Design an Energy Efficient MAC protocol for Wireless Sensor Networks

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Abstract
This paper is based on designing proposed algorithms that worked on star topology and with simulate with the single hop architecture. So that, the work can be focused on different topologies, multi-hop that provides better results in terms of energy efficiency.

Keywords: WSN, MAC, energy, sensor;

Introduction

Wireless Sensor Networks: When large numbers of sensors are attached with the controllers and organizing stations directly, an enhancing number of sensors exchange the gathered data wirelessly to a centralized organizing station. It is must because numerous network applications need many hundreds of sensor nodes usually deploy in far and unreachable places. Hence a wireless sensor contains not just a sensing component, although on-board managing, communication and data storage activities too. As many sensors coordinately observe a large physical area, a wireless sensor network is formed. Sensor nodes not only communicate with one another, they also communicate to the base station also with their wireless radios, permitting them to distribute their sensor data to distant processing, analysis, mining and storage systems[1]. For instance, fig. 1.1 displays two sensor field supervising the two various geographic areas and linking to the internet with their base stations.

Fig.1 Wireless Sensor Networks

The abilities of sensor nodes vary broadly that is to monitor a single physical phenomenon, a simple sensor node is required, although complex devices combine various sensing techniques (e.g. magnetic, electric, acoustic, optical etc.). They perform different communication abilities, like using infrared, radio frequency or ultrasound techniques having different latencies and data rates. Simple sensor can only gather and transform information about the observed environment, while strong devices (i.e. devices having large energy, storage and processing capabilities) can also perform massive processing and collective functions. These devices are usually supposed to have additional responsibilities in WSN, for instance they have communication backbones which is used by further resource-constrained sensors to get to the base station [1].

According to Smart Dust Program of Defence Advanced Projects Agency(DARPA), WSN is defined as , “A sensor network consists of huge numbers of small, inexpensive, self-sustained device which can compute, sense and communicate with further devices for the goal of gathering local information which makes global decisions about a physical environment”[2].

Till today studied WSN is known as remarkable technologies for 21st century. Empowered by current advances in micro electromechanical systems(MEMS) and wireless communication technologies, small, economical, smart sensors employed in physical areas and networking with wireless links and the internet gives flawless opportunities for a huge number of civilian and military applications, i.e. environmental observing, battlefield monitoring and industry process[3][4][5][6][7][8]. Unique characteristics of WSN are denser level of node implementation, larger unreliability of sensor nodes and major energy calculations and energy storage constraints, which introduces various new challenges in the growth and applications of WSNs. From past few years, WSN has attained huge glory from academic and industry all over the world[9]. A very clarifying initial definition of a WSN is proposed by Hill [10]. The equation:

Sensing + CPU + Radio = Thousands of potential applications

(1.1)

The above equation defines accurately that tiny embedded electronic system with wireless capabilities can provide wide range of application to sense different physical quantities (Temperature, Vibrations or light). In a WSN a large number of sensor nodes transmit information with each other using wireless communication. Sensor nodes are tiny embedded device having low computational and memory capacity. These sensor nodes are used to transport the collected sensor data in a network [2].

Literature Review

Raja Vara Prasad Y, RajalakshmiPachamuthu (2014) [11], well analysedReliability and delay of a single cluster wireless network in the literature. Multi-hop communication is essential to scale the network over the number of clusters. Analytical model for
reliability and end-to-end delay optimization for multi-hop clustered network is presented in this paper. Proposed model is a three dimensional markov chain. Model assumes wakeup rates for each cluster. Results show that reliability and delay have significantly improved than previous analytical models proposed. It has been observed that the overall reliability of multi-hop link is improved, with reduction in end-to-end delay is reduced even at lower wakeup rates of a cluster.

Rahul R Lanjewar, Dr D S Adane (2014) [12], discussed the different MAC layer protocols. Whenever we are talking about MAC layer protocols we need to give stress on energy efficiency factor. There are few other issues like high throughputs and delay. In the early development stages, designers were mostly concerned with energy efficiency because sensor nodes are usually limited in power supply. Recently, new protocols are being developed to provide multi-task support and efficient delivery of bursty traffic. Therefore, research attention has turned back to throughput and delay. Designing an efficient MAC layer protocol is an important task as it coordinates all the nodes to share the wireless medium. In [13] classification of MAC layer protocols is carried out in four categories viz. Asynchronous, Synchronous, Frame-Slotted and Multichannel. We are carrying the same classification. In our survey we have compared different MAC protocols in terms of energy efficiency, data delivery efficiency, and overhead to maintain a protocol along with their advantages and disadvantages.

Simone Brienzo, Domenico De Guglielmo (2013) [14], discussed that recent studies have shown the IEEE 802.15.4 MAC protocol may suffer from severe limitations if CSMA/CA parameter settings are not appropriate, in terms of reliability and energy efficiency. On the other hand, choosing the setting that guarantees the application requirements with minimum energy usage may not be a small task in a real environment, where the operating conditions change over time. In this paper they have proposed Learning based Adaptive Parameter tuning (LEAP) algorithm that, in addition to adapting the CSMA/CA parameter settings to the time-variant operating conditions, also exploits the past history to figure out the most appropriate settings for the current conditions. Simulation results show that, in stationary conditions, the performance of the proposed algorithm is very close to an ideal (but unfeasible) algorithm. It is shown that LEAP is able to select the optimal settings faster than related algorithms in dynamic scenarios.

Vaddina PrakashRao and Dimitri Marandin (2006) [15], did a study of the backoff exponent (BE) management in CSMA–CA for 802.15.4 is conducted. The Bes determines the number of backoff periods the device shall wait before accessing the channel. The power consumption requirements make CSMA–CA use fewer Bes which increase the probability of devices choosing identical Bes and as a result wait for the same number of backoff periods in some cases. This inefficiency degrades system performance at congestion scenarios, by bringing in more collisions. This paper addresses the problem by proposing an efficient management of Bes based on a decision criterion. As a result of the implementation potential packet collisions with other devices are restricted.

Zigbee is a promising new wireless technology in the home/industrial automation field. With its promises of reliable short range communications at low data rates, and ultra low power consumption, it has created a market for itself. However, minor inefficiencies do not allow it to display its ultimate capability. One such problem (the inefficient backoff management) is addressed here, and a workaround (ABE) has been introduced. Also, results indicate the percentage of improvement that can be obtained by applying ABE.

Tijs van Dam, Koen Langendoen (2003) [16], described T-MAC, a contention-based Medium Access Control protocol for wireless sensor networks. Applications for these networks have some characteristics (low message rate, insensitivity to latency) that can be exploited to reduce energy consumption by introducing an active/sleep duty cycle. To handle load variations in time and the location T-MAC introduces an adaptive duty cycle in a novel way: by dynamically ending the active part of it. This reduces the amount of energy wasted on idle listening in which nodes wait for potentially incoming messages, while still maintaining a reasonable throughput. We discuss the design of T-MAC, and provide a head-to-head comparison with classic CSMA (no duty cycle) and S-MAC through extensive simulations. Under homogeneous load, T-MAC and S-MAC achieve similar reductions in energy consumption (up to 98 %) compared to CSMA. In a sample scenario with variable load, however, T-MAC outperforms S-MAC by a factor of 5. Initial energy consumption measurements provide insight into the internal workings of the T-MAC protocol.

Wei Ye, John S. Heidemann, and Deborah Estrin (2002) [17], proposes S-MAC, a medium-access control (MAC) protocol designed for wireless sensor networks. Wireless sensor networks use battery-operated computing and sensing devices. A network of these devices will collaborate for a common application such as environmental monitoring. We expect sensor networks to be deployed in an ad hoc fashion, with individual nodes remaining largely inactive for long periods of time, but then becoming suddenly active when something is detected. These characteristics of sensor networks and applications motivate a MAC that is different from traditional wireless MACs such as IEEE 802.11 in almost every way: energy conservation and self-configuration are primary goals, while peer-node fairness and latency are less important. S-MAC uses three novel techniques to reduce energy consumption and support self-configuration. To reduce energy consumption in listening to an idle channel, nodes periodically sleep. Neighbouring nodes form virtual clusters to auto-synchronize on sleep schedules. Inspired by PAMAS, S-MAC also sets the radio to sleep during transmissions of other nodes. Unlike PAMAS, it only uses in-channel signaling. Finally, S-MAC applies message passing to reduce contention latency for sensor-network applications that require store-and-forward processing as data move through the network. We evaluate our implementation of S-MAC over a sample sensor node, the Mote, developed at University of California, Berkeley. The experiment results show that, on a source node, an 802.11-like MAC consumes 2–6 times more energy than S-MAC for traffic load with messages sent every 1–10s.
Problem Statement:
The sole purpose of this thesis is design and development of a novel energy efficient MAC algorithm without losing other performance parameters so that one can communicate at longer distances with minimum energy consumption. In this thesis two MAC algorithms are taken. As in WSN, the MAC algorithms are application specific. So we simulate the existing algorithms on Castalia simulator for SHM application for 100 to 1000 nodes and check which algorithm is best suitable for SHM application in terms of energy.

Simulation of MAC Algorithm
Energy Efficiency in MAC Protocol: Energy Efficiency is the main problem in WSN. We have to investigate Sensor Node energy consumption for optimizing the energy efficiency. The energy is consumed by four modules of sensor node, a processing unit, a radio communication system, memory and sensing device. The passive sensor does not consume energy. The active sensor may have its own energy source. If we compare computation energy with communication energy then its ratio is 1:190. So we can conclude that most of energy is consumed by the communication devices.

Radio device have four modes of operation, Transmitting (Tx), Receiving (Rx), Idle Listening, Sleeping. The energy of Transmission and receiving node is given by eq. 4.1

\[
\text{Energy} = (m \times \text{Packet Size}) + b
\]

Where, b is State transition energy consumption

m is transmitting and Receiving energy consumption

SMAC Protocol: S-MAC protocol is a contention-based protocol which is designed to optimize energy efficiency for the WSNs. S-MAC has algorithm to reduce an energy consumption without useful. S-MAC has investigated four causes of waste energy.

i. An idle listening in contention-based MAC protocol.
ii. A packet collision.
iii. An overhearing is an event that a sensor node receive packet belong to other sensor node.
iv. A control packet transmission.

To optimize energy efficiency, S-MAC has an algorithm to reduce waste energy. Firstly, S-MAC uses a period of sleep and listen for solving the idle listening problem. S-MAC assumes the WSNs are low data traffic network that a transmission occurs only when an event is detected. A sensor node can sleep for the most of time to save energy and wake up for a short period to synchronize with the network. The S-MAC cycle time is shown in figure 2. S-MAC nodes have their own sleep/wake period which is called “schedule”. The adjacent may use same schedule in the order to reduce control packet overhead. For transmitting data, S-MAC node is necessary to know a schedule of destination node.

A schedule exchanging is done by broadcasting synchronize (SYNC) packet. All S-MAC nodes broadcast their SYNC packet on every their listen period. At the first time after sensor nodes are deployed to an operating area, all sensor nodes will listen to a medium in the order to receive SYNC packet from their adjacent node. If S-MAC nodes receive SYNC packet then they follow the schedule that attached in the SYNC packet. If S-MAC node does not receive any SYNC packet then it will generate own schedule and broadcast to the network. The S-MAC nodes which generate the SYNC packet are known as “synchronizer node”. The S-MAC nodes which receive SYNC packet from synchronizer node are known as “follower node”. A “border node” is a synchronizer node that receives a different schedule form SYNC packet. The border node is necessary to active on every schedule which it knows. For it is possible to have a multi schedules for a large network hence a large network is divided to a virtual cluster. The virtual cluster is a group of sensor node which use same schedule. S-MAC uses an IEEE 802.11 DCF mode to prevent a collision and an overhearing. A RTS/CTS/DATA/ACK mechanism is preferred to manage a data transmission. All of packets contain an estimate transmission time which receiving node uses to set a network allocation vector (NAV) timer. The virtual sensing is done by observing at NAV timer. The running of NAV means that some adjacent nodes are transmitting then it necessary to keep quite till that transmission end. The sensor nodes have to operate the virtual sensing and the carrier sensing before transmission. S-MAC has also proposed a message passing algorithm to prevent the control packet transmission problem. The Message passing algorithm breaks a data packet to small fragment to increase a successful rate. All of data fragments are transmitted in only one RTC/CTS exchanging. The message passing has been developed from MANET algorithm that the RTS/CTS exchanging is done for every data fragment.

An Energy/Delay Trade-Off in S-MAC Protocol: Because of a sleep period, a data transmission is necessary to wait for both communication peers waking up. The waiting time is called a “sleep delay time”. The sleep delay time is proportional to a number of data hop. For a large network, a sleep delay causes the network to slowly transmit. If the probability of packet transmission is equal then we can use equation 4.2 to estimate the sleep delay time.

\[
D_s = \frac{T_{frame}}{2}
\]

\[
T_{frame} = T_{listen} + T_{sleep}
\]

Ds is a sleep delay time. If we increase a sleep period thus we can save more energy but the sleep delay time is also increased. The sleep period is use to indicate an energy saving, as you can see in equation 4.3.

\[
E_s = \frac{T_{sleep}}{T_{frame}} - 1 = 1 - \frac{T_{listen}}{T_{frame}}
\]
Normally $E_s$ is less than one. It indicate that the energy is less consumed when compare with no sleep period.

**TMAC Protocol: Above** Figure shows the basic scheme of the T-MAC protocol. Every node periodically wakes up to communicate with its neighbors, and then go to sleep again until the next frame. Meanwhile, new messages are queued. Nodes communicate with each other using a Request-To-Send (RTS), Clear-To-Send (CTS), Data, Acknowledgement (ACK) scheme, which provides both collision avoidance and reliable transmission\(^{[83]}\). This scheme is well known and used, for example, in the IEEE 802.11 standard. A node will keep listening and potentially transmitting, as long as it is in an active period. An active period ends when no *activation event* has occurred for a time $TA$. An activation event is:

i. the firing of a periodic frame timer;
ii. the reception of any data on the radio;
iii. the sensing of communication(through RSSI from the radio) on the radio, e.g. during a collision;
iv. the end-of-transmission of a node’s own data packet or acknowledgement;
v. the knowledge, through overhearing prior RTS and CTS packets, that a data exchange of a neighbor has ended.

A node will sleep if it is not in an active period. Consequently, $TA$ determines the minimal amount of idle listening per frame. The described timeout scheme moves all communication to a burst at the beginning of the frame. Since messages between active times must be buffered, the buffer capacity determines an upper bound on the maximum frame time.

Calculation $TA$ - A node should not go to sleep while its neighbors are still communicating, since it may be the receiver of a subsequent message. Receiving the start of the RTS or CTS packet from a neighbor is enough to trigger a renewed interval $TA$. Since a node may not hear, because it is not in range, the RTS that starts a communication with its neighbor, the interval $TA$ must be long enough to receive at least the start of the CTS packet. This observation gives us a lower limit on the length of the interval $TA$:

$$TA > C + R + T \quad (4.4)$$

Where $C$ is the length of the contention interval, $R$ is the length of an RTS packet, and $T$ is the turn-around time (the short time between the end of the RTS packet and the beginning of the CTS packet).

**Simulation Setup**

To explore the results, we conduct a detailed simulation using a Castalia 3.2 designed for Wireless Sensor Networks (WSN), Body Area Networks (BAN), and generally networks of low-power embedded devices. In our simulation no of sensors from 100 to 1000 are scattered over the 100 meter Bridge Test, one of the SHM application. Other simulation parameters are listed in Table 1. The resource manager module of Castalia is responsible to calculate amount of energy used in different operations like transmission, reception etc. The default value is 18720 joules. It is a typical energy of AA battery. Energy is linearly subtracted based on overall power drawn and time passed. Modules that model hardware devices (i.e., the radio and the sensor manager) send messages to the resource manager in order to signal how much power they currently draw. Energy consumption by radio module is separately defined by Castalia. To define the main operating parameters of a radio, Castalia follows a specific format. Castalia defines 2 radios: CC1000 and CC2420. CC2420 and CC1000 define the real-radios of the same name by Texas Instruments.

![Diagram of Basic Data Exchange](image)

**Fig 3:** A Basic Data Exchange. Node C overhears the CTS from Node B and will not disturb the communication between A and B. $TA$ must be Long enough for C to hear the start of CTS.

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Application Name</td>
<td>100 meter Bridge Test, SHM Application</td>
</tr>
<tr>
<td>2</td>
<td>Simulation Time</td>
<td>100 s</td>
</tr>
<tr>
<td>3</td>
<td>X axis</td>
<td>100 m</td>
</tr>
<tr>
<td>4</td>
<td>Y axis</td>
<td>20 m</td>
</tr>
<tr>
<td>5</td>
<td>No of sensor nodes</td>
<td>100</td>
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<tr>
<td>6</td>
<td>Deployment Type</td>
<td>Grid, [0]→center, 3 x 3</td>
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<tr>
<td>7</td>
<td>Routing Protocols</td>
<td>Gpsr, Multihop, Range, No Routing, Leach</td>
</tr>
<tr>
<td>8</td>
<td>Sink Node</td>
<td>Node 0</td>
</tr>
<tr>
<td>9</td>
<td>Radio Type</td>
<td>CC2420</td>
</tr>
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</table>

Table 1: Simulation Parameters

**Results and Analysis:** In this section various MAC protocols are considered to find out the average energy consumption by varying the no of nodes with SHM application.

**AVERAGE ENERGY CONSUMPTION FOR 100 M BRIDGE TEST WITH ALL MAC ALGORITHMS BY VARYING NO OF NODES**
Table 2: Average Energy Consumption for 100 m Bridge Test with all MAC Algorithms

<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>TMAC</th>
<th>SMAC</th>
<th>justCarrierSenseMAC</th>
<th>BypassMAC</th>
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</thead>
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<tr>
<td>100</td>
<td>2.063</td>
<td>1.427</td>
<td>6.788</td>
<td>6.796</td>
</tr>
<tr>
<td>150</td>
<td>2.066</td>
<td>1.429</td>
<td>6.797</td>
<td>6.797</td>
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<tr>
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<td>1.435</td>
<td>6.794</td>
<td>6.798</td>
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<tr>
<td>250</td>
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<td>1.448</td>
<td>6.798</td>
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<tr>
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</tbody>
</table>

Fig 4: Average Energy Consumption for TMAC with 100 m Bridge Test by varying no of nodes

The result of above graph shows that TMAC protocol shows best performance with 310 nodes by considering 100 m Bridge test application of Structural Health Monitoring (SHM) with average 2.077 unit of energy. The worst case is with 250 nodes having average energy consumption 6.683 unit.

Fig 5: Average Energy Consumption for SMAC with 100 m Bridge Test by varying no of nodes

The result of above graph shows that SMAC protocol shows best performance with 799 nodes by considering 100 m Bridge test application of Structural Health Monitoring (SHM) with average 1.464 unit of energy. The worst case is with 100 nodes having average energy consumption 1.677 units.

Fig 6: Average Energy Consumption for justCarrierSenseMAC with 100 m Bridge Test by varying no of nodes

The result of above graph shows that justCarrierSenseMAC protocol shows best performance with 100 nodes by considering 100 m Bridge test application of Structural Health Monitoring (SHM) with average 6.788 unit of energy. There is no significant difference with all remaining no of nodes.

Fig 7: Average Energy Consumption for BypassMAC with 100 m Bridge Test by varying no of nodes

The result of above graph shows that Bypass MAC protocol shows best performance with 250 nodes by considering 100 m Bridge test application of Structural Health Monitoring (SHM) with average 6.792 unit of energy. There is no significant difference with all remaining no of nodes.

COMPARISON OF AVERAGE ENERGY CONSUMPTION FOR DIFFERENT MAC ALGORITHMS WITH 100 M BRIDGE TEST BY VARYING NO OF NODES
After analysis of the above graphs it is clear that the average energy consumption of SMAC protocol with 100 m Bridge SHM application is minimum among all other MAC protocols such that TMAC, justCarrierSenseMAC, Bypass MAC.

**Conclusion**

After comparison of different MAC Protocols, with 100 meter Bridge SHM Application, by varying the no of nodes from 100 to 1000, it is concluded that the SMAC is the best energy saving MAC scheme.

**Scope for Future Work**

As the new proposed algorithms worked on star topology and with simulate with the single hop architecture. So in future, the work can be focused on different topologies, multi-hop. Also in future if the Improved ZIGBEE MAC algorithm is dumped on MSP430F5438A (Texas instrument) board then the proposed algorithm would give better results in terms of energy efficiency. The Improved ZIGBEEMAC Algorithm shall also be used in real life scenarios like structural health monitoring, underground mining, critical health care etc. And for SHM application using WSN, our work can be implemented on real bridges.

**References:**


[17]. A.Nikolidakis, DimitriosD.Vergaods “A performance evaluation of S-MAC protocol in combination with energy efficient protocols for WSN”