A Channel Adaptive MAC Protocol with Traffic Aware Distributed Power Management in Wireless Sensor Networks

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***Abstract*—Wireless sensor networks are battery operated computing and sensing devices. The sensor nodes will be deployed in an ad hoc fashion with individual nodes remaining inactive for large periods of time but suddenly becoming active on detecting an event. Energy management is a major issue in wireless sensor networks. In this paper, we describe AEMAC, a channel adaptive MAC protocol with traffic aware distributed power management in wireless sensor networks. We evaluate the performance of the AEMAC scheme, over a sensor network with SMAC and ZMAC schemes, in terms of energy consumption, delay and throughput for varying node densities and transmission rates. AEMAC shows a highly superior performance in terms of energy consumption and throughput compared to SMAC and ZMAC schemes.**

Keywords- Ad hoc, MAC, energy efficiency, throughput.

I. INTRODUCTION

Advancements in communication and MEMS technology have facilitated the development of sensors. Sensors are low power, highly sensitive, cheap devices with limited processing and computing resources. They have the ability to sense, measure and transmit the environmental data to the end user. Wireless sensor networks are dense networks equipped with many sensor nodes and have a processor, memory and power supply circuits. With enhanced accuracy, wireless sensor networks facilitate the monitoring and controlling of physical environment from remote locations. They find various applications for environment monitoring, military purposes and in medical field [13], [16 to 20] and [24].

All wireless sensor networks are equipped with limited power resources. In many applications, replacement of the exhausted batteries is not possible. Sensor lifetime is strongly influenced by the battery lifetime. Due to their economical nature and adhoc method of deployment [7], sensor nodes have a range of energy and computational constraints. So energy consumption is the major significant factor to be dealt with in wireless sensor networks. Energy constraints in wireless sensor networks affect the whole network lifetime and connectivity. Efficient energy management should be introduced in all the levels of system hierarchy from the hardware to the software architecture and from operating system to the communication protocols. All the system components will affect the energy dissipation depending on the application [21]. Therefore energy awareness must be involved in all the levels of system design and operation, to maintain the connectivity and lifetime of the sensor network [1], [6] and [9].

Highly efficient power management leads to a longer lifetime of the sensor network existing in an unattended environment [22]. System lifetime can be prolonged by applying the energy efficient techniques to all the levels of system hierarchy [1]. Extensive research is going on to have a decrease in the energy consumption in various aspects of system design, data processing, network protocols and operating system. Supply voltage can be adjusted in Dynamic Voltage Scaling (DVS) in conjunction with the clock frequency in response to the CPU utilization [2]. Dynamic Modulation Scaling similar to DVS is proposed in [2]. By proper design of the operating system for sensors, the different node components can be made to enter various states (idle/ sleep/ active), so as to save energy at the expense of some degree of system performance degradation [3].

Supplementary energy savings can be attained by Dynamic Power Management (DPM). DPM is widely used in wireless sensor networks. This involves shutting down the sensor node during no event and waking it up when needed. Thus good energy savings can be achieved. But the dominance of start up energy needs a careful implementation of DPM. Operation in any energy saving mode is energy efficient only if the time spent in that mode is greater than a decided Threshold. Energy efficient DPM is proposed in [10] to keep minimum number of nodes in the active mode.

The time varying nature of the wireless channels is also disregarded in most existing energy saving schemes. If the effects of the varying channel quality are neglected, loss of precious battery resources result, which further leads to the depletion of the whole network. So the time varying properties of the wireless channel must be taken into account [14], to understand the true energy saving in a wireless environment. To realize the true energy saving in a wireless scenario, the time varying properties of the wireless link is taken into account [21]. Results proved a 40% increase in energy saving compared to the other protocols without any channel adaptation.

To extend the lifetime of the network, designing a distributed power management protocol is a good technique. For considering the design of sensor networks [15], latency and throughput are two significant features to be considered in addition to the energy efficiency. The nodes stay in an idle listening state at low traffic to conserve power.

II. RELATED WORK

DPM schemes involve shutting down devices when not needed and waking them up when necessary. This method gives significant energy savings [22]. But sensor nodes communicate using short data packets. So the dominance of start up energy is significant [4]. In order to extend the life of a sensor node, DPM should be implemented cautiously.

To have efficient energy management, MAC supported by the Data Link Layer is also an important functionality to be considered. MAC schemes should efficiently establish communication links to enable reliable data transfer and prevent collisions between the data transferred from the sensor nodes. MAC schemes should be implemented carefully to prevent the energy wastage in wireless sensor networks.

SMAC [5] and [11] is one of the well known energy efficient protocols for wireless sensor networks. It is a contention based random access protocol with a preset listen/ sleep cycle and uses a synchronized sleep mechanism. A time frame in SMAC is separated into two parts: one for a listen period and the other for a sleep period. For the purpose of announcement and synchronization for the subsequent data transmission, SYN and RTS/CTS control packets are broadcasted during the listen period based on the CSMA/CA mechanism. Any two nodes exchanging RTS/CTS packets in the listen period, require to be in the active state and to enter the data transmission without entering the sleep mode. To avoid the energy wastage due to idle listening, all the other nodes enter the sleep mode. The duration of a listen period is always fixed in SMAC. This results in redundant energy wastage.

TMAC [8] resolves this problem by following an aggressive power conserving policy. It is a variation of SMAC with an adaptive length of the active state by a fine time out. Nodes can go to an early sleep state resulting in an augmented latency and a lesser throughput.

Data gathering MAC (DMAC) [12] is a different protocol using an adaptive duty cycle. It gives a low node to sink latency in converge cast communication by staggering the wake up times of the nodes in the converge cast tree. DMAC outperforms SMAC in having a lower latency and higher energy efficiency.

A new hybrid MAC scheme (ZMAC), [26] is used for sensor networks to merge the strengths of TDMA and CSMA. Its adaptability to the level of contention in the network is the major aspect of ZMAC. Under low contention, it acts like CSMA and under high contention like TDMA. It is robust to energetic topology changes and time synchronization failures regularly occurring in wireless sensor networks.

III. BASIC PROTOCOL

A channel adaptive MAC protocol with traffic aware DPM (AEMAC), is proposed for competent packet scheduling and queuing in a sensor network, with the time varying characteristics of wireless channels taken into account. A network system has been proposed to execute the fundamental idea in an actual situation wherein each sensor can choose the state of the communication component considering the link condition.

The utilization of energy during the packet transmission through a link of high quality is lesser than that of a bad link. Based on this aspect, every sensor node chooses the state of its communication unit, respecting the current condition of the wireless link among it and the sink, in this scheme. For each competing flow, every node estimates the channel state and the link state at the LLC queue. The flag can take three values: Good, Bad or Probe. Based on these flags, the proposed protocols calculate a joint weight value. By means of any routing protocols, the weight value is sent together with the data packets of the flows. Transmission is permitted for those nodes owning a high weight value. Nodes trying to access the wireless medium with a low cost value will be permitted to broadcast later, when their weights turn high. The packets temporarily get buffered until the channel quality rises to the required Threshold. This avoids their transmission considering the fact that a wireless link with worse channel quality results in higher energy expenditure.

The energy consumed in an idle mode is less than the active mode but considerably greater than the sleeping mode. Thus the energy can be saved by wisely switching to the sleep mode whenever possible. A traffic aware DPM has been designed in this paper. Lessening the energy consumption by constantly turning off the radio interface of the redundant nodes not incorporated in the routing path is the design objective of this DPM scheme. Depending upon the state defined by the data transmission, nodes are classified as: Current Transmitting Sensor (CTS), Future Transmitting Sensor (FTS) and No Transmission Sensor (NTS).

In ordinary CSMA/CA schemes, adopted in SMAC, RTS/CTS packet exchange is needed before data transmission. So all the other nodes go to sleep mode for the duration of NAV (Network Allocation Vector) time and when it expires it comes to the on state. This needs mandatory wake up even if it does not get involved in further routing. Here in this protocol, RTS packets also exchange the information of the sink. So the node on getting an RTS packet invokes its routing agent to find the next hop node. The next hop address is also appended along with the CTS packet. Now this next hop node alone turns on, on expiration of the NAV timer [27]. All the other neighboring nodes on receiving this CTS packet continue to sleep. Thus unnecessary wake up –sleep transitions leading to excess energy consumption is avoided

IV. Results and Discussion

We consider sensor nodes deployed in a sensing field. The following properties are assumed to simplify the network model. All sensor nodes have limited batteries and recharging is not possible. Links are symmetric. All nodes have equal capabilities with respect to data processing, wireless communication and battery power. All sensor nodes have the same transmission and reception power levels of 0.360 and 0.395 watts respectively. The sensor network is simulated using the Network Simulator NS2. The simulated network consists of many sensor nodes distributed in a grid pattern 1000×1000 . Each node is equipped with a transceiver capable of transmitting a signal at a rate of 100 Kb/s up to 500Kb/s. Each node has an initial energy of 2.7 Joules. Maximum number of packets that are maintained in the Interface Queue is 500. The packet size is 500 bytes. Different MAC schemes AEMAC, SMAC and ZMAC are compared.

A. *Set up 1*

We have compared the AEMAC scheme with the SMAC and ZMAC schemes, in terms of energy consumption, delay and throughput with respect to the node density. The number of nodes was increased from 25 to 100.

Figure 1 presents the energy consumption graph of AEMAC, SMAC and ZMAC schemes with respect to the number of nodes. Initially ZMAC has a higher energy consumption compared to SMAC and AEMAC schemes for a low node density. When the node density is increased, the energy consumption increases for all the 3 schemes due to the large number of forwarding packets. When the number of nodes increase, more routing can be involved to have a reliable data transfer. So the total energy consumption also increases. But AEMAC scheme proves to have a much superior performance than the other 2 schemes since when the node density increases more number of nodes can be brought to the sleep mode as the mandatory wake up involved in the other power saving schemes is not involved here. ZMAC exhibits minimum energy consumption.

TABLE I. PARAMETERS

Parameters	**Value**
Transmission power	0.360 watts
Reception power	0.395watts
Initial node energy	2.7 Joules
Maximum number of packets in Interface queue	500
Packet size	500 bytes
Transmission rate (set up 1)	100 Kbps
Number of nodes (set up 1)	varied from 25 to 100
Transmission rate (set up 2)	varied from 100 Kbps to 500 Kbps
Number of nodes (set up 2)	50

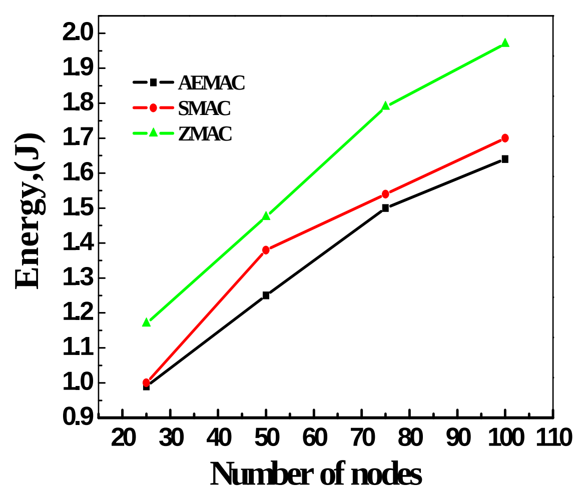

Figure 1. *Variation of energy consumption with respect to number of nodes*

Figure 2 shows the Throughput level of the network with respect to the node density. Initially when the number of nodes is less, the Throughput is a low value for SMAC compared to ZMAC and AEMAC. This is because in SMAC only the active part of the frame is used for communication. Throughput for ZMAC is almost independent of the number of nodes. As the number of senders increase, the number of senders transmitting during their own slots also increases. So during high contention it maintains a good throughput since it behaves like TDMA [25]. As the number of nodes increase to

50, Throughput decreases for AEMAC and ZMAC schemes and increases for SMAC. In a less dense topology, the Throughput of SMAC increases initially accounting for the static listen periods involved. In ZMAC and AEMAC, as the node density increases, lot of data collisions occur and only few data packets get the chance to arrive at the sink and only few nodes can send data to the sink successfully [26]. But when the node density increases from 50 to 75, Throughput of SMAC decreases, due to the disadvantages involved in the static scheme. When the node density further increases to 100, Throughput remains the same for SMAC whereas it increases for AEMAC and ZMAC due to its improved methodology. This proves that the static scheme may be better initially for a lesser node density, but for a higher node density the other schemes especially AEMAC proves better in terms of Throughput. This is accounted to the fact that, when the number of nodes exceed beyond 75, AEMAC not only considers the link and channel quality but also the energy and bandwidth available in a node to perform the routing. So only the nodes with maximum residual energy and bandwidth gets involved

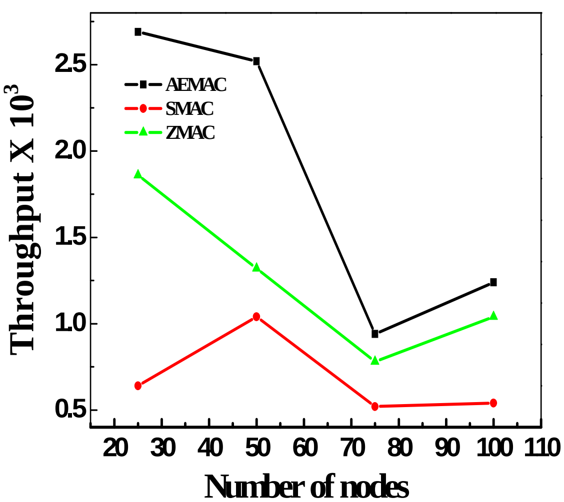

Figure 2. *Variation of throughput with respect to number of nodes*

Figure 3 presents the delay level with respect to the node density for the 3 schemes. The delay level is much lesser for AEMAC scheme compared to SMAC and ZMAC schemes. Delay is higher for SMAC due to the unwanted delay involved due to the fixed duty cycle involved in the scheme. Moreover a message generating event may occur during sleep time and the message will be queued till the start of the next active part [23]. ZMAC exhibits a lesser delay since the strengths of CSMA and TDMA are merged in this scheme. The delay encountered by the packets in the network decreases till the node density increases to 75. This is because of the fact that a better routing and better packet delivery to the destined node can be achieved as the node density increases. But on a further increase in the node density beyond 75, the sensor network reaches a state of equilibium and so the delay remains constant. Overall, SMAC shows the greatest delay and AEMAC shows the least delay but when node density is 100, delay of both the schemes AEMAC and ZMAC coincide.

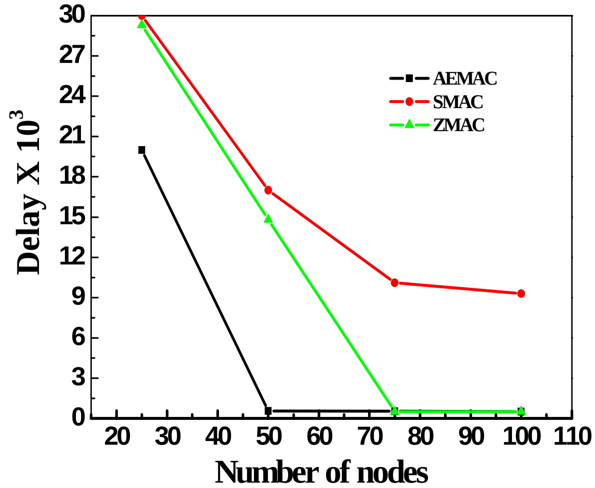

Figure 3. Variation of delay with respect to number of nodes

B. Set up 2

The energy consumption, delay and Throughput are compared for all the 3 schemes AEMAC, SMAC and ZMAC in terms of the Transmission rate. The transmission rate is varied from 100 Kb/s to 500 Kb/s.

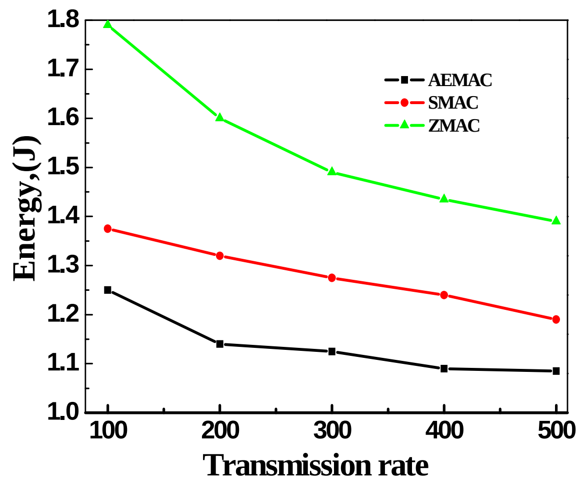

Figure 4. Variation of energy with respect to transmission rate

Figure 4 presents the energy consumption for the 3 schemes with respect to the transmission rate. As the node transmission rate increases, the energy consumption decreases for all the 3 schemes. SMAC shows medium energy consumption. ZMAC shows the highest energy consumption for varying transmission rates because nodes tend to wake up longer for transmission due to their large back off window sizes and also because clock synchronization messages are periodically sent [26]. AEMAC exhibits an energy consumption maintained at a low value compared to the other 2 schemes and as the transmission rate increases the energy consumption further decreases to a lesser value. Moreover only the highly efficient routing path is considered

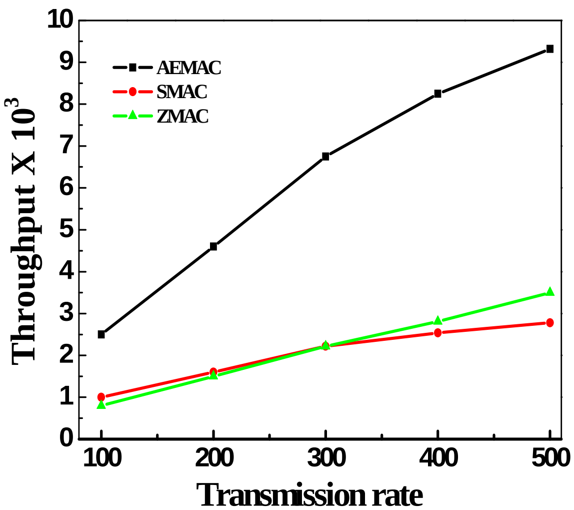

Figure 5. Variation of throughput with respect to transmission rate

Figure 5 shows the changes in throughput for a change in the transmission rate. As the transmission rate increases, the Throughput level increases for all the 3 schemes .Better slope is observed for AEMAC and ZMAC schemes. Unwanted energy wastages being eliminated in AEMAC scheme, shows the highest Throughput level.

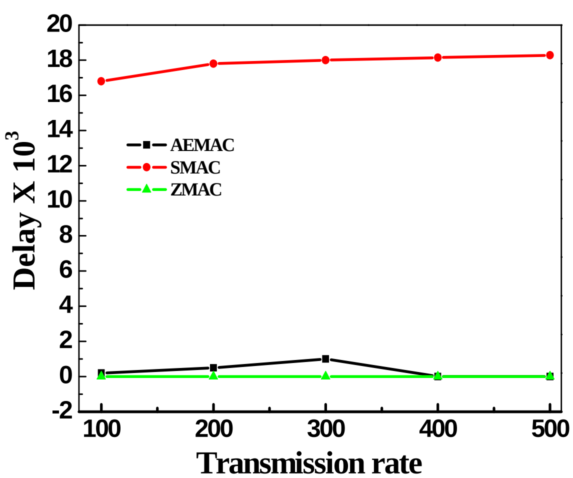

Figure 6. Variation of delay with respect to transmission rate

Figure 6 shows the changes in delay for the 3 schemes with respect to the transmission rate. SMAC exhibits the highest delay. This is because the latency is increased due to the periodic sleep of each node. Delay is lesser for AEMAC and ZMAC schemes. Superior performance is exhibited by ZMAC scheme. But the delay for AEMAC scheme is slightly inferior compared to the ZMAC scheme initially with an increasing slope till a rate of 400Kb, but when the rate increases from 400Kb, it approximates to the best performance as exhibited in ZMAC scheme.

V. CONCLUSIONS

Energy consumption should be dealt critically in wireless sensor networks since energy is of main concern in such networks. Moreover, the Throughput level and the delay suffered by the packets in the network should also be taken into account, while improving the performance of such networks. It was already proved that ZMAC shows a higher Throughput and lower delay compared to the SMAC scheme even though a higher overhead is incurred at the beginning [26]. Along with proving this, we have designed a new scheme AEMAC that reduces the energy consumption while attaining a higher Throughput. We have also considered the time varying nature of the wireless channel into account in the optimization of energy management in a sensor network. By simulation, we have proved that AEMAC scheme, exhibits a superior performance compared to the SMAC and ZMAC schemes in terms of energy consumption, delay and Throughput with respect to the node density and the transmission rate. By considering the decreased energy consumption and increased Throughput of the AEMAC scheme, it is quite convincing that such a power management scheme which also considers the link quality of the wireless link will be a promising technique to be adopted in wireless sensor networks, as a solution to its energy problem. Moreover, by increasing the transmission rate AEMAC exhibits the minimum energy consumption. However the increase in delay with respect to the increase in the transmission rate for the AEMAC scheme compared to the ZMAC scheme should be dealt with and necessary improvements introduced in this aspect.

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