EX-SMAC: An Adaptive Low Latency Energy Efficient MAC Protocol

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Abstract - In wireless sensor network the efficient use of energy leads to enhance the network lifetime. As idle listening, collision, control overhead and over hearing are the main reasons of energy waste. Many typical MAC protocols are designed to conserve energy and enhance network lifetime. In this paper we propose a new contention based energy efficient protocol called Extended S-MAC (EX-SMAC) for wireless sensor networks. It is designed with three main features namely Low duty cycle, less number of collisions and minimum overhearing. As the name indicates it is the extension of S-MAC protocol, so this paper also eliminates the long latency of packets at intermediate nodes which is one of the demerits of S-MAC. Sensor nodes in Extended S-MAC have a very short listening time, hence reduces the energy required to communicate with other nodes i.e. idle listening. Also the number of collisions in cases where two or more nodes try to send packets at the same time is minimized in Extended S-MAC, hence retransmission cost for lost packets reduces and also overhearing by other nodes is also minimized by this protocol by having a very short listening time for each node of the sensor network. With such improvements over existing MAC protocol the performance is expected to be much better.

Keywords— ***Wireless sensor network, Idle listening, Collision, Overhearing, Control overhead***

I. INTRODUCTION

Wireless Sensor network is an emerging technology that has a wide range of potential applications including environment monitoring, smart spaces, medical systems and robotic exploration. Such a network normally consists of a large number of distributed nodes that organize themselves into a multi-hop wireless network. Each node has one or more sensors, embedded processors attached with a limited memory and low-power radios for transmission and reception, and is normally battery operated. Communication in wireless sensor networks can, like most network communication, be divided into several layers. One of these is the Medium Access Control (MAC) layer. This layer is operated by a MAC protocol, which tries to ensure that no two nodes are interfering with each other's transmissions, and hence deals with the situation. Wireless sensor networks are designed to be application aware and deployed accordingly. Most sensor nodes are battery operated and normally they cannot be recharged due to its deployment in harsh and remote environment. Therefore, energy efficiency is a very critical issue to prolong the networks lifetime. In this paper, we lay stress on the contention-based protocols, which use an active/sleep mode frame to save energy consumption. There are four major sources of energy waste.

- Collision: When a transmitted packet is corrupted it has to be discarded, and the retransmission increases the energy consumption.

- Overhearing: A node picks up packets that are destined to other nodes.
- Control packet overhead: Sending and receiving control packets, consume energy too.
- Idle listening: Listening to receive possible traffic that is not sent. This is especially true in many sensor network applications. If nothing is sensed, nodes are in idle mode for most of the time.

However, in many MAC protocols such as IEEE 802.11 or CDMA nodes must listen to the channel to receive possible traffic. Many observations have shown that idle listening consumes 50–100% of the energy required for receiving. Along with the four major causes of energy inefficiency, we have to also consider that the network performance must not be hampered. So per-hop fairness and latency of the data packets in the network should be maintained. In wireless sensor network, each node desires equal opportunity and time to access the medium, *i.e.* sending or receiving packets for their own applications. Per-hop MAC level fairness is thus an important issue. However, in sensor networks, all nodes cooperate for a single common task. At certain time, a node may have dramatically more data to send than some other nodes. In this case fairness is not important as long as application-level performance is not degraded. In existing S-MAC protocol the concept of message passing is utilized for efficient transmission of a very long message. The basic idea is to divide the long message into small fragments and transmit them in a burst. The result is that a node which has more data to send gets more time to access the medium. This is unfair from a per-hop MAC level perspective, for those nodes which only have short packets to send, since their short packets have to wait a long time for very long packets.

Latency can be important or unimportant depending on what application is running and the node state. During a period that there is no sensing event, there is normally very little data flowing in the network. Most of the time nodes are in idle state. In existing S-MAC protocol nodes periodically sleep if otherwise they are in the idle listening mode. In the sleep mode, a node will turn off its radio. This approach reduces the energy consumption due to idle listening. However, the latency is increased, since a sender must wait for the receiver to wake up before it can send out data.

In this paper, a new MAC protocol scheme, called Extended S-MAC (EX-SMAC) protocol is proposed. In the proposed technique we have tried to reduce the node's power consumption beyond that is achieved by S-MAC, T-MAC and D-MAC by reducing the idle listening time, reducing the number of collisions and also by reducing the overhearing. EX-SMAC is a distributed contention based MAC protocol where nodes discover their neighbours based on their radio signal level. Also, EX-SMAC is a self-organizing MAC protocol that does not require a central node to control the operation of the nodes. The proposed protocol also uses the clustering scheme to group the neighbouring nodes. These clusters are subjected to change after a specific interval of time and new clusters are formed as per the network traffic load. This specific protocol is an extension of existing S-MAC protocol which is also an energy efficient protocol that tries to reduce the basic causes of energy inefficiency but results in longer latency of data packets which reduces the performance of the network. Taking into account the aspect of a better performance of the network, we had proposed the protocol which reduces the latency of the data packets by a great extent also being able to conserve more energy as compared to the existing protocols.

II. RELATED WORK

The medium access control is a broad research area, and many researchers have done research work in the new area of low power and wireless sensor networks and developed a number of MAC protocols. A good wireless MAC protocol must possess the following primary attributes [1]: energy efficiency, scalability, adaptability to changes, latency, throughput, and bandwidth utilization. MAC protocols can be classified into two types depending on the way the access is being controlled: reservation-based and contention-based [2]. Each of these access methods has its own advantages and disadvantages. In reservation-based MAC protocols, the channel is reserved for the nodes for a certain amount of time. Reservation-based MAC protocols have many disadvantages like coordination to allocate and maintain the reservation slots, clock synchronization and lack of scalability [3] that make them difficult to implement for wireless sensor networks. However, reservation-based MAC protocols are collision-free since each node is assigned a specific slot that is reserved specifically for a node to use for communication leading to very low duty cycle [5]. Also, when nodes turn off their radio port during reservation slots for others, they are not affected by others' traffic. Therefore, reservation-based MAC protocols reduce the energy consumption from most of the major sources of energy waste, i.e., idle listening, collision, and overhearing. TRAMA, ER-MAC are two reservation based MAC protocols

In this paper we deal with contention based protocols. Nodes in contention-based MAC protocols determine if they can access the medium by sensing the shared channel and competing to get access to it instead of defining schedules for access. Contention-based MAC protocols have some drawbacks in the attributes related to the sources of energy consumption, as contention-based protocols consume more power than reservation-based protocols. The IEEE 802.11[14] is an international standard of physical and MAC layer specifications for wireless networks. It uses CSMA/CA (carrier sense multiple access with collision avoidance). It is a simple and reliable MAC protocol that is widely used in many traditional ad hoc wireless networks. However, it is not suitable for sensor networks because throughput, latency, and fairness are the primary design criteria, not power consumption. Some of the widely used contention based protocols in sensor network are: S-MAC, T-MAC, D-MAC.

The main goal in S-MAC protocol [4] is to reduce energy consumption, while supporting good scalability and collision avoidance. The protocol tries to reduce energy consumption from all the sources that we have identified to cause energy waste, *i.e.* idle listening, collision, overhearing and control overhead. To achieve the goal, S-MAC consists of two major components:

i. Periodic listen and sleep
ii. Collision and overhearing avoidance

i. Periodic listen and sleep: In many sensor network applications, nodes are in idle for a long time if no sensing event happens. If it is given that the data rate during this period is very low, it is not necessary to keep nodes listening all the time. So S-MAC protocol reduces the listen time by allowing nodes to go into periodic sleep mode. For example, if in each second a node sleeps for half second and listens for the other half as shown in fig-1, its duty cycle is reduced to 50%. So S-MAC achieves close to 50% energy savings.

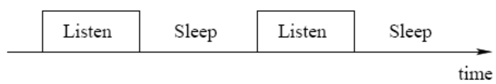

Fig. 1. Periodic sleep listen schedule

ii. Collision and overhearing avoidance: Since multiple senders may want to send to a receiver at the same time, they need to contend for the medium to avoid collisions. S-MAC protocol follows both virtual and physical carrier sense and RTS/CTS mechanism to avoid collision and overhearing [10]. But there is a tradeoff between energy saved and latency due to nodes sleep schedules. Packets are delayed due to the sleep delay i.e. when a sender gets a packet to transmit, it must wait until the receiver wakes up.

T- MAC is another protocol [8] which also concentrates on the energy consumption due to idle listening and also one of the very efficient protocols of the MAC layer. It tries to overcome the demerits of S-MAC protocol .This protocol uses the same sleep and wake up schedule but what makes it more efficient than S-MAC is that it uses the dynamic sleep/ wakeup schedule as shown in fig-2 which reduces the sleep delay to a much extent.

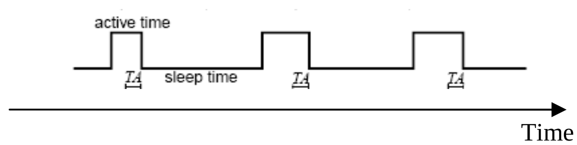

Fig. 2. Dynamic sleep/wakeup schedules

Hence the basic idea of the T-MAC protocol is to reduce idle listening by transmitting all messages in bursts of variable length, and sleeping between bursts. To maintain an optimal active time under variable load, it dynamically determine its length. T-MAC ends the active time in an intuitive way: it simply time out on hearing nothing. But still the problem of sleep delay is not reduced for a great extent

D-MAC [11] deals with those sensor network applications in which the major traffic pattern consists of data collected from several source nodes to a sink through a unidirectional trees. D-MAC overcomes the limitations of the above two energy efficient protocols based on sleep and wake up schedule i.e. they both suffer from a data forwarding interruption problem, whereby not all nodes on a multi-hop path to the sink are notified of data delivery in progress resulting in significant sleep delay. D-MAC solves the interruption problem and allows continuous packet forwarding by giving sleep schedule a node an offset that depends upon its depth on the tree as shown in fig-3.

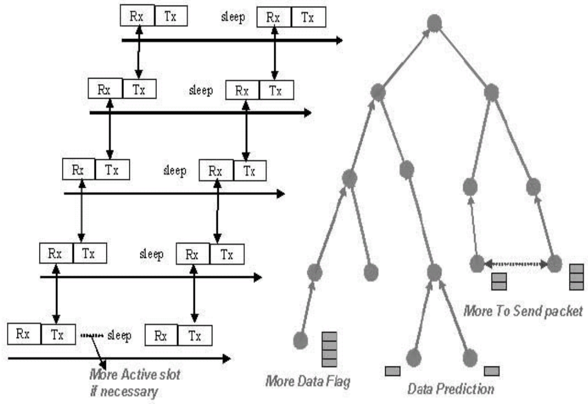

Fig. 3. Staggered sleep/wakeup schedule

D- MAC adopts a staggered wake up schedule i.e. it staggers the activity schedule of nodes on the multi-hop path to wake up sequentially like a chain reaction. The above figure shows a data gathering tree and the staggered wake up scheme. It basically reduces the sleep delay. But the protocol can only be applicable under the specific data gathering tree scenario for unidirectional communication flow from multiple sources to a single sink which is one of the biggest demerits and the second one is that it is efficient for those type of sensor networks where traffic is light.

III. EXTENDED S-MAC PROTOCOL DESIGN

We proposed one of the advanced versions of S-MAC protocol which not only tries to minimize the energy consumption but also tries to reduce the latency of packets delivery to a great extent. It is a distributed contention based MAC protocol where nodes discover their neighbours based on their radio signal level. It is also a self-organizing MAC protocol that does not require a central node to control the operation of the nodes. Here the nodes are assumed to be evenly distributed over the region and all the nodes are clustered, based on the technique called virtual clustering. Frame synchronization is one of the techniques of virtual clustering of sensor nodes which we had implemented in our proposed protocol.

A. CLUSTERING OF SENSOR NODES

Before each node starts its periodic listen and sleep, it needs to choose a schedule and exchange it with its neighbours. Each node maintains a schedule table that stores the schedules of all its known neighbours. It follows the steps below to choose its schedule and establish its schedule table.

Step 1: The node first listens for a certain amount of time. If it does not hear a schedule from another node, it randomly chooses a time to go to sleep and immediately broadcasts its schedule in a SYNC message, indicating that it will go to sleep after t seconds. We call such a node a *synchronizer*, since it chooses its schedule independently and other nodes will synchronize with it.

Step 2: If the node receives a schedule from a neighbour before choosing its own schedule, it follows that schedule by setting its schedule to be the same. We call such a node a *follower*. It then waits for a random delay and rebroadcasts this schedule, indicating that it will sleep. The random delay is for collision avoidance, so that multiple followers triggered from the same synchronizer do not systematically collide when rebroadcasting the schedule.

Step 3: If a node receives a different schedule after it selects and broadcasts its own schedule, it adopts both schedules (i.e., it schedules itself to wake up at the times of both is neighbour and itself). It broadcasts it own schedule before going to sleep.

The described synchronization scheme, urges nodes to form clusters with the same schedule, without enforcing this schedule to all nodes in the network.

B. NON-OVERLAPPING EXTENSIONS

As shown in fig. 4, the time in Extended S-MAC is divided into frames and each frame is divided into two periods: listen and sleep. The active period is sub-divided into M non-overlapping extensions as shown in the below figure. After the efficient formation of clusters, since we had taken into grant that the nodes in the region is evenly distributed so the density of each cluster is approximately equal. Then each cluster is assigned to one of the extensions. Each extension follows a listen/sleep schedule that is skewed in time compared to the schedules of the other extensions. Therefore, the listen periods of the nodes in different extensions are non-overlapping. A node in Ex-SMAC protocol wakes up only at its assigned extension. Therefore, EX-SMAC requires a lesser amount of energy than S-MAC because the listen period of a node in EX-MAC is shorter than the listen period of the frame in S-MAC.

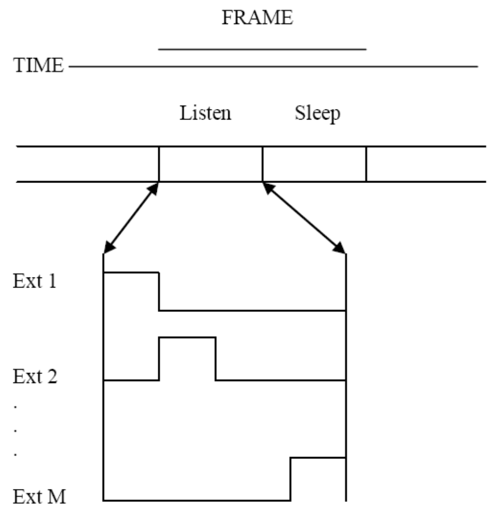

Fig. 4. Non-Overlapping M extensions of listen period

There are three main advantages of adopting multiple extensions in EX-SMAC:

1) Reduced energy consumption: The listen period for the nodes in each phase is reduced in proportion to the number of extensions employed. Therefore, energy loss during listen periods in EX-SMAC is reduced compared to S-MAC protocol.

2) Low average traffic reduces collision*:* The number of nodes associated with a extension in EX-SMAC is a fraction of the total nodes in the network. This results in less average traffic and a reduced chance of collisions. Therefore, the probability of collision in EX-SMAC is reduced, which saves the energy required for retransmitting the collided packets and also the associated control packets.

3) Overhearing reduces: Since the number of nodes associated with a extension in EX-SMAC is a fraction of the total nodes in the network, so overhearing by nodes reduces.

4) Extended network lifetime: By reducing the energy consumption in the nodes, the lifetime of the nodes and the network are increased

C. Low Latency Mechanism

Among many attributes of a good protocol design, latency of packets is one of the important characteristic which should be looked after for the better performance of the protocol. Till today many protocols have been developed keeping in mind the major causes of energy inefficiency but the performance of the protocol degrades due to the delay in receiving of packets at the destination. So in this protocol we not only tried to eliminate the major causes of energy consumption but also maintain the performance of the protocol. So while assigning the clusters which are having nearly equal number of sensor nodes to the extensions of the listen period we had taken into account the network traffic at the particular time and those clusters which are closer to the region of high traffic, those clusters are assigned to the beginning extensions since those clusters will be the one who will be communicating before any other clusters .If assigned at the lower depth extensions will lead to delay since they have to wait for their turn .The network traffic is subjected to change after a specific interval of time , so the protocol also designed as per the changing traffic . The clusters are reformed after a specific duration and also the assignment of clusters change according to the current network traffic load. So the reduction in latency is achieved by taking these majors in our protocol which will be evaluated by the help of ns-2 simulations.

IV CONCLUSION

Wireless sensor networks are used in a variety of applications which require continuous monitoring and detection of distributed events. They can be used in industrial, medical, consumer and military applications. Sensor nodes are operated and constrained by battery lifetime which cannot be recharged or replaced. Therefore, energy efficiency is the most important design factor in wireless sensor networks. In this paper we have described the Extended S-MAC protocol which is the advanced version of S- MAC that helps us not only to avoid the energy consumption issue but also reduces the latency of packets by a great extent. In this protocol the listen period is subdivided into a number of extensions and it depends on the number of clusters formed initially by the synchronization scheme. So a few number of nodes are active in a specific extension and that reduces idle listening, collision, overhearing. Apart from that the performance of the protocol is also maintained by forming the clusters again and again after each time duration and assigning the clusters to the extensions depending upon the network traffic. This reduces the delay in delivery packets to the destination which is otherwise called as latency.

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