An Energy-Efficient QoS-Aware Media Access Control Protocol for Wireless Sensor Networks

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Abstract— **We present an innovative MAC protocol (Q-MAC) that minimizes the energy consumption in multi-hop wireless sensor networks (WSNs) and provides Quality of Service (QoS) by differentiating network services based on priority levels. The priority levels reflect application priority and the state of system resources, namely residual energy and queue occupancies. The Q-MAC utilizes both intra-node and inter-node arbitration. The intra-node packet scheduling is a multiple queuing architecture with packet classification and weighted arbitration. We also introduce the *Power Conservation MACAW (PC-MACAW)* - a power-aware scheduling mechanism which, together with the *Loosely Prioritized Random Access (LPRA)* algorithm, govern the inter-node scheduling. Performance evaluation are conducted between Q-MAC and S-MAC with respect to two performance metrics: energy consumption and average latency. Simulation results indicate that the performance of the Q-MAC is comparable to that of the S-MAC in non-prioritized traffic scenarios; when packets with different priorities are present, Q-MAC supiors in average latency differentiation between the classes of service, while maintaining the same energy level as that of S-MAC.**

I. Introduction

The key in the wireless sensor networks (WSNs) design always centers around transmission reliability and energy efficiency, to which significant research effort has been devoted toward [1]–[3]. However, less attention [4], [5] has been put in providing certain quality of service (QoS) guarantees in a multi-hop wireless networks, where prioritizing data packets and providing different services based on application specifics is very important.

The solution we present is an energy-efficient, QoS-aware media access control (Q-MAC) protocol. The most distinguishable feature of Q-MAC is that it allows sensor networks to reflect on the criticality of data packets originating from the different sensor nodes, thereby yielding a *Loosely Prioritized Random Access*. As a result, high priority data packets are always transmitted first thus experiencing lower latencies.

II. The Q-MAC Protocol

The Q-MAC consists of intra-node and inter-node scheduling. The intra-node scheduling scheme adopts a multi-queue based queuing architecture to classify data packets according to their application and MAC layer abstraction. The *MAX-MIN fairness algorithm* and the *packetized GPS algorithm* are used to determine the next packet to be served from the multi-queue mechanism within each node. The inter-node scheduling employs the *power conservation MACAW protocol* and the *loosely prioritized random access protocol* for multiple access of the channel among neighboring sensor nodes.

Intra-Node Scheduling: The multiple first-in-first-out (FIFO) queuing systems of the Q-MAC are as in Fig. 1. Such systems do not rely on in-queue searching algorithms, which is indispensable in a single FIFO system. A received packet is classified based on its criticality and then stored into the appropriate queue. The number of queues thus determines the number of network service levels. The challenge is to choose a proper number of queues and to establish the size of each queue,and to compromise between node resources and the expected QoS provisioning.

The priority of an incoming packet is determined by the application and the MAC layer abstractions. The application layer abstraction prioritize packets based on content importance. In Q-MAC, we append five extra bits of information to every message, two for identification of the types of applications and three for the types of sensing data. In practice, the selection of number of bits can be justified according to the specific network constructions. The MAC layer abstraction, on the other hand, tries to provide fair, efficient network services between self-generated and relayed packets and among the relayed packets with different transmitted hops. As a result, packets that have gone through more hops have a higher priority. In the current implementation of Q-MAC, we refer to a packet based on the actual hop number it is associated with. For example, originating packets are the 1-hop packets and ect. The factor of MAC layer abstraction can thus be determined by normalizing with the maximal permitted hops. The queuing

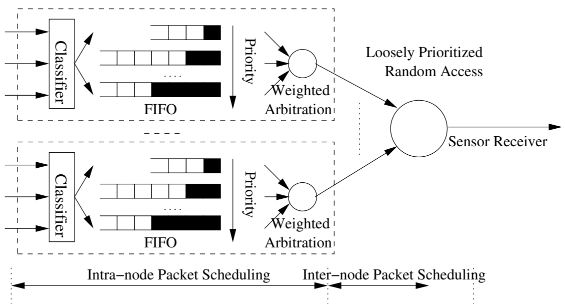

Fig. 1. The multi-queue queuing architecture

architecture in Q-MAC consists of five queues with one specified as an *instant queue*, or deterministic queue, meaning that any packet stored in this queue will be instantly served. Such design allow us to allocate a trapdoor for centralized network management traffic (e.g. network synchronization) and to offer extremely urgent traffic a path for rapid service. The rest of

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the queues use the the MAX-MIN fairness algorithm [6] to allocate rate and the packetized GPS algorithm [7] to select the next serviced packet.

Inter-Node Scheduling: One of the most important function of the MAC layer is to coordinate and schedule data transmissions among multiple nodes sharing the same channel. Due to the high cost of retransmission, inspired by MACAW [8], we introduce the *Power Conservation MACAW* protocol as means of scheduling data transmissions in WSNs, and a *Loosely Prioritized Random Access* (LPRA) protocol to coordinates data communication between sensor nodes.

The Power Conservation MACAW (PC-MACAW) is a modified version of MACAW, which conquer the energy consumption problem with the classic method. Since idle listening, collision, communication overhead and overhearing contribute most to energy wastage. We aim at a simple and distributed protocol to minimize collision and idle listening.

In PC-MACAW, we redefine the term "frame" to represent one RTS-CTS-DATA-ACK message exchange. As shown in Fig. 2, a frame space (FS) exists between any two consecutive frames. Each frame consists of two parts, the contention period (CP) and the packet transmission period (TP). A short space (SS) is introduced between the contention period and the transmission period. During the contention period, a node needs to send out RTS and wait for CTS to access the channel. After successfully accessing the channel, the source node can start transmitting a data packet within the designated packet transmission period. Noticing that ACK is used to acknowledge successful data packet transmissions. Here, we use time slots (TS in microsecond) as the minimal interval to partition the time axis of each sensor node. Such framing allow potential receiver nodes to hear RTS/CTS correspondences while the high priority nodes continuously contend for channel, which in turn increases the probability of a successful data transmission during a frame interval. Also, this mechanism is easy to implement and has a good scalability attributes, the key for large scale wireless sensor networks. The fairness of data transmission among neighboring nodes is ensured by allowing each node contend for the channel at an identical starting point. Such fairness forms the foundation of the proposed Loosely Prioritized Random Access protocols (LPRA), in which we use contention time of each node to regulate the order by which nodes access the channel.

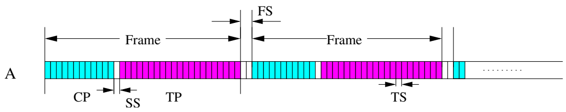


Fig. 2. The sensor node frame structure.

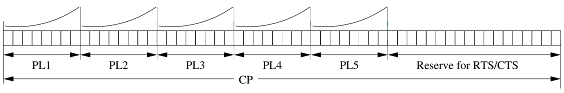


Fig. 3. The prioritized contention period with each priority level (PL) following the truncated, increasing geometric distribution.

Let μ denote the transmission urgency of a node that contains packets waiting to be sent. It is influenced by four factors. *Packet criticality* reflects the perspective of application layer. *Transmission hops* represents the needs from the view of retransmission cost. *The residual energy* addresses the energy constraints and *the queues' proportional load* is to avoid overflow. The urgency of a node can thus be calculated as

$$\mu = \frac{1}{4} \times (\frac{E_c}{E_{max}} + \lambda + \frac{C_c}{C_{max}} + \frac{H_c}{H_{max}}) \quad (1)$$

where $\lambda = \frac{1}{2} \times \left(\frac{\sum_{i=1}^{n} w_i Q_c(i)}{\sum_{i=1}^{n} w_i Q(i)} + max_{k=1...n}(\frac{Q_c(k)}{Q(k)}) \right)$ represents the *proportional load*. E_c , H_c, and C_c represent the residual energy, the transmitted hops and the criticality of a packet, respectively. E_{max}, H_{max}, and C_{max} refer to the initial energy, maximum permitted hops, and the maximum criticality level of a packet. $\frac{1}{4}$ is a normalizing factor. n is the number of queues. w_i denote the service weight of the i^{th} queue. Q_i and $Q_c(i)$ denote the maximal and instant load respectively. The priority ρ and the contention time t_{CT} of a sensor node become,

$$\rho = \min(\lfloor(1-\mu) \times N\rfloor, N-1) \quad (2)$$

$$t_{CT} = \rho \times CW + rand(CW) \quad (3)$$

where N is the priority level supported and CW is the contention window size. $rand(x)$ generates a random number between 1 and x.

However, as the value of CW decreases, the the possibility of collision increases. The probability of collision is

$$Pr(\text{without collision}) = \sum_{i=1}^{CW-1} n \times p(i) \left(\sum_{j=i+1}^{CW} p(j) \right)^{n-1} \quad (4)$$

where n is the number of neighboring nodes, and $p(i)$ is the probability to pick up transmission time at the i^{th} time slot. We use the near optimal solution proposed in [9],

$$p(i) = \frac{(1-\alpha)\alpha^{CW}}{1-\alpha^{CW}} \times \alpha^{-i} \ for\ i = 1, ..., CW, \quad (5)$$

where $0 < \alpha < 1$ is the distribution parameter. Using a simple mathematical induction method, we infer that $p(i)$ must be increasing to maximize the probability of no collision happening. This distribution is illustrated in Fig. 3. Once the non-uniform probability distribution is decided, the contention time can be easily generate through random number generator.

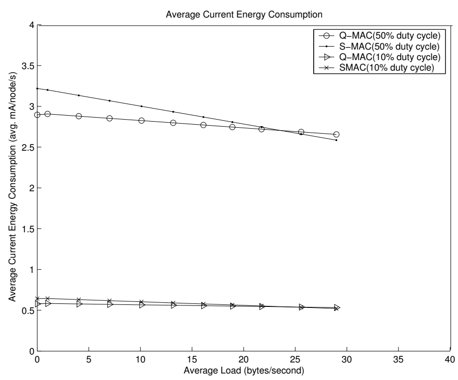
Two type of collision recovery schemes are used in the Q-MAC, i.e. doubling the CW size and setting packets dropping threshold according to applications. When the difference between the sensing time and the current time is beyond this predefined threshold, packets are immediately dropped.

III. Simulation and Performance Analysis

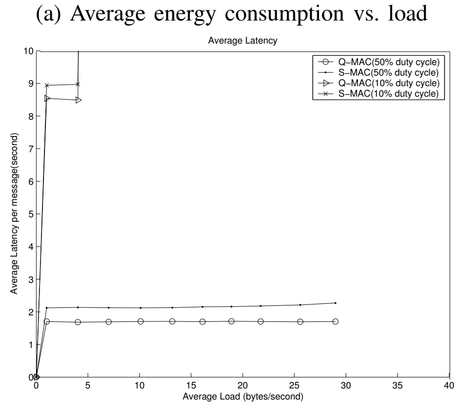
The performance of Q-MAC and S-MAC is evaluated by our java-based wireless sensor network simulator (SENSIM). Some physical layer parameters are taken from the Berkeley Mica2 sensor Motes [10] configurations, the same settings as in S-MAC. To simplify the simulation process, we predetermine the routing table for each node and assume all the packets are destined to the senor sink. Two scenarios are considered. The effects of different packet generation models and the existence of packet criticality on the network latency and energy consumption are compared.

In the first scenario, the simulated sensor network has 15 sensor nodes with at most 3 hops from the sensor sink. The frames and messages are both 100 bytes long. The contention period (CP) for both protocols is 115ms with six subdivisions. Five CWs of length 15ms and a 40ms period for RTS/CTS control packet exchange is used. The simulation is repeated 10 times. Each time every node generates in total 100 messages. It is designed to compare the performance of S-MAC and Q-MAC when all nodes are of equal criticality. Simulation results in Fig. 4 indicate that the Q-MAC and the S-MAC are at about the same energy consumption level, while the Q-MAC has lower latency due to shorter contention time and synchronized data transmission.

In the second scenario, the simulated sensor network has 25 nodes of different packet criticality with the same parameters as in senario 1. The simulation results are shown in Fig. 5. Q-MAC can achieve overall better energy saving compared due to shorter contention window size and better collision recovery scheme for RTS/CTS packets. This advantage degrades as the load gets heavier. The results of average packet latency indicate that the Q-MAC successfully differentiates network services based on packet priorities. The higher priority packets are always accompanied with lower latency.

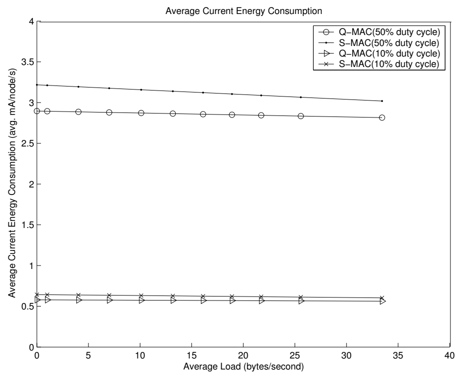


(a) Average energy consumption vs. load

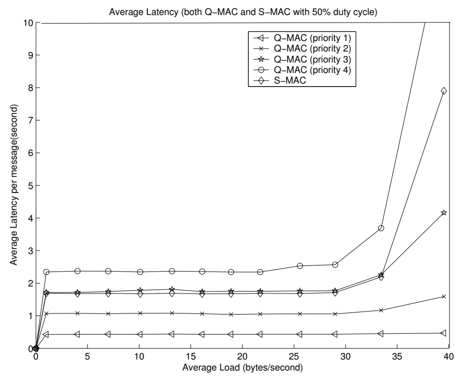


(b) Average latency vs. load

Fig. 4. Scenario 1: periodic traffic and equal criticality.



(a) Average energy consumption vs. load



(b) Average latency vs. load

Fig. 5. Scenario 2: periodic traffic and different packet criticality.

IV. Conclusion

We presented the Q-MAC, a novel energy-efficient, QoS-aware MAC protocol for the WSNs. It involves both intra-node and inter-node scheduling to provide differentiated services while retaining low energy consumption. Simulation results demenstrated that the Q-MAC offers the same degree of power efficiency as that of the S-MAC, while providing flexible differentiation between different service classes.

References

[1] W. Ye et.al, "An energy-efficient mac protocol for wireless sensor networks," in *INFORCOM*, 2002.
[2] W. Heizelman et.al, "Energy-efficient communication protocols for wireless microsensor networks," in *Proc. of the Hawalli International Conference on System Science*, 2000.
[3] C. Intanagonwiwat et.al "Directed diffusion: A scalable and robust communication paradigm for sensor networks," in *MOBICOM*, 2000.
[4] R. Iyer and L. Kleinrock, "Qos control for sensor networks," *ICC*, 2003.
[5] M. Younis et.al, "On handling qos traffic in wireless sensor networks," *Proc. of the HAWAII International Conference on System Sciences(HICSS-37)*, 2004.
[6] D. Bertsekas and R. Gallager, *Data Networks*. Prentice Hall, 1987.
[7] A. Parekh and R. Gallager, "A generalized processor sharing approach to flow control in integrated services networks: The single-node case," *Proc. IEEE INFORCOM*, 1992.
[8] V. Bharghavan et.al , "Macaw: A media access protocol for wireless lans," *Proc. ACM SIGCOMM*, vol. 24, no. 4, 1994.
[9] K. Jamieson et.al, "Sift: A mac protocol for event-driven wireless sensor networks," *MIT Laboratory for Computer Science, Tech. Rep. 894*, 2003.
[10] "Crossbow technology, inc." http://www.xbow.com.