

QoS Challenges and QoS-Aware MAC Protocols in Wireless Sensor Networks

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Abstract: *Wireless Sensor Networks (WSN) comprises a group of tiny sensor nodes which sense the environment and transfer the processing information through wireless links. Environmental monitoring, Healthcare, Target detection and Tracking, Industrial Process Monitoring, Intelligent Buildings, and Disaster Relief Operations are some of the applications of WSN. An efficient deployment of WSN depends on successful implementation of Quality of Service (QoS). Providing QoS in WSN refers that a set of service requirements includes bandwidth, throughput, delay, energy consumption, etc., to be satisfied when transmitting a packet from source to destination. QoS mechanism provides reliable and timely information in WSN. Providing QoS support is a challenging issue due to highly resource constrained nature of sensor nodes, unreliable wireless links, harsh operation environments, and the dynamic behavior of sensor nodes. QoS can be achieved in all the Open Standard Interconnection (OSI) layers. But, improving QoS in MAC layer is important because without the assumption of MAC layer QoS can't be achieved in Network or Transport layer. This paper explains QoS challenges and QoS aware MAC Protocols which achieves energy efficiency and service differentiation.*

Keywords: Wireless Sensor Networks, Quality of Service, Medium Access Control, QoS Challenges, QoS aware MAC Protocols

1. Introduction

WSN can be defined as a network of nodes, which sense the environment and communicate the sensing information to a sink node (also called as monitor, destination, or controller) through wireless links. Unlike centralized system, sensor network is subject to the resource constraints such as finite on-board battery power, limited bandwidth, limited memory etc. Each sensor node communicates wirelessly to other nodes within the radio communication range. Communicating one bit over wireless medium consumes far more energy than the processing. Sensor network is designed to collect information from physical environment. WSN application includes Environmental monitoring, Industrial sensing and diagnostic, Infrastructure Protection, Battle field awareness, Context-aware computing, Health care monitoring. Providing reliable and timely information is more important in WSN because of its real time and critical applications.

Data Delivery model in WSN includes event driven data delivery model, query driven data delivery model and continuous data delivery model. In event driven data delivery model, the node sends the sensing information only when the event of interest occurs than sending periodically. In query driven data delivery model, the user who wants the data should send an explicit query to the sink node. The sink node then forwards that query to the set of sensor nodes which could collect the appropriate data. After collecting the necessary information the sensor nodes will send that information back to the sink node. The queries may be continuous queries (Report the temperature for next 6 days) verses one shot queries (Report the temperature measured by a node X), Aggregate queries (Report the calculated average temperature of all nodes in a region Y) verses Non-aggregate queries (What is the measured temperature of node Z), Complex (What are the values of the variables X,Y,Z) verses Simple queries (What is the value of a variable X), Queries for unique data (Response from one node) verses Queries for replicated data (Is there atleast one

target in the area). In continuous data delivery model, each node reports the data periodically. The radio of each node will be turned on only during the period when it sends data. The network which contains the combination of any two model is known as hybrid data delivery model.

The term QoS is widely used in various kinds of network areas but still it's not having any exact meaning. International Telecommunication Union Recommendation E.800 defined QoS as: "Totality of a telecommunications service that bears on its ability to satisfy stated and implied needs of the user of the service". [2] classifies the QoS perspective into two categories namely application-specific perspective and network-specific perspective.

Challenges involved in achieving QoS in WSN are node deployment, multiple traffic types, resource constraints, Topology Changes etc., which have been explained in section 2.

Although by having these many challenges, QoS can be improved by parameters includes minimizing energy consumption, minimizing medium access delay in MAC layer which results in optimized latency, minimizing collisions by carrier sensing methods such as adapting contention window size according to the traffic requirements in case of contention based protocols and adapting time slots in contention free protocols, minimizing interference, maximizing adaptivity to changes and maximizing reliability by acknowledgement mechanism.

QoS can be achieved in all OSI layers whereas MAC layer is important since QoS support in Network layer or Transport layer cannot be provided with the assumption of MAC protocols. MAC protocols solve the problem of medium sharing, service differentiation and provide efficient and reliable communication.

QoS mechanism in WSN at MAC layer includes adaptation and learning, power control, error control and service

differentiation. Different services requires different QoS levels. The network should be able to provide required QoS depend on the requirements of the application.

Service Differentiation: Sensor networks may have different types of data and different importance. The importance may change based on the content of the data, and traffic. For example, temperature sensor nodes have been deployed over a forest. A sensor node containing 60F refers a normal data whereas the sensor node containing 1000F means forest fire. In this case the sensor node containing 1000F data is more important than the node which contains 60F. In case of traffic, Real time traffic (Voice, Video, Multimedia, etc) have more importance than Non real traffic and best effort traffic. Depending upon the importance, the network must make effort to deliver them.

2. QoS in WSN

2.1 QoS Perspective in WSN

QoS in WSN has been classified into two categories.

2.1.1 Application Specific Perspective

In Application Specific perspective, QoS focuses only on the quality of the application. Quality of the application depends on the number of sensor nodes, deployment of nodes, camera resolution, quality of sensing, lifetime, coverage etc.

2.1.2 Network Specific Perspective

In Network specific perspective, QoS focuses on the service quality during the data delivery by the communication protocol stack. QoS in this perspective can be achieved by utilizing the resources efficiently at each layer to achieve energy efficiency, latency, throughput, avoiding packet loss etc.

2.2 Challenges in QoS

Challenges involved in achieving QoS in WSN are node deployment, multiple traffic types, resource constraints, topology changes, etc.

2.2.1 Node Deployment

Node deployment can be done either by deterministic or random. In deterministic, nodes are deployed by hands and routing is established by the predefined path. In random, nodes are deployed randomly so optimization is done in an adhoc manner. Hence neighbor discovery, path discovery, geographical information of nodes, and clustering are the issues to be solved.

2.2.2 Multiple Traffic Types

Sensor node which contains the ability of sensing or observing various phenomena can generate different traffic. For example, the application may need the streaming of multimedia, target tracking and detection, periodic temperature measure at the same time. So, the application requiring existence of multiple traffic add the challenge to QoS support.

2.2.3 Resource Constraints

Resource constraints in sensor nodes includes the limited bandwidth, memory, processing capability and energy since the sensor nodes cannot be recharged.

2.2.4 Topology Changes

Node mobility, Link failure, node malfunctioning, energy depletion may cause the changes in topology. Sleep and wakeup schedule in energy efficient MAC protocols also results in topology changes. Dynamic behavior of sensor nodes add the extra challenges for QoS support.

Although by having these many challenges QoS can be improved by the following: minimizing energy consumption, minimizing medium access delay, minimizing collisions, minimizing interference and maximizing concurrency, maximizing adaptivity to changes, maximizing reliability.

2.3 Parameters in QoS

2.3.1 Minimizing energy consumption

Minimizing energy consumption is important due to the battery-limited operation of sensor nodes. In MAC Layer, Energy consumption can be minimized by avoiding collisions thereby reducing the retransmission of data.

2.3.2 Minimizing delay

It is known that, for reducing end-to-end delay between sensor source and sink nodes routing layer is important. In MAC Layer, medium access delay can be minimized to minimize the end-to-end delay which results in optimized latency.

2.3.3 Minimizing Collisions

Collisions, and consequently retransmission both are having direct impact on the overall network metrics such as throughput, delay, and energy efficiency. Since MAC Layer is responsible for sharing the medium it is responsible to minimize the collisions. Collisions can be prevented by carrier sensing methods such as adapting contention window size according to the traffic requirements in case of contention based protocols.

2.3.4 Maximizing reliability

Acknowledgement mechanisms can be used to provide reliability in MAC Layer.

2.3.5 Minimizing interference and maximizing Concurrency

Since wireless medium is a shared medium, there is a chance that unwanted transmissions may cause interference to the intended transmission. Interference causes packet losses and it affects the metrics such as throughput, delay, energy consumption. In MAC Layer interference can be minimized by adjusting the values of contention windowing, timing, transmission power and operating channel.

2.3.6 Maximizing Adaptivity to changes

In WSN, nodes may deplete from battery and removed from the network and new nodes may be added to network. Links may also change due to the environmental changes. Therefore, MAC Layer should take adaptive actions according to the network dynamics.

2.4 QoS Mechanisms in WSN at MAC Layer

QoS mechanisms in WSN at MAC layer are adaptation and learning, power control, error control, service differentiation. In Adaptation and Learning, each sensor nodes are trying to learn the characteristics of network for necessary changes without waiting for response. Power control, improves the channel utilization by increasing the concurrent communication and by decreasing interference. Error control mechanisms such as Forward Error Correction (FEC), Automatic Repeat Request (ARQ), Hybrid Automatic Repeat Request methods are being used for avoiding retransmission of data to achieve energy efficiency. Service differentiation can be achieved either by priority assignment methods or by differentiation method. Priority assignment has two types i.e., Static and Dynamic priority assignment. In static priority, the priority assigned to a packet will not change until it reaches the destination. The parameter for static priority assignments are traffic class, data delivery model, source type. The ability of changing the priority of a packet in the middle is dynamic priority assignment. The parameter for dynamic priority assignments are packet deadline, remaining energy, remaining hop count, traversed hop count, traffic load. Differentiation method includes changing the contention window size, changing back off exponent, changing active time, changing transmission slot scheduling, etc.

3. MAC Protocols

In wireless communication, channel medium is being shared for multiple accesses. Medium Access Control layer is responsible for channel access control mechanisms, and error control. MAC protocol is used for the avoidance of packet collision. MAC layer consists of many protocols with different criteria such as energy efficiency, delay, reliability, throughput, data delivery ratio and latency. MAC Protocol has been classified as schedule based and contention based. The schedule based protocols are based on strict time synchronization requirements. It schedule transmit & listen periods, thus avoiding collisions, overhearing and idle listening. These protocols are based on Carrier Sense Multiple Access (CSMA) technique, and have higher costs for message collisions, overhearing and idle listening. The contention based protocols relax time synchronization requirements and can easily adjust to the topology changes which occurs while joining new nodes.

3.1 Sensor MAC (SMAC)

Sensor MAC is a contention based MAC Protocol which is specially designed for energy efficiency. Basically in MAC Protocols energy wastage is due to four main reasons such as idle listening, Collisions, Overhearing, and Control Overhead.

Idle Listening: In sensor network, since each node is not aware of the receiving time of its own, it is listening to all the packets which is not destined for that node. So each node has to turn on their radio in receive mode when it is not transmitting. Thus energy is being wasted.

Collision: Since MAC Protocol uses the shared medium and large number of nodes is deployed in a small area, there is a

chance that two nodes can send the data at a time simultaneously. Thus Collision occurs.

Overhearing: It is not necessary for each node to listen for the data that is being sent to the neighbor node which causes energy wastage.

Control Overhead: Due to the presence of control packets such as Request to Send (RTS), Clear to Send (CTS), Beacon and Acknowledgement (ACK) energy is being wasted.

In Sensor MAC, to reduce energy wastage it has four major components namely periodic listen and sleep, collision avoidance, overhearing avoidance and message passing.

3.1.1 Periodic Listen and Sleep

In periodic listen and sleep, SMAC allow nodes to sleep periodically which saves energy but it increases the end to end delay. Because sender has to wait until the receiver wakes up for receiving data. In order to decrease delay it uses adaptive listen technique, which allows nodes to sleep adaptively from its listening period when there is no active communication between nodes.

3.1.2 Collision Avoidance

Before transmitting, each node needs to contend the medium to access. The collision avoidance technique present in SMAC is as same as that of 802.11 MAC protocol which includes physical carrier sensing, virtual carrier sensing and RTS/CTS to avoid hidden node terminal problem. Each transmitted packet contains the duration field which indicates how long the transmission will be. So the node knows when to sleep by the use of duration field in packet. The node records this information in a variable called Network Allocation Vector (NAV) and it sets a timer. Whenever the NAV timer fires, the node decreases the NAV by one until it reaches the value zero. If the NAV is zero, it means that the medium is idle or the medium is busy. This is called virtual carrier sensing. The physical carrier sensing is being done by the physical layer. With the help of physical and virtual carrier sensing, one can find whether the medium is free or not.

3.1.3 Overhearing Avoidance

For effective virtual carrier sensing, each node listens all the transmissions of other nodes which results in overhearing. In SMAC, to avoid overhearing each node goes to sleep state after listening RTS and CTS packet from neighbor nodes. Basically, Data Packets are larger than Control packets such as RTS and CTS and this approach prevent neighbor nodes from overhearing the data packets and acknowledgements.

3.1.4 Message Passing

While sending long message in a single packet, if only few bits have been corrupted in transmission causes high cost of retransmission. The solution to avoid retransmission of whole message is fragmentation. After fragmentation, sending each fragment with RTS and CTS results in control overhead and it increases end to end delay. To decrease both retransmission cost and delay, in SMAC, the long message is being divided into fragments and those fragments is being sent in a burst with one RTS and CTS packet. After sending each fragment, the sender has to wait for the

acknowledgement from receiver. If sender fails to receive acknowledgement, it will send only the last fragment.

3.2 QoS Aware MAC (Q-MAC)

Q-MAC protocol is designed for energy efficiency and additionally it increases the QoS by differentiating the service with the help of intra node and inter node scheduling. Intra node scheduling is used to differentiate the service within the node and inter node scheduling is used to allocate the channel between the multiple neighbor nodes.

3.2.1 Intra Node Scheduling

Intra node scheduling consists of multi queue architecture to differentiate the service, based on its application and MAC layer abstraction. The architecture consists of five FIFO queues including one instant queue which serves the services instantly. From application point of view, the differentiation is done based on the content. In this protocol, it adds extra five bits for identification of priority. In five extra bits, two bits are used to know the type of application and the remaining three bits for the identification of type of sensing data. From MAC Layer abstraction point of view, the differentiation is based on whether the data is self regulated data or relayed data. In relayed data the priority is given based on transmitted hops. If the packet has gone through many hops, it is given with higher priority. It uses MAX-MIN fairness algorithm[3] for allocating the rate, and Packetized GPS Algorithm[1] for the selection of next packet.

3.2.2 Inter Node Scheduling

The main aim of MAC protocol is to allocate the channel for multiple neighbor nodes effectively. It uses Power Conservation MACAW (PC-MACAW) due to the high transmission cost of MACAW. Frame space (FS) is used between two frames. Each Frame consists of Contention Period (CP) and Transmission Period (TP). Between contention period and transmission period, short space (SS) is used. For fairness transmission between neighbors the nodes contend the channel at an identical start point. Loosely Prioritized Random Access Protocol uses the contention time for regulating the order in which the node has to access the channel. Transmission Urgency is being calculated for the identification of packet which has to be sending first. The calculation is based on four parameters namely packet criticality which represents the perspective of application, Transmission Hops for identifying the retransmission cost, The residual energy for energy consumption and queue's proportional load to avoid the overflow. In terms of collision, for recovery this MAC protocol doubles the contention window or setting threshold for each packet. If it crosses the threshold it dropped the packet immediately.

3.3 Query Based MAC (QMAC)

Query based MAC protocol provides an energy efficient sleep schedule to achieve minimum latency in query based WSN. In Query based networks, the user who wants information must send an external query to sink node, which forwards the query to appropriate sensor nodes for required data. The sensor nodes collect the needed information and send it back to the sink node. Some kind of queries like

aggregate queries (Identify the number of nodes in which the temperature exceeds 80F) needs information from multiple destination and a simple query (what is the temperature sensed by the node X) needs only from a single destination. This protocol provides two sleep schedules i.e., static sleep schedule and dynamic sleep schedule for achieving minimum latency.

3.3.1 Static sleep schedule

Consider a set of nodes which are located in different regions which are one hop, two hops, three hops, and four hops away from sink node. When there is no query, the node follows static sleep schedule. Each node is synchronized in such a way that the next hop node is made active before the previous hop node goes to sleep state.

3.3.2 Dynamic sleep schedule

When the sink node sends a query, it gets information from the destination. The nodes in different region dynamically schedules between them. It has two cases that whether the sink node is aware of its destination or the sink node is unaware of its destination.

3.3.2.1 Dynamic sleep schedule when destination not known

When the destination is not known, the sink node forwards a query. The nodes that are receiving the query will forward the query and it will turn their radio on until it gets a reply. After receiving the reply from neighbor nodes it forward the data to sink node and it follows the actual sleep schedule. The delay is minimized by the use of this sleep schedule.

3.3.2.2 Dynamic sleep schedule when destination Known

When the sink node knows a destination, the intermediate nodes follow the sleep schedule dynamically according to the arrival time of the packet. The arrival time of a packet in intermediate nodes are being calculated by the following values: The time when it forwards the query packet, the distance of the destination, and the time required to send the data for each hop. Each node wake up and forwards data based on the calculation.

3.3.2.3 Dynamic sleep schedule when multiple destination

In case of aggregate queries, it needs more information from destination. The sink node forwards the query to destination node through intermediate nodes. The destination node start sending the packets and finally it sends the control information for indicating the end of packet transmission. While the destination start sending the packets, the intermediate nodes made on until the control packet comes from a destination.

3.4 I-MAC

I-MAC is hybrid MAC protocol designed by I.SLAMA et. al in 2010. It is the combination of both contention and schedule based protocol and it assigns priority to each node. TDMA scheduling has two kinds i.e., broadcast and link. In broadcast scheduling, the conflict may happen in all nodes between two-hop neighbors and in link scheduling, the conflict may happen between one hop neighbors. I-MAC concentrates on broadcast scheduling. I-MAC has two phases namely setup phase and transmission phase.

3.4.1 Setup Phase

In setup phase, the work done by each node is as follows: neighbor discovery, slot assignment, Local Framing and global synchronization.

3.4.1.1 Neighbor Discovery

The aim of neighbor discovery is to list all the one hop and two hop neighbors. Neighbor discovery can be achieved by the ping command which is being sent for every 30 seconds. The output of neighbor discovery is given as input to the slot assignment.

3.4.1.2 Slot Assignment

In slot assignment, slot is assigned to each node in such a way that no two nodes are having the same slot as that of graph coloring concept. In I-MAC, for slot assignment it uses Distributed Neighborhood Information Based Algorithm (DNIB) which lets each node to assign a slot by their own with the help of two-hop neighbor list information.

3.4.1.2a Distributed Neighborhood Information Based Algorithm

DNIB algorithm[10] consists of two procedures that are slot assignment procedure and update procedure. In slot assignment procedure, each non-assigned slot assigns a minimum unassigned slot. In Update procedure, after assigning a slot, each node sends the slot information to its one hop neighbors and two hop neighbors. The details included in one-hop broadcast messages are scheduled node id, assigned slot id and two-hop broadcast schedule, which defines the one-hop neighbor slot to broadcast two-hop neighbor broadcast message.

3.4.1.3 Local Framing

The next phase of slot assignment is local framing to know the size of TDMA frame of each slot. The slot assigned by a node can be assigned to another node after a particular time period. The identification of that period is being done by the Local Framing.

3.4.1.4 Global Synchronization

In setup phase, the global synchronization is done after local framing. Each node starts the time slot 0 when the global clock is synchronized to zero. At the end of setup phase, each node broadcasts the slot number and the local time frame size to its two hop neighbor. After broadcasting, each node knows the one hop neighbor and two hop neighbors time slot and then it starts the global clock synchronize to 0 and start transmitting data. In transmission phase, each node performs local synchronization.

3.4.2 Transmission Phase

In transmission phase, each node contends the channel before transmitting. If the channel is idle it sends the message. If the channel is busy, the channel access is done based on its priority. Contention window size varies for different priority levels and for the nodes which is the owner of the slot. High priority packets are having small contention window size. If the slot assigned to the node i.e., owner of the slot is not having any data, the non-owner can contend the channel and can send data. The non-owner assignment to the particular owned slot is given based on the priority levels.

I-MAC protocol consists of two queues namely data queue and overhearing queue. The data queue stores the data which belongs to that sensor node and the overhearing queue stores the overheard message from its neighbor node. The node may send either data from data queue or from overhearing queue based on its mode. It has two modes selfish mode and selfless mode. In selfish mode the node will send from data queue and in selfless mode it sends from overhearing queue.

3.5 DIFFMAC

DIFFMAC Protocol is designed for service differentiation with priority assignment. It is CSMA/CA based protocol. As in I-MAC it has two phases namely setup phase and transmission phase. Setup phase consists of neighbor discovery, slot assignment, local framing and global synchronization. The difference in DIFFMAC compared to IMAC is that it uses Distributed Randomized Time Slot Scheduling Algorithm (DRAND) [5] algorithm for slot assignment.

The additional features present in DIFFMAC are as follows:

1. For the reduction of retransmission cost, as in SMAC it has fragmentation and message passing which fragments the long message into small fragments and sending them as a burst.
2. DIFFMAC adjusts the contention window based on its traffic for reducing delay.
3. It adapts the duty cycle for energy consumption.

3.6 AMPH Protocol

Adaptive MAC Protocol for Heterogeneous WSN (AMPH) is a hybrid channel access method. It is mainly based on the time division principle, but nodes may transmit during any time slot in order to maximize channel utilization and minimize latency. Time is divided into several recurrent time slots of fixed duration. Nodes are assigned to time slots in such a way that no two nodes within a two-hop communication neighborhood are assigned to the same slot. This protocol contains two phases called setup phase and transmission phase. In setup phase, it performs neighbor discovery by the use of ping command for every 30 seconds, Slot assignment by DRAND algorithm, framing and synchronization which is same as in I-MAC Protocol. In transmission phase, time is divided into recurrent time slots. The MAC routine performs at the start of time slot. Depending on whether the node has data to transmit or not, it decides which node to send.

AMPH Protocol also achieves Service Differentiation by having two traffic classes namely real time traffic (RT) and best effort traffic (BE) and also based on the information that whether the node is the owner of the slot or non-owner. The node assigned to a given slot is called owner of the slot and the others are called as non-owner slot. The Contention window size changes depend on the traffic classes and the information about owner or non-owner. If the traffic is real time traffic and the node is the owner of the slot, the contention window size will be small. And if the traffic is best effort traffic and the node is not the owner of the slot, the contention window size will be large. Thus the contention window size changes accordingly.

AMPH outperforms than the contention based protocols namely CSMA/CA and Diff-MAC in terms of channel utilization, latency and reliability.

4. Comparison

Table 1: Comparison between QoS Aware MAC Protocols

Name of the Protocol	Type	Energy Awareness	Service Differentiation	Priority Assignment
Sensor MAC (SMAC)	Contention based protocol	Yes	No	No
QoS Aware MAC (Q-MAC)	Contention based Protocol	Yes	Yes	Hybrid
Query Based MAC (QMAC)	Contention based Protocol	Yes	No	No
I-MAC	Both Contention and Schedule based	No	Yes	Dynamic
DIFFMAC	Both Contention and Schedule based	Yes	Yes	Hybrid
AMPH	Both Contention and Schedule based	Yes	Yes	Hybrid

5. Conclusion

Thus, in this paper the need for improving QoS in WSN at MAC Layer has been discussed. Survey of various MAC protocols based on Service differentiation and Energy efficiency has been carried out. Comparison of those protocols in terms of type, energy awareness, service differentiation, priority assignment, have also been discussed.

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