New Approach for Media Access in Wireless Sensor Networks

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Abstract

As the nodes in Wireless Sensor Networks (WSNs) have limited power, energy conservation is essential at different layers of the protocol stack to prolong their lifetime. In our previous work, Priority based Slot Allocation for media access in Wireless Sensor Networks (PSAWSN), the probability based priority scheme is used to allocate slots to competing nodes. Limitations of this work include 1) It does not handle dynamic and variable slot allocation based on the varying requirements of nodes. 2) Error control and flow control are not taken into account. To overcome some of these limitations, we propose "New Approach for Media Access in Wireless Sensor Networks" (NAMWSN) that generates Priority Index (PI) to allocate varying slots based on parameters: node energy (NE), number of requests (NR), message length (ML) and message urgency (MU). Simulation results for energy efficiency, throughput and dynamic slot allocation show an improved performance for various message sizes and error conditions.

Keywords: MAC, message length, energy efficiency, and message urgency;

1 Introduction

Energy conservation for prolonging network lifetime in WSN makes traditional MAC protocols unsuitable for WSNs. To coordinate and control access to shared medium, we have assumed node with higher energy known as 'Manager Node (MN)'. The MN after considering the requests and the messages with different priorities and lengths, generates the PI for each node based on which slots are allocated to each node. To access shared medium, there are different number of requests being received from different nodes with their own residual energy component, and messages with different priorities and lengths. Sometimes the MN receives urgent messages from nodes indicating that priority should be given to such nodes. To handle such a dynamic situation, there needs to be a common Observation Period (OP) during which these requests are considered by MN. Dynamic slots are allocated by the manager based on the requirements.

Sensor nodes are typically battery-powered and should operate without attendance for a relatively long time where it is very difficult and even impossible to change or recharge batteries for the sensor nodes [1]. The parameters:NE,NR,ML and MU affect the way the PI is generated. PI is then used by the MN to allocate media slots. The paper is organized as follows. Section II describes Media access control using PI with models for all the listed parameters. Section III talks about priority decision making system. Section IV describes PI generation. Section V describes simulation parameters. Section VI talks about the results and finally, the section VII concludes the paper with mention of future work.

1.1 Related Works

The work proposed in [2] describes full duplex techinque with significant energy and delay gains compared to normal MAC protocol. This scheme provides two slots that are simultaneously available; one for upload and the other for download. Full duplex nodes outperform half duplex nodes both in terms of energy and delay. In the work [3], researchers proposed a contention based MAC protocol that attempts to reduce the impact of hidden and exposed nodes thus minimizing the energy consumption. The duration of the listen period is normally fixed depending on physical and MAC layer parameters. The duration of sleep period can be changed according to different application requirements, which actually changes the duty cycle [4]. In [5], the researchers attempt to dynamically adjust sleep, wakeup cycle times based on the current energy consumption level and the average latency experienced. However sleep, wake up scheduling incurs an additional delay for packet delivery when a node needs to wait for its next hop relay node to wake up that could be unacceptable for delay sensitive applications [6]. Traditional approach to message length optimization involves point to point link where the goal is to make sure a successful and efficient transmission mechanism based on efficiency metrics [7]. In WSN, the generated traffic is directly related to the physical phenomenon being sensed and the characteristics of the sensors [8]. It can be observed that an increase in payload length decreases the MAC failure rate [9]. There is an increase in energy efficiency with smaller messages. But message length is a substantial parameter in Wireless Multimedia Sensor Network (WMSN). In this case, larger the length, the higher is the throughput [10]. In controlling access to shared medium, the number of requests from nodes also plays an important role in deciding the slot allocation. In this regard, one of the ways to resolve contention is to describe these request events by the Poisson probability distribution function and compute request probability [11]. Researchers in [12] have proposed a hybrid MAC protocol that tackles emergency response requirements using parent child relationships among the nodes and allows synchronized loose slot structure so that the nodes can modify schedules locally. The works mentioned above do not consider the combination of listed parameters (NE, ML, NR, and MU) to reduce energy consumption in WSNs. The proposed scheme (NAMWSN) employs all these parameters to generate PI for media access control thus increasing network lifetime.

1.2 Our Contributions

The proposed approach (NAMWSN) is inspired by examining the distinctive drawbacks of existing schemes. The work proposed in this paper is an extension of our previous work, PSAWSN [11] to handle dynamic slot allocation with detailed functioning of the scheme. In this paper our contributions are : 1) Defining and demonstrating the listed parameters. 2) Building model for each parameter. 3) Generating static and dynamic slots for each contending node based on the listed parameters. 4) Analysis of energy consumption, throughput and average server utilization. 5) Simulation tests and results analysis.

2 Media Access Control using Priority Index

This section begins with the demonstration of models for each listed parameter.

2.1 Energy Model

As transmitting one bit of information requires more energy than processing the same bit, sensor node needs to reduce the number of redundant transactions as far as possible. Time to send or receive n-bit message is given in the equation 1.

$$T = S/B \tag{1}$$

where S is the message size and B is the bandwidth. Energy consumed for various operations also depends on the model of sensor node (for e.g. μAMPS, Mica2 motes etc.). The MIT microAdaptive Multidomain Power-aware Sensor (μAMPS) concentrates on low-power hardware and software including microcontrollers capable of dynamic voltage scaling in order to reduce power consumption [13]. The μAMPS uses transmission rate of 1Mbps with the characteristics summarized in table I. The

Table 1: Classification of Node Energy for μAMPS

Radio Mode	Power
Transmit	1040 mW
Receive	400 mW
Idle	400 mW
Sleep	0 mW

time required to send/receive one bit with transmission rate of 1Mbps is 1μsec. Energy consumed can be expressed as shown in equation 2

$$E = Power \times Time \tag{2}$$

By using equation 2 and referring to Power value (1040mW) against Radio Mode 'Transmit' in table I, the energy for transmitting one bit is computed as 1.04μJ/bit. Similarly, the energy required to receive one bit is 0.4μJ/bit. Each node in WSN has its own initial energy and every operation costs some energy leaving the node with residual energy (E_{Res}) categorized as low, medium, moderate and high depending on the percentage of energy left in the node as shown in table II. We have assumed

Table 2: Classification of Node Energy

Energy	% of Energy	Description
Low	0-25	Transmit 240 messages
Medium	25-50	Transmit 480 messages
Moderate	50-75	Transmit 721 messages
High	75-100	Transmit 961E03 messages

initial energy ($E_{Initial}$) of $2J$ in each node, a channel bandwidth of 500Kbps and a fixed message size of 1000 bits to arrive at the number of transmissions and receptions possible with a specific range of (as depicted in table II) E_{Res}. The time to transmit or receive one packet is calculated to be $2msec$ by using equation 1. The energy required to transmit one packet is computed as $2.08mJ$. Similarly, the energy required to receive one packet is calculated as $0.8\mu J$. For low range, E_{Res} is assumed to be 0 to 25 percentage of $E_{Initial}$. As $2.08mJ$ of energy is required to transmit one packet, the maximum number of packets that can be transmitted with 0.5J is computed as 240. Similarly, the maximum number of packets that can be received with 0.5J of energy is $625E03$. In this case, a sensor node can either transmit 240 packets or receive 625E03 packets. For medium range, E_{Res} is assumed in the range of 25 to 50 percentage of $E_{Initial}$ (i.e 50% of 2J = 1J). The maximum number of packets that can be transmitted with 1J of energy is 480. Accordingly, the maximum number of packets that can be received with 1J (E_{Res}) of energy is $1250E03$. In this case, a sensor node can either transmit 480 packets or receive 1250E03 packets. In the moderate range, E_{Res} is assumed to be 50 to 75 percentage of $E_{Initial}$ (i.e 75% of 2J = 1.5J). In this case, the possible number of transmitted packets (Tx_{max}) in 1.5J are 721. Similarly, the maximum number of packets that can be received (Rx_{max}) with 1.5J of energy is $1875E03$. In this case, a sensor node can either transmit 721 packets or receive 1875E03 packets. In the high range, E_{Res} is assumed to be in the range of 75 to 100 percentage of $E_{Initial}$ (100% of $E_{Initial}$ is 2J). In this case, the maximum number of packets that can be transmitted (Tx_{max}) with 2J of energy is computed to be $961E03$. Accordingly, the maximum number of packets that can be received with 2J of energy is calculated to be $2500E03$. Here, the number of transmitted and received packets is more compared to all the other cases. Usually, in all the cases (Low, Medium, Moderate and High), number of messages transmitted is less than the number of messages received. This is because the power required to receive one packet is less than that required to transmit one packet of same length.

2.2 Model for Message Length

The larger the message size, the higher is the rate of collision due to the fact that MAC layer frame size is settled by assuming a fixed traffic. The probability that a message (L bits long) is received successfully (P_s) at the receiver is given in equation 3.

$$P_s = (1 - BER)^L \tag{3}$$

where Bit Error Rate (BER) is the percentage of bits in error to the total number of bits transmitted, received or processed in a given time. The Packet Error Rate (PER) is expressed in terms of P_s in equation 4.

$$PER = (1 - P_s) \tag{4}$$

PER is defined as the ratio of the number of packets that are not received successfully to the total number of packets sent. The throughput T_{put} can be computed in terms of message length and PER by using the equation 5.

$$T_{put} = L \times (1 - PER)/D \tag{5}$$

where D is end to end latency. The larger the message size, the higher is the latency. Based on the size of the message, the message length is categorized as Smallest, Smaller, Medium and Large as shown in table III. The smallest message consists of control information. Other messages can carry

Table 3: Classification of Message Length

Message	Message Contents
Smallest	Control information
Smaller	Control information and Data
Medium	Control information and Data
Large	Control information and Data

data along with control information if required.

2.3 Model for Number of Requests

The number of requests from the competing nodes can be significant in determining the order in which the nodes can access the shared medium. The requests coming from each node can be used to find request probability that can further be applied to compute the priority. The number of requests in a particular period of time can be modelled by Poisson distribution. The probability distribution of a Poisson random variable X representing the number of events occurring in a given time is given in equation 6.

$$P(X) = \frac{e^{-\mu}\mu^x}{x!} \tag{6}$$

where x is the number of requests in question, e=2.718,and μ is the mean number of requests. The priority that allows a node to access the medium can be found out by using equation 7.

$$Priority = [1 - P(X)]c \tag{7}$$

where $P(X)$ is the request probability and c is a constant. As the number of requests from the node increases, so does it's request probability, thus higher is the priority to access the medium and the preference would be given to that node by MN in allocating the media slot. These numbers of requests vary from node to node and can be classified as shown in table IV.

Table 4: Classification of Number of Requests

RequestType	Range (No of Requests)
Smaller	5 to 10
Medium	10 to 15
Moderate	15 to 20
High	20 to 25

2.4 Model for Message Urgency

In real time applications of WSNs, some critical findings need to be notified faster and this message should have some kind of information distinguishing it from other normal messages. Usually the first few bits in the message represent the priority bits indicating urgency. The purpose of these bits is to convey that this message needs to be delivered in time. We have assumed a single bit (Flag) at the beginning of a message to indicate whether a message is urgent or not. If the Flag is '1' then the message is urgent as shown in figure 1. where Data is the actual payload and TR is the trailer used for

Flag	Data	TR

Figure 1: Message Format

error control. A node with urgent data would be given highest priority by the MN in allocating slot.

3 Priority Decision Making System

Priority Decision Making System (PDMS) acts like an expert system that makes use of expert knowledge to make decisions by reasoning about the knowledge represented primarily as if-then rules on the left side and the corresponding actions at the right side. In this scheme, the combination of all the parameters at the left hand side will lead to some kind of action on the right hand side (as shown in equation 8) that help MN analyze and generate the PI.

$$P1UP2U...UPn = A_i \tag{8}$$

where P1,P2,...Pn are listed parameters and A_i is the corresponding action for ith combination of parameters. The frame format used by PDMS is shown in the figure 2. where MU is 1 for urgent

NE	ML	NR	MU

Figure 2: Frame format for making decisions

data. To demonstrate PDMS, we have considered six combinations of parameters leading to six corresponding interpretations that MN uses to generate PI as shown in table V. Each entry in table

Table 5: Rules and Interpretations table

NR	ML	NE	MU	Interpretation and Decision
3	4	4	1	Urg large msg - longer slot on priority
4	2	3	1	Urg msg, high reqs - shorter slot on priority
4	2	1	1	Urg msg, low NE - shorter slot on priority
2	1	2	0	Smaller reqs, low NE - shorter slot
1	3	4	0	Smaller reqs, high NE - shorter slot
3	4	4	0	Large msg, high NE - longer slot

V indicates the range of parameters. MN considers all these combinations and interpretations for a period of time called observation period (OP) shown in figure 3 to generate PI. For instance, for the last row in table V, MN allocates a longer slot because it has large message to transmit and also contains sustainable energy for this operation.

OP	PI	...

Figure 3: Time Frame Format

4 Priority Index Generation with Case studies

In static slot allocation, MN uses fixed numbers associated with each node for various message lengths to generate PI. In case of dynamic slot allocation, the manager considers the various combinations of listed parameters to generate PI. The PI is then used to decide on the slot (shorter or longer) allocation.

4.1 Case 1: Static Slot Allocation

In static slot allocation, the slots to be allocated to the nodes are fixed. Each node in this scheme is associated with messages of different ranges of lengths as shown in table VI. Each entry in the table VI indicates the number of messages that can be exchanged among the nodes. MN uses these fixed numbers as inputs to equation 9 to generate PI for each node.

$$P_j = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(a_i)^2} \tag{9}$$

Table 6: Static Slot allocation - Message Length classification

Node	Smallest	Smaller	Medium	Large
1	6	3	4	5
2	9	2	5	7
3	7	4	5	6
4	11	5	7	9
5	5	1	3	4

where a_i is the total number of messages from the node i, N is the total number of sizes (4) of message and P_j is the priority number of node j. Once the priority numbers are generated, the PIs for each node are generated from these priorities. Then these PIs are ordered in ascending order. The node with highest PI will be at the top of this ordered list and is allowed to access medium first, followed by other nodes as per the order.

Algorithm 1 Computation of Priority Index for static slot allocation

```
Input: An array of nodes with ranges of messages.
Input: Number of Smallest, Smaller, Medium and Large messages for each node.
Output: Array of PIs sorted in ascending order.
for i = 1 to n in steps of 1 AND i ≤ n do
    Make use of ranges of messages to generate priority numbers using equation ??
    Use Priority numbers P_i as input to equation (1-P_i/100) to compute PIs.
end for
for i = 1 to n in steps of 1 AND i ≤ n do
    Sort the PIs in ascending order;
end for
Allocate slots as per the order of PIs.
for i = 1 to n in steps of 1 AND i ≤ n do
    Display the node numbers as per which the slots are allocated.
end for
```

4.2 Case 2: Dynamic Slot Allocation

In dynamic slot allocation, variable slots are generated based on the requirements from nodes. MN uses the knowledge base to infer on the available information and make dynamic decisions in generating the PIs to allocate a next variable slot. As shown in table V, interpretations are based on the rules and are generated by collaborating the knowledge obtained from the rules. Each entry in the table V indicates the number of messages in the ranges: Smallest, Smaller, Medium and Large (symbolically given values 1,2,3 and 4 respectively in algorithm 2). Importance is given to the nodes with urgent messages and slots are allocated to these nodes first. If there is more than one node with urgent message, then MN considers other parameters: NR, ML and NE to compute PI. If the ML is small to medium (i.e. if it falls between 1 and 2) then shorter slot is allocated. If the ML is higher than medium, then longer slot is allocated to the respective node. Algorithm 2 describes the detailed procedure to generate PI for dynamic slot allocation.

Algorithm 2 Computation of Priority Index for dynamic slot allocation

1: Input: An array of structures of nodes with members as parameters: ML,NR,NE,MU and values (numbers) for each parameter.
2: Input: Dynamic, Urgent.
3: Output: Array of structures (PI) with members: PI and slot (seconds).
4: **for** $i = 1$ to n in steps of 1 $AND\ i \leq n$ **do**
5:     **if** $Urgent = 1$ **then**
6:         Read ML, NR and NE to generate PI list1 array for nodes with urgent data using equation **??**
7:         **if** More than one node has urgent message **then**
8:             **if** $1 \leq ML \leq 2$ **then**
9:                 Go for shorter slot for this node.
10:             **else**
11:                 Go for longer slot for this node.
12:             **end if**
13:             **if** NE is Low **then**
14:                 Go for shorter slot for this node.
15:             **else**
16:                 Go for longer slot for this node.
17:             **end if**
18:             **if** NR is Smaller to Medium **then**
19:                 Go for shorter slot for this node.
20:             **else**
21:                 Go for longer slot for this node.
22:             **end if**
23:             Update PI list1 array.
24:         **end if**
25:     **else**
26:         Repeat the steps 8 to 22.
27:         Generate PI list2 array for nodes with normal data (Not urgent) using equation **??**
28:     **end if**
29: **end for**
30: Append PI list2 to PI list1 to generate final PI list array.
31: **for** $i = 1$ to n in steps of 1 $AND\ i \leq n$ **do**
32:     Sort the PIs in ascending order.
33: **end for**
34: Allocate slots as per the order of PIs.
35: **for** $i = 1$ to n in steps of 1 $AND\ i \leq n$ **do**
36:     Display the node numbers as per which the slots are allocated.
37: **end for**

5 Simulation Inputs

The proposed scheme is simulated in NS3 using the following simulation inputs: bandwidth of 500 Kbps, BER ranging from 10^{-2} to 10^{-6}, the number of nodes ranging from 5 to 20, mean number of requests , λ = 9,12,15, the nodes are placed 1 to 2 meters apart with initial energy of 2J in each node and the number of servers equal to 1 i.e. MN. The following performance parameters are assessed.

- *Energy Efficiency*: The energy efficiency is defined as the ratio of the amount of data delivered to the total amount of energy consumed as shown in equation 10.

$$E_{eff} = \frac{Total amount of data delivered}{Total amount of energy consumed} \times C \tag{10}$$

  where C is defined as in equation 11.

$$C = (1 - PER) \tag{11}$$

- *Average Server Utilization (ASU)*: It is defined as the fraction of time the server is busy serving requests from competing nodes. It is expressed as shown equation in 12.

$$ASU = \frac{AverageRequestRate}{NumberOfServers \times AverageServiceRate} \tag{12}$$

  The system can be modelled as single queue in which both interarrival times and service times are exponentially distributed. Average Service Rate is the average number of customers served in a given period of time.

- *Throughput*: It is the number of messages delivered per second and is measured in bits per second.

6 Results

Results analysis shows improvements in energy efficiency, ASU and throughput.

6.1 Analysis of Energy Efficiency

The effect of message length over energy efficiency (in Mbits per Joule) for different BERs is being analyzed here. BER is a measure of transmission quality at the link layer. Many links operate quite well with the BER in the range 10^{-5} to 10^{-8} where as BER of 10^{-12} is effectively error free for many applications. It is the fact that when message size increases, the energy required to transmit the message increases. There is a need for an optimal message size at which maximum energy efficiency can be achieved. As shown in figure 4 energy efficiency is plotted against the message length for different values of BERs (10^{-4} to 10^{-6}). As shown in the graph there is a high energy efficiency

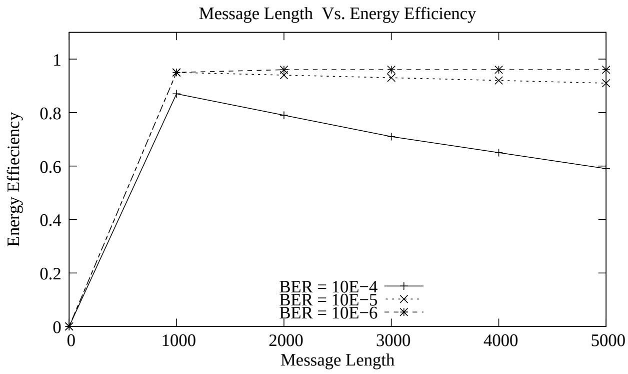

Figure 4: Energy Efficiency Vs. Message Length

for low BER (10^{-6}) as the message length increases. This is because of the less number of errors being found in the messages and most of the messages would be accepted by the receiver thus saving the energy required for retransmission and increasing energy efficiency. For higher BER values, energy efficiency drops significantly as the number of errors would result in receiver requesting for retransmissions thus spending extra energy. Higher the message length, the longer will be the slot allocated to a node provided if it has enough NE with it to sustain the message length otherwise the shorter slot is allocated.

6.2 Analysis of Average Server Utilization

For energy efficiency, the MN should be busy almost all the time serving the requests from competing nodes rather than being idle for long durations. The service time of manager is modelled by Exponential distribution given the mean arrival rate of requests. A random variable X is said to be exponentially distributed [14] if its probability density function (pdf) is given by equation 13.

$$p(x) = \lambda e^{-\lambda x} \tag{13}$$

where λ is the mean arrival rate of requests from the contending nodes and is measured in terms of mean number of requests per second. As shown in figure 5, there are three plots drawn for ASU (in

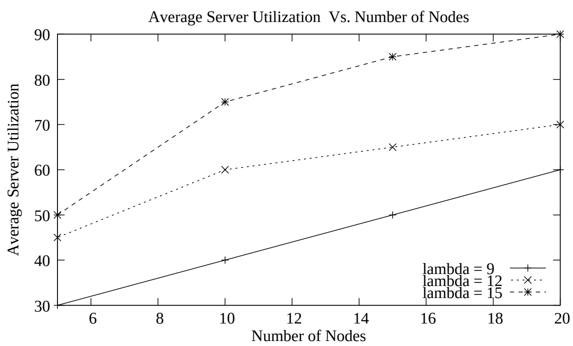

Figure 5: Average Server Utilization(%) Vs. Number of Nodes

percentage) against the number of nodes for different mean arrival rates of requests λ. ASU increases as the number of nodes increase in each plot for a particular λ. As λ increases the number requests per second from the nodes increases, thus keeping the manager busy all the time. As the number of requests is increased, ASU increases as indicated by three plots. This is because the requests keep on coming from the nodes to MN and the MN is found busy most of the time serving requests thus reducing idle time. As the number of requests from a node increases, there are higher chances of getting an early slot allocated (for media access) to this node by the MN. That is, more the number of requests, higher will be the PI of a node.

6.3 Analysis of Throughput

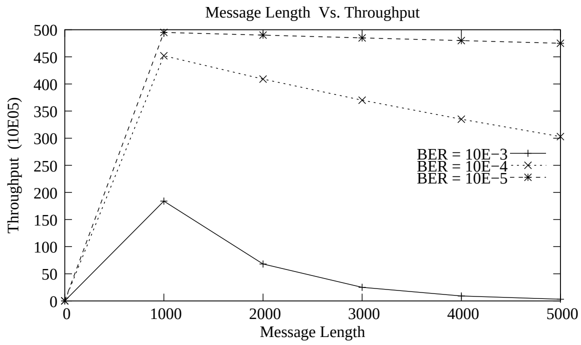

Figure 6: Throughput Vs. Message Length

As shown in figure 6, throughput is plotted against the message length for different BER values. For higher BER value, the throughput rises with a message length up to some point and then drops significantly as the message length increases. This is because some of the messages get lost or corrupted due to errors and could not reach the receiver decreasing throughput. But in case of lower BERs, the throughput increases initially and later decreases very slowly since the error rate is low. In all these three cases, there is some point where the throughput would be at its maximum value for an optimal message length. In general, as the message length increases, initially the throughput increases up to some point and then decreases. This is because when the message length increases, the end to end delay also increases. As the end to end delay increases, the throughput declines.

7 Conclusion

In this paper, we proposed a scheme, ”New Approach for Media Access in Wireless Sensor Networks”, (NAMWSN) that generates PI for slot allocation using parameters: ML, NE, NR and MU. Our contributions are motivated by the disadvantages of existing schemes to rope in all these listed parameters together with the goal to reduce energy consumption and improve energy efficiency in WSNs. We have developed model for each of these parameters to generate static and dynamic slots for each contending node. Analysis of energy consumption, throughput and server utilization is done. Simulation study and result analysis for energy efficiency, throughput and dynamic slot allocation show an improved performance for various message sizes and error conditions. Our future research work includes the designing and developing of an energy efficient error control and flow control schemes in WSNs.

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