simple feedback in the form of a few bytes of ACK from the sink node.**

In this paper we propose and study a new MAC protocol that enables effective communication between the sensor nodes and sink in such a network. We develop an analytical model to evaluate the performance of the MAC protocol and verify these results through extensive simulations. We also present results from the implementation of the protocol on a test bed consisting of XSM motes and evaluate its performance in a real world scenario.

I. INTRODUCTION

This work focuses on a new class of low complexity, low power and low cost wireless sensor networks. Such networks typically consist of a number of sensor nodes that are within a *single hop* communication range to a sink. Every T time units, these sensor nodes collect data and transmit a relatively small data frame to the sink. The throughput requirement of each sensor nodes is low, typically on the order of a few hundred bytes per second. These networks typically deploy battery driven sensor nodes and hence, energy efficiency of the nodes is a significant factor in the design and implementation of the sensor node and the MAC protocol it uses.

This work is applicable to many different wireless sensor networks such as Smart Home [1], Intelligent Transportation [2], Smart Kindergarten [3], Medical Monitoring [4] [5] and Intra-Vehicular Networks [6]. These wireless sensor network applications are gaining significant importance and many products are already available in the market [7] [8] [9].

Most of the existing sensor systems make use of standard radio modules for the sensor nodes that consist of a fully functional transceiver, that is, the transceiver is capable of transmitting as well as receiving radio signals of a particular physical layer modulation and channel coding. Typically, the receiver module of the transceiver is significantly more complex and costly. More specifically, [10] suggests that, out of the total cost of the transceiver, the ratio of the cost of the receiver module to that of the transmitter module is about 70 to 30. The study also shows that, although the transmitter module consumes significant energy to amplify and transmit the electromagnetic signals, a receiver module that is capable of receiving the signals transmitted by it, consumes an equal amount of energy. *Thus there is an opportunity to significantly minimize the cost and energy consumption of a sensor node by reducing the complexity of the receiver module used by the sensor nodes.*

Hence, we propose the use of an asymmetric transceiver architecture. The transceiver consists of a transmitter module that can transmit at a relatively high data rate using standard physical layer modulation schemes (e.g. OFDM). However, the receiver module has limited capability and can receive only low data rate radio signals that are modulated using basic schemes (e.g. BPSK). With such an asymmetric transceiver design, the ratio of the maximum data rate of the transmitter module to that of the receiver module could be as high as 100 to 1.

The proposed asymmetric transceiver architecture is suitable for the class of networks considered, as the sensor nodes communicate only with the sink and there is no communication between sensor nodes. Hence, we require only the sink node be equipped with a transceiver module that is capable of receiving the signals transmitted by the sensor nodes.

A. Related Work and Motivation

Existing MAC protocols that are used widely in wireless sensor networks are 802.11 [11], 802.15.3 [12], S-MAC [13], B-MAC [14] and their derivatives. They rely on the existence of symmetric physical communication channels for their operation. The protocols rely heavily on the channel sensing capability of the transceiver. However due to the design constraint mentioned earlier, the asymmetric transceivers do not have this capability and hence the use of any of these protocols is ruled out. Further, the performance of these protocols in terms of packet delivery probability and latency deteriorates considerably when there is a significant amount of contention for the shared wireless channel, as is the case in networks consisting of a large number of sensor nodes that periodically transmit data to a sink.

Since new data is generated periodically by the sensors, it is required that the current data packet be transmitted to the sink before the next data packet is generated. For example, in the Intra-Vehicular Network application [6], each data sample generated by the brake sensor has to be transmitted to the Anti-skid Braking System (ABS), before the next sample is generated, in order to ensure the accurate performance of the ABS. It is redundant (and in this case dangerous) if the

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ABS receives an older sample after a newer sample of data. Consequently, a deterministic upper bound on the latency of each packet is required. We note that none of the existing protocols mentioned previously, by design, can guarantee a deterministic upper bound on the latency of each packet.

Another important aspect of such networks is the fact that they can consist of various categories of sensor nodes and the significance of the data generated by each category might be different. For example, in a medical sensing application, the data generated by the heart rate sensor is considerably more important than that generated by the body temperature sensor. In other words, the heart rate sensor requires a higher Quality of Service (QoS) in terms of the packet delivery probability as compared to the body temperature sensor.

Although the 802.11e [15] protocol provides differentiated QoS it is too complex and energy hungry to be implemented in low complexity, low cost, low power sensor nodes. The other existing protocols do not offer the capability of providing differentiated QoS at the MAC layer.

We also note that the existing protocols, with the exception of B-MAC and its derivatives, require some form of synchronization between the sink and the sensor nodes. This is achieved by either using the hardware based techniques or time synchronization protocols like FTSP [16]. However, this consumes considerable amount of energy and also generates significant traffic on the downlink channel. Considering the limited downlink channel bandwidth and capabilities of the receiver module, it might not be feasible to perform any form of time synchronization. Further, it is desirable that the MAC protocol does not require any form of global synchronization in order to keep the complexity of the sensor nodes and the network to a minimum.

B. Overview

This paper proposes a new MAC protocol that is capable of providing a guaranteed minimum delivery probability and an upper bound on the latency of each packet, without requiring channel sensing capability, complex feedback mechanisms or time synchronization. Further, we present certain optimizations that can be used to effectively provide differentiated QoS to the sensor nodes in the network.

The major contributions of the paper are as follows. The use of an asymmetric transceiver architecture in a *single hop* network has never been studied before. In fact, only recently, researchers have studied sensor networks where sensor nodes have transmitters only, that is, without any receiving modules [17] [18] [19], and to our best knowledge, this is the first study of a MAC protocol for networks with asymmetric transceivers (with very simple receivers). We have shown, through comprehensive analysis and simulation, that the proposed MAC scheme performs considerably better than the existing protocols, in terms of delivery probability, energy consumption and implementation complexity. Further, we present the results from the implementation of the protocol on a practical test bed consisting of XSM motes and study the performance of the protocol in a real world scenario.

The rest of the paper is organized as follows. Sec. II describes the design of the MAC protocol and Sec. III presents the analysis of the protocol in terms of delivery probability and energy consumption. Sec. IV presents the performance results of the protocol from the analysis, simulations and test bed implementation. It also compares the performance of the proposed MAC protocol to existing protocols including 802.11 and QoMoR [19]. In Sec. V we describe a method to provide differentiated QoS to the sensor nodes using the proposed MAC protocol and Sec. VI concludes the paper.

II. MAC PROTOCOL DESIGN

The class of networks considered in this work poses an interesting set of constraints. In this section we analyze and translate them into the design requirements of the protocol. We also present the detailed design of the protocol.

As detailed in the discussion in Sec. I, the receiver module hardware has limited capability and can only receive at low data rates. Due to the asymmetric design of the transceiver, it is also not capable of channel sensing as the receiver module cannot detect signals transmitted by other sensor nodes. Further, due to the low downlink data rate it might not be possible to perform global time synchronization between the sensor nodes. Consequently, we cannot use any centralized scheduling mechanisms to coordinate the transmissions of the sensor nodes. Since the receiver modules of the sensor nodes cannot receive signals from other sensor nodes it is also not possible to use channel access mechanisms like RTS/CTS as used in 802.11.

Thus, in the design of the MAC protocol, we assume that the following standard features/mechanisms that can otherwise be used with standard receiver modules are unavailable

1. Channel Sensing
2. Global time synchronization
3. Centralized scheduling mechanisms

The MAC protocol is required to provide a guaranteed minimum delivery probability and a deterministic upper bound on latency under the above mentioned conditions.

The unavailability of channel sensing places a significant constraint on the access strategies that can be used by the MAC protocol. In fact, each sensor node is only capable of transmitting the data packets at random instants of time chosen based on its local clock. This is similar to the legacy ALOHA MAC protocol [20]. The design challenge, however, is to be able to provide a guaranteed minimum delivery probability and differentiated QoS. The proposed MAC scheme develops some simple yet effective methods to meet these requirements.

A. Preliminaries

We can formally describe the system as a network consisting of n sensor nodes and one sink node. Each sensor node periodically generates a data packet every T units of time and attempts to transmit it to the sink. The interval T is called the data generation interval. Each sensor node in the network requires a minimum delivery probability of p.

As discussed earlier, given the above mentioned design constraints, we observe that the only viable access strategy is for each sensor node to transmit at a random instant of time within the data generation interval. However, such random transmissions by multiple sensor nodes will result in collisions. Thus if a sensor node transmits each data packet once within each data generation interval there is no way of guaranteeing a minimum delivery probability. Hence we propose that *each sensor node attempts x transmissions of the data packet at random instants of time within each data generation interval* in order to achieve the required minimum delivery probability. This is feasible because the size of each data packet, and hence its transmission duration, is very small compared to the data generation interval. From here on in the paper, the phrase 'number of transmission attempts' and the symbol x will be used interchangeably.

Note that, however, a greedy approach in which all the sensor nodes try to transmit as many times as possible will only lead to a large number of collisions, leading to a considerable decrease in the delivery probability that can be achieved by all the sensor nodes in the network. In our previous work on networks with transmitter-only nodes, we designed the QoS-aware MAC protocol based on Optimal Retransmissions (QoMoR) [19] and have shown that there is an optimal value for the number of retransmission attempts that each sensor node should make within each data generation interval T, such that, all the sensor nodes in the network can achieve the minimum delivery probability of p.

In [19], depending on the size of the network and other parameters, we have shown that the value of x_{opt} can vary between 1 and 10. An analysis of this scheme, however, also shows that, in most cases, the packet is successfully delivered to the sink after the first few, say x', transmission attempts, where $x' < x$. In each case, the additional $x - x'$ transmission attempts that occur after the packet has been successfully delivered to the sink, contribute not only to wasted energy, but also to an unnecessary increase in the background traffic and hence contention for the shared wireless channel.

The idea behind the MAC protocol proposed in this paper is to take advantage of the (rudimental) receiver at each sensor node in order to eliminate these unnecessary transmissions and hence improve the overall delivery probability that can be achieved by the system. In order to accomplish this, there is a need for some form of feedback from the sink to the sensor nodes. Hence, in the proposed protocol we use a very short ACK packet that is transmitted by the sink immediately after it receives a successful transmission from a sensor node.

B. The Asymmetric QoMoR Protocol

In this section we describe a simple medium access scheme called *Asymmetric QoMoR (A-QoMoR)*. The A-QoMoR MAC, upon receiving a packet generated by the higher layers, randomly picks x_{max} instants, $t_1, t_2, \cdots, t_{x_{max}}$, within the data generation interval T. As illustrated in Fig. 1, it *may* attempt to transmit the packet at each of these instants.

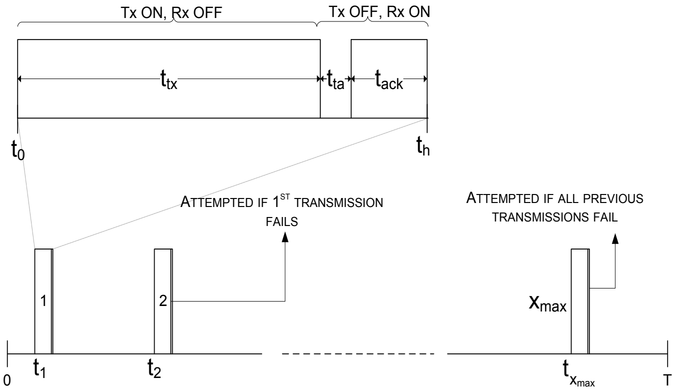


Fig. 1. The A-QoMoR MAC channel access strategy

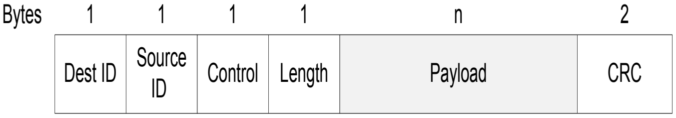
To conserve energy, the sensor node is initially in a sleep state, during which both the transmitter and receiver modules are turned off. At the first chosen transmission instant, t_1, the sensor node turns on its transmitter and transmits the packet as shown in Fig. 1. The sink is expected to send a short acknowledgement (ACK) packet as soon as it successfully receives the packet from a sensor node. We note that there is a small duration between the time the sink completes receiving a packet successfully and the time it starts to transmit the ACK. This is known as the turnaround time, t_{ta}, and is the sum of the processing delays at the sink and the time taken by the sink to switch its transceiver from receiving to transmitting mode.

On completion of the transmission, whose duration is denoted by t_{tx}, the sensor node turns off the transmitter module and turns on the receiver module. In order to minimize the energy consumed by the receiver module, the sensor node turns off the receiver module, *irrespective of whether an ACK was received or not*, after a fixed duration of time called the receiver-on-time, which is denoted by t_{ro}. The receiver-on-time is calculated taking into account the turnaround time of the sink node, t_{ta}, and the transmission of duration of the ACK packet, t_{ack}. Assuming that the propagation durations are negligible, it is given by $t_{ro} = t_{ta} + t_{ack}$. The total channel access duration, t, for each transmission attempt of a sensor node is thus

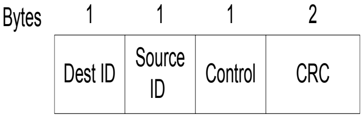
$$t = t_{tx} + t_{ta} + t_{ack} \tag{1}$$

If an ACK was received during the receiver-on-time, the sensor node goes into the sleep state until the next packet is generated by the higher layers and *does not* transmit at any of the remaining transmission instants it had chosen. Otherwise, it will go through the process of waking up and transmitting the packet at the next chosen transmission instant. This process repeats until either an ACK is received or x_{max} transmissions are completed.

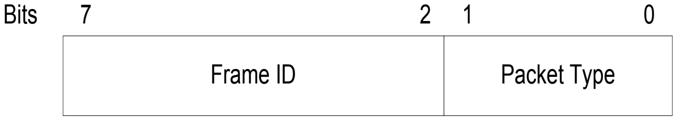
If no ACK is received after x_{max} transmissions, the packet is considered to be lost and will be discarded. *Thus a successfully delivered packet has a maximum delay of T.* Thus, we are able to guarantee a deterministic upper bound on the latency of successfully delivered packets which is currently



(a) Frame format for data packets



(b) Frame format of the ACK packets



(c) Format of the Control Field

Fig. 2. Packet Formats used by the A-QoMoR protocol

not guaranteed by any of the CSMA based protocols.

When a new packet is generated, the process repeats by picking x_{max} random transmission instants within the data generation interval and performing the transmissions.

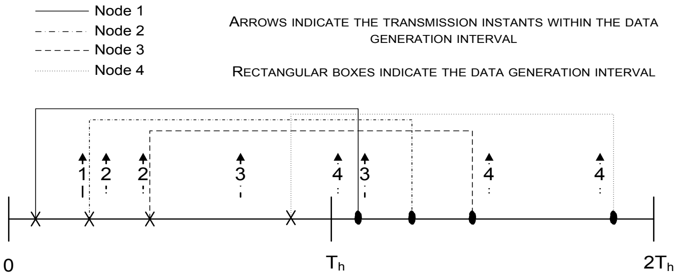
C. Frame Formats

The A-QoMoR MAC protocol uses only two types of packets viz. 1) Data Packet and 2) ACK packet. The data packet is transmitted by the sensor nodes to the sink and the ACK packet is transmitted by the sink to the sensor nodes. In the following we present the headers used by the protocol.

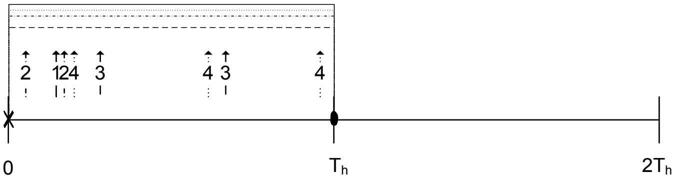
The A-QoMoR MAC protocol adds a total of 6 bytes of overhead to each payload packet received from the higher layers before transmitting it. As shown in Fig.2(a), the headers consist of four fields, Destination ID, Source ID, Control Field and Length. The Destination and Source ID fields contain the device ID of the device to which the packet is intended and the device that transmitted the packet. Each of these fields is one byte long and hence a maximum of 256 different devices can be addressed. The Length field indicates the length of the payload and is also one byte long allowing a maximum payload size of 256 bytes. Considering the nature of packets generated by the class of networks we study in this work this is acceptable. A standard 16-bit Cyclic Redundancy Check (CRC) is added to the end of the payload in order to detect bit-errors in the packet at the receiver.

The Control Field is further subdivided into two sub-fields that represent the Packet ID and the Packet Type. As shown in Fig.2(c) the most significant 6 bits are allocated for the Packet ID. The Packet ID field is incremented (modulo-64) each time a new packet arrives from the higher layers. It is also used in the ACK packet to identify the packet that is being acknowledged. The least significant 2 bits are used to indicate the Packet Type, namely, Data or ACK packet.

Whenever the sink successfully receives a data packet with a particular Packet ID, it sends an ACK packet acknowledging the reception. The size of the ACK packet is kept to a minimum in order to reduce t_{ack}. As shown in Fig.2(b), it consists of a Destination ID, Source ID, Control Field and CRC. The Destination ID, Source ID and CRC fields perform the same function as in the data packet. The Packet ID sub-field is set to the same value as the Packet ID of the data packet that was successfully received and the Packet Type sub-field is set to the ACK packet type.



(a) Random starting points for the data generation intervals



(b) Same starting points for the data generation intervals

Fig. 3. Variation of Traffic for Asynchronous and Synchronous Data Generation Intervals

III. THEORETICAL ANALYSIS OF THE A-QOMOR PROTOCOL

In the A-QoMoR protocol, the sensor nodes will stop retransmitting the packet once they receive an ACK from the sink, the number of transmission attempts that each sensor node will make for each packet will be different. The major challenge in the analysis of A-QoMoR is the modeling of the traffic generated by the sensor nodes, as the number of transmissions they attempt for each packet is different. Although x_{max} might be set to a high value, the average number of transmissions attempted by a sensor node to successfully deliver a packet is typically much lesser. We denote this parameter by x_{avg}. Since the energy consumed by each sensor node is directly proportional to x_{avg}, it is an important metric that quantifies the performance of A-QoMoR.

Before proceeding with the analysis, we define the variables used - n, T, t are the total number of sensor nodes, the data generation interval and the channel access duration of the sensor nodes. It is assumed that the size of the packets generated by all the nodes and the ACK packet generated by the sink is a constant and hence the transmission duration, t, is also a constant. Further, it is also assumed that $t \ll T$.

A. Preliminaries

Since the transmissions from all the sensor nodes are independent and asynchronous events, we observe that the data generation intervals of the sensor nodes are not "synchronized" in that, they have different starting times for their data generation intervals. Alternately, the arrival of packets to the MAC layer of each sensor node is not synchronized.

Since all the sensor nodes in the network have the same data generation interval T, the start of these intervals can be assumed to be uniformly distributed within the interval T. Further, each sensor node transmits at random instants of time within *its* data generation interval. A closer inspection reveals that, although each sensor node might transmit a different number of times (until its packet is successfully delivered to the sink) within each of its data generation intervals, the transmissions from all the sensor nodes in the network tend to be uniformly distributed over time.

Fig. 3(a) illustrates this phenomenon. The figure depicts the transmissions of four sensor nodes in the network where *Node 1* successfully delivers its packet on the first transmission attempt, *Nodes 2* and *3* succeed on the second transmission attempt while *Node 4* succeeds on the third attempt. As we can see, the start of the data generation intervals of the four sensor nodes are uniformly distributed in the interval $[0, T]$ and the transmissions of all the sensor nodes are uniformly distributed in the interval $[0, 2T]$. *Consequently, we can deduce that the average number of transmissions, x_{avg}, is always constant with respect to time.*

B. Analysis of the General Case

Since the transmissions from all the sensor nodes are independent, asynchronous events and the packet transmission durations are very small compared to the data generation interval, the arrival of packets to the channel can be modeled as a Poisson process [21]. Consequently, the probability of k frames being transmitted during some time period t is given by

$$P_{t,k} = e^{-\lambda t} \frac{(\lambda t)^k}{k!} \tag{2}$$

where λ is the rate of background traffic.

The background traffic, is defined as the traffic generated by all the *other* sensor nodes in the network. More specifically, the rate of background traffic, λ, can be expressed as

$$\lambda = \frac{(n-1)x_{avg}}{T} \tag{3}$$

For a transmission by a sensor node to be successful, we need that $k = 0$ frames be transmitted by all the other sensor nodes during the interval $[t_0 - t, t_0 + t]$, where t_0 is the start of the packet transmission. Accordingly, the probability of a transmission by a sensor node being successful is

$$p_s = e^{\frac{-2(n-1)x_{avg}t}{T}} \tag{4}$$

Since the sensor nodes use the wireless medium that is inherently unreliable for communications, excluding the packet errors caused due to the nature of the wireless medium will result in a significant error in the calculation of this probability. In order to account for packet loss due to the wireless medium we introduce a factor L, which is defined as the probability that there are no bit errors in the packet. We can calculate L as

$$L = (1 - BER_{tx})^{b_{tx}} \times (1 - BER_{ack})^{b_{ack}} \tag{5}$$

where BER_{tx} is the Bit Error Rate of the wireless medium for the modulation used by the transmitter, b_{tx} is the length of the transmitted packet in bits, BER_{ack} is the Bit Error Rate of the wireless medium for the modulation used by the receiver and b_{ack} is the length of the ACK packet in bits. This model is able to capture the errors caused by the physical medium and hence the average packet loss, with sufficient accuracy.

Thus the probability that a transmission by a sensor node is successful can be modified as

$$p_s = e^{\frac{-2(n-1)x_{avg}t}{T}} \times L \tag{6}$$

The achieved delivery probability, P, is the probability that at least one of the transmissions of the sensor node results in the successful delivery of the packet to the sink. It is thus given by

$$P = 1 - (1 - p_s)^{x_{max}} \tag{7}$$

We now proceed to calculate the average number of transmissions attempted by each sensor node, x_{avg}, to successfully deliver a packet to the sink. First, it should be noted that number of transmissions attempted by a sensor node is a random variable. Next, we observe that, irrespective of any other event, every sensor node will attempt at least one transmission in each data generation interval. So, the transmission attempts by the sensor nodes can be categorized as, one transmission (the first transmission attempt for a packet within each data generation interval) followed by, at most, $x_{max} - 1$ retransmissions. A critical observation here is that, these are two dissimilar events as the first transmission is *always* attempted while each of the retransmissions *may or may not* be attempted.

Hence, we calculate $x_{avg} = 1 + x_{retx}$, where, x_{retx} is the average number of retransmissions attempted to successfully deliver a packet to the sink.

Since the number of retransmissions attempted by each sensor node is also a random variable, by the definition of the mean of a random variable, it is given by

$$x_{retx} = \sum_{i=1}^{x_{max}-1} i \times (1-p)^i \tag{8}$$

and hence

$$x_{avg} = 1 + \sum_{i=1}^{x_{max}-1} i \times (1-p)^i \tag{9}$$

Eq. (6) and (9) form a system of non-linear equations involving two variables. These equations can be solved under the constraint $P \geq p$ and the corresponding value of x_{max} can be calculated. We note that there may be many solutions for x_{max}, however, in order to minimize the energy consumption, we would like to choose the minimum of all the possible solutions.

C. Calculation of the Lower Bound

In the analysis of the general case, we assumed that the start of the data generation intervals and hence the transmissions were uniformly distributed over time. We however note that, if the start of the data generation intervals is *non-uniformly* distributed, the distribution of the transmissions over time is also non-uniform. As illustrated in Fig. 3(b), if we assume that the data generation intervals of all the sensor nodes start at the same time, the background traffic in the channel will initially be high and gradually reduce as more and more sensor nodes successfully deliver their packets and stop further retransmissions. This is because each sensor node randomly chooses x_{max} instants to transmit within its data generation interval, but will stop their remaining transmissions after receiving an ACK.

Thus, if the start of the data generation intervals are non-uniformly distributed, the average number of transmissions, x_{avg} *is no longer a constant over time.*

Since the x_{max} transmission instants chosen by each sensor node are still uniformly distributed in the interval T, we can approximate that all the sensor nodes will attempt their first transmission during the same sub-interval $[0, \frac{T}{x_{max}})$. Subsequently, all the sensor nodes whose first transmission failed will attempt their second transmission (or first retransmission) during the second sub-interval $[\frac{T}{x_{max}}, \frac{2T}{x_{max}})$ and so on. This clearly is an over estimation of the contention for each transmission and hence gives us an upper bound on the background traffic in the channel. Since the delivery probability and the background traffic in the channel are inversely proportional to each other, this also gives us the lower bound on the delivery probability.

To calculate λ_1, the rate of background traffic for the first transmission of a sensor node, we consider the worst case scenario, where all the n sensor nodes in the network contend for the channel with their first (mandatory) transmission during the first sub-interval $[0, \frac{T}{x_{max}})$. Thus, we have $\lambda_1 = \frac{(n-1)x_{max}}{T}$.

The probability that the first transmission of a sensor node will be successful is denoted by p_1. On an average, $p_1 \times n$ sensor nodes will successfully deliver the packet on the first attempt. Consequently, only $(1 - p_1) \times n$ sensor nodes will attempt a second transmission. Further, the nodes only have $x_{max} - 1$ remaining transmission attempts. Accordingly, the rate of background traffic for a sensor node attempting its second transmission, λ_2, will be $\frac{((1-p_1)n-1)(x_{max}-1)}{T}$.

In general, the rate of background traffic for the j^{th} transmission of a node, λ_j, is given by

$$\lambda_j = \frac{((\prod_{k=1}^{j} 1 - p_{k-1})n - 1)(x_{max} - (j-1))}{T} \quad (10)$$

where the delivery probability of the j^{th} transmissions is given by

$$p_j = e^{-2\lambda_j t} \times L \quad (11)$$

It should be noted that the above analysis has been done considering the worst case scenario for the rate of the background traffic. Since the rate of background traffic is inversely proportional to the delivery probability and directly proportional the average number of transmission attempts, the following expressions for the delivery probability and the average number of transmission attempts provide the corresponding lower and upper bounds.

The lower bound on the delivery probability, P_s^l, can then be calculated as the probability that at least one of the transmissions attempted by a sensor node results in the successful delivery of a packet to the sink. It is thus given by

$$P_s^l = 1 - \prod_{j=1}^{x_{max}} (1 - p_j) \quad (12)$$

Proceeding in a manner similar to the calculation of the average number of transmissions in Sec. III-B, we can calculate the upper bound on the average number of transmissions that will attempted by each sensor node as

$$x_{avg}^u = 1 + \sum_{j=1}^{x_{max}-1} (\prod_{k=1}^{j} 1 - p_k) \times j \quad (13)$$

D. Energy Consumption

The simplicity of the A-QoMoR MAC protocol also allows us to analytically calculate the average energy consumed by the sensor nodes. This is an important tool in accurately determining the lifetime of the network.

Let E_{tx}, E_{rx} be the energy consumed by the sensor node per unit time for transmitting and receiving respectively. Let E_s be the energy consumed by the sensor node when it is sleeping.

The energy consumed for each transmission attempted by a sensor node is thus

$$E = E_{tx} t_{tx} + E_{rx} t_{ro} \quad (14)$$

In each data generation interval the sensor node attempts an average of x_{avg} transmissions and sleeps for the rest of the time. Thus the average energy consumes per data generation interval is given by

$$E_{avg} = E \times x_{avg} + E_s(T - t \times x_{avg}) + E_{dev} \times T \quad (15)$$

where E_{dev} is the average energy consumed for the operation of the other circuits in the device, for example, the microprocessor, memory etc.

IV. PERFORMANCE STUDY

To study the performance of A-QoMoR, we perform simulations using the $NS-2$ simulator. The protocol was implemented at the MAC layer of the $NS-2$ framework. First, we present the results from the analysis and simulation of the A-QoMoR protocol. Next, we present results from the practical implementation of the A-QoMoR protocol on a network consisting of XSM motes deployed and compare them to the analytical and simulations results.

The A-QoMoR protocol is designed for sensor nodes that are equipped with asymmetrical transceivers. Hence, we compare the A-QoMoR MAC protocol to the QoMoR scheme developed in [19] that is also capable of operating using the same hardware.

The performance study would however be incomplete without comparisons to existing MAC protocols. Hence, we setup a network consisting of sensor nodes equipped with asymmetric transceivers running the A-QoMoR MAC protocol and another network consisting of sensor nodes equipped with fully functional transceivers running the 802.11 protocol. We study and compare the delivery probability and energy consumption of the sensor nodes in both networks under the same traffic conditions.

A. Simulation Setup

To establish a common base for the comparison of the protocols, we fixed the rate of data generated by the higher layers and the physical layer parameters like channel bandwidth, transmit power and receiver sensitivity. The following are the parameters used in the simulations.

A total of a 100 nodes were placed in a random flat-grid topology within a $50m \times 50m$ region. The uplink channel datarate was set to $2Mbps$ and the downlink channel datarate was set to $250Kbps$. The transmit power of the radio module used was set to $200mW$ while the receive power was set to $100mW$. The physical layer propagation model was chosen to incorporate the shadowing and multipath characteristics of the typical operating environment of these networks. The size of the MAC payload was set to $64bytes$ and the data generation interval T was set to $250msec$. These parameters were chosen from the typical requirements of the applications described in [1] [2] [3] [4] [6] and standard device specifications.

The frame formats described in Sec. II-C were used to construct the packets in the simulations. Thus, the total data packet size, including the MAC overhead, is 70 bytes resulting in a transmission duration of $t_{tx} = 284\mu sec$. For A-QoMoR, the total ACK packet size is 5 bytes. Consequently, the transmission duration of the ACK packet is $t_{ack} = 160\mu sec$. The turnaround time t_{ta} was set to $10\mu sec$, resulting in a channel access duration of $t = 454\mu sec$ per transmission. These values were used in calculating the performance of A-QoMoR analytically.

B. Analysis and Simulation results of A-QoMoR

The analysis and simulation results of A-QoMoR for the setup described above are presented here.

Fig.4 shows the variation of the delivery probability, P_s, achieved by the nodes for different values of x_{max}. The delivery probability monotonically increases with x_{max}. This follows from the fact that a higher number of transmission attempts improves the delivery probability. Further, the results indicate that the theoretical model and the simulation results concur with each other.

Fig. 5 shows the simulation and analysis results of the average number of transmissions (x_{avg}) attempted by A-QoMoR for different values of x_{max}. The results show that x_{avg} initially increases relatively slowly as compared to x_{max}. This result concurs with our initial prediction that, although x_{max} may be set to a high value, most packets are successfully delivered in the first few transmission attempts. Fig. 5 also shows the energy consumption of the nodes in the network and we can see that it is proportional to the average number of transmission attempts.

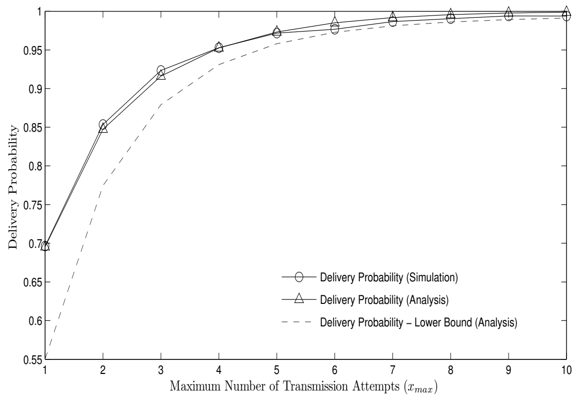


Fig. 4. Analysis and simulation results for Delivery Probability

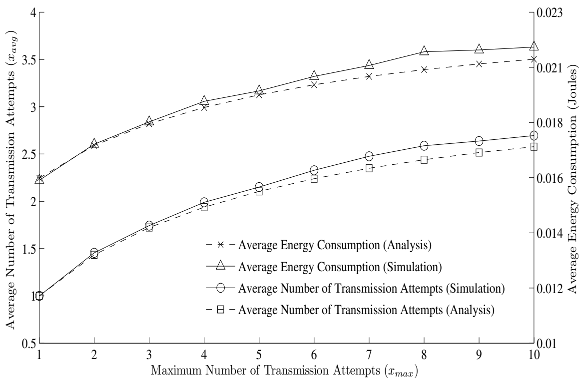


Fig. 5. Analysis and simulation results for Energy Consumption and Average Number of Transmission Attempts

C. Implementation of A-QoMoR on XSM motes

The A-QoMoR protocol was implemented on a test bed consisting of 15 XSM motes. The XSM motes were chosen as they have a CC1000 radio module that is typical of a low cost sensor node and has a data rate of 19.2Kbps. Due to the unavailability of off-the-shelf hardware with asymmetric transceivers, we used the fully functional transceiver of the XSM motes, albeit, without using its capability to sense the channel. To simulate a lower data rate downlink channel the length of the ACK packet was increased 8 fold to ensure that the ratio of the uplink to downlink datarate remains the same as in the simulation setup.

From the analysis in Sec. III, we note that the delivery probability of the nodes is proportional to the factor $\frac{t_f \times n}{T}$. Since only 15 XSM motes were available we setup the parameters t_f and T such that the factor remains the same

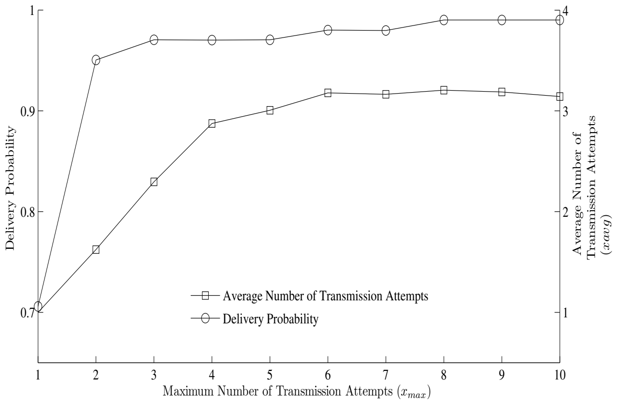


Fig. 6. Performance of A-QoMoR on a Practical Test-Bed

as in the simulation setup. Hence, we can compare the results in Fig.6 and Figs.4 and 5.

The test was setup with the motes placed randomly in an office room that had a lot of obstructions in the form of furniture. Further, there was interference from other wireless devices like an 802.11 access point and cellular devices. This environment was chosen in order to study the performance of the protocol in a setup that is close to a realistic deployment of such networks.

The results from the test bed have the same general trend as the simulation results. We do however, observe that the average number of transmissions are slightly higher than that from the simulation results. This can be attributed to the fact that the simulation does not take into account interference from other sources like wireless LAN and cellular devices. However, the results do indicate the same trend further corroborating the theoretical model of the protocol.

D. Comparison of A-QoMoR and QoMoR

In order to provide a common base for comparing A-QoMoR and QoMoR, the same MAC headers were used for the data packet. The receiver module was completely switched off while simulating QoMoR.

A comparison with the delivery probability achieved when the sensor nodes use QoMoR shows that A-QoMoR outperforms QoMoR significantly. Note that even the lower bound on the delivery probability for A-QoMoR is higher than the achieved delivery probability of QoMoR. When QoMoR achieves its highest delivery probability of $P = 0.86$, at $x = 4$, A-QoMoR achieves a much higher delivery probability of $P = 0.95$ for a corresponding value of $x_{max} = 4$.

In terms of energy consumption, A-QoMoR consumes a significantly lower energy than QoMoR in most cases, as seen in Fig. 7. This is due to the fact that, even though x_{max} is high, the average number of transmissions, which directly affects the energy consumption in A-QoMoR, is low. Hence the extra energy consumed by the receiver module is offset by the smaller number of transmissions attempted. Fig. 7 shows that, at $x_{max} = 4$, when QoMoR achieves its maximum delivery probability, A-QoMoR achieves a much higher delivery probability while consuming about 10% lesser energy.

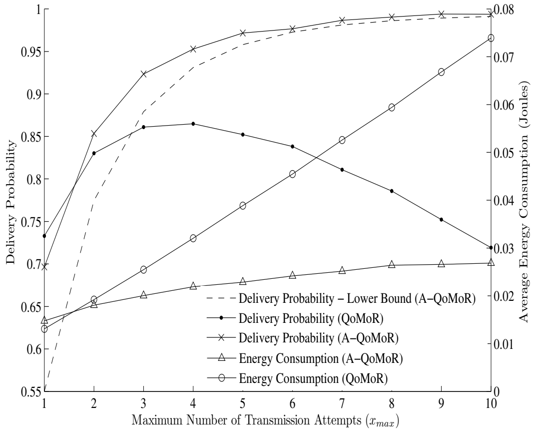


Fig. 7. Comparison between A-QoMoR and QoMoR

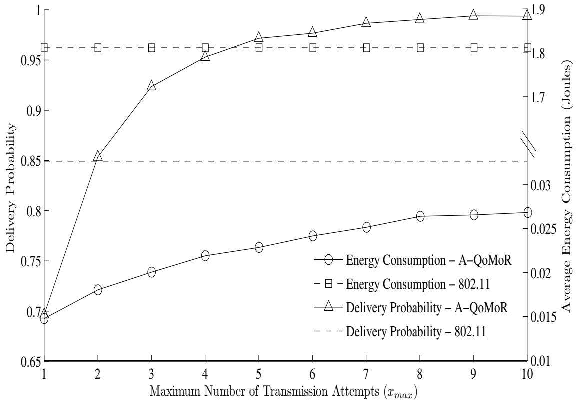


Fig. 8. Comparison between A-QoMoR and 802.11x

A-QoMoR achieves significant performance gains over QoMoR because they make use of their capability to receive. However, this also makes them more complex than the sensor nodes used in [19]. Hence, there is a definite cost-performance trade off introduced by A-QoMoR.

E. Comparison of A-QoMoR and 802.11

In this section, we study the performance of the 802.11 MAC protocol in terms of packet delivery probability and energy consumption and compare it to A-QoMoR. As mentioned earlier, the same rate of data generated by the higher layers and the same physical layer parameters were used to establish a common base for comparison. Two independent simulations were set up - one consisting of nodes equipped with fully functional transceivers to study the performance of 802.11 and another consisting of nodes equipped with asymmetrical transceivers to study the performance of A-QoMoR. The following presents the results for delivery probability and energy consumption obtained from these setups.

Fig.8 shows that A-QoMoR is able to achieve a higher delivery probability than 802.11 for values of x_{max} greater than one. As the value of x_{max} is increased A-QoMoR performs significantly better than 802.11.

It is worth noting that given the simulation settings, the aggregate traffic is about $200Kbps$, which is much smaller than the channel bandwidth. Further, the size of each packet is relatively small (64bytes) and the number of contending sensor nodes is high (100). Since the $802.11x$ protocol has a significant overhead in terms of control packets and the exponential back off mechanisms lead to bandwidth wastage, it performs poorly. This also implies that for the many applications described in [1] [2] [3] [4] [6], where there are many sensor nodes and small data packets are generated at short, periodic intervals, 802.11 is not a suitable protocol. Instead, new protocols such as A-QoMoR will be needed.

In terms of energy consumption per node, the 802.11 protocol consumes $1.8 Joules$ as compared to $0.015 - 0.028 Joules$ (depending on the value of x_{max}) consumed by A-QoMoR for the same simulation duration. This is due to the fact that, in 802.11, all the sensor nodes keep their receivers ON all the time and consequently receive packets that are not intended for them. This wasteful energy consumption is the reason for the significantly high energy consumption of the 802.11 protocol.

V. QOS PROVISIONING IN A-QOMOR

In this section we describe a method to provide differentiated QoS to the sensor nodes, in terms of packet delivery probability, using the A-QoMoR MAC protocol. We study a system consisting of two QoS classes, a high priority class Q_h and a low priority class Q_l. The total number of sensor nodes n are divided into n_h high priority sensor nodes and n_l low priority sensor nodes requiring a minimum delivery probability of p_h and p_l respectively, where $p_h > p_l$. The data generation intervals and the channel access durations of the sensor nodes in the two classes are T_h, T_l and t_h, t_l respectively.

The results presented in Sec. IV show that the delivery probability achieved by the sensor nodes increases with the maximum number of transmission attempts x_{max}. Therefore an intuitive way to provide differentiated QoS to the sensor nodes is to program them with different values of x_{max}. Alternately, we can program all the sensor nodes in class Q_h with a maximum number of transmissions equal to $x_{h_{max}}$ and the sensor nodes in class Q_l with $x_{l_{max}}$, where $x_{h_{max}} > x_{l_{max}}$. The following analysis develops expressions to calculate the optimum value of $x_{h_{max}}$ and $x_{l_{max}}$ in order to achieve the required minimum delivery probabilities of p_h and p_l for the two classes.

As observed in Sec. III, the rate of background traffic affects the delivery probability that can be achieved by each class. The rate of background traffic for a high priority sensor node is given by

$$\lambda_h = \frac{(n_h - 1)x_{h_{avg}}}{T_h} + \frac{n_l x_{l_{max}}}{T_l} \tag{16}$$

Similarly, the total background traffic for a low priority sensor node is given by

$$\lambda_l = \frac{(n_l - 1)x_{l_{avg}}}{T_l} + \frac{n_h x_{h_{max}}}{T_h} \tag{17}$$

Let the delivery probabilities achieved by the two classes Q_h and Q_l be P_h and P_l respectively. Following the same steps used to derive Eq. (7) in Sec. III we have

$$\begin{aligned} p_{h_s} &= e^{-2\lambda_h t_h} \times (1 - L) && (18)\\ p_{l_s} &= e^{-2\lambda_l t_l} \times (1 - L) && (19)\\ P_h &= 1 - (1 - p_{h_s})^{x_{h_{max}}} && (20)\\ P_l &= 1 - (1 - p_{l_s})^{x_{l_{max}}} && (21) \end{aligned}$$

We can calculate the average number of transmissions that each sensor node in Q_h and Q_l as below

$$\begin{aligned} x_{h_{avg}} &= 1 + \sum_{i=1}^{x_{h_{max}}-1} i \times (1 - p_{h_s})^i && (22)\\ x_{l_{avg}} &= 1 + \sum_{i=1}^{x_{l_{max}}-1} i \times (1 - p_{l_s})^i && (23) \end{aligned}$$

Eqs. (18) (19) (22) (23) form a system of four equations in four variables that can be solved under the constraints $P_h \geq p_h$ and $P_l > p_l$ to obtain the values of $x_{h_{max}}$ and $x_{l_{max}}$. There may be many solutions for $x_{h_{max}}$ and $x_{l_{max}}$, however, we would like to choose the pair-wise minimum of the all the possible solutions in order to minimize the energy consumption.

VI. CONCLUSION

This paper has proposed a novel medium access protocol called the Asymmetric QoS-aware MAC protocol based on Optimal Retransmissions (A-QoMoR), for low complexity, low power, low cost, single hop wireless sensor networks. The common goal of the proposed schemes is to provide guaranteed delivery probability and latency bounds for networks consisting of sensor nodes equipped with asymmetrical transceivers and transmit data to a sink node periodically.

We have shown through extensive analysis, simulations and test bed implementations that it achieves a relatively higher delivery probabilities and lower latency bounds than established protocols like 802.11. Further, the A-QoMoR protocol is also capable of providing differentiated QoS in terms of delivery probability to a network consisting of different classes of sensor nodes.

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