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Analysing And Designing Energy Efficiency In Wireless Sensor Networks

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Abstract

Wireless Sensor Networks are battery-operated computing and sensing devices, mainly used for environmental monitoring, wild life management, industrial process monitoring, and battle fields. Energy efficiency is one of the fundamental research themes while designing wireless sensor network nodes. Efficient medium access control (MAC) protocols are needed to achieve energy savings along with low latency, low power and high throughput in wireless sensor networks. Energy-efficient MAC protocols applied for WSNs can be classified into two main categories: contention-based and schedule-based protocols, according to their wireless media access strategy. At present there are plenty of MAC protocols available for WSNs in literature but the main aim is minimizing the energy consumption so that the lifetime is increased. This paper summarizes the key requirements for MAC protocol and also analysing and designing energy consumption in wireless sensor networks.

Key words: TDMA, wireless sensor, S-MAC, T-MAC, R-MAC.

1. Introduction

A wireless sensor network has become a hot area of research in recent years. As the sensor nodes are very cheap, large number of sensor nodes can be used for many applications [1]. The application of sensor networks includes environmental monitoring, military operations, surveillance, home security, earthquake monitoring, industrial machine monitoring and detection of forest fires. Each sensor node has computing, sensing and communication capabilities. These nodes which can be randomly distributed to the observed medium, able to recognize each other and realize the measurement in a wide area together.

The four states of sensor nodes are: transmit, receive, idle and sleep. However most of the energy is consumed in transmitting and receiving, energy consumption in sleep mode is very less [2]. In clustering network, nodes are grouped into clusters and every cluster has cluster head. Clustering methods are more attractive to save energy in efficient way. Medium Access Control (MAC) layer has direct access to the radio control making responsible for energy consumption, because sensor nodes are battery powered [3][4]. The battery has limited capacity and generally impractical to be replaced or recharged, due to cost constraints. MAC protocols also responsible for throughput, latency and fairness.

2. Related work

Many energy-efficient MAC protocols have been proposed in literature which is classified into two main categories, contention-based protocols [5][6][7] and TDMA-based protocols [8][9]. The contention based MAC protocols are the most suitable for wireless sensor networks due to their self-organizing nature and fairly good scalability while TDMA based MAC protocols provide excellent trade-offs between energy savings and throughput performance. In TDMA based protocols, the nodes are assumed to be synchronized and access the communication channel by scheduling and reservation of time slots. Such protocols by nature preserve energy as they have duty cycle built-in and an inherent collision-free medium access.

The major problems in TDMA based protocols consist in their high complexity due to non-trivial problem of synchronization in WSNs. TDMA based protocols do not support node changes and inclusion of new nodes and also managing inter-cluster communication is a difficult task. Each of the MAC protocols has advantages and disadvantages, and there is no general agreement on which one is the best for Sensor Networks. Some protocols appear to perform better in some applications and other protocols may be well suited in other situations.

The idea is to minimize the total power consumption of the network, finding an optimum number of channels that depends upon the relation between the power consumption of the transmitter and the power consumption of the receiver. If the transmitter has bigger power consumption, TDMA is preferred. The main characteristics of WSNs protocols are:

2.1 Idle listening

Idle listening occurs when a station listening an inactive medium. For example Chipcon CC2420 transceiver of 250 kbps [10] node can transmit 4.1ms energy. Suppose a node can transmit and receive one 10ms message every second, then listening an idle channel for the remaining 980ms that means idle time is 98% . As many wireless sensor radios consume more energy in idle listening than normal transmissions, many energy efficient MAC protocols have been developed to reduce energy in idle listening. There are four techniques to reduce idle listening. They are: static sleep scheduling, dynamic sleep scheduling, preamble scheduling and off-line scheduling.

2.1.1 Static sleep scheduling. S-MAC protocol [5] designed to increase network life time, every frame is divided into listen and sleep period. Listen period is further divided into synchronization period and data transfer period. The nodes periodically announce their sleep schedules thereby increasing 10% network life time. In sleep period a node listen for a SYNC message from its neighbor. That means the sender intends to sleep in t seconds. When a node hears its other nodes schedules, it adopts the same schedule and retransmits the schedule for other nodes to adopt. Within the time period, if a node does not hear any SYNC message then the node will set and broadcast its own sleep schedule.

2.1.2 Dynamic sleep schedule. T-MAC [7] protocol introduces a listening timeout mechanism by dynamically adapting an active listen period in response to network traffic to improve idle listening overhead. In TMAC the nodes go to sleep as soon as all network traffic has completed. TMAC adapts a time out TA mechanism the longest period in which the hidden node would have to wait before hearing the first bit of CTS message. TMAC effectively divides the number of messages into smaller time frame thereby reduce idle time. Suppose a node is waiting a timeout period without sensing any traffic, the node goes to sleep until the next scheduling time.

2.1.3 Preamble scheduling. Berkeley-MAC [11] and WiseMAC [12] approach to organize sleep schedules by allowing nodes to adopt sleep schedule with fixed sleeping cycle frequency. Both the approaches use low power listening (LPL) method. if a node senses activity, it wakes up, synchronizes and receives the packet. In BMAC authors have used MICA Mote for their experiments in which a sender must transmit a preamble length greater than each node's sampling cycle to ensure that the node is awake for synchronization. This strategy is used to reduce idle listening but works well in networks with scarce traffic. Wise MAC is the improvement of BMAC in which instead of sending a long preamble, they can send a standard one during receiver's sensing time period. The control packet overhead is reduced by keeping every node's sleeping schedule in all other packet's header. The main problem is that the multicast messages must span the entire frame.

2.1.4 Offline scheduling. Traffic-Adaptive MAC (TRAMA) is a schedule-based protocol [13] that optimizes power savings during inactive periods by introducing Scheduling Exchange Protocol (SEP) and Neighbor Protocol [NP] release unused timeslots for reuse. TRAMA uses an Adaptive Election Algorithm (AEA) to randomly assign timeslots. TRAMA establishes collision-free data transfer to maximize sleep time for effective utilization of channel utilization and minimize latencies.

TRAMA frame is divided into contention and contention-free time periods. The contention period is used to exchange control messages to synchronize time and establish data transmission requirements. Contention-free period is for collision-free transmissions of all scheduled packets. Nodes with no activity may sleep during this time period.

The Neighbor Protocol (NP) creates the 2-hop neighborhood for every node for local synchronization, indicates the number of nodes added to and deleted from the sending node's neighbor database. TRAMA to establish a 99% [14] probability of successful transmission. For example, Given M number of 2-hop neighbors, a frame needs to retransmit an individual packet seven times over a retransmission interval T = 1.44* M signal slots. Sensor network radios transmit extremely limited data rates on the order of 250 kbps [10]; therefore, frame sizes may be on the order of 25msec.

The Schedule Exchange Protocol (SEP) allots time slot for each individual packet. SEP saves energy by allowing nodes with no data to send or receive to sleep during the contention-free period and increases data throughput by reallocating empty timeslots for reuse.

The Adaptive Election Algorithm schedules the transmitters for a given time rendering to the neighbourhood and schedule information exchanged in NP and SEP. The time slot of the node priority can be calculated for each of its contending 2-hop neighbouring nodes for every time slot. With the time slot t and the node's identification number k, AES uses the hash function for priority.

Priority(k,t) = hash(k concat t)

The highest priority node has the opportunity to transmit data in that time slot or give it up for reuse. If the highest priority node gives up the time slot, then the next highest priority node that announced a scheduled requirement will transmit during the time slot. But the main drawback of TRAMA is the protocol uses excessive control packets to exchange control packets. That means TRAMA faces more overhead.

2.2. Frame collisions

When a wireless sensor node sends a MAC protocol frame, or message, which collides in time with another message frame, collision occurs. In most single-channel radios, the radio cannot simultaneously receive while in transmit mode and the message sender's only indication of a collision is the absence of a message acknowledgement from the receiver node. Finite radio receive-to-transmit transition times ranging from 250 µs to 500 µs after sensing a clear channel; propagation delays between distant stations; and hidden nodes which are out of range of the sender, are the leading causes for wireless frame collisions.

SMAC and TMAC protocols use contention and RTS-CTS exchanges to reduce collisions. BMAC offers RTS-CTS as an option available to the application and both the messages contain duration period of the transmission exchange. BMAC protocol significantly reduces the frame collisions after the initial RTS has seized the channel.

2.3. Protocol overhead

Generally, wireless protocol overhead consumes both energy and bandwidth and the networks serve as an integrated system to transfer data between distributed application layer programs, but maintaining a network and providing reliable data delivery requires tradeoffs in effective throughput and energy efficiency. Adding data message headers and 2-to-1 Manchester encoding to the RFM TR1001 [15] transceiver reduces an effective 60% [16] reduction. Standard error detection and correction codes double the data size to add redundant data information in each message for corrupted data recovery. By adding the forward error correction (FEC) overhead significantly reduces the application data rate, but prevents costly retransmissions in noisy channels.

2.4. Message Overhearing

Receiving and discarding messages projected for other nodes is called message overhearing. Receiving all messages is an efficient method will increase throughput and decrease latency specifically in cases where the radio receive mode expends more energy than the transmission mode. Energy-efficient techniques used to reduce message overhearing include early rejection and message passing. Early rejection allows a sensor node to turn off its radio once it has read the destination field for an incoming unicast message or for a broadcast message. Message passing technique permits nodes to schedule a sleep period during an overheard RTS-CTS handshake sequence and this technique is implemented in SMAC and TMAC. Power consumption model for receive mode power-down mode for CC2420 and CC1000 is given in table 1.

Table 1 Current Consumption

Radio	**Receive Mode**	**Power-down mode**
CC2420 [4]	19.7 A	1 A
CC1000 [4]	9.6 A	0.2 A

2.5 Node energy capacity

IEEE 802.15.4 WSN transceiver platforms operates on two AA batteries and can achieve approximately 3000mAh assuming a 2.1 volt cutoff and a 20mA slow drain application [17]. The energy consumption rates for the devices in receive, transmit, and sleep modes are experimentally measured as average current consumption rate and the lifetime capacity of a node is set to 3 Amp-hours or 10.8 x 10 mA-seconds.

3. Designing energy efficiency

3.1. Energy consumption

Main constraint on sensor network is that sensors rely on batteries. As sensors used in large numbers it will be difficult to change or recharge batteries in the sensors. A classical energy model was proposed by [18], consists of low power consumption radio. Energy consumption for different states is given in table 2.

Table 2 Energy consumption model

Radio Mode	**Energy Consumption**
Transmitter Electronics ($E_{Tx\text{-}elec}$) Receiver Electronics ($E_{Rx\text{-}elec}$) $Eelec = E_{Tx\text{-}elec} = E_{Rx\text{-}elec}$	50nJ/bit
Transmitter Amplifier (E_{amp})	100 pJ/bit/m^2
Idle (E_{idle})	40nJ/bit
Sleep	0

Energy used in transmitting or receiving one bit is found by using power value, i.e.

Energy = power * time.

The energy consumption of Mica2 is the sum of energy transmitting, receiving, listening, sampling and sleeping [19]. The calculation of energy in transmitting and receiving one bit is given as:

Energy = Current * Voltage * Time.

It is possible to estimate sensor network lifetime for different protocols as per different states are known. Suppose, several nodes running simultaneously then calculations would be different due to the flooding effect inherent to the protocol. It is possible to find an upper limit for the energy consumption of the motes, Maria Gabriela shown in his experiment the life time of the battery.

According to [16][20], a node send a packet every 80msec every, packet will take 9msec for sending and receiving. When a node receives a packet it will retransmit immediately. Let B is the bakeoff time, time to switch to radio mode is STx, ie. 250 µsec, Time to transmit a frame is Txt and Srx be the time to switch to receive mode. Then Time Frame can be calculated as:

TF = B + STx + Txt + Srx.

If Rxt is the time taken to receive a frame, then the time cycle can be calculated as,

T = B + 2STx + Rxt + Txt.

Typical sources of energy loss wireless sensor networks include idle listening, packet collisions, protocol overhead, and message overhearing.

Energy efficiency is defined as the ratio of throughput verses energy consumed [13].

Energy Efficiency = Throughput / Energy consumed.

Total energy consumption = Total throughput /Total energy consumption.

Energy consumption in ordinary sensor node is computed as follows:

Sensing energy energy Es: the energy used to activate sensing circuitry within the node. The magnitude of this energy depends on task that is assigned to the sensor.

Transmitter energy Et: the energy needed for transmission of data. It is depending on transmitter power, size, and the data transfer rate.

Receiver energy Er: a sensor node also responsible to receiving packets from other nodes.

Computation energy Ec: sensor processing unit must be activated to process the circuitries. The total energy Etot is computed as follows.

Etot = Es + Et + Er + Ec.

Energy claculation in Election Phase: The distance d between a cluster head CH and base station BS for long distance l is given by ld. The energy consumed to transmit b bits of message E_{trl} is given by:

$$E_{trl} = b * E_{elec} + b * E_{amp} * ld. \quad (1)$$

Where E_{amp} is the energy consumed by amplifier and E_{elec} is energy consumed by Electronic circuit. Energy consumed for transmission with b bits of message E_{trs} for shorter distance sd is given by:

$$E_{trs} = b * E_{elec} + b * E_{fs} * sd. \quad (2)$$

Where E_{fs} is Energy consumed in short distance by the amplifier. Energy consumed to receive b bits of message E_{rc} is given by:

$$E_{rc} = b * E_{elec}. \quad (3)$$

Normally all the sensor nodes have same amount of energy and energy consumption is same for all the clusters. In token bus algorithm, each cluster head broadcast an advertisement message to the rest of the nodes. When all non-cluster nodes receive this advertisement message, they decide where they want to go.

Let number of sensor nodes is n and c is the clusters, then totally n/c nodes in each cluster. The energy consumed by cluster head CH from equations (2) & (3) is given by:

$$\mathrm{Ech} = b * \mathrm{Eelec} + b * \mathrm{Efs} * \mathrm{sd} + \{(n/c - 1) * (b * \mathrm{Eelec})\}. \qquad (4)$$

Energy consumed by non-cluster head Enc is given by:

$$\mathrm{Enc} = (K * b * \mathrm{Eelec}) + \{(b * \mathrm{Efs} * \mathrm{sd}) + (b * \mathrm{Eelec})\}. \qquad (5)$$

Energy consumed to receive messages from the remaining nodes that are not part of the group of cluster head [14] is given by:

$$\mathrm{Enrc} = (n/c - 1) * (\mathrm{Eelec} + \mathrm{Eag}). \qquad (6)$$

Where E_{ag} is the energy consumed during data aggregation. Generally at the time of data transfer, the nodes transfer messages to cluster head and cluster head transfer the messages to base station. The total energy consumed by cluster head from equation (1) and (6) is given by:

$$E_{cht} = (b * E_{elec} + b * E_{amp} * ld) + \{(n/c - 1) * (E_{elec} + E_{ag})\}. \qquad (7)$$

Normally the sensor nodes sense the environment and transmit data to the cluster heads. The cluster head receive all the data and aggregates it before sending it to the base station. Aggregation is needed only in data transfer phase not in election phase [14].

4. Results and discussion

We use Castalia 3.0 in OMNET++ [21][22] software to simulate the three MAC protocols under same scenario. Every node except sink collects information and sends messages to the sink node through several hops. We have done different tests to measure energy consumption. Figure 3 shows the energy consumption of S-MAC, L-MAC and T-MAC protocols. It shows that S-MAC uses more energy than L-MAC and T-MAC. It is seen that when message inter arrival time increases T-MAC can save more energy than S-MAC and L-MAC protocols due to idle listening.

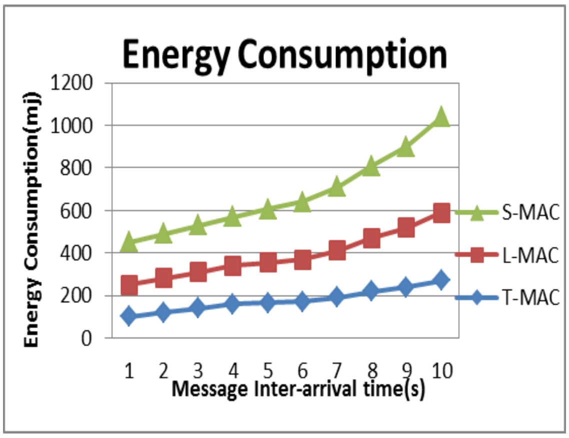

Fig. 3 Energy consumption in S-MAC, T-MAC and SMAC

5. Summary and future work

In this paper we have analyzed and designed energy efficiency in wireless sensor networks. Medium Access Control (MAC) layer has direct access to the radio control making responsible for energy consumption. The main objective is to minimize the energy consumption and to maximize the life span of sensor nodes. The classical energy model was proposed, used in election algorithm. In future the proposed can be used to test the existing protocols and the results must be compared using different simulators.

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