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Energy Efficiency of Adaptive-Rate Medium Access Control Protocols for Sensor Networks

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***Abstract*—**Energy efficient protocol design is the aim of current researches in the area of sensor networks where limited power resources impose energy conservation considerations. In this paper we care for Medium Access Control (MAC) protocols and after an extensive literature review, two adaptive schemes are discussed. Of them, adaptive-rate MACs which were introduced for throughput enhancement show the potency to save energy, even more than adaptive-power schemes. Then we propose an allocation algorithm for getting accurate and reliable results. Through a simulation study we validated our claim and showed the power saving of adaptive-rate protocols.

***Keywords*—**Adaptive-rate, adaptive-power, MAC protocol, energy efficiency, sensor networks.

I. INTRODUCTION

RECENT advances in wireless sensor networks have led to many new protocols specifically designed for sensor networks where energy awareness is an essential consideration [1]. Like in all shared-medium networks, medium access control (MAC) is an important technique that enables the successful operation of the network. One fundamental task of the MAC protocol is to avoid collisions so that two interfering nodes do not transmit at the same time. There are many MAC protocols that have been developed for wireless voice and data communication networks. Typical examples include the time division multiple access (TDMA), code division multiple access (CDMA), and contention-based protocols like IEEE 802.11 [2].

Energy is an important factor in sensor networks. Hence, extensive researches are going on in order to find the proper algorithms which not only increase the throughput of the network but also reduce energy consumption in the nodes. Therefore, designing MAC layer protocols which minimize transmission power as a metric could be a good approach to develop a power efficient sensor network.

The reminder of this paper is organized as follows. We first explore some special proposed MACs for sensor networks and explain their advantages and disadvantages thoroughly, in Section II. Then, in Section III a comparison is made between adaptive-power and adaptive-rate MACs that are developed to increase power efficiency and throughput, respectively. The next two Sections will give our proposed rate adaptation strategy and bring with the related simulations. Our conclusions are summarized in Section VI.

II. RELATED WORK

The MAC protocol in a wireless multihop sensor network must achieve two goals. The first is the creation of the network infrastructure. The second objective is to fairly and efficiently share communication resources between sensor nodes. Both fixed allocation and random access versions of medium access have been proposed for this reason [3]. Power conservation is achieved by the use of power saving operation modes and by preferring time-outs to acknowledgements, wherever possible. It has been reasoned that since radios must be turned off during idling for precious power savings, the MAC scheme should include a variant of TDMA. Constant listening times and adaptive-rate control schemes can help achieve energy efficiency in random access schemes for sensor networks. Reducing power consumption can be achieved by avoiding 1)Retransmission; by collision avoidance using, for example, scheduling (TDMA based), 2)Overhearing; by sleeping when neighbors are transmitting and then waking up to relay or transmit, and 3)Idle listening; by frequent sleep modes in the radio. Some of the proposed MAC protocols are discussed here.

SMACS is a distributed infrastructure- building protocol which enables nodes to discover their neighbors and establish transmission/reception schedules for communication without the need for any local or global master nodes. In this protocol, the neighbor discovery and channel assignment phases are combined so that by the time nodes hear all their neighbors, they would have formed a connected network. Such a scheme avoids the necessity for network-wide synchronization, although communicating neighbors in a subnet need to be time synchronized. Power conservation is achieved by using a random wake-up schedule during the connection phase and by turning the radio off during idle time slots.

Another protocol named PAMAS (Power Aware Multi-Access Protocol with Signaling) avoids the overhearing among neighboring nodes by using out-of-channel signaling [4]. On the other hand, the protocol in [2], called S-MAC (sensor-MAC), prevents overhearing by in-channel signaling, using the RTS (Request To Send) and CTS (Clear To Send) packets as in IEEE 802.11. When an interfering node hears a

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RTS and/or CTS packet, it goes into sleep mode. This protocol also avoids idle listening through periodic listen and sleep modes, the schedules of which are known by neighboring nodes. The problem with this protocol is that it uses RTS/CTS packets to avoid contention. The effect of these control packets on energy consumption is significant when the data packet length is on the order of RTS/CTS packet length. In addition, the latency increases since a sender must wait until the receiver wakes up before it can transmit the packet. Furthermore, per-node fairness is traded off against energy savings.

DE-MAC is a distributed energy-aware protocol [6]. Unlike several existing protocols which treat all nodes equally with respect to energy conservation, this protocol is based on the crucial observation that over a period of time, there are several critical sensor nodes in the network, which must be treated differently (preferentially, in most cases) with respect to energy consumption. The criticality of a sensor node is a function of a sensor's location within dynamically changing query routing trees. Motivated by the fact that a weaker node should be used less frequently in a routing in order to accomplish load balancing, DE-MAC performs a local election procedure and chooses the worst-off nodes as the winners and makes them sleep more than the other neighboring nodes.

STEM (Sparse Topology and Energy Management) [7] protocol trades energy savings for latency through listen/sleep modes but by using a separate radio. When a node wants to send a packet, it polls the target node by sending wake-up messages over a paging channel. This scheme is effective only for scenarios where the network spend most of its time waiting for events to happen. Otherwise, the polling through a stream of wake-up messages, collisions and overhearing may cancel out the energy savings obtained by sleep modes.

STEM is known as pseudo-asynchronous scheduled scheme. Another protocol which is similar with STEM in this sense is what uses RICER (Receiver Initiated CyclE Receiver)/ TICER(Transmitter Initiated CyclE Receiver) [8] while RICER/TICER imposes no scheduling or time synchronization, which makes the protocol simple and with less overhead to preserve power efficiency. Furthermore, traffic is distributed in time in this scheme which produces fewer collisions and less overhearing than STEM.

T-MAC [9] improves on S-MAC's energy usage by using a very short listening window at the beginning of each active period. After the SYNC section of the active period, there is a short window to send or receive RTS and CTS packets. If no activity occurs in that period, the node returns to sleep. By changing the protocol to have an adaptive duty cycle, T-MAC saves power at a cost of reduced throughput and additional latency. T-MAC, in variable workloads, uses one fifth the power of S-MAC. In homogeneous workloads, TMAC and S-MAC perform equally well.

B-MAC, a carrier sense media access protocol for wireless sensor networks provides a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization [10]. To achieve low power operation, B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening (an adaptive-rate scheme). B-MAC supports on-the-fly reconfiguration and provides bidirectional interfaces for system services to optimize performance, whether it is for throughput, latency, or power conservation. By comparing B-MAC to conventional 802.11- inspired protocols, specifically S-MAC, we see that B-MAC's flexibility results in better packet delivery rates, throughput, latency, and energy consumption than S-MAC. By deploying a real world monitoring application with multihop networking, validations to protocol design and model illustrate the need for flexible protocols to effectively realize energy efficient sensor network applications.

III. COMPARING ADAPTIVE-POWER AND ADAPTIVE-RATE MACS

A. Adaptive-Power MACs

In adaptive-power MACs transmission power is changed upon nodes' distance. The easiest protocol is BASIC. In this protocol sender and receiver nodes interchange RTS and CTS with maximum allowable power. Upon receiving CTS by the sender, it calculates the minimum necessary power in order to receive the DATA packets correctly and adjust T_x power accordingly. But as explained in the literature [5], BASIC protocol not only increases power consumption due to more collisions, but also decreases network throughput. The Power Control MAC (PC-MAC or PCM in the original reference) [5] was proposed in order to overcome the shortcomings of BASIC scheme. In PC-MAC like BASIC, RTS and CTS are exchanged with maximum power wherever DATA and ACK are transmitted with minimum acceptable power changing periodically to the highest power level.

B. Adaptive-Rate MACs

In adaptive-rate MACs instead of varying the power levels, transmission rates are changed. Rate determination is based on the received SNR. The larger the SNR is, the better the chance of receiving data with the lower BER would be. In addition, some modulation schemes are performing better than the others for transmitting information within a given SNR and bandwidth.

Adaptive-rate schemes commonly use a threshold-based scheme to predict the proper rate. The first scheme is called auto rate fallback (ARF) [11]. In ARF, the sender selects the best rate based on information regarding previous data frames. It increases or decreases the rate after a number of consecutive successes or losses respectively. ARF decisions are based on previous not present channel condition which could be a disadvantage of the scheme.

The second scheme is the receiver-based auto-rate (RBAR) protocol [12]. The key idea of RBAR is to allow a receiver to estimate channel quality and to select an appropriate rate during RTS/CTS frame exchange for the next data frame. Since the rate selection is done by a receiver during latest

RTS/CTS exchange, the channel quality estimation is closer to actual condition than the sender-based approaches, such as ARF. However, the receiver chosen rate must be carried back to the sender by a CTS frame.

The last medium access control protocol we consider here is an Adaptive Rate MAC (AAR) [12] protocol which is another receiver-based approach. Accordingly, the features and issues of AAR are also similar to the RBAR, except that AAR applies an adaptable rate to transmit each fragment. The rate information for the next fragment is carried back to the sender by the latest ACK frame. By using per fragment adaptation, AAR exhibits better transfer rate adaptability. Besides per fragment adaptation, AAR allows further extension of sending duration to fully utilize a high quality channel during the coherence time interval. Theoretically, this enhances network throughput further. However, predicting the coherence time interval is a difficult task.

C. Comparison

At the first glance, it's difficult to find out the strong relation between adaptive-rate and adaptive-power MACs. But as we explain here, adaptive-rate schemes can both improve throughput and reduce power consumption. In order to justify the claim that how adaptive-rate MACs can reduce power consumption, we first define a metric which is used in order to compare different schemes. A useful metric is the average energy consumed for a successful received bit, that is to say, Joules/bit.

As it is clear, one of the most important factors that increase our Joules/bit metric is the consumed power in unsuccessful transmissions due to collision. When sender and receiver nodes are in normal channel state and normal distance, both adaptive-rate and adaptive-power MACs perform like IEEE802.11 MAC; hence, not using any facility of these modified MACs. But in situations where nodes are close to each other or the channel state is very good, the adaptive-power MACs use minimum necessary power to transmit data in order to save power. On the other hand, the adaptive-rate MACs increase their transmission rate. Increasing transmission rate can save energy in two ways. Firstly, increasing rate decreases the transmission time; therefore, the probability of collision decreases. Less collision means less retransmission which is equal to saving more power. Secondly, in the same time periods, adaptive-rate MACs can deliver more data than non-adaptive-rate schemes. Although we will need more power for transmitting more bits, but the percentage of data received correctly is more than the increase in percentage of needed power. Hence, the Joules per bits will decreased and the scheme could be power efficient too.

According to the above discussion, we claim that although the aim of adaptive-rate MACs is to improve throughput, they are also power efficient. But adaptive-power MACs try to decrease power consumption in a way that throughput tends to be near IEEE802.11 MAC. Therefore, adaptive-rate MACs can be more power efficient than adaptive-power schemes. On the other hand, adaptive-rate MACs will enhance the throughput beyond IEEE802.11 MAC and further conserve the total power.

In brief, we think adaptive-rate MACs perform better than adaptive-power MACs, whereas they improve both throughput and data bits delivered per Joule.

IV. RATE AND POWER ALLOCATION ALGORITHM

Here we will use a piece-wise linear scheme for rate and power allocation to different transmitting sensor nodes. The rate assignment is depicted in Fig. 1, and Fig. 2 shows the power allocation strategy based on PC-MAC for comparison purposes. These schemes are both tried versus richness of the channel conditions, that is to define channel quality to be $10\log\left(P_r/P_{th}\right)$, where P_r is the received power at the receiver sensor node and P_{th} would be the minimum acceptable power level.

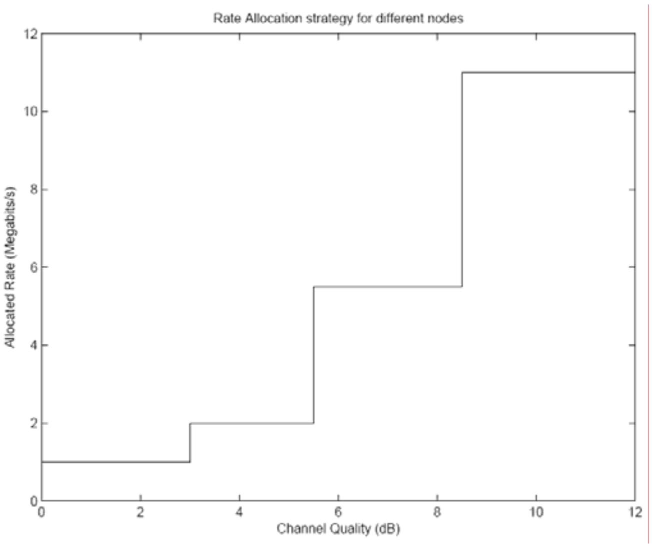

Fig. 1 Rate allocation scheme for an adaptive-rate MAC

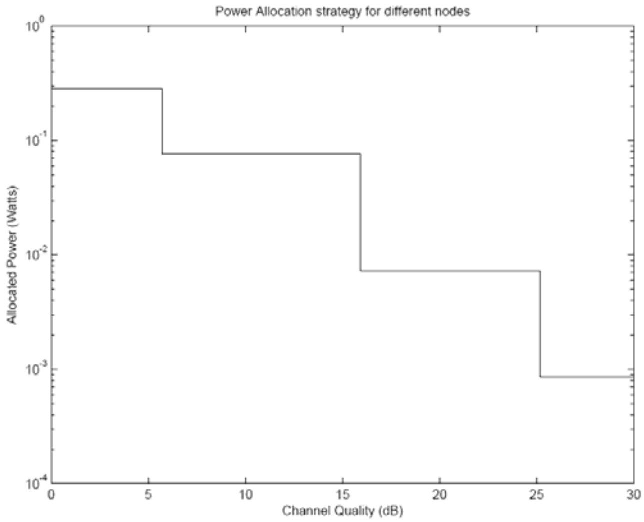

Fig. 2 Power assignment strategy for an adaptive-power MAC like PC-MAC

It is noteworthy to say that in either case, we have only limited amount of power or total rate to be allocated. So whatever the allocation strategies would be, e.g. a piece-wise linear scheme, an optimized value from an optimization statement, etc. it must observe the resource limitations. Otherwise, the results would not be accurate and might be misleading in many cases.

Normally the outputs of this problem take either positive or negative values; however, in practice we do not have negative power to be allocated to a sensor node. An obvious way is to omit that node from transmitting (zero power is assigned to nodes with negative allocated value). However, the fact that this node's properties like distance, channel state information, remaining battery charge, etc. were of course effective in our optimization problem, insists that neglecting the node without careful consideration on the problem criterions like limited total power (or in the case of rate-allocation scheme, the channel capacity), would be harmful and will end to wrong outcomes. Therefore we suggest a general allocation strategy where by careful considering of resource limitations, the power or rate assignment could be done efficiently and without errors. The proposed algorithm is depicted in Fig. 3.

Firstly we assume a constant total power/rate to be allocated to transmitting sensor nodes (say X_{total}). These nodes are indexed with $i = 1,\ldots,N$ and the variable to be assigned would get this index to show the amount of power/rate which is assigned to that node, say, x_i. Then consider a set S which its members are the index values whose allocated amounts are negative due to optimization problem outcomes (neither power nor rate could be negative values). The algorithm's main idea is that upon getting a negative value for a node, the allocation procedure needs to be restarted neglecting such node to have effect in the assignment, i.e. the rejected nodes should be allocated with zero amount of power/rate and the procedure should be restarted for remaining sensor nodes, since the problem assumptions have changed after discarding that node.

In addition, the optimization solution should also take into account disregarding rejected nodes from being effective in the allocation process. It can be shown that this algorithm will effectively remove common mistakes in the simulation study, avoid misleading outcomes, and give accurate results.

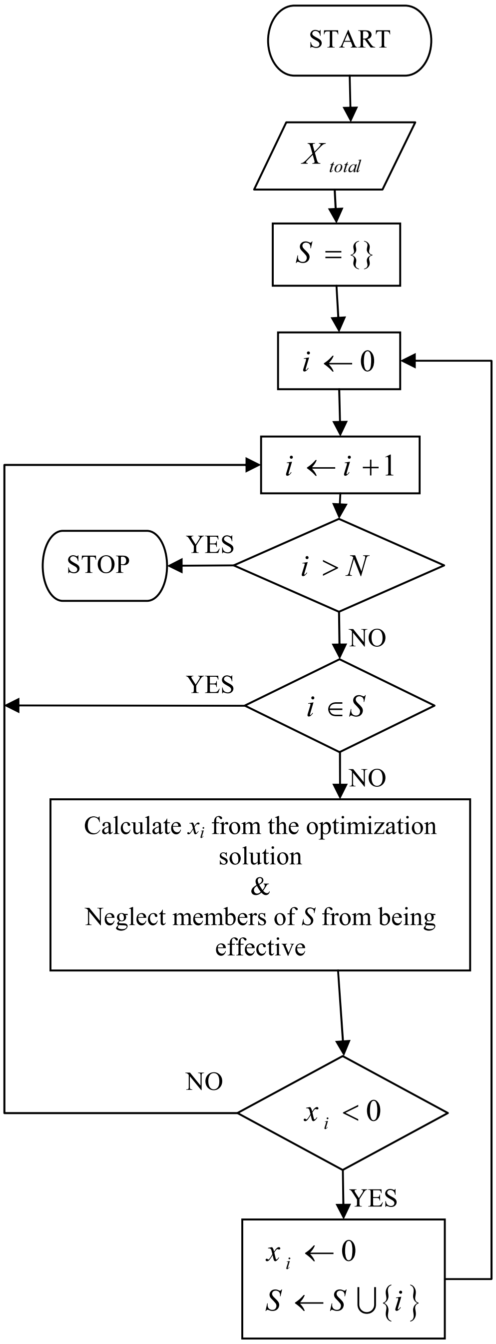

Fig. 3 Power/Rate allocation algorithm from an optimization-like problem

V. SIMULATION RESULTS

By the previous Section's definitions and regulations, we are ready to compare adaptive-rate and adaptive-power MACs in the sense of energy consumption and aggregate throughput. These simulations are tried many times to ensure reliable outputs and accurate results which could be used to verify the claim of energy efficiency for adaptive-rate MACs in addition to their throughput enhancement.

A. The Simulation Environment

The simulation is done on a random topology for 25 nodes placed in a flat 1000(m) x1000(m) square area. The channel propagation model is two-ray ground with our desired MACs above it and a DSR routing protocol running in the network layer.

B. Results

Simulation results are shown in Fig. 4 and Fig. 5 for energy efficiency in Joules/bit and throughput in Megabits. A constant bit-rate scenario is also included for comparison purposes.

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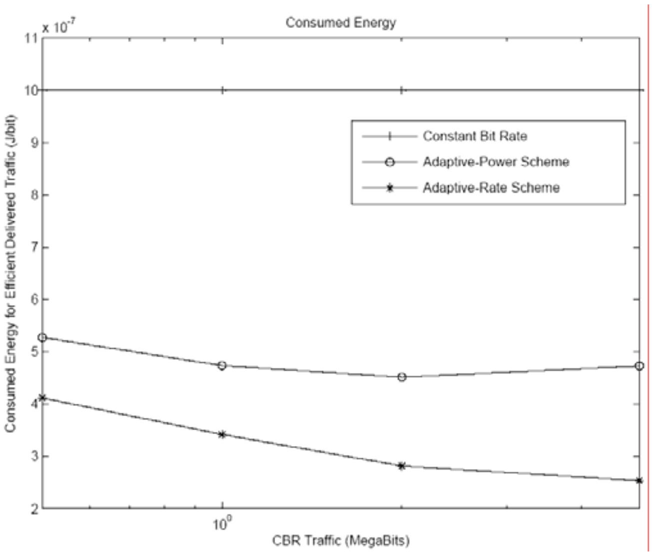

Fig. 4 Consumed energy per efficient delivered bit (Joules/bit)

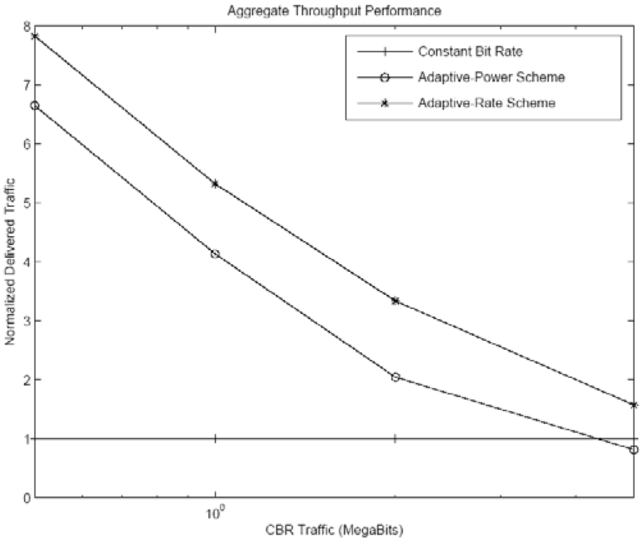

Fig. 5 Aggregate throughput performance against CBR traffic

VI. CONCLUSION

As the results clearly show, the adaptive-rate MACs which basically were proposed to enhance the throughput performance of wireless networks are also more energy efficient than adaptive-power MACs, since in an optimal transmitting rate, the communication times would be reduced and more collisions are avoided. And this was the reason we considered such schemes for wireless sensor networks where energy efficiency is a critical metric.

We also suggested an important algorithm when allocation amounts are drawn from an optimization solution, which is to ensure problem criteria to be held at all times. Neglecting such a fact would end to inaccurate and misleading results in simulation studies.

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