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Cross Layer Optimization Techniques in Sensor-MAC

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Abstract— Wireless Sensor Networks (WSN) is a field which has gained much importance in the past decade. WSN contain sensor nodes which are battery powered and hence reducing energy consumption is the most challenging issue in such systems. One important method to reduce energy consumption in WSN is to do cross layer optimization. Cross layer design can be between different layers of the OSI model. This paper is a survey on cross layer optimization involving Sensor-MAC (S-MAC).

Index Terms— Cross layer optimization, Energy conservation, Sensor-MAC (S-MAC), Wireless Sensor Networks (WSN).

I. INTRODUCTION

Communication is the means of sending and receiving information. For a communication engineer it is of two types: Wired and Wireless communication. Wireless communication is among technology's biggest contributions to mankind. Wireless communication involves the transmission of information over a distance without help of wires, cables or any other forms of electrical conductors. The transmitted distance can be anywhere between a few meters (for example, a television's remote control) and thousands of kilometers (for example, radio communication). Wireless technology offers several advantages for those who can build wired and wireless systems and take advantage of the best technology for the application. A Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions. A WSN system incorporates a gateway that provides wireless connectivity back to the wired world and distributed nodes. A WSN is made up of sensor nodes and each node includes the radio, battery, microcontroller, analog circuit, and sensor interface. One of the key constraints of WSN systems is the battery which is the source of energy. The technology consideration for WSN systems is the battery. To extend battery life, a WSN node periodically wakes up and transmits data by powering on the radio and then switching it off to conserve energy. WSN radio technology must efficiently transmit a signal and allow the system to go back to sleep with minimal power use. This means the processor involved must also be able to wake up, and return to sleep mode efficiently. Hence energy conservation is important in any WSN system design. Cross layer optimization is a method by which energy consumption can be reduced. Section II presents the need for cross layer optimization and it is followed by Section III which gives a brief idea on what is cross layer optimization. Section IV describes the Sensor MAC protocol and Section V gives the state of the art of the technique of cross layer optimization in S-MAC followed by Section VI which gives an idea of the different metrics used for the performance evaluation of a cross layer design. Finally section VII concludes the paper.

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II. Need for Cross Layer Optimization

There are different reasons for energy consumption in a WSN like:

i. Idle listening in which the transceiver of sensor node should be in receive mode whether there is a need to receive a message or not.
ii. When two nodes try to transmit simultaneously the transmitted packet will get corrupted due to collision and hence will be discarded resulting in retransmission of the packet.
iii. Sending and receiving control packet overheads, that contain less useful data, consumes much energy.
iv. Overhearing in which a node picks up packets that are destined to other nodes thus increasing power consumption due to retransmissions.
v. Over emitting in which a sensor node receives a packet during the sleep mode resulting in retransmissions.
vi. Unnecessarily high transmitting power results in higher power consumption.
vii. Sub-optimal utilization of the available resources also results in increased energy consumption.

Therefore, developing approaches to optimize the energy consumption has been a major consideration in WSNs [1]. Different optimizations have been proposed to overcome the constraints of WSNs ever since its emergence. Furthermore, the proposals of new applications for WSNs have also created new challenges to be addressed. Cross-layer approaches have proven to be the most efficient optimization techniques for these problems, since they are able to take the behavior of the protocols at each layer into consideration. Layered architecture is not suitable for wireless networks. The wireless network has several advantages like flexibility, mobility, cheaper and faster deployment, easier maintenance and upgrade procedures. These issues make way to cross layer optimization and the main problem addressed by this technique is reducing energy consumption of wireless sensor nodes.

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III. Cross Layer Optimization

A general definition of a cross layer optimization is "any violation or modification of the layered reference architecture" [31]. It is used to exploit the information obtained different layers and to jointly optimize performance of those layers. Cross layer optimization may be defined as the breaking of OSI hierarchical layers in communication networks or protocol design by the violation of reference layered communication architecture with respect to the particular layered architecture. The breaking of hierarchical layers or the violation of reference architecture includes merging of layers, creation of new interfaces, or providing additional interdependencies between any two layers. Today there exist many cross-layer design proposals. It can be classified based on how the layers are coupled and which all layers are coupled. The layered architecture can be violated by:

i. Creating new interfaces
ii. Merging adjacent layers
iii. Design coupling without forming new interfaces and
iv. Vertical calibration across layers [2]

Another way of classification is based on the different layers involved in cross layer design. It can be between two or more layers depending on the application. PHY-MAC is the most prominent cross layer design. The authors in [13]-[20] provide cross layer designs involving physical and MAC layers. Similarly network, transport and application layers can be involved in cross layer design. The authors in [21]-[29] gives an idea of cross layer designs involving network, transport and application layers. Different parameters are used at different layers for optimization. The optimization of these parameters at each layer affects the parameters in other layers also [30]. This paper gives the state of the art of cross layer design involving S-MAC.

IV. Sensor MAC

The sensor-MAC (S-MAC) protocol is designed to reduce energy wastage caused by collision, idle listening, control overhead, and overhearing. The aim of this protocol is to increase energy efficiency and at the same time achieve a high level of stability and scalability. But, per-hop fairness and latency of the system decreases. Its main feature is periodic listen and sleep pattern [4]. Each node sets a wake-up timer and goes to sleep for the specified interval of time. At the expiration of the timer, the node wakes up and listens to its neighboring nodes and determines whether there is a need to communicate with other nodes. The total listen and sleep interval is referred to as a frame. Each frame is characterized by its duty cycle, defined as the ratio of listening interval to frame length. The periodic sleep and listen scheme is shown in Fig. 1.

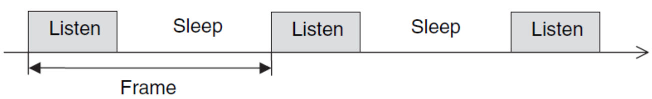

Fig. 1. Sleep and listen cycle of S-MAC [4].

It is preferable for the nodes to schedule its sleep wake cycle with its neighbors in order to reduce the control overhead necessary to achieve communications between these nodes. To coordinate their sleep and listen pattern, each node selects a schedule and exchanges it with its neighbors during the synchronization period. A schedule table is maintained by each node which contains the schedule of all its known neighbors [4].

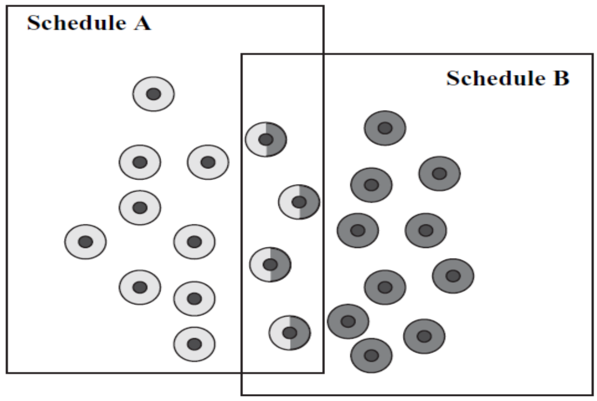

Fig. 2. Border node schedule selection and synchronization [4].

To select a schedule, a node first listens to the channel for a fixed amount of time and if the node does not hear a schedule from another node, it immediately chooses its own schedule and broadcasts SYNC packets to all its neighbors announce its schedule. If the node receives a schedule from a neighbor before choosing and announcing its own schedule, the node sets its schedule to be the same as the schedule received and announce it in the next synchronization period. If the node is aware of other neighboring nodes that have already adopted its schedule, then it adopts both the schedules. Then the node adaptively wakes up at the listen intervals of the both the schedules. This is shown in Fig. 2.

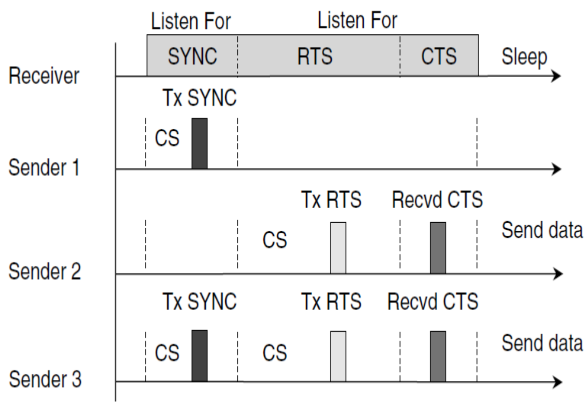

Fig. 3. Timing difference between a receiver and different senders [4].

For a node to receive both DATA packets and SYNC packets, the listen interval is divided into two subintervals as depicted in Fig. 3. The channel is accessed by contending nodes during the subintervals regulated using a multi slotted contention window. A contending station randomly selects a time slot after performs carrier sensing and starts sending its packet if it detects that the channel is idle. RTS/CTS handshake is used to access the channel and this process guarantees that the neighboring nodes receive the transmitted packets which include both the SYNC and DATA packets.

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If a sensor is to follow its sleep schedule strictly, data packets may be delayed at each hop. In order to avoid this adaptive listening is used. Based on this, a node in a system adapts to the sleep wake cycle according to the available resources [4]. S-MAC uses a CSMA/CA-based procedure which includes both physical and virtual carrier sensing. RTS/CTS handshake is used to reduce the hidden and exposed terminal problems. Physical carrier sensing is performed by listening to the channel to detect ongoing transmission. Virtual carrier sensing is achieved with the help of the network allocation vector (NAV) which is initially, set to value equal to the value carried in the duration field of the packet transmitted. This value is decremented each time the channel is free and once it reaches zero, a node initiates its own transmission plan [4]. Virtual carrier sensing may result in packet overhearing and in order to avoid this S-MAC allows nodes to move into sleep mode after they hear the exchange of an RTS or a CTS packet between two other nodes. They also activate their NAV timer and remain in sleep mode until NAV value reaches zero and this shown in Fig. 4.

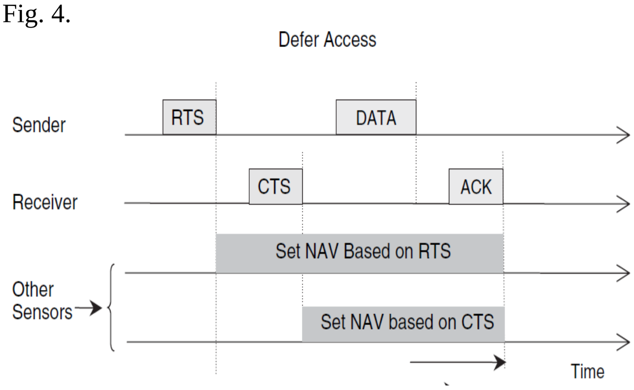

Fig. 4. S-MAC collision avoidance scheme [4].

S-MAC introduces the concept of message passing, where each message is divided into small fragments and these fragments are then transmitted in a single burst. The fragments of a message are transmitted using a single RTS/CTS exchange between the sending and receiving nodes. At the completion of this exchange, the medium is reserved for the time necessary to complete the transfer of the entire message successfully. The mechanism is shown in Fig. 5.

V. State of the Art

The word cross layer was first used in [5] where cross layer optimization was done in scatternet of Bluetooth for link formation, IP routing and service discovery to reduce power consumption by putting nodes to sleep when they are inactive.

A. Cross layer involving Physical and MAC layers

Zhiwei Zhao et.al [6] propose PSMAC, a transmission Power control in S-MAC, in which the transmission range of the nodes are adjusted by controlling the transmission power. It gives a physical–MAC cross layer design. In this paper the ideal transmission power in synchronization period is assessed since the overhead of assessing the ideal transmission power is very little. For this, the transmission power of the nodes are divided into five different levels each

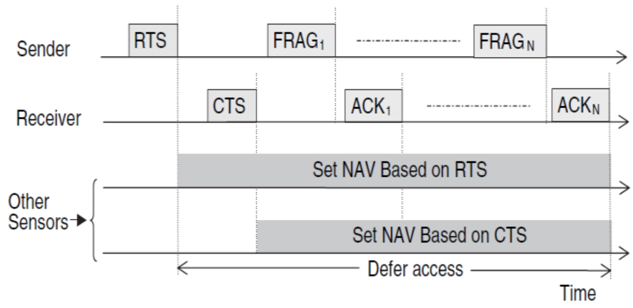

Fig. 5. Message passing mechanism in S-MAC [4].

indicating different transmission range. In the synchronization period, each of the nodes transmits the SYNC packets with the maximum transmission power. When a node receives a SYNC packet from its neighbor, it calculates the power intensity of the receiving SYNC packet according to the RSSI readings which is used to obtain the ideal transmission power which is added to the neighbor list of all the nodes. For unicast messages the nodes use the ideal transmission power while for broadcast messages they use maximum transmission power. In [7], a new improved MAC protocol is designed based on cross-layer architecture. Here nodes can switch their transmission mode adaptively according to the interface queue length. It is an intra layer cross layer design which involves the MAC layer. If the interface queue is above a threshold, it starts continual data transmission where a node broadcasts SYNC packet in each schedule to its neighbors. In the first stage of the scheme the node will transmit data in the data period of listen duration of one cycle and goes to sleep in next cycle while in second stage the node will keep awake and continue to send packets to its neighbors. When the sender activates the continual data transmission mode, the values of maximum contention windows both for SYNC packets and data packets are reduced to the half of their original values; while those of other nodes working in normal mode remain unchanged. This shows that graded window schemes is adaptive to continual data transmission. Small contention windows can shorten the duration of carrier sense, and hence reduce the energy consumed in listening.The authors in [8] provide an enhancement in S-MAC protocol by utilizing the information from physical layer. This paper proposes an Announce To Send (ATS) mechanism which reduces the problem of idle listening. Here each node proactively informs its neighbor nodes about its transmission plan in the current frame. This mechanism broadcasts ATS packets which are dummy packets whenever the node wants to transmit any packets. If a node is not transmitting any packets, it starts a timer and listens to the channel. The timer stops if the node senses any packet. Otherwise it expires and continues with the usual S-MAC protocol.

B. Cross layer involving MAC and Network layers

The authors in [9] developed a cross layer design involving routing and MAC layer. This scheme constructs multiple data collection trees and the S-MAC protocol make these different trees wake up and sleep at different times.

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Here each tree is assigned an unique schedule within the frame unlike in other systems where each node is assigned an unique schedule within the frame. A formal cost function is used in the construction of multiple trees and it tries to reduce the cost function of the system. Care was taken by the authors to ensure that schedule of two nodes does not overlap for optimum performance, and to find an optimum schedule was an NP hard problem. This information exchange reduces congestion, improve delivery ratio, and optimize energy usage of the system.

Yuexia Hou et.al [10] present an Event-Driven Sensor MAC protocol (ED-SMAC), a cross-layer protocol for Event-Driven WSNs. It is a cross layer design which involves MAC and network layers. The network layer defines two statuses: regular status and event status. On regular status the nodes work with the normal S-MAC protocol which reduces energy consumption of the system. On event status, sensor nodes detect a specific event in the network, and the information of the event must be transmitted to the sink node immediately which consumes much energy. So in order to reduce energy consumption, an event based cross layer deign involving a cluster formation algorithm is proposed. The data arrival rate is monitored to detect a specific event. Under this, only one cluster head is formed based on the remaining energy when an event occurs and this information is given to MAC layer. As a result the nodes that didn't detect the event will set go to sleep for an estimated time. When the cluster head node receives no data, then the specific event ends and the cluster is dissolved and hence it will broadcasts a cluster OVER message which results in the nodes to return to the regular status.

The authors in [11] introduce a Sensor-MAC with Dynamic Duty Cycle (SMAC-DDC), a new MAC protocol that adjusts the duty cycle of sensor nodes according to the network traffic of the system. When a node has a small duty cycle, it remains in the sleep mode for a longer time, which increases the latency and at the same time reduces the total number of packets delivered to the sink. To avoid this, the routing protocol informs the MAC protocol whether a node belongs to the route or not. Based on this information, the MAC protocol increases the duty cycle of the nodes that belong to the route and decreases the duty cycle of the nodes which are not a part of the route. First, the source node sends an exploratory packet towards sink node to create the route. To this, the sink node sends a positive reinforcement to define the nodes that belong to the route used in data delivery. When the node receives a positive reinforcement packet, it increases its duty cycle. In order to delete a route, the sink node sends a negative reinforcement and hence when the node receives a negative reinforcement, it decreases the duty cycle.

C. Cross layer involving MAC and Application layers

The authors in [12] propose a MAC-application cross layer design in which each node uses the semantic technology to know the meaning of data. As a result nodes can directly process and transmit application. Here nodes decide whether they should transmit or process data. This reduces the redundancy of data and hence decreases the energy consumption. The cluster header aggregates the applications finished by the nodes. First the cluster head broadcast information regarding task to all the nodes. Nodes on receiving the information check whether they can participate in the task. If they can't participate they go back to sleep mode to save energy. Otherwise they will transmit Task transmission request packet. On receiving the Task transmission request packet, the cluster head checks whether the particular node can participate in the task. If it is possible, it will merge the IDs of all nodes taking part in the task and sent this to all the participating nodes. On receiving this response the nodes will start is task. The MAC protocols employing application semantics can decrease the energy consumption rate by more than 20% as the nodes can go to sleep according to application semantics.

VI. Metrics for Performance Evaluation

All metrics that have influence on performance and energy consumption of wireless sensor networks should be evaluated in a system [3]. The main goal for most of the optimization methods is to optimize energy consumption. The metrics used for performance evaluation are:

i. Energy consumption: which include submetrics such as total energy consumption (in some time interval), average energy consumption per received packet or per node
ii. Network lifetime: which is the time until first node fail
iii. Packet delivery ratio: which is the ratio of number of total packets successfully received to the number of total packets sent
iv. Average packet delay: which is the average time taken by the packets to reach its destination
v. Routing overhead: which is the number of routing bytes required by the routing protocols to construct and maintain routes
vi. Throughput: which is the average rate of successful packet delivery per amount of time
vii. Average delay: which is the difference between the time at which the sender generated the packet and the time at which the receiver received the packet
viii. Response time: which is calculated for event driven sensor networks
ix. Total data aggregation: which is the ratio of amount of information sensed to the amount of the power consumed by all nodes
x. Standard deviation: which is the difference between energy levels of a node before and after cluster formation
xi. Sampling frequency: which is the number of samples taken by each sensor per second.

VII. Conclusion

Even though Cross layer design can improve the system performance, it has some disadvantages like:

i. Unintended Cross-Layer Interaction: The creation of new interactions among layers can cause unforeseen dependencies which may not be predicted through simulations since practical applications may have unforeseen scenarios.
ii. Stability: Stability of the system decreases with cross layer optimization since random variation occurs at the application and physical layers. Hence performance of any cross layer design must be carefully characterized against these system variations, which is tedious.

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iii. Long-term Sustainability: Cross-layer design affects the modularity of any system, since each layer depends on non-standard interfaces with other layers. Therefore without careful consideration, a change made at any given layer could affect the working of any other layer [31].

Wireless communication is quickly becoming the dominant mode of data transfer as wireless network has several advantages over the wired technologies like flexibility, mobility, cheaper and faster deployment, easier maintenance and upgrade procedures [30]. Layered approach in communication systems design is not suitable for wireless communications due to the random nature of the wireless channel, which makes way to cross-layer design. This paper presents a basic idea of cross layer optimization, need for it and presents the state of the art of cross layer designs involving S-MAC. Along with it some metrics for performance evaluation are also listed. Using cross-layer design, researchers are creating better and smarter communication systems, which are configured according to application requirements in order to meet specific optimization goals.

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