Comparative Analysis of Medium Access Control Protocols for Wireless Sensor Networks

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***Abstract*—**
The new age technologies like Micro-Electro-Mechanical Systems for development of smart sensors, small transceivers and low-priced hardware are fueling increased interest in Wireless Sensor Networks. Functioning of Wireless Sensor Networks is distributed across nodes and there is no fixed infrastructure control. This in turn requires carefully designed Medium Access Control layer protocols. This paper surveys, classifies, simulates using Network Simulator NS2 and analyzes well referred Medium Access Control layer protocols namely IEEE 802.11, S-MAC, D-MAC, ATMA and Z-MAC for Wireless Sensor Networks. The quantitative and qualitative metrics presented for comparison framework can be used to analyze tradeoffs produced by different Medium Access Control design approaches. They can be design guidelines for Wireless Sensor Networks Medium Access Control layer protocols.

***Keywords*—** **Medium Access Control Protocols, Wireless Sensor Networks, Survey, Simulation and Analysis**

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a network of sensors that, senses specified parameter(s) related to environment; processes data locally in a distributed manner and communicates information to central Base Station (BS). Sensor nodes in WSN being constrained in energy, storage and computation necessitate development of resource conscious protocols at all layers of OSI Model.

The remainder of paper is organized as follows: Section 2 discusses MAC protocols analysed in paper, Section 3 presents qualitative and quantitative parameters used to analyse the protocols, Section 4 discusses simulation and analysis of MAC protocols. Finally Section 5 gives conclusion of paper.

II. MAC PROTOCOLS FOR WSN

A. Contention-Based MAC Protocols

In Contention-Based MAC Protocols Nodes contend for transmission media. Collision during contention is avoided through some probabilistic coordination.

1) IEEE 802.11 [1]

The distributed coordination function (DCF) architecture of IEEE 802.11 with virtual carrier sense, binary exponential back-off, and fragmentation support is widely used in ad hoc networks [1]. In Power saving mode of DCF nodes periodically listen and sleep. A sender first sends out ATIM (Ad hoc Traffic Indication Message) packet to which the receiver replies. In response the sender starts sending data.

IEEE 802.11 is basically designed for single hop network and there are questions about its performance in multi hop networks [8]. High bit rates, fairness makes it well suited for wall powered devices while high idle listening, address centric ness nature and unclear strategy about node's sleep periods makes it unsuitable for WSN.

2) S-MAC [2]

S-MAC is for peer to peer node communication. A SMAC frame consists of a complete cycle of listen and sleep periods. A node's frame begins with a listen period, where it communicates with other nodes, next is a sleep period, during which if it has no data to send or receive radio is completely turned off and a timer is set to awake. On awakening node listens to see if it needs to communicate with any other node. The listen period consist of small intervals for sending or receiving SYNC, RTS, and CTS packets. While the duration of listen period depends on radio bandwidth and contention window size, sleep period duration can be changed depending on application requirements, which further changes duty cycle saving energy waste in idle listening.

Due to loose co ordination among nodes makes S-MAC robust to topology changes. On the downside degraded per-hop fairness, throughput and latency performance makes it suitable only for applications having long idle periods. The sleep periods increases latency with increase in number of hops. Finally with fixed duty cycle S-MAC cannot adapt to traffic variation.

3) D-MAC [3]

D-MAC enables uninterrupted data forwarding from several sources to BS on a multihop path by staggering node's schedule to wake them up sequentially. Node's schedule is divided into three periods: receiving (node receives a packet and sends an ACK), sending (node forwards a packet to its next hop and receive an ACK), sleeping (node turns off its radio). The receiving and sending periods have identical length μ long enough for transmitting and receiving one packet. If d is the depth of node in data gathering tree, node sets its wake-up schedule d μ ahead from BS schedule and periodically goes into receiving, sending, and sleeping states.

Thus when there is no collision, packet is sequentially forwarded along multihop path to BS without sleep latency.

The media access combined with packet routing decreases latency and energy spent for packets to travel from several sources to BS. The duty cycle is adaptive to traffic variation. On the other side D-MAC is designed for tree based multihop topology and does not consider the node fairness. Further, interference between nodes in same depth is to be handled carefully and MTS messages add to protocol overhead.

B. Contention-Free MAC Protocols

In contention free MAC protocols medium is divided into sub channels in terms of time, frequency, or orthogonal codes. Each node occupies a sub channel which avoids collision and allows node to share the medium.

1) ATMA [4]

ATMA (Advertisement based Time-division Multiple Access) is distributed TDMA-based protocol. Time is divided into frames of order of a second, which is 10^4 times normal clock drifts. Frame begins with SYNC period used for synchronization. Next is contention-based advertisement period for data advertising and slot reservation. Finally for a contention free data exchange data period is divided into slots. Data slots are set slightly larger than duration of data and ACK packet to minimize effect of clock drifts in the contention-free data period.

The positives of ATMA are that it utilizes the bursty or periodic nature of traffic to prevent energy waste through advertisements and reservations for data slots and does not sacrifice success rate or latency. On downside optimal value of ADV is to be decided to decrease its delay and energy consumption. Finally all TDMA based protocols get complicated as nodes are added or deleted in the network.

C. Hybrid Protocols

Hybrid protocols combine the features of both contention-based and contention-free protocols.

1) Zebra-MAC (Z - MAC) [5]

Z-MAC is a hybrid MAC that performs like CSMA when there is low contention and achieves high channel utilization with low latency. On high contention, it performs like TDMA and achieves high channel utilization and reduced collisions among 2-hop neighbours. Timeslot assignment is performed by DRAND [6], a distributed implementation of RAND [7], a centralized channel scheduling algorithm. Slots are reused in predetermined period, called frame. Node performs carrier sensing and transmits a packet when the channel is idle. The contention window size is adjusted so that slot owners get earlier chance to transmit than non-owners. When owners do not have data to transmit, non - owners can use slot.

Under low contention Z-MAC achieves high channel utilization and low latency and under high contention it achieves high channel utilization and reduces collision among two-hop neighbours. On the other side a high energy cost and high delay in setting up TDMA schedule complicated by topology changes, inclusion of contention window leading and ECN message lead to increased latency and energy consumption under high contention networks.

III. MAC'S PERFORMANCE METRICS

A. Quantitative metrics:

1) Network Lifetime: It is time until the First Node Dies used for network with spare deployment of nodes, HNA (Half of the Nodes Alive) used for dense network, and LND (Last Node Dies) used for redundantly deployed network.

2) Network settling time: Time required for collection of nodes to organize them automatically and transmit first message.

3) Energy consumption per node: It measures the total energy consumed for data transmission averaged over every node.

4) Network throughput: The number of bits per second received at receiver nodes.

5) Success Rate/Delivery ratio: Total number of packets successfully arrived at receivers against the total number of packets sent by all sources.

6) Network scalability: The maximum number of nodes that protocol can scale to while preserving reliable communication.

7) Protocol overhead: Total bytes of control packets required to maintain proper network operation.

8) Goodput: Total number of unique data packets in bits per second excluding the control packets received at receiver.

9) Latency: Average time between start of disseminating data from source nodes and its arrival at corresponding receiver nodes.

B. Qualitative metrics:

1) Adaptation to Transmission media: In decision making protocols should consider characteristics of wireless transmission media like hidden, exposed terminal problem, High BER, fading, spatial reuse etc.

2) Traffic Adaptability: Protocols should adapt to traffic fluctuation varying over time and part of network to another.

3) Dependability and QoS: Depending on application WSN design may be required to offer reliable, real time, secured, private communication and facilitate mobility.

4) Fairness: In order to let BS have full information of entire sensed area, protocols should provide fair bandwidth allocation and access among all sensor nodes.

5) Heterogeneity: For work distribution among nodes and BS protocol must consider fact that BS has good power, storage and processing capabilities as compared to nodes.

6) Time Synchronization: Time synchronization either strict or loose is required for synchronizing sleeping cycles of nodes.

7) Topology change control: In case of change in topology the protocol might need information regarding complete restructuring or only incremental updates.

8) Bidirectional or unidirectional links: Protocol may perform efficiently in upstream (node to BS) or downstream (BS to node) links.

9) Application dependently: WSN may be deployed on land, underground, underwater or space. The sensor may have to detect event or do periodic measurement. Protocols should aim at providing solutions for all these different possibilities.

10) Node density: Number of nodes per unit area can vary considerably for different application or within the same application over time and space. Protocols should adapt to such variations.

11) Delay-predictability: MAC-layer plays a key role in delay predictability through careful packet transmission scheduling and predictable strategy for medium arbitration.

IV. Simulation Results and Analysis

All the simulations were carried out using Network Simulator NS2. Table I shows the basic simulation settings for all the protocols.

TABLE 1 Simulation settings for all simulations

Number of nodes	5-100
Transmission Range	250 mts
Interference Range	500 mts
Propagation	Two Ray Ground
Antenna	Omni Antenna
Area	300 x 300 mts
Initial energy	200 Joules
Simulation Time	1500 secs
Topology	Random
Sleep Power	0.003 mW
Transition Power	30 mW
Transition Time	2.45 ms

To reduce the occasionalism, five simulations with different seeds were carried out for each scenario and average values were adopted as the results. The simulation results are shown in Table 2. For analysing the scalability of nodes we varied the number of sources in the network from 20 to 50 and measured the packet success rate, average packet latency and average energy consumed per node. Figure 1, 2 and 3 show that as the number of source increases packet success rate decreases and average packet latency and energy consumed per node increases. This effect is more in IEEE 802.11 and S-MAC because both protocols are pure CSMA based MAC protocols in which as number of source increase, interferences increases resulting in increase in packet latency and energy consumption. TDMA based protocols being collision free show improved performance for large number of nodes. On the other hand idle timeslots increase delay and decrease throughput. Performance of Z-MAC is moderate as it combines strengths of TDMA and CSMA. ATMA being a distributed TDMA has further reduced energy consumption due to a smaller duration of advertisement period where one ADV-ACK exchange can reserve a slot for consecutive frames. Thus, ATMA adapts well to varying sources, providing good energy consumption with success rate and low latency. D-MAC uses a cross layered approach which combines media access with packet routing. It is the only MAC protocol that routes packet from source to sink and has best energy efficiency, network lifetime, throughput and success rate and exhibits good scalability among all the protocols. The qualitative analysis of the protocols based on metrics presented in Section III is shown in Table 3.

V. Conclusions

It is evident that majority of the MAC protocols for WSN aim at optimizing energy consumption of nodes and thereby increasing the lifetime of network. The complexities introduced by severely limited processing capabilities, memory and power supply in the sensor node at one end and the design needs of versatile applications at the other end has made the task of developing a generic protocol framework for optimizing WSN behavior more challenging. The issue can be addressed through some extent by cross layer approaches. These approaches attempt to exploit a richer interaction among communication layers by information sharing or integrating functionality of adjacent layers. Cross layering allows the network parameters to be optimized based on its requirements. For example cost function can be used to equip MAC protocol to exercise media access by coordinating effectively with physical, network and application layers. This is evident from the fact that among the protocols simulated and analyzed in this paper D-MAC a cross layer protocol outperforms its layered counterparts.

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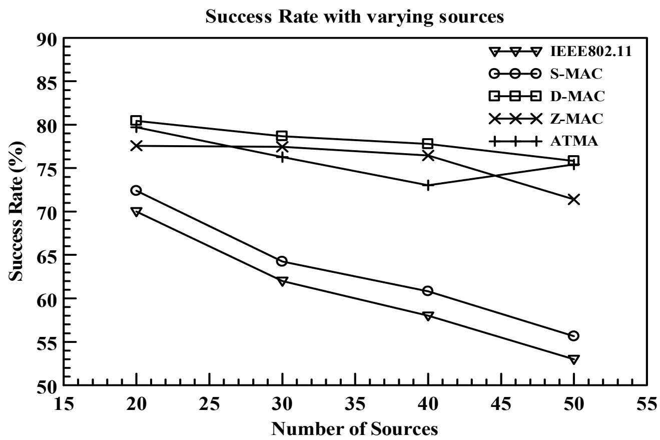

Figure 1. Success Rate with different numbers of sources

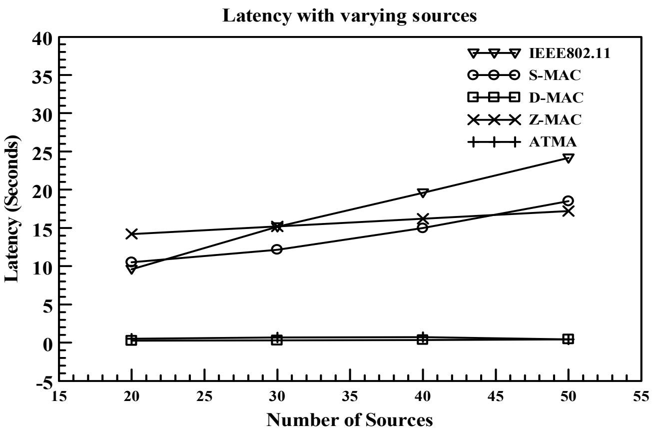

Figure 2. Packet latency with different numbers of sources

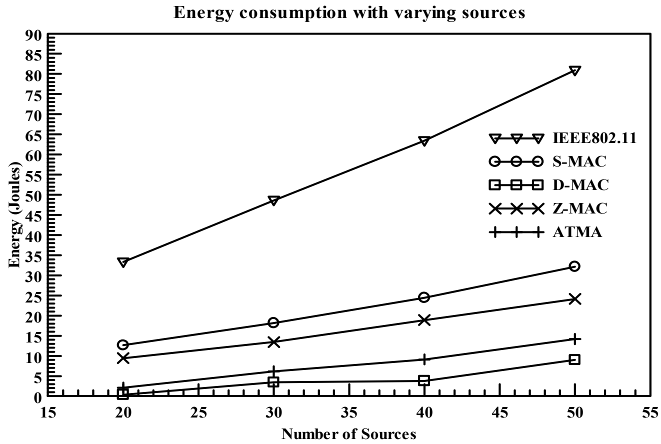

Figure 3. Energy consumed per node with different numbers of sources

TABLE 2 Quantitative Analysis of Medium Access Control Protocols for Wireless Sensor Networks

Parameter	IEEE 802.11	S-MAC	D-MAC	ATMA	Z-MAC
Network Lifetime – First Node Dies (Seconds)	201.78	1261.07	> 1500	> 1500	> 1500
Network settling time (Seconds)	5.00	15.56	2.56	45.76	10.05
Total Network throughput (Bps)	52.40	55.82	10564.73	1985.31	1016.48
Total Network overhead (Bytes)	36720	22032	7344	14688	3672
Total Network Goodput (Bps)	27.92	41.13	10559.83	1975.51	1014.03
Energy consumed in initial network setup (Joules)	1.001	17.206	0.003	0.517	0.0001
Initial Network setup time (Seconds)	5.0088	15.56	2.561726	45.76894	0.051030

TABLE 3 Qualitative Analysis of Medium Access Control Protocols for Wireless Sensor Networks

Parameter	IEEE 802.11	S-MAC	D-MAC	ATMA	Z-MAC
Adaptation to Transmission media	RTS/CTS/ACK avoids Hidden/ Exposed terminal problems	RTS/CTS/ACK avoids Hidden/Exposed terminal problems	Link layer ARQ through ACK packet and data retransmission for harsh wireless channel	No specific packets for the same	Explicit Contention notification is used to avoid hidden terminal problem
Traffic Adaptability Support	ATIM adjusted according to traffic	Message passing and adjusting duty cycle for traffic adaption	Data prediction and More to Send signal for change in traffic	ADV/A-ACK packet to adapt to burst/periodic transmission	HCL and LCL modes support traffic variation
Dependability and QoS	In DCF higher priority station can choose small contention window	Adaptive listening support to reduce latency	Reduces latency by performing routing during media access	No support	Owner of the slot is given priority for sending data
Fairness	PCF and variants of DCF support high fairness	Fairness is scarified for energy efficiency	Does not explicitly consider fairness	TDMA approach makes it highly fair	Priority for node slot allocation makes it fair
Heterogeneity	PCF considers it	Focuses on peer to peer communication	Not considered	Focuses on peer to peer communication	Focuses on peer to peer communication
Time Synchronization	Strictly required, done with beacon signal	Loose local synchronization required, done through exchange of relative timestamps	Local synchronization required, done through reference broadcast scheme	Done in same way as S-MAC	Local synchronization is required, technique from Real time transport protocol is adopted
Topology change control	Does not consider it	Taken cared of by schedule sleeps which are sent periodically	Does not consider it	Nodes joining have to wait till end of frame to transmit data	Taken care of by DRAND algorithm for slot allocation
Bidirectional or unidirectional links	PCF is defined for bidirectional operation	Peer to Peer communication	From multiple sources to single sink	Peer to Peer communication	Node to node and base station
Application dependently	Suitable for wall powered or devices in which power can be replenished	Suitable for applications having long idle periods	Designed for tree based network	Suitable for bursty applications	Suitable for applications that require to set node's priority for channel access
Node density	ATIM size varies to adapt to node density	Schedule table varies with node density	Duration of on-off schedule varies with node density	Frame size varies with node density	DRAND schedule varies dynamically with node density
Delay predictability	PCF for delay predictable applications	No support	Support to some extent	Support to some extent	Support to some extent
Improvement areas	Nodes contention window can be set on basis of its distance to destination	Dynamic duty cycle with feedback from application layer to adapt to the varying traffic can be explored	Selection of next hop node should consider residual energy, buffer capacity, distance, relay input etc. , Node fairness is to be considered	Length of ADV/Data slot can be optimized based on the feedback from application layer and number of nodes in network	Time slot can be created based on packet length