AS-PW-MAC: An Adaptive Scheduling Predictive Wake-up MAC Protocol for Wireless Sensor Networks

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Abstract--- The problem of idle listening is one of the most significant sources of energy consumption in wireless sensor nodes. Many techniques have been proposed based on duty cycling to reduce this idle listening. This paper presents Adaptive Scheduling Predictive-Wakeup MAC (AS-PW-MAC), a new MAC protocol based on asynchronous duty cycling. AS-PW-MAC introduces RTE and RAS messages for pending data transmission. RTE and RAS are beneficial for varying traffic loads. We evaluate the performance of AS-PW-MAC through detailed ns-2 simulation and compare it to RI-MAC and PW-MAC, two well-known MAC protocols. Our evaluation includes clique, grid and random network scenarios. In all experiments, AS-PW-MAC significantly out performs RI-MAC and PW-MAC protocols. AS-PW-MAC achieves higher packet delivery ratio under a wide range of traffic loads compared to RI-MAC and PW-MAC. Especially, when there are contending flows, such as bursty traffic or transmissions from hidden nodes, AS-PW-MAC significantly improves the packet delivery ratio and delivery latency. The delivery latency for AS-PW-MAC is less than 21% compared to RI-MAC and PW-MAC. In all experiments, AS-PW-MAC maintained approximately 100% packet delivery ratio.

I. INTRODUCTION

Idle listening is one of the main sources of energy consumption in wireless sensor network [1, 8] and it wastes energy where sensors are low powered devices with a limited one time battery [12]. This minimizes energy consumption of wireless sensor node. RI-MAC [10] protocol is receiver-initiated protocol which uses wake-up beacons. Each node circulates beacon with its wakeup schedule. If there is no incoming packet for certain time duration [5], the node goes back to sleep state. PW-MAC achieves near-optimal energy efficiency both at receivers and senders. In an optimally energy-efficiency MAC protocol, when there is a packet to send, the sender and receiver wake-up at the same, transfer the packet reliably, and both then quickly go to sleep again. This makes RI-MAC and PW-MAC performs well under light traffic loads. But when high traffic load is concerned, we found that performance of RI-MAC and PW-MAC protocol decreases. Further, its energy packet delivery ratio degrades due to its inefficient retransmission mechanism resulting in large number of collisions under bursty traffic. Considering these drawbacks, we are proposing AS-PW-MAC. The goal of AS-PW-MAC protocol is to enable a sender to predict the wake-up time of intended receiver; every node is required to compute its wake-up time. This may be done by using pseudo-random scheduling generator rather than a random schedule [9]. AS-PW-MAC adjusts its duty cycle and becomes adaptive to dynamic traffic levels. It attempts to utilize the medium efficiently to overcome the issue of high traffic load. AS-PW-MAC protocol utilizes RTE (Ready to Extend) and RAS (Resilient Active Scheduling) within the fixed Adaptive Scheduling (AS) period. Length of the RAS in each operational cycle can be adaptive to the varying traffic load. We believe this is the first attempt to apply the idea of receiver initiated transmission with adaptive scheduling coupled with predictive wake-up mechanisms. The contributions of this work are as follows:

- We present a new asynchronous duty cycle MAC protocol, called AS-PW-MAC which

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employs receiver-initiated transmissions, in order to efficiently and effectively operate over a wide range of high traffic loads.

- We have implemented AS-PW-MAC in ns2 network simulator and evaluate it in a network of sensor nodes.

The rest of this paper is organized as follows. Section II describes related work. Section III presents proposed AS-PW-MAC protocol, and Section IV presents the performance evaluations of AS-PW-MAC protocol. Finally, Section V presents conclusions.

II. RELATED WORK

Many asynchronous duty-cycling MAC protocols have been proposed recently in the literature. Such protocols do not require multi-hop time synchronization compared to synchronous duty-cycling protocols [5]. Early examples of asynchronous duty-cycle MAC protocols [2] are B-MAC and X-MAC, both are unscheduled MAC protocols. X-MAC [1] uses short strobes in which Target ID is encoded. Before sending a DATA frame, a sender sends a preamble of time duration longer than receiver's wake up time interval, which serves as the notification of pending DATA frame. B-MAC [11] uses a tone to wake up sleeping neighbours and hence sends very long continuous preambles for message delivery. It uses local schedules and sends preamble that is slightly longer than the sleep period. Similar to B-MAC, WiseMAC [6] is also a sender initiated MAC protocol. It was proposed for the downlink of wireless networks. It is a medium access protocol based on CSMA based on preamble samples which minimizes idle listening. The receiver-initiated wake up beacons are used in RI-MAC [10], due to which channel is utilized increasingly and efficient collision is detected. Each node circulates beacon with its wakeup schedule and upon receiving a beacon, sender transmits DATA to the intended receiver. DATA is acknowledged by the receiver with another beacon. After the beacon broadcast, if there is no incoming packet for certain time duration, the nodes goes back to sleep state. PW-MAC [9] is a receiver-initiated protocol with independent pseudo-random sequence mechanism. The goal of PW-MAC is for a sender to switch on its radio and wake up just before the intended receiver. If there is a packet to send, both sender and receiver wake up constantly and transfer the packet reliably. After transmission both quickly go to sleep state. The sender requires waking up at prescheduled rendezvous times for communication with the receiver. Whereas the receiver wakes up at the scheduled beacon time. It will avoid neighboring nodes to wake up at the same time interval which may cause increase in collisions from senders that are hidden from each other. If collisions occur, prediction-based retransmission mechanism maintains high energy efficiency. SEA-MAC [3] is a MAC protocol which introduces dual adaptive mechanisms: an adaptive scheduling and a self-adaptive duty cycle mechanism. An adaptive scheduling is the algorithm designed to schedule in high traffic load for rapid circulation of data and hence reduces latency. Whereas a self-adaptive duty cycle mechanism adjusts the duty cycle and makes SEA-MAC adaptive to dynamic traffic loads. Whenever network experiences very low or very high traffic, it adjusts traffic dynamically.

III. PROPOSED AS-PW-MAC PROTOCOL

In this section, we present the detailed design of the AS-PW MAC protocol for wireless sensor networks. AS-PW-MAC addresses predictive wake-up mechanism and adaptive scheduling introducing new messages RTE and RAS. We first describe overview of AS-PW-MAC in Section A. Section B presents the path setup using beacon and Section C describes predictive wake-up mechanism. In Section D adaptive scheduling based transmission is discussed.

A. Overview of AS-PW-MAC

Each node periodically wakes up and broadcasts a beacon 'B' to announce that it is awake and ready to receive the DATA packets. If S has a packet to send to R, S does not have the prediction state of R, S turns on its radio and waits for a beacon from R. After receiving R's beacon, when S transmits the DATA packet, S then sets a special flag in the DATA packet header to request R's prediction state. Once R receives this DATA packet, R sends another beacon that serves both to acknowledge the DATA packet reception, i.e., an ACK beacon and to send additional

DATA packets to R in response to the prediction state request from S. Additionally if S has more packets for R, S will send RTE message to R in order to request R to extend contention period for pending DATA. Once R will receive RTE message, S will send RAS message to ask the receiver stay awake for required time period until pending DATA will be transmitted to it. R will receive RAS message from S and learns its information and stays awake until S sends its complete DATA. When R receives this DATA frame, it sends another beacon in response that serves as both to acknowledgement the DATA packet reception and to allow additional DATA packets to be sent to R.

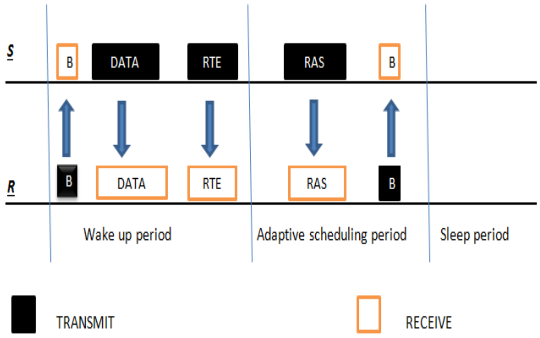

Figure- 1: AS-PW-MAC Operation Overview

B. Path Setup using Beacon

In AS-PW-MAC, each node wakes up periodically based on its own schedule and checks whether there is any incoming DATA frames. If node wakes up and senses medium is busy, R goes to back off condition and transmits beacon later. But if medium is idle, node immediately broadcasts beacon "B" after turning on its radio. This announces that node is awake and ready to receive intended DATA frame. A node S with pending DATA frame to transmit silently waits for beacon from the intended receiver. Upon receiving beacon from R, S immediately starts sending intended DATA to the receiver. A beacon's role is twofold in AS-PW-MAC, as an acknowledgement for previously received DATA frame and initiation of the new DATA transmission.

C. Predictive Wake-up Mechanism

Similar to PW-MAC, AS-PW-MAC uses using linear congruential generator (LCG) [17] in Equation 1 [9].

$$Xn + 1 = (aXn + c) \bmod m \qquad (1)\quad [9]$$

Here, modulus is 'm>0', multiplier is the 'a' (0 < a < m), increment is the 'c' (0 ≤ c < m), and current seed is the 'Xn' (0 ≤ Xn < m). Each Xn+1 generated can be used as a pseudo-random number and becomes the new seed [13]. If node S learns the m, a, c and Xn pseudo-random number generator of a node R, then S can deduce the values of all pseudo-random numbers generated. S wake-up right before R does whenever S wants to send DATA to R. In AS-PW-MAC, a sender needs 10 bytes of memory to store the prediction state of the receiver. It consists of current seed and parameters of the pseudo-random number generator of R and current time difference between S and R which are of 6 bytes and 4 bytes respectively.

D. Adaptive Scheduling

In AS-PW-MAC, sensor nodes with pending data contend for channel access using RTE and RAS messages, called Adaptive Scheduling period (AS). AS period [4] has goal to send message to R in order to transmit large pending data that node S is holding for transmission to node R. It is useful to schedule in high traffic load to send the data rapidly hence reducing latency and in light traffic load reducing idle listening and saving energy. AS-PWMAC protocol uses Ready to Extend (RTE) and Resilient Active Scheduling (RAS) within the fixed AS period. RTE is basically defined as extending time period of DATA transmission in order to stay awake for pending data.. The high traffic loads requires node to stay awake long enough so no excessive latency will occur due to insufficient wake-up duration. Therefore, sender requests the receiver to extend its wake up time to send pending data. RTE includes the information of pending data with node and time duration a node will take to send its pending data to the destination.AS-PW-MAC designed a timeout-based RAS within fixed adaptive scheduling period. RAS is defined as active schedule in which sensor node stays awake for pending data. Sensor nodes can change the length of RAS within an operational cycle and be adaptive to the varying traffic loads. Under high traffic load, RAS will be prolonged to enable the nodes to transmit more data. While under low traffic load, the RAS will be shortened to enable nodes to sleep early without reserving channel. Since the RAS is active period used to schedule the data transmission, RAS in ASperiod can be taken as measurement of traffic load.

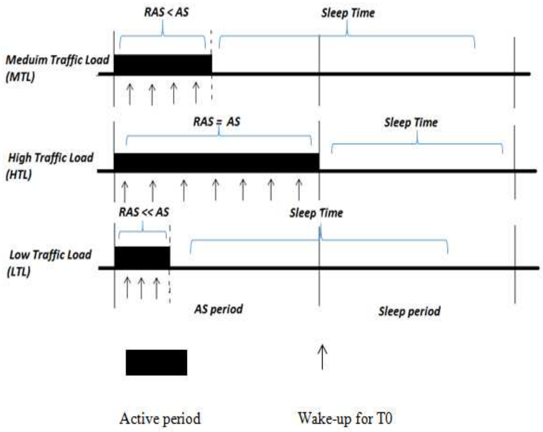

Figure- 2: Adaptive change of RAS

IV. PERFORMANCE EVALUATIONS

We evaluate the performance of AS-PW-MAC, RI-MAC, and PW-MAC under clique network, grid network, and random network.We use 3 simulations runs to evaluate AS-PW-MAC's performance in different networks, especially large network topologies which are hard to deploy and experiment with. Simulations are conducted in ns-2 network simulator by considering parameters given in Table I.

Bandwidth	250 kbps
SIFS	192 µs
Slot time	320 µs
Tx range	250 m
Size of ACK	5 B
CCA check delay	128 µs
Carrier sensing range	550 m
Back-off window	0-255
Special frame	Beacon
Special frame size	6-9 B
Retry limit	5
AS period (TAS)	0.2 s
Sleep period (TSleep)	1 s
Timeout (To)	0.022 s
Dwell time	Variable

Table I. Simulation MAC Protocol Parameters

We used key parameters as shown in Table I to simulate the radio of each sensor node, which are from the data sheet of CC2420 radio [7]. Carrier sensing range and transmission range depend on the factors like antenna, transmission power, and environment. We use 32 as the initial back-off window and 8 as the congestion back off window. For beacon transmission, the BW size is fixed at 32 slots [10]. No network used in our simulation is partitioned and nodes are half-duplex. For each node, initial wakeup time is randomized in our evaluation.

a) Clique Network:

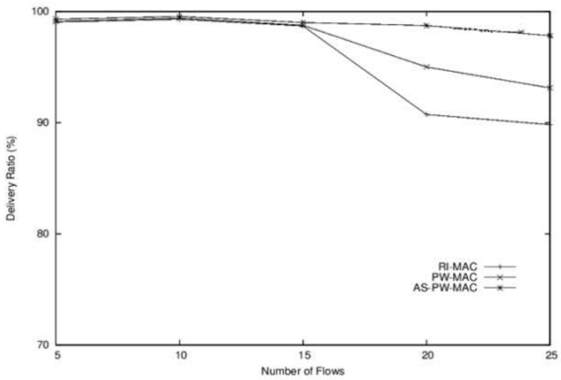

Figure-3: Clique Network Delivery Ratio

Figure 3 shows that when the number of flows is under 15, packet delivery ratio of all protocols is almost same. For 20 flows or above, the delivery ratio of AS-PW-MAC is around 10 to 20% better than PW-MAC and RI-MAC respectively. Delivery ratio in the case of AS-PW-MAC is nearly 100% because in AS-PW-MAC, sender sends RAS to receiver node so that it stays awake until pending data is completely processed.

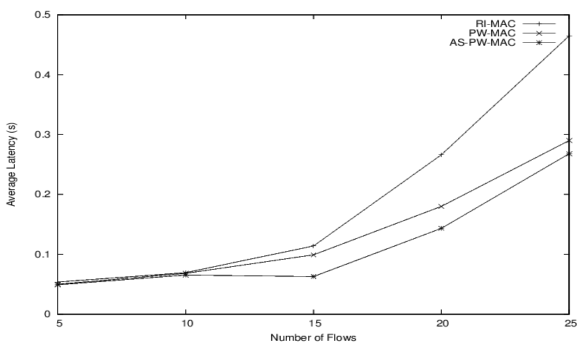

Figure-4: Clique Network Average Latency

Figure 4 shows that average latency of the AS-PW-MAC is less as compared to RI-MAC and PW-MAC. For 20 flows, the average latency of AS-PW-MAC is 0.12 and 0.23 seconds less than PW-MAC and RI-MAC respectively. In AS-PW-MAC source node will send RTE and RAS for transmission of pending data with it, which will reduce excessive end-to-end delay.

b) Grid Network:

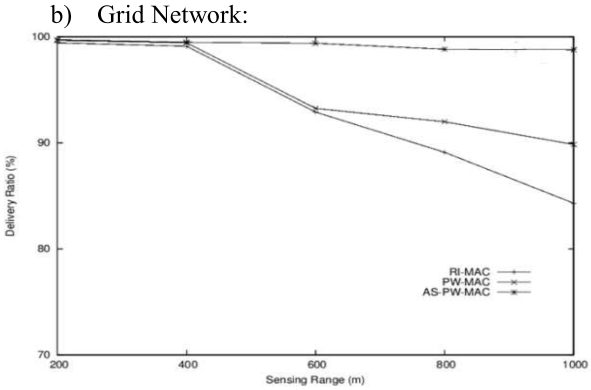

Figure-5: Grid Network Delivery Ratio

Figure 5 shows that when the sensing range is less than 400 meters, packet delivery ratio of all protocols is nearly same. However, when the sensing range exceeds 400 meters, AS-PW-MAC is better for the packet delivery ratio as compared to PW-MAC and RI-MAC. For sensing range 800 meters, delivery ratio of AS-PW-MAC is 9-16% better than PW-MAC and RI-MAC. Delivery ratio in the case of AS-PW-MAC is better because in AS-PW-MAC, sender sends RAS to receiver node so that it stays awake until pending data is completely processed.

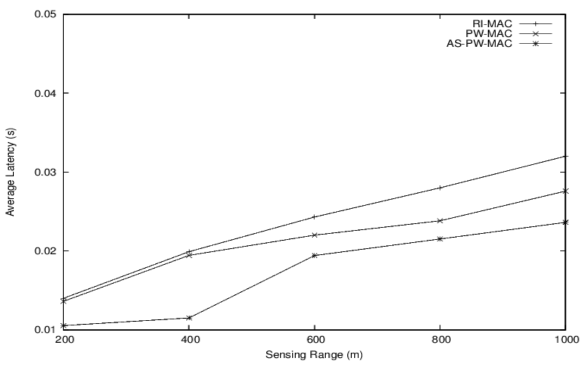

Figure-6: Grid Network Average Latency

Figure 6 shows when sensing range is 400 meters, difference of average latency for AS-PW-MAC is 0.008 seconds from PW-MAC and RI-MAC. AS-PW-MAC performs better and shows less delay time for transmission of packets compared to PW-MAC and RI-MAC. In AS-PW-MAC, sender transmits RTE and RAS for continuous pending data transmission which consumes less time duration to complete the high traffic load transmission.

c) Random Network:

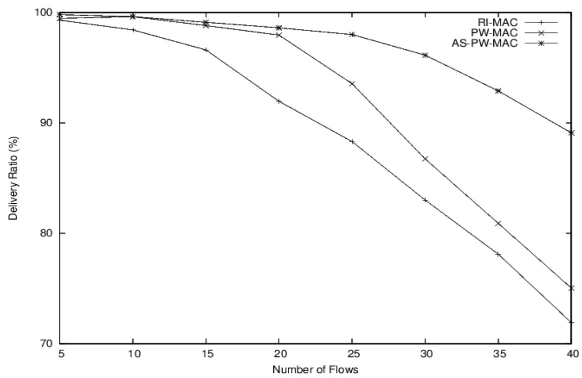

Figure-7: Random Network Delivery Ratio

Figure 7 shows that when the number of flows is less than 20, packet delivery ratio of all these protocols is above 97%. However, when the number of flows exceeds 20, the packet delivery ratio of the AS-PW-MAC is 13.25% better compared to PW-MAC and RI-MAC. Source node sends RTE and RAS messages to receiver if it is having pending data. Due to these messages, nodes can be adaptive to varying traffic load. In AS-PW-MAC, packet delivery ratio is much better than PW-MAC and RI-MAC because of RTE and RAS messages.

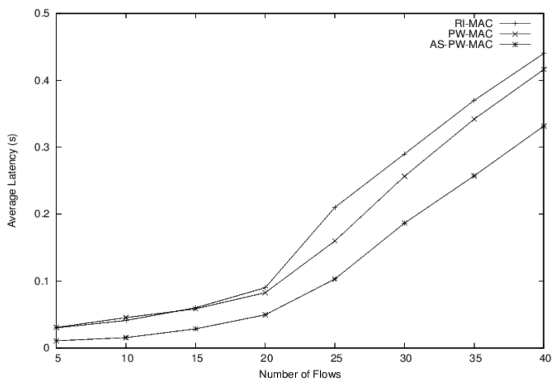

Figure-8: Random Network Average Latency

Figure 8 shows that average latency of the AS-PW-

MAC is less compared to PW-MAC and RI-MAC. AS-PW-MAC takes about 17.8 seconds less than PW-MAC and RI-MAC for successful packet transmission. This is because in AS-PW-MAC, nodes are adaptive to varying traffic loads. RTE and RAS messages are used for adaptiveness. Source node requests for extending time duration so that it can send pending data or large data in single attempt.

V- CONCLUSION

This paper has presented the design and evaluation of AS-PW-MAC protocol. AS-PW-MAC uses receiver-initiated data transmission in order to efficiently and effectively operate over a wide range of traffic loads. AS-PW-MAC introduces RTE and RAS messages in order to extend the time duration for pending data to be transmitted in single contention. RTE and RAS make nodes adaptive to varying traffic loads. We conducted experiments through detailed ns-2 simulation to evaluate the performance of AS-PW-MAC. Compared to RI-MAC and PW-MAC, AS-PW-MAC achieves higher throughput, and higher packet delivery ratio under a wide range of traffic loads. For example, evaluated on scenarios with 15 concurrent transceivers in the network, the delivery latency for AS-PW-MAC in these scenarios is less than 21% of that of RI-MAC and PW-MAC. AS-PW-MAC maintained around 100% packet delivery ratio in all experiments.

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