Performance Evaluation of Synchronous Energy Efficient MAC Protocols for Wireless Sensor Networks

Alak Roy\textsuperscript{a,\ast}, Nityananda Sarma\textsuperscript{b}

\textsuperscript{a}Department of Information Technology, Tripura University, Suryamaninagar - 799022, India
\textsuperscript{b}Department of Computer Science and Engineering, Tezpur University, Tezpur - 784028, India

Abstract

Energy efficient medium access control (MAC) protocol designs for wireless sensor networks (WSNs) have already generated interests among researches due to ever increasing range of applications of WSNs. Nodes in a WSN typically operate unattended with a limited power source, energy efficient operations of the sensor nodes especially at the MAC level is very important because majority of energy expenditure take place at the radio level. MAC protocols in WSNs for diverse applications with different objectives have been proposed by researchers. In this paper, we investigate three energy-efficient synchronous MAC protocols for WSNs emphasizing their strength and weakness. Our analysis as well as simulation studies reveal the suitability of these protocols in deployed sensor fields. As a result of our investigation, we found out some open research issues in energy-efficient MAC layer design which we highlighted toward the end of this paper.

1. Introduction

Wireless Sensor Networks (WSNs) are widely being used in many application to capture, gather and analyze live environmental data [1]. The application areas includes target detection and tracking, smart spaces, localization, environmental monitoring, military, industrial process monitoring, scientific purpose, defense, medical systems and robotic exploration, agriculture, medicine, transportation and so on [1]. WSN typically consists of a base station and a group of sensor nodes. Nodes in WSNs are equipped with battery powered

\* Corresponding author. Tel.: +91-943-624-3766.
\textit{E-mail address:} alakroy@yahoo.co.in, nitya@tezu.ernet.in
sensors and low power radios [1, 11]. The sensor nodes are capable of communicating with each other and the base station through radios. The base station, on the other hand, serves as a gateway for the sensor network to exchange data with applications to accomplish their missions. While the base station can have continuous power supply, the sensor nodes are usually battery powered. The batteries are inconvenient and sometimes even impossible to replace. When a sensor node runs out of energy, its coverage is lost and also when the energy level at the node goes down to zero, no more packets can be received or transmitted by the node. Hence, to effectively cover the target region, sensor networks are composed of large number of nodes. Nodes in WSNs typically operate unattended with a limited power source; hence energy efficient operations of the nodes are very important [3, 11]. Energy efficiency is a critical issue in WSNs since batteries are the only energy source to power the sensor nodes. Energy efficiency is a fundamental theme pervading the design of MAC [2] layer protocols developed for WSNs. One of the primary mechanisms for achieving low energy operation in energy-constrained WSNs is duty cycling. In this approach, each sensor node periodically cycles between an awake state and a sleep state. In a sensor node sensing, computation and radio operations are main sources of energy consumption. Out of those three sources, energy loss due to radio operation is the maximum one. Not only transmitting costs energy; receiving, or simply scanning the wireless channel for communication, can consume up to half as much, depending on the type of radio [3, 11]. In WSNs since the communication of sensor nodes will be more energy-consuming than their computation; it is a primary concern that the communication is minimized while achieving the desired network operation. In particular MAC protocols must minimize the radio energy costs in sensor nodes. Energy conservation in communication can be performed in different layers of the TCP/IP protocol suit, but Energy conservation at MAC layer is most effective one due to its ability to control the radio directly [3, 11]. To ensure a long-lived network of wireless communicating sensors, we are in need of a MAC protocol that is able to improve energy efficiency by maximizing sleep duration, minimizing idle listening and overhearing, and eliminating hidden terminal problem or collision of packets. Traditional MAC protocols [4, 5, 6, 7] are designed to minimize latency, maximize packet throughput, and provide fairness, protocol design for WSNs focuses on minimizing power or energy consumption.

1.1. MAC Attribute and Tradeoff

The following attributes reflect the characteristics of a good MAC protocol for wireless sensor networks:

- **Collision Avoidance:** When and how a node can access the medium and send its data.
- **Energy Efficiency:** It is very difficult to replace and recharge exhausted batteries; hence prolonging lifetime of each node is critical issue.
- **Scalability and Adaptability:** A good MAC protocols should accommodate changes in network size, node density and topology.
- **Channel Utilization:** How well the entire bandwidth of the channel is utilized in communications.
- **Latency:** Delay in receiving packet by receiver, when a sender has a packet to sent.
- **Throughput:** Amount of data successfully transferred from sender to receiver in a given time.
- **Fairness:** Ability of different nodes to share channel equality.

1.2. Source of Energy Waste in Wireless Sensor Networks

The major sources of energy waste in a MAC [2] protocol for WSNs are collision, control packet overhead, idle listening, overhearing. Collision occur when a transmitted packet is corrupted it has to be discarded, and the follow-on retransmissions increase energy consumption. Control Packet Overhead: Sending and receiving control packets consumes energy too, and less useful data packets can be transmitted. The major source of inefficiency is idle listening i.e. listening to receive possible traffic that is not sent can consume extra energy.
Overhearing means that a node picks up packets that are destined to other nodes can unnecessarily consume energy. The main goal of any MAC protocol for sensor network is to minimize the energy waste due to idle listening, overhearing and collision.

In this paper, we investigate the existing synchronous energy efficient MAC protocols to find the main causes of energy wastes in MAC layer of wireless sensor network and their existing solutions. The rest of the paper is organized as follows: a brief survey of related works and organized study of the existing synchronous energy efficient MAC protocols are presented in Section 2 followed by their performance evaluation in section 3. Finally, section 4 concludes the paper with some direction for future works.

2. Related Work

Most of the MAC [2] protocols for WSNs proposed by researchers; aim is to improve energy efficiency by consuming less energy in transmitting packets between nodes. These protocols also have the goals of low delay and minimum packet loss. A MAC protocol decides when competing nodes may access the shared medium and tries to ensure that no two nodes are interfering with each other’s transmissions. In many WSNs, the traffic loads are low. For continuous monitoring applications nodes generate traffic periodically, while in event driven application, traffic tends to be bursty. The most common method of saving power is to use a periodic duty cycling mechanism; by turning off the radio when there is no packet exchanges [3]. Existing MAC protocols can be categorized into synchronous and asynchronous MAC protocols [3]. Here in this paper we are taking synchronous energy efficient (duty-cycling) MAC protocols for performance evaluation in term of energy efficiency.

Synchronous energy efficient MAC protocols are in general require a mechanism to establish a non conflicting schedule regulating which participant may use which resource at which time. Schedule can be fixed or computed on demand. Time synchronization is needed and time is divided into slot. In synchronous energy efficient MAC protocol like in SMAC [4], TMAC [5], SCPMAC [6], AEEMAC [7] periodic sleeping supported by some means to synchronize wake up of nodes, to ensure meeting between sender and receiver.

IEEE 802.11 DCF (distributed coordination function)[8,10] employs a low energy consumption mechanism to prolong the battery lifetime of sensor nodes and adapt CSMA/CA to avoid hidden terminal problem, and uses RTS/CTS mechanism to silence the neighboring nodes. To improve the deficiency of the IEEE 802.11 mechanism, a variety of low energy consumption mechanism [4, 5, 6, 7] for WSNs have been proposed by researchers are explained here in this paper. ‘Fig.1’ shows continuous communication pattern in IEEE 802.11 DCF, and fixed duty cycled communication in SMAC and adaptive duty cycled type in TMAC.

SMAC also known as ‘Sensor MAC’ proposed by Ye et al [4] was the first duty cycling MAC protocol explicitly designed for wireless sensor networks. SMAC is a low power RTC-CTS based MAC protocol that makes use of loose synchronization between nodes to allow for duty cycling in sensor networks. In SMAC, active period is of constant length; hence if no traffic flow actually occurs, nodes stay awake needlessly long. Energy savings in SMAC depend on duty cycle. The protocol uses three novel techniques to reduce energy consumption and to achieve low power duty cycling: periodic sleep, virtual clustering, and adaptive listening. It locally manages synchronizations and periodic sleep-listen schedules. Neighboring cells form virtual clusters to set up a common sleep plan or schedule. If two neighboring nodes reside in two different virtual clusters, then they wake up at listen intervals of both clusters. Collision avoidance is achieved by carrier sense and RTS/CTS packet exchanges as in IEEE 802.11 DCF standards. However, this idea is only used in unicast communication. Periodic sleep may result in high latency especially for multi-hop routing algorithms, since all immediate nodes have their personal sleep schedules. Adaptive waking up or listening technique was proposed to improvise the sleep delay, hence the overall latency. In SMAC all nodes in a neighborhood simultaneously wake up and listen to the channel. A drawback of this scheme is the need for a long uptime that has to include the collision avoidance bakeoff, RTS/CTS exchange and compensation for clock drift as well as waiting for eventual
transmissions from the neighbors. Few drawbacks of SMAC are: it uses fixed duty cycle hence it is not optimal and if message rate is less, energy is still wasted in idle-listening.

TMAC also known as ‘Timeout MAC’ proposed by Dam et al [5] reduces the uptime of SMAC by using a timer that shortens the uptime if the channel is idle; however, its uptime is also much longer than LPL time because the timeout should be longer than the summation of the length of the contention interval, the length of an RTS packet and the turn-around time. In SMAC when there is no traffic in the nodes they stay awake needlessly long time. Therefore, a solution is to prematurely go back to sleep mode when no traffic has happened for a certain time (equal to timeout). In TMAC [5] nodes transmit all messages in bursts of variable length and sleep between bursts. It uses RTS-CTS-ACK scheme and synchronization is done similar to SMAC. A Node keeps listening and transmitting as long as it is in an active period else it sleeps. A node is in active mode until no activation event occurs for timeout period TA. TMAC improves on SMAC by shortening the awake period when it is IDLE. TMAC has an adaptive duty cycle. Active time is dynamically adjusted by timeout on hearing nothing during time period. TMAC suffers from an early sleeping problem (a node goes to sleep when a neighbor still has messages for it) due to the asymmetric communication, but it overcomes the problem using FRTS (Future-Request-To-Send).

Scheduled channel polling MAC (SCPMAC) proposed by Ye et al [6], minimizes the preamble by combining preamble sampling and scheduling techniques, by finding optimal parameters under periodic traffic; however, it does not prevent energy loss due to overhearing; in addition, due to its synchronization procedure, it results in increased contention and delay. SCPMAC adapts to variable traffic. Its major approaches are synchronize all nodes in virtual cluster like SMAC, preamble sampling technique, adaptive channel polling, multi-hop streaming and two-stage contention. SCP synchronizes neighbors’ channel polling time. Increase duty cycle at heavy traffic. Basic idea of SCPMAC is based on SMAC and TMAC. It can detect bursty traffic, and it dynamically adds additional, high-frequency polling slots to nodes on the paths.

AEEMAC proposed by Roy et al [7] is as an optimization over SMAC which employs a duty cycling to save energy by avoiding idle listening, but incorporates three additional optimizations to further improve energy efficiency at MAC layer. Incorporation of three optimization schemes gives better energy efficiency for AEEMAC. In the protocol, adaptive sleeping and reusing of channel scheme and two ‘combined transmission’ schemes are proposed, in which control messages can be piggybacked in the messages with reservation slot(s). These schemes save slots resource and reduce the collision probability of RTS. According to the paper [6], AEEMAC achieves better energy performance than SMAC. Furthermore, AEEMAC considerably reduces energy consumption while providing good end-to-end delay, packet delivery ratio and throughput in comparison with SMAC.

‘Table I’ compares the different Synchronous energy efficient MAC protocols discussed in this section by taking parameter scheme used, energy saving, advantages, disadvantages.

| Table 1. Comparative Study of Energy-Efficient MAC Protocols |
### Protocol Name | Scheme Used | Need Scheduling | Energy Saving | Advantages | Disadvantages
--- | --- | --- | --- | --- | ---
IEEE 802.11 DCF [8] | RTS/CTS mechanism, CSMA/CA mechanism | No | Lower than SMAC | Consumes twice the energy consumed by SMAC | Always in active state
SMAC [4] | Fixed duty cycle, virtual cluster, CSMA | Yes | Power savings over standard CSMA/CA MAC | Low energy consumption when traffic is low | Sleep latency, problem with broadcast packets
TMAC [5] | Adaptive duty cycle, overhearing, FRTS | Yes | Uses 20% of energy used in SMAC. | Adaptive active time | Early sleeping problem
SCPMAC [6] | Minimized preamble sampling, schedule, multi-hop stream. | Yes | Low energy consumption than TMAC. | Adapt to variable traffic | Preamble dominates energy/packet
AEEMAC [7] | Adaptive sleeping & reusing of channel, combined ‘SYNC-RTS’, ‘ACK-RTS’ | Yes | Lower than TMAC | Adaptive sleeping & reusing of channel | Not found yet

### 3. Performance Evaluation
To evaluate the performance of synchronous energy efficient MAC protocols, we have carried out simulation studies in the networks of grid topologies as shown in ‘Fig.2’ using Network Simulator 2 [9]. For performance evaluation, we compare the energy efficiency of IEEE 802.11 DCF [8] with SMAC and TMAC. The aim of this simulation study is to evaluate how much energy efficiency SMAC and TMAC can provide and whether it can conserve energy without degrading service quality in terms of end-to-end delay, average throughput, and packet delivery ratio compared to IEEE 802.11 DCF protocol.

#### 3.1. Simulation Setup and Parameters
For simulation we have chosen a sample grid topology of network as shown in ‘Fig.2’, in which both single hop as well as multihop communication is required to deliver packets from source to destination. Rate of packet drop due to collision is higher due to multihop transmission. The scenario consisting of fifteen nodes, arranged in a 3x3 grid, in which nine nodes (nodes 1, 2, 3, 5, 6, 7, 8, 9, 10) actively participates in data transmission whereas rest six nodes (nodes 0, 4, 11, 12, 13, 14) are idle nodes. There is a possibility of collision at the nodes 2, 6 and 9, but collision rate is much higher at node 2 (sink node) as compared to nodes 6 and 9. This topology represents the data gathering application runs on a densely deployed WSN. The grid topologies was chosen because information from sensor nodes are usually collected at a central node for processing, typically a sink node. Apart from the sensed data, the information that is exchanged by the sensor nodes is the routing information, we computed the energy consumed at the all nodes by keeping track of all the transmission. ‘Table 2’ shows the values of different parameters used in our simulation study which are same as in [4] to facilitate comparison of SMAC and TMAC. For performance evaluation, we measure total remaining energy, energy consumption in idle and sleep state, energy consumption in transmission and reception, of source node when using different MAC protocols.

#### 3.2. Simulation Results
To evaluate the performance of synchronous energy efficient MAC protocols, we choose energy consumption as the parameter, which is defined as the average energy consumption per node to deliver a certain amount of packets from source nodes to a sink. The energy consumed is expressed in unit of Joules. We monitor changes in the radio states to measure the energy consumption. We have used counters that accumulate time in each states of the radio (for e.g., listen, sleep, transmit, and receive). At the end of the experiment,
considering the energy consumption in each state in ‘Table 2’, we compute the total energy consumption. The metric shows the energy efficiency of the synchronous energy efficient MAC protocols.

Fig. 3. (a) Remaining energy analysis of IEEE 802.11 DCF and SMAC; (b) Remaining energy analysis of SMAC and TMAC

Fig. 4. (a) Energy analysis of IEEE 802.11 DCF and SMAC in idle state; (b) Energy analysis of SMAC and TMAC in idle state

Fig. 5. Sleep state energy analysis

According to the experimental results obtained, IEEE 802.11 DCF consume more than twice the energy consumed by SMAC, when traffic is heavy as shown in ‘Fig.3.(a)’. SMAC save energy by periodically switching between sleep and wakeup mode. IEEE 802.11 is always in an active mode because it has to continuously exchange synchronization packets with its neighbouring node as shown in ‘Fig.3.(b)’, which consumes its energy quickly. ‘Fig.3.(b)’ shows the total energy consumption results obtained for SMAC with respect to TMAC protocol through the whole simulation time. According to the ‘Fig.3.(b)’, we can see that for every round of simulation time the energy saving ratio is above two, which is 2.17 in average. It means that TMAC protocol saves double the energy as saved by basic SMAC. Hence we can conclude that TMAC outperforms SMAC by a factor of 2.17 times. Overall, TMAC can save energy than SMAC and IEEE 802.11 DCF significantly and works more efficiently. For instance, with grid topology as in ‘Fig.2’, and with the configuration as explained in ‘Table 2’, TMAC saves as much as 57% of the energy over SMAC.

In multihop grid network scenario, IEEE 802.11 DCF uses more energy than SMAC in idle state as shown in ‘Fig.4.(a)’ where as ‘Fig.4.(b)’ shows that TMAC uses less energy than SMAC. ‘Fig.5’ shows energy consumption for IEEE 802.11 DCF, SMAC and TMAC in sleep state, where energy consumption in TMAC and SMAC are almost same. Due to overhearing avoidance and collision avoidance using RTS packet as explained in TMAC leads to less number of packet collision which saves a lots of energy. When node have collision and overhear RTS of other nodes then nodes go to sleep mode by overhearing RTS, and hence saves energy by going to sleep mode as shown in ‘Fig.5’, and hence spend less energy in idle state as shown in ‘Fig.4.(b)’. Fig.6.(a)’ and ‘Fig.6.(b)’ depicts the result of energy consumption for transmission and reception, obtained for IEEE 802.11 DCF compared to SMAC, and SMAC compared to TMAC at various time for multihop grid network scenario. IEEE 802.11 DCF uses more energy than SMAC for transmission and reception. Since in TMAC less packet collision and overhearing avoidance takes place, hence less energy are used for data transmission and reception between nodes, which saves over all energy of all nodes.
Fig. 6. (a) Transmission and Reception energy analysis of 802.11 and SMAC; (b) Energy Analysis of SMAC and TMAC

Table 2. Simulation Parameters

| Parameters          | Values       |
|---------------------|--------------|
| Radio propagation model | TwoRayGround |
| Routing protocol    | DSDV         |
| Initial energy (Joule) | 1400        |
| Receive power (Joule) | 1.5          |
| Transmit power (Joule) | 1.6          |
| Transition power (Joule) | 0.059   |
| Idle power (Joule)   | 1.05         |
| Sleep power (Joule)  | 0.003        |
| Transition time (in sec) | 0.018     |
| Total simulation time (in sec) | 1200   |
| Traffic rate (in kbps) | 256         |
| Type of Traffic     | CBR          |
| Packet size (in byte) | 512          |

Table 3. Performance Comparison

| Parameter                   | IEEE 802.11 DCF | SMAC | TMAC |
|-----------------------------|------------------|------|------|
| Total Remaining Energy (J)  | 623.56           | 957.37 | 1289.94 |
| End to end Delay (s)        | 812.423          | 789.870 | 448.358 |
| Packet Delivery Ratio (PDR) (%) | 3.235            | 5.236 | 13.719 |
| Throughput (kbps)           | 0.17             | 0.4  | 1.1  |

3.3. Throughput, Delay, PDR with respect to Energy Efficiency

With ‘energy efficiency the other metrics for performance evaluation for MAC protocols in WSNs are ‘end to end delay’, ‘packet delivery ratio’ (PDR) and ‘throughput’. In this section, we evaluate the metrics for both IEEE 802.11 DCF, SMAC and TMAC protocols in grid topology. ‘Table 3’ shows the energy efficiency comparison of IEEE 802.11 DCF, SMAC and TMAC with respect to total remaining energy, delay, packet delivery ratio, throughput parameters. Delay is end to end delay or known as average message delay, defined as the average delay of all successfully transmitted data messages. Packet delivery ratio (PDR) is the ratio of ‘no of packet received at receivers’ and ‘no of packets sent from senders’. Throughput is the number of bits received per second during the simulation time. As expected, the delay of TMAC is close to SMAC. On the other hand, delay for SMAC protocol is less than that of IEEE 802.11 DCF. Moreover, the TMAC protocol has a moderately lower average message delay. This is because of adaptive sleeping in TMAC than the original SMAC protocol. In addition, the retransmission mechanism adopted in the TMAC protocol also reduces the queuing time of data messages. The packet delivery ratio of TMAC is very close to SMAC. On the other hand, the packet delivery ratio of SMAC is much higher than that of IEEE 802.11 DCF for grid topology. The throughput of the TMAC protocol is almost the same as that of the SMAC protocol for simple and linear topology and high for grid topology. TMAC achieves a higher throughput than the SMAC protocol, and the maximum throughput of the improved protocol is 1.1 kbps higher than that of the SMAC protocol which is 0.4. This is because there always are some DATA bursts queuing to transmit and consequently there are controls messages waiting for transmission when sending messages in reserved slot(s) and these control messages can be piggybacked in the message transmission with reservation slots.

From the above discussion and experimental results as shown in above figures and in ‘Table 3’, we can conclude that TMAC is more energy efficient then SMAC and IEEE 802.11 DCF. Overall, TMAC can provide
energy efficiency and it can conserve energy without degrading service quality in terms of end-to-end delay, average throughput, and packet delivery ratio compared to SMAC and IEEE 802.11 protocol.

4. Conclusion

Designing a MAC protocol which can improve energy-efficiency to extend network lifetime in WSNs is a challenging problem due to stringent resource limitation in sensor nodes and peculiarity of wireless media. Several synchronous energy-efficient medium access control protocols for the wireless sensor network that have been proposed by the researchers are presented in this paper. We performed a comparative study by the evaluating the performance of SMAC, TMAC, SMAC and IEEE 802.11 DCF with simulation study. The simulation results show that TMAC can greatly prolong sensor networks lifetime when the transmission is limited and achieves better energy performance than SMAC. TMAC considerably reduces energy consumption while providing good end to end delay, packet delivery ratio and throughput in comparison with SMAC. The design of an optimized synchronous energy efficient MAC protocol also depended on the actual applications. Till now, none of the MAC protocols has been acknowledged as a standard. Another reason is the lack of standardization in sensor hardware and in lower layers. Therefore, it will be difficult to have a standard MAC protocol which can work for all WSNs applications. Therefore, yet a lot of research has to done in working out a MAC protocol which can adapt its behavior based on the application’s requirement.

References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless sensor networks: a survey”, Computer Networks (Elsevier), Vol.38, No.4, pages 393-422, 2002
[2] LAN-MAN Standards Committee of the IEEE Computer Society, Wireless LAN medium access control (MAC) and physical layer (PHY) specification, IEEE, New York, NY, USA, IEEE Std 802.11-1997 edition, 1997
[3] G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, “Energy Conservation in Wireless Sensor Networks: a Survey”, Ad Hoc Networks, Vol.7, No.3, pages 537-568, May 2009.
[4] Wei Ye, John Heidemann, and Deborah Estrin, “An energy-efficient mac protocol for wireless sensor networks”, In Proceedings of the IEEE Infocom, pages 1567–1576, New York, NY, June 2002. IEEE.
[5] Tij van Dam and Koen Langendoen. An adaptive energy-efficient mac protocol for wireless sensor networks. In Proceedings of the First ACM SenSys Conference, pages 171–180, Los Angeles, California, USA, November 2003. ACM.
[6] Wei Ye, Fabio Silva, John Heidemann, “Ultra-Low Duty Cycle MAC with scheduled Channel Polling”, ACM SenSys 2006, November, 2006.
[7] Alak Roy, Nityananda Sarma, “AEEMAC: Adaptive Energy Efficient MAC Protocol for Wireless Sensor Networks,” India Conference (INDICON), 2011 Annual IEEE, pages 1-6, 16-18 Dec. 2011, Print ISBN: 978-1-4577-1110-7. doi: 10.1109/INDCON.2011.6139409
[8] Official Homepage of the IEEE 802.11 Working Group, http://grouper.ieee.org/groups/802/11/.
[9] Network Simulator 2, available at http://www.isi.edu/nsnam/ns/
[10] Joseph Kabara and Maria Calle, “MAC Protocols Used by Wireless Sensor Networks and a General Method of Performance Evaluation,” International Journal of Distributed Sensor Networks, vol. 2012, Article ID 834784, 11 pages, 2012.
[11] Stankovic, J. A. & He, T. 2012 Energy management in sensor networks. Phil. Trans. R. Soc.A 370,