Adaptive Quorum Based MAC Protocol in Non Uniform Node Distribution of Wireless Sensor Networks

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Abstract. The lifetime of a sensor network depends mainly on the sensor node's battery power. Therefore it is necessary to use sensor node battery power very efficiently. Most of the existing powers saving protocols have been designed in such a way that the sensor nodes are put into sleep state when there is no transmission. These protocols fail to adjust dynamically a sensor node's sleep duration based on its traffic load. This periodic and regular sleep and awake method of these protocols cause high latency and high energy consumption. A host must be allowed to sleep longer if it is not involved in data transmission frequently. Thus, to efficiently manage a host's energy, we need not only have a power saving mechanism but also a scheme to guarantee data transmission. In this paper we propose an Adaptive Quorum Based MAC Protocol (AQMAC) that enables sensor nodes to sleep under light loads in non uniform node distribution thereby decreasing the latency and increasing the throughput. We also used q-Switch Routing coupled with the non uniform node distribution strategy that switches the data flow among its corresponding next-hop forwarding nodes in order to balance energy dissipation among them and to reduce the transmission latency.

Keywords: Power Saving Protocol, MAC, Non Uniform Node Distribution, Quorum, Energy Hole Problem.

1 Introduction

Wireless Sensor Network (WSNs) is widely used in a variety of applications like health care, object tracking, battlefield surveillance, environmental monitoring, industrial automation etc. Sensor nodes are often operated by batteries and have limited processing and memory resources. Thus, it is important to design energy-efficient protocols for WSNs

In wireless sensor networks, Medium Access Control plays a key role in determining utilization of channels, delays in networks and energy consumption. Sensor nodes are able to sense, collect and transmit data to other sensor nodes within their transmission range. Most of the energy in sensor nodes is wasted in idle listening as nodes wait for other node to send data and also because nodes can transmit data only to nodes that are not in sleep mode. These constraints make the node to wake up

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often to check if the other node is awake and also ready for transmission. Several MAC protocols have been proposed to reduce the time a sensor node spends in idle listening by maintaining a schedule that indicates when a sensor should be awake for data transmission. However these MAC protocols suffer from long latency and fail to adapt to node's traffic load. The main aim of this paper is to efficiently put the nodes in sleep state and dynamically adjust the nodes sleep duration based on its traffic load and thus prolong the node's lifetime and increase the throughput.

The proposed protocol in this paper is a synchronous MAC protocol which is based on quorum based wake-up scheme in non uniform node distribution [5] of wireless sensor networks. The wake-up frequency of a sensor node is determined according to each node's traffic load. A node is allowed to sleep longer if less traffic is involved. Since latency is also an important issue, we have also used q-Switch Routing [5] technique with non uniform node distribution strategy. This identifies q or (q-1) relay candidates for the source node to send the data to the sink. The rest of this paper is organized as follows. Related works are presented in Section 2. Preliminaries are described in Section 3. Section 4 describes the details of the proposed protocol. Section 5 presents the simulation results.

2 Related Work

Many MAC Protocols like SMAC [9], TMAC [10] PMAC [7] and QMAC [4] were introduced to conserve energy. SMAC puts the sensor nodes to sleep periodically if the sensor nodes are not involved in data communication and hence avoids idle listening. By keeping the duty cycle low SMAC reduces sensor node's power consumption. This fixed duty cycle in SMAC may result in long transmission delay. SMAC fails to adjust the duty cycle based on the traffic load of each sensor node.

TMAC is an extension of SMAC and follows adaptive duty cycle. A sensor node will go to listen state and will not come to sleep state until there is no activity for a time $T_{A.}$ By minimizing the amount of time spent in idle listening, TMAC saves considerable amount of energy which may cause early sleeping problem wherein potential receivers may go to sleep too early. This problem reduces the number of hops a data can travel in a time frame which will further cause long transmission latency.

PMAC is another MAC protocol wherein sensor nodes exchange patterns to get information about the activity in its neighbourhood. Based on these patterns, when there is no traffic in the network a sensor node can put itself into a long sleep for several time frames. If there is any activity in the neighbourhood, a node will know this through the patterns and will wake up when required.The disadvantage here is two sensor nodes will not be able to meet if they do not correctly receive the other's pattern. This results in idle listening and long transmission delay.

The QMAC protocol achieves power saving by increasing the amount of sleep intervals. For an $n \times n$ grid, each host is awake for $(2n-1)/n^2$ intervals. The quorum size that is fixed for all nodes in the same corona remains the same throughout its lifetime. Thus during extreme traffic conditions the network suffers due to latency in transmission.

3 Preliminaries

We made the following assumptions in this paper.

- All the nodes are static after deployment and have the same transmission range.
- Each sensor node has a unique ID and sends the data to the sink node placed at the center.
- All the nodes are deployed non uniformly i.e. the number of nodes around the sink is more, and more the distance from the sink, the number of nodes deployed is lesser.
- The circular area is divided into R adjacent coronas i.e. the ith corona is denoted as C_i. The width of each corona is 1 unit length.
- Sink node can communicate directly with the nodes in the corona nearer to the sink C_1.

3.1 Non Uniform Node Distribution

Nodes that are closer to the sink not only transmit data sensed by them but also transmit the data that are sent by the nodes in outer coronas [3]. Therefore the nodes in the inner corona that are nearer to the sink deplete their energy much faster than the nodes in the outer corona that are farther from the sink which will lead to energy hole problem [5]. An efficient way to overcome this problem is by adding more and more nodes to these heavy traffic areas i.e. in the inner most corona. The node density in the innermost corona C_1 will be high. Since the width of each corona is 1 unit length, data can be transmitted from the source node in the outer most corona to the next inner corona via one hop and to the sink via i hop. The nodes in the outermost corona C_R needs to forward only the data generated by them. The numbers of inner corona's nodes are increased in geometric progression with a common ratio of q [5].

4 Adaptive Quorum Based MAC Protocol (AQMAC)

In non-uniform node distribution, the sensor nodes that are closer to the sink are heavily loaded. A protocol has to be designed in such a way that they not only be capable of adjusting each sensor node's listen/sleep frequency according to their traffic loads but also guarantee sensor nodes to meet each other. QMAC allows the nodes to meet each other using quorum [8]. It makes use of fixed quorum size and fails to adjust the quorum size based on the traffic load of each sensor node which will lead to latency in transmission. In order to reduce the energy consumption further we present our Adaptive Quorum Based MAC protocol (AQMAC) that achieve power conservation and guarantee that any two hosts will wake up concurrently during the same time intervals through the use of adaptive quorum size based on its traffic load [4] and [6].

4.1 Quorum Concept

The quorum concept ensures intersecting time intervals for any two nodes [8]. If the quorum size is large for both the nodes then fewer intersecting time frames are obtained whereas for smaller quorum size more intersecting time frames are achieved. To handle heavy traffic the quorum size is reduced and during light traffic quorum size can be increased. Because grid based quorums are used, any two nodes can wake up and meet each other at some time frame. In a grid-based quorum, one row and one column are picked in an n × n grid. For an n × n, each host is awake for $(2n-1)/n^2$ intervals. Figure 1 show an example of quorum interval selections, where the first row and first column is selected by host A and the second row and second column is selected by host B [2] and [4]. Host A will wake up at time intervals 0, 1, and 2 while host B will wake up at time intervals 1, 2, and 3. Host A and B will have the intersecting time intervals 1 and 2 during which the data will be transmitted.

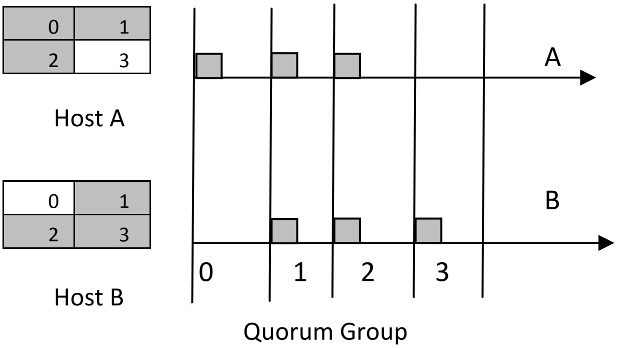

Fig. 1. Host A and Host B meet each other interval at 1 and 2 in a fixed quorum of size 2

In the QMAC protocol, all hosts in a corona share the same grid size of n × n [4]. When there is heavy traffic the quorum size is reduced so that the number of wake up time intervals will be increased and can send the data during the wake up time intervals. During light traffic quorum size can be increased so that the number of wake up time intervals can be reduced. On the other hand, the amount of conserved energy can be reduced with a small grid size [2]. In order to achieve better performance, it is necessary to dynamically adjust the grid size for each individual host since they have different traffic loads and different performance requirements.

Two hosts with different grid size will intersect with each other. For example, in Figure 2 host A has a 3 × 3 grid and its quorum intervals are 1, 4, 6, 7 and 8. Host B has a 4 × 4 grid and its quorum intervals are 2, 6, 8, 9, 10, 11 and 14. Host A wakes up more frequently than host B, but they have intersections during host B’s quorum group. Host A and Host B will have the intersecting time intervals 6,8 and 10 during which the data will be transmitted. This adaptive quorum will increase the intersecting time intervals. Based on the defined traffic load limits, the quorum size will be chosen dynamically by each sensor node.

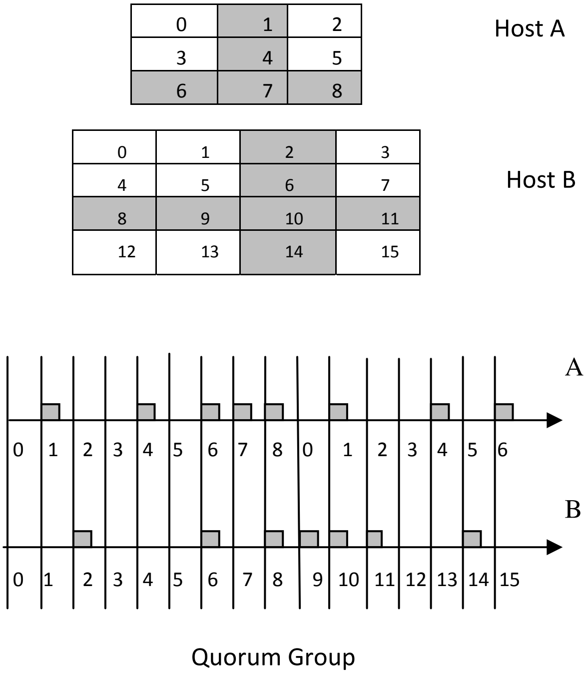

Fig. 2. Host A with grid size 3x3 and Host B with grid size 4x4 meet each other

The idea behind AQMAC is to increase a sensor node's grid size, in order to prolong its sleep duration when its traffic is light, and to decrease its grid size, making it wake up more frequently, when its traffic load is heavier [6]. In AQMAC, the grid size is selected according to its traffic load, TL_i. Four grid sizes can be selected based on the three traffic limits, limit1, limit2, and limit3. We assume the network environment to be overloaded when each host's traffic load was more than 10 kbps. Therefore we set grid size to 1×1 when its traffic load exceeds 10 kbps. Hence we assume limit1 = 10 kbps. When the traffic load decreases, a sensor node's wake up frequency should also be reduced, accordingly. The limit2 and limit3 are defined as being proportional to the wake up frequency, when compared to a 1×1 grid. In an $n \times n$ grid, we picked 2n-1 among n^2 time intervals as the quorum intervals. That is, a sensor node with a grid size of $n \times n$ woke up at the fraction of $(2n-1)/n^2$, compared to a node with a grid size of one. When a host's packet arrival rate is reduced to $(2n-1)/n^2$, when compared to being overloaded, we should also increase its grid size to $n \times n$, this implies

limit2 = 10 $*(2n-1)/n^2$ where n = 2 then limit2 = 7.5 Kbps
limit3 = 10 $*(2n-1)/n^2$ where n = 3 then limit3 = 5.5 Kbps
limit4 = when TLi < 5.5 kbps

Therefore the following four grid sizes are selected based on the conditions

1×1 grid size is selected if ($TL_i \geq 10$Kbps)
2×2 grid size is selected if (10 Kbps > TL_i ≥7.5 Kbps)
3×3 grid size is selected if (7.5 Kbps > TL_i ≥5.5 Kbps)
4×4 grid size is selected if (5.5 Kbps > TL_i)

4.2 Latency Reduction Using q-Switch Routing

In order to reduce the latency further in AQMAC we used q-Switch routing [5] in AQMAC which will be termed as AQMAC-LR (Latency Reduction). The sensor nodes will be deployed from the outer most corona to the inner most corona in such a way that the number of nodes in the coronas increases with the geometric progression with a common ratio of q. Each sensor node in corona C_R can communicate directly with (q-1) different nodes in $C_{R-1.}$ Each sensor nodes in C_{i+1} can communicate directly with q different nodes in C_i, where $1 \leq i \leq R-2$. Therefore either (q-1) or q nodes will be deployed in the reachable area in the next inner corona for each node in C_i. The process can be repeated until deployment in C_1 is finished. In network initialization phase the sensor nodes find their relay nodes and record their ID numbers. When the initialization phase gets finished there are N_R q-ary trees formed. Among all the relay nodes, the node with highest energy will be considered as relay node. The node in outer corona treated as source node. It chooses a relay node among its q or q-1 relay nodes, and forwards data of its own to the selected relay node or child node. The selected relay node sends its own data and those from the upstream node or so-called parent node. This process will be repeated until the data arrive at a node in corona C_1 from where the data will be delivered to the sink.

5 Simulation Results

We implemented the proposed protocol using NS2 simulator [1]. We also implemented PMAC, QMAC, and QMAC-LR (Latency Reduction) which uses

Table 1. Simulation Parameters

Parameter	Value
Number of nodes	28
Common ratio of geometric progression	3
Number of nodes in outer most corona	1
Total number of corona	4
Transmission range of a sensor node	25m
Width of each corona	25m
Transmit energy of each node	60mW
Receive energy of each node	45mW
Idle energy of each node	45mW
Sleep energy of each node	0W

q-Switch Routing on QMAC for comparison purposes. 2 nodes are deployed in C_2 and 6 nodes are deployed in C_3 and 18 nodes are deployed in C_4 based on the geometric progression whose value is 3. Each node has an initial energy of 50J. Packet size was set to 128 bytes and hosts were supplied with different constant bit rate traffic, between 1 and 24 packets per second to simulate light loads and heavy loads. Below we have made observations from three different aspects.

5.1 Impact of Alive Nodes

Figure 3 explains the fraction of live sensor nodes of different MAC protocols. The outer corona has large amount of live sensor nodes in C_4 since the node in outer corona have light traffic load whereas the number of live nodes in corona C_1, C_2 and C_3 are quite low since the nodes in inner coronas have heavy traffic. Since more number of nodes are deployed in the corona C_1 near the sink the proposed protocol AQMAC and AQMAC-LR retains maximum remaining energy compared to that of PMAC, QMAC, and QMAC-LR.

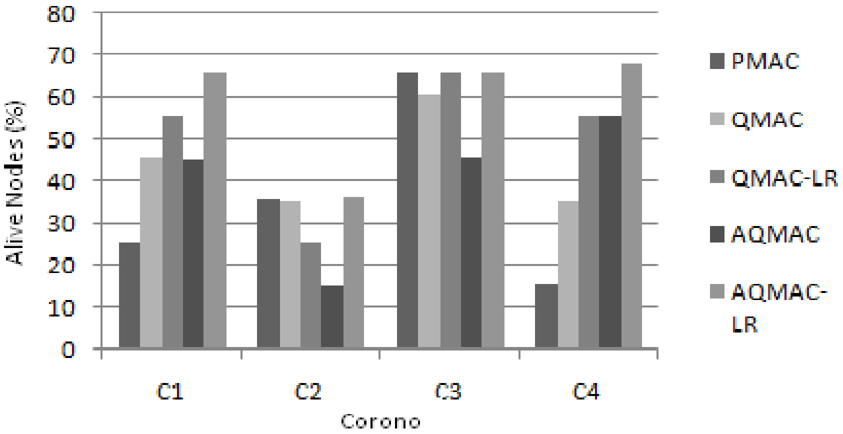

Fig. 3. Fraction of live sensor nodes of different MAC Protocols

5.2 Impact of Successful Transmission Ratio

The successful transmission ratio represents the ratio of the number of the number of data packets sent by the source node to the number of packets received by the sink node. Here the successful transmission ratio of protocols like PMAC and QMAC is low since more energy is depleted than AQMAC and AQMAC-LR protocols. QMAC's lowest transmission ratio implies most of the nodes in C_1 have exhausted their energy and thus packets are not allowed deliver the data to the sink successfully. Figure 4 explains the differences among PMAC, QMAC, QMAC-LR, AQMAC and AQMAC-LR. Compared to PMAC and QMAC we observe that the AQMAC-LR shows high successful transmission ratio.

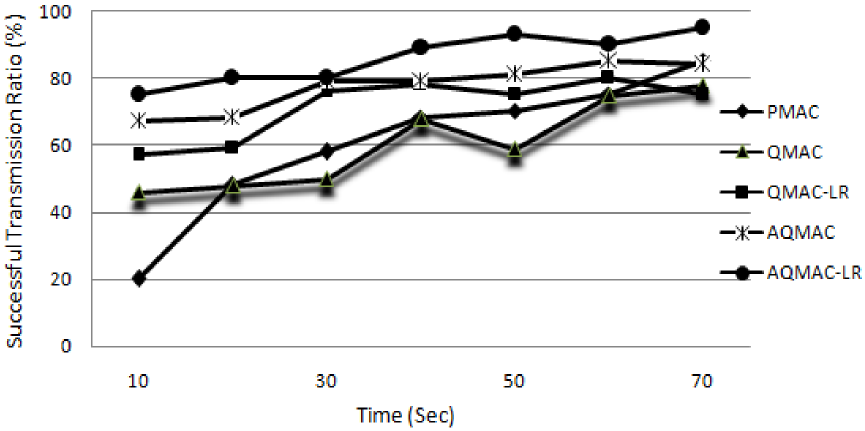

Fig. 4. Successful Transmission Ratio of different MAC Protocols

5.3 Impact of Latency

Latency represents the delay between the moment a data packet is sent by the data source and the moment the sink receives the data packet. Figure 5 explains that AQMAC has lower latency compared to PMAC. Initially PMAC has lower latency because nodes in PMAC remain awake at every time frame. QMAC-LR is the latency reduction that is done on QMAC using q-Switch Routing. With multiple next-hop candidates capable of achieving the relay job, sensor nodes running AQMAC-LR have lot of chances to meet one of their next-hop group members and transmit their data whenever they want. Thus they have a lower delay when compared with nodes running AQMAC. As time increases, all the protocols produce a longer delay because of the pending packets that has to be delivered.

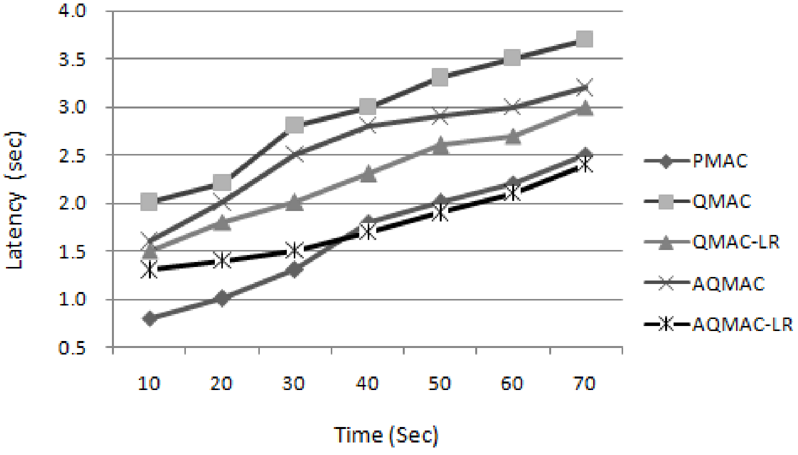

Fig. 5. Latency of different MAC Protocols

6 Conclusion

Energy conservation is essential in wireless sensor networks. Deployment of more number of nodes near the sink reduces considerable amount of energy conservation. Based on their distance from the sink the sensor nodes have different loads. Hence we applied the concept called quorum to make the sensor nodes to adjust their sleep and awake time dynamically based on their traffic loads. In this paper we have proposed a new energy-conserving MAC protocol that applies the concept of adaptive quorum to enable the sensor nodes to adjust their sleep durations based on their traffic load in non uniform node distribution of sensor networks. To reduce the transmission delay we have also used q-switch routing by enabling a group of next-hop nodes to accomplish the relaying job. Simulations proved that our AQMAC and AQMAC-LR is an improved MAC protocol in terms of energy efficiency and throughput for non uniform node distribution in sensor networks. In these protocols it is very hard to determine fixed traffic limits to change the quorum sizes. In future, issues such as each node's pending packets, transmission delay should also be taken into consideration for finding the quorum sizes.

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