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A comprehensive study of Medium Access Control Protocols in Wireless Sensor Network

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Abstract: Wireless Sensor Networks (WSNs) have a broad range of applications. Since sensor nodes are battery powered and have therefore limited energy resource, keeping the network operational over long periods of time is challenging. Replacement of the batteries on sensor nodes is either highly cumbersome or impractical. In most of the WSN applications, the major expenditure on energy consumption comes from data communication. Therefore, energy efficient communication, especially the role of Medium Access Control (MAC) protocols becomes very important. Generally, traffic load in WSNs is very small and therefore the radio does not necessarily need to be active all the time. In an ideal case for conserving energy, sensor nodes switch on the radios only for data transmission/reception and turn them off when there is no traffic in the network. While it is easy to define when data transmission is required, reception is usually unpredictable to a sensor node. Sensor nodes therefore, need to listen to the channel periodically in anticipation of potential packets.

Introduction

Recent Wireless sensor networks have attracted a considerable attention from thev researchers in the recent past as described in previous chapters in this book. Though the initial impetus came from military applications, the advancements in the field of pervasive computing have led to possibilities of a wide range of civilian, environmental, bio-medical, industrial and other applications. In order to practically realize such networks, Medium access control (MAC) is one of the basic protocol functionality that has to be appropriately defined.

The wireless medium being inherently broadcast in nature and hence prone to interferences requires highly optimized medium access control (MAC) protocols. This holds particularly true for wireless sensor networks (WSNs) consisting of a large amount of miniaturized battery-powered wireless networked sensors required to operate for years with no human intervention. There has hence been a growing interest on understanding and optimizing WSN MAC protocols in recent years, where the limited and constrained resources have driven research towards primarily reducing energy consumption of MAC functionalities. In this paper, we provide a comprehensive state-of-the-art study in which we thoroughly expose the prime focus of WSN MAC protocols, design guidelines that inspired these protocols, as well as drawbacks and shortcomings of the existing solutions and how existing and emerging technology will influence future solutions.

Sensor networks have been researched and deployed for decades; their wireless extension, however, has witnessed a tremendous upsurge in recent years. This is mainly attributed to the unprecedented operating conditions of wireless sensor networks (WSNs). As of today, a major problem in deploying WSNs is their dependence on limited battery power. A main design criterion is to extend the lifetime of the network without jeopardizing reliable and efficient communications from sensor nodes to other nodes as well as data sinks. A prominent example of today's non-optimized WSN deployment experiences is that the start-up alone costs the network a third of its battery power .

Optimizing every facet of the communication protocols is therefore vital and imperative. Such stringent design requirements can be met by a plethora of approaches, e.g. using crosslayer design paradigms, collaborative protocols, etc. This has led to copious novel distributed signal processing algorithms, energy-efficient medium access control and fault-tolerant routing protocols, self-organizing and self-healing sensor network mechanisms, reliable data aggregation algorithms, etc.

The Medium Access Control (MAC) layer sits directly on top of the Physical layer and controls the radio. MAC protocols for sensor-nets focus on energy efficiency (single most important goal) instead of meeting traditional goals for wireless

MAC design such as fairness, delay, and bandwidth utilization . These protocols tradeoff performance (fairness, delay, bandwidth utilization) for energy cost. Main sources of energy wastage at the MAC layer are collisions, idle listening, overhearing, and control packet overhead. Unlike the 802.11 WLAN cards where the MAC is usually included as part of the chipset, in sensor-nets the MAC designer has absolute control on the MAC layer design. This absolute control, and the fact that the wireless interface is the primary consumer of battery in energy constrained sensor-nets, has made “medium access for sensor networks” a very active research area. However, recent studies on MAC protocols for sensor-nets observe that there is no clear trend indicating that medium access for sensor-nets is converging towards a unique best solution .

Nodes in a sensor network are spatially distributed autonomous devices that co-operate among themselves through unattended, short-range communication to fulfil bigger tasks that single node couldn’t. The nodes are self-organizing and constitutes a multi hop network that transmit the time series of sensed phenomenon to sink where computations are performed and data are fused.

A node in a sensor network constitutes of four main components:

a) Sensing devices (one or many): These are radio frequency modules that work on half duplex mode of communication for the purpose of data acquisition.

b) Transceiver: It’s a low power transceiver or other wireless communication device for communication between the nodes in the sensing field. It can also have some moderate amount of memory.

c) Embedded processor: The data being collected by the sensor nodes from the sensing field is first processed locally before its delivery to the sink. For this purpose of local data processing the embedded processors are included in the composition.

d) Energy source: The energy is the major concern for the functioning and the lifetime of the sensor networks. Thus an efficient battery source is required for efficient working of WSN.

Overview of a Wireless Sensor Networks Communication Architecture

WSN is a rapidly emerging field with a lot of applications in real world scenario. With the advancement of software and the underlying hardware components i.e. the micro-electronic components, the sensor networks are proving to be applicable for a large number of subjects. A number of autonomous sensor nodes are deployed in difficult or possibly unreachable terrains to monitor the desired physical or chemical phenomenon.

The communication process is controlled and managed by the MAC protocols. Due to the small size and the hardware constraints sensor networks usually face some problems regarding energy efficiency. Wireless sensor networks consist of individual nodes that are able to interact with the environment by sensing or controlling physical parameters. These nodes have to collaborate to fulfill their tasks. The nodes are interlinked together and by using wireless links each node is able to communicate and collaborate with each other.

Sensor nodes

Sensor nodes are the network components that will be sensing and delivering the data. Depending on the routing algorithms used, sensor nodes will initiate transmission according to measures and/or a query originated from the Task Manager. According to the system application requirements, nodes may do some computations. After computations, it can pass its data to its neighboring nodes or simply pass the data as it is to the Task Manager. The sensor node can act as a source or sink/actuator in the sensor field. The definition of a source is to sense and deliver the desired information (see Figure 1). Hence, a source reports the state of the environment. On the other hand, a sink/actuator is a node that is interested in some information a sensor in the network might be able to deliver.

Gateways

Gateways allow the scientists/system managers to interface Motes to personal computers (PCs), personal digital assistants (PDAs), Internet and existing networks and protocols. In a nutshell, gateways act as a proxy for the sensor network on the Internet. According to [1], gateways can be classified as active, passive, and hybrid. Active gateway allows the sensor nodes to actively send its data to the gateway server. Passive gateway operates by sending a request to sensor nodes. Hybrid gateway combines capabilities of the active and passive gateways.

Task Managers

The Task Manager will connect to the gateways via some media like Internet or satellite link . Task Managers comprise of data service and client data browsing and processing. These Task Managers can be visualized as the information retrieval and processing platform. All information (raw, filtered, processed) data coming from sensor nodes is stored in the task managers for analysis. Users can use any display interface (i.e. PDA, computers) to retrieve/analyze these information locally or remotely

Communications Protocols in Wireless Sensor Networks

This subsection continues survey the MAC protocols that are developed for the wireless sensor networks. After this review, an appropriate MAC protocol will be preliminary recommended for this project for our application purpose. MAC protocols control how sensor nodes access a shared radio channel to communicate with neighbors. Traditionally, this problem is known as the channel allocation or multiple access problems. Though MAC protocols have been extensively studied in traditional areas of wireless voice and data communications (e.g. Time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA) [4], ALOHA [5] and carrier sense multiple access (CSMA) sensor networks requirements of a MAC protocols differ from these traditional wireless voice or data networks in several ways. First of all, most nodes in sensor networks are likely to be battery powered and it is often very difficult to change batteries for all the nodes. Second, nodes are often deployed in an ad-hoc fashion rather with careful pre-planning.

Hence after deployment, the sensor nodes must quickly organized themselves into a communication network. Third, many applications employ large numbers of nodes. Finally, most traffic in the network is triggered by sensing events, and it can be extremely bursty. All these characteristics suggest that traditional MAC protocols proposed for the past wireless networks are not suitable for wireless sensor networks without modifications . The design of MAC protocols in wireless sensor network depends on the expected traffic load patterns in the application context. For example, if a wireless sensor network is deployed to continuously observe a physical phenomenon like time dependent temperature distribution in a forest, a continuous and low load with significant fraction of periodic traffic can be expected. On the hand, if the goal is to wait for occurrence of an important event and upon its occurrence to report as much data as possible, the network is close to idle for a long time and then is faced with bulk of packets that are to be delivered quickly.

Since this project is designed to detect extreme event (e.g. to forecast flooding), the system thus has to remain operational for months or years while only sensing if a flood has started. Once a flooding is detected, this information must be forwarded to the system management quickly and accurately. Based on the project application requirement, CSMA based MAC protocol is a preferred choice as compared to the TDMA based protocols due to the following reasons: • TDMA based protocols needs control channels to send scheduling messages to each sensor node in order for each node to get the right time slot, the control message overhead is high, and may wait a lot of energy; also in a small and cheap sensor node, it will be very difficult to implement separate communication channels. • TDMA based protocols needs very actuate time synchronization requirements; For a small and cheap sensor node like the available from the current technology, it is still very difficult to achieve the very actuate time synchronization between the neighboring nodes; on the other hand, for CSMA based contention protocols, no actuate requirements for the time synchronizations between the node. Due to the above two major reasons, CSMA based MAC protocols are recommended for the usage in this project application. A review has been done on the MAC layer protocols designed for wireless sensor networks.

Medium Access Control Protocols in WSN

Medium Access Control (MAC) protocols that have been designed for typical ad hoc networks have primarily focused on optimizing fairness and throughput efficiency, with less emphasis on energy conservation. However, the energy constraint is typically considered paramount for wireless sensor networks, and so many MAC protocols have recently been designed that tailor themselves specifically to the characteristics of sensor networks. Protocols such as MACAW and IEEE 802. However, it has been shown that idle power consumption can be of the same order as the transmit and receive power consumption, and if so, can greatly affect overall power consumption, especially in networks with relatively low traffic rates. Thus, the focus of most MAC protocols for sensor networks is to reduce this idle power consumption by setting the sensor radios into a sleep state as often as possible.

Sensor-MAC

(S-MAC) S-MAC was one of the first MAC protocols to be designed for sensor networks]. The basic idea behind SMAC is very simple — nodes create a sleep schedule for themselves that determines at what times to activate their receivers (typically 1 − 10% of a frame) and when to set themselves into a sleep mode. Neighboring nodes are not necessarily required to synchronize sleep schedules, although this will help to reduce overhead However, they must at least share their sleep schedule information with others through the transmission of periodic SYNC packets. When a source node wishes to send a packet to a destination node, it waits until the destination's wakeup period and sends the packet using CSMA with collision avoidance. S-MAC also incorporates a message passing mechanism, in which long packets are broken into fragments, which are sent and acknowledged successively following the initial RTS-CTS exchange. In addition to avoiding lengthy retransmissions, fragmentation helps address the hidden node problem, as fragmented data packets and ACKs can serve the purposes of the RTS and CTS packets for nodes that wake up in the middle of a transmission, having missed the original RTS-CTS exchange.

Timeout-MAC (T-MAC)

Several protocols have been developed based on S-MAC that offer solutions for various deficiencies and limitations of the original S-MAC protocol. T-MAC seeks to eliminate idle energy further by adaptively setting the length of the active portion of the frames [15]. Rather than allowing messages to be sent throughout a predetermined active period, as in S-MAC, messages are transmitted in bursts at the beginning of the frame. If no "activation events" have occurred after a certain length of time, the nodes set their radios into sleep mode until the next scheduled active frame. "Activation events" include the firing of the frame timer or any radio activity, including received or transmitted data, the sensing of radio communication, or the knowledge of neighboring sensors' data exchanges, implied through overheard RTS and CTS packets. An example of how T-MAC works is shown for a transmission from node A to node E in Since nodes D and E cannot hear node A's transmissions, they timeout after a delay of TA. The end-to-end transmission from A to E is resumed during the next active period. The gains achieved by T-MAC are due to the fact that S-MAC may require its active period to be longer than necessary to accommodate traffic on the network with a given latency bound. While the duty cycle can always be tuned down, this will not account for bursts of data that can often occur in sensor networks (e.g., following the detection of an event by many surrounding neighboring sensors).

DMAC

As many wireless sensor networks consist of data gathering trees rooted at a single data sink, the direction of packets arriving at a node, if not the arrival times, are fairly stable and predictable. DMAC takes advantage of this by staggering the wakeup times for nodes based on their distance from the data sink . By staggering the wakeup times in such a way, DMAC reduces the large delays that can be observed in packets that are forwarded for more than a few hops when synchronizing schedules as in S-MAC and T-MAC. The wakeup scheme consists of a receiving period and send period, each of length μ (set to accommodate a single transmission), followed by a long sleep period. Nodes on the data gathering tree begin their receiving period after an offset of $d * \mu$, where d represents the node's depth on the tree. In this way, a node's receiving period lines up with its upstream neighbor's send period and a node simply sends during downstream neighbors' receive periods, as shown in . Contention within a sending period is accomplished through a simple random back off scheme, after which a node sends its packet without a preceding RTS-CTS exchange.

Traffic-Adaptive Medium Access (TRAMA)

While the aforementioned protocols attempt to minimize power consumption by reducing the time that the radio remains in the idle state, TRAMA attempts to reduce wasted energy consumption caused by packet collisions. Nodes initially exchange neighborhood information with each other during a contention period via a Neighbor Protocol (NP) so that each node has knowledge of all two-hop neighbors. These random access periods are followed by scheduled access periods, where nodes transmit schedule information via the Schedule Exchange Protocol (SEP) as well as actual data packets. Using the neighbor information acquired using NP and the traffic schedule information acquired using SEP, nodes determine their radio state using the Adaptive Election Algorithm (AEA). In AEA, each node calculates a priority for itself and all two-hop neighbors for the current slot using a hashing function. If a node has the highest priority for that slot and has data to send, it wins that slot and sends its data. If one of its neighbors has the highest priority and the node determines that it should be the intended receiver through information acquired during SEP, it sets itself to the receive mode. Otherwise, it is able to sleep and conserve energy. Since two nodes within the two-hop neighborhood of a node may consider themselves slot winners if they are hidden from each other, nodes must keep track of an Alternate Winner, as well as the Absolute Winner for a given time slot, so that messages are not lost. For example, consider a node N who determines that the Absolute Winner for a time slot is one of its two hop neighbors N2−hop. If a one-hop neighbor N1−hop who does not know of N2−hop believes that it has won the slot, and wishes to send to N, N must stay awake even though it does not consider N1−hop to have won the slot. Since a node may win more slots than necessary to empty its transmission buffer, some slots may remain unused that could have been used by nodes who won too few slots. To accommodate for this, the Adaptive Election Algorithm assigns priorities for the unused slots to the nodes needing extra slots. 2.5 Sparse Topology and Energy Management (STEM) In the case of many sensor network applications, it is expected that nodes will continuously sense the environment, but transmit data to a base station very infrequently or only when an event of interest has occurred. In STEM, all sensors are left in a sleep state while monitoring the environment but not sending data and are only activated when traffic is generated. In other words, transceivers are activated reactively rather than proactively, as with the other MAC protocols described in this section. When data packets are generated, the sensor generating the traffic uses a paging channel (separate from the data channel) to awaken its downstream neighbors. Two versions of STEM have been proposed—STEM-T, which uses a tone on a separate channel to wake neighboring nodes, and STEM-B, in which the traffic generating node sends beacons on a paging channel and sleeping nodes turn on their radios with a low duty cycle to receive the messages (the paging channel simply consists of synchronized time slots within the main communication channel). While STEMT guarantees that minimal delay will be met (since receivers are turned on nearly instantaneously after data is generated), it requires more overhead than STEM-B since the receivers on the channel where the tones are sent must be idle listening all of the time. Also, STEM-T may require extra hardware as a separate radio is needed for this channel.

Conclusions

When designing network protocols for wireless sensor networks, several factors should be considered. First and foremost, because of the scarce energy resources, routing decisions should be guided by some awareness of the energy resources in the network. Furthermore, sensor networks are unique from general ad hoc networks in that communication channels often exist between events and sinks, rather than between individual source nodes and sinks. The sink node(s) are typically more interested in an overall description of the environment, rather than explicit readings from the individual sensor devices. Thus, communication in sensor networks is typically referred to as data-centric, rather than address-centric, and data may be aggregated locally rather than having all raw data sent to the sink(s).

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