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Impact of IEEE 802.11 MAC Packet Size on Performance of Wireless Sensor Networks

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Abstract: *Wireless Sensor Networks (WSNs) comprise of nodes, which are particularly used for sensing and data collection purposes, and they use the wireless medium for data exchange. These sensor nodes are typically battery-powered and thus face the problem of limited lifetime, due to the finite number of charging and discharging cycles of batteries. Medium Access Control (MAC) protocols in WSNs have to be properly designed so as to ensure the efficient utilization of the wireless medium by the nodes in the network. The performance of the network can be improved by minimizing the energy consumption of the nodes, reducing the latency and increasing the Packet Delivery Ratio (PDR). This paper studies the impact of packet sizes on the above parameters of the network, so as to identify the optimum packet size for obtaining sustained network performance.*

Keywords: *Energy consumption, Medium Access Control, Packet size, Wireless Sensor Network.*

I. Introduction

Wireless Sensor Networks (WSNs) consist of sensor nodes, which are distributed in specific areas, so as to collect data required for specific applications [1], like habitat monitoring, structural monitoring and data logging. These sensor nodes are small in size and are generally powered by batteries. The batteries have the disadvantage that they have a finite lifetime, due to the limitation in the number of charging and discharging cycles. Also, it is difficult to replace or recharge the batteries when the nodes are placed at inaccessible locations. Thus the lifetime of WSNs depend on how efficiently the energy from the battery is utilized by the nodes for their operation [2].

Medium Access Control (MAC) protocols in WSNs determine how nodes share the wireless medium. Proper design of MAC protocols aims to increase the efficiency of a WSN by improving the Packet Delivery Ratio (PDR) and reducing the latency. The sensor nodes operate in different states like transmit, receive, idle and sleep. The energy consumption in WSNs can be due to collisions, idle listening, overhearing and additional overheads [3]. By minimizing these factors, the energy efficiency of the network can be further improved. Thus the MAC protocol design in WSNs also aims to reduce the energy consumption of the network, in order to ensure longer lifetime.

A major parameter that influences the energy consumption pattern of the sensor nodes is the packet size. The wireless medium is prone to errors, which can affect the performance of sensor networks, in terms of increased end-to-end delay and higher packet loss rates. These disadvantages negatively affect the applications which require timely delivery of data. Generally, the MAC protocols in WSNs use checksums to detect errors in packets. The packets with longer lengths suffer from higher loss rates because they are more prone to errors in the wireless medium. Again, this depends on the application scenario and the conditions of the wireless medium. On the other hand, shorter packets are greatly affected by protocol overheads. Thus the data packets generated by the different nodes should neither be too long nor too short. The identification of optimum packet size is crucial to ensure good performance of the network, such that the latency decreases and the PDR increases.

The packet size optimization techniques proposed in literature are basically categorized into two approaches: (a) using fixed size packets and (b) using variable size packets. According to the approach of using fixed size packets, the format of a packet is as shown in Fig. 1. A packet consists of the data payload, header and tail. The data payload is the actual data content to be sent to the receiver. The header field consists of protocol-related information, like the current segment number, total number of segments, packet identifiers and sender and receiver identifiers. The tail portion includes information such as the parity bits for error control. These constitute the overhead associated with each data packet.

HEADER	DATA PAYLOAD	TAIL

Figure 1. Typical format of a data packet.

The variable size approach uses a Dynamic Packet Length Control (DPLC) scheme, which creates variable sized packets depending on channel conditions. This scheme generates shorter packets for congested channels and longer packets for relatively free channels. This method enhances overall throughput and efficiency of the network. But it creates a large amount of overhead at each node, in terms of packet size calculations at each node. So the fixed size approach is employed here because it is simple to implement and creates less overhead.

In this paper, the impact of packet size on the performance of IEEE 802.11 MAC protocol [4] has been analyzed. The Transmission Control Protocol (TCP) packets of different sizes have been generated and their effects on the PDR, average end-to-end delay and the energy consumption of the network have been studied, based on NS-2 simulations. The results show that the performance of the WSN can be improved by choosing an optimum packet size for the data packets.

The rest of the paper is organized as follows: Section II gives an overview of the IEEE 802.11 MAC. Section III describes the related work on packet size optimization in WSNs. Section IV focusses on the simulation scenario. The simulation results are described in Section V. Section VI concludes the paper and provides directions for future work.

II. Overview of IEEE 802.11 MAC

IEEE 802.11 defines the MAC and Physical Layer (PHY) specifications for Wireless Local Area Networks (WLANs). The IEEE 802.11 MAC protocol is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The 802.11 MAC uses a Distributed Coordination Function (DCF) mechanism that either uses a basic access mode or a Request to Send/Clear to Send (RTS/CTS) access mode, for data packet transmission.

In the basic access mode, also called the two-way handshaking mode, the sender node sends a DATA packet to the receiver. The receiving node responds with an ACK packet, when it successfully receives the DATA packet. If a node has a packet to be transmitted, it first senses the channel. If the channel is idle for a duration of Distributed Inter Frame Spacing (DIFS), then the node sends the packet over the channel. If the channel is found to be busy, then the node does not transmit the packet till the channel is idle for DIFS duration. Once this idle duration is detected, the node generates a random backoff interval, in order to avoid packet collisions. The backoff interval is reduced in terms of the slot time, and when the backoff counter reaches zero, the sender node sends the packet. If the receiver receives the packet successfully, then it waits for a Short Inter Frame Spacing (SIFS) duration and then sends the ACK (acknowledgement) packet. If the sender does not receive the ACK packet within a particular timeout duration, the data packet is considered as lost and a retransmission is initiated. The number of retransmissions is determined by the retry counter at the sender node. This counter is incremented by one, every time there is an unsuccessful packet transmission attempt. The packet is discarded when the number of retransmissions exceeds the maximum value of retry counter.

The backoff procedure in IEEE 802.11 MAC is based on the Binary Exponential Backoff (BEB) algorithm [7]. The backoff interval is chosen from the uniform distribution ranging from $[0,W_i-1]$, where i is the number of backoffs (i ranges between the values 0 and the retransmission limit m) and W_i is the contention window (CW) size. Initially, the contention window of a packet is set equal to CW_{min}. The contention window CW is doubled after every unsuccessful packet transmission, upto a maximum value $CW_{max}=2^{m'}CW_{min}$, where m' is the number of CW sizes. Once CW reaches the value CW_{max}, it remains constant until it is reset to the value CW_{min}, which occurs after a packet is successfully transmitted or when the retransmission limit of the packet is reached.

The RTS/CTS access mode, also called the four-way handshaking mode, employs the same backoff procedure. Before data transmission, the sender node sends a short RTS packet, to check whether the channel is idle. The receiving node replies to the RTS packet with a CTS packet, after a SIFS time interval. After receiving the CTS packet, the sender node sends the DATA packet. When the receiver successfully receives the DATA packet, it sends an ACK packet to the sender node, to acknowledge data transmission. If the CTS packet does not reach the sender node, then the retry counter is incremented by one, and the sender again sends an RTS packet.

The sensor nodes in the network have different power consumption rates in different states of operation, like transmit, receive and idle. In addition to these, collision is one major source of energy consumption in WSNs because of the contention behavior of IEEE 802.11 DCF. When more than one sensor node tries to transmit packets simultaneously to the same receiver, there are chances of collision, resulting in the packet not being successfully transmitted. Also, longer packets are more susceptible to transmission errors. Thus the RTS, CTS and ACK packets, which are shorter than DATA packets, are less affected by errors caused due to channel conditions. In both the situations, the sender node does not receive the ACK packet from the receiver node. Then the sender node will backoff using the BEB algorithm and try to retransmit the packet, till the packet successfully reaches the receiver node, or till the maximum number of retransmissions is reached. Thus a large number of retransmissions occur, which is another major cause of energy consumption. Thus it is necessary to optimize packet sizes so that they are less susceptible to collisions and transmission errors.

III. Related Work

Energy efficiency is a crucial factor for ensuring good performance of WSNs. Many papers in literature have dealt with the problem of energy-efficient design of WSNs. I. Joe in [5] has proved that the power management mechanism does not improve the energy efficiency of the sensor nodes. The power management mechanism involves turning off the transceiver when the node is in the idle state, which helps to save energy. Instead, the author suggests packet size optimization as an important aspect in energy-efficient design of WSNs. This optimization tries to attain a compromise between the large overheads associated with short packets and the large error rates associated with long packets.

Y. Sankarasubramaniam et al. in [6] discuss packet size optimization in sensor nodes suffering from energy constraints, by choosing energy efficiency as the optimization metric. In case of such nodes, the energy consumptions during start-up have to be taken into consideration, while determining the optimum packet size. The authors in [6] also suggest reducing overhead by using fixed packet sizes. The use of fixed length packets is also beneficial on account of the limited resources available and the energy constraints in the sensor nodes. Moreover, [6] investigates the effects of retransmissions, error control techniques and the energy consumption profiles of encoding and decoding operations on the energy efficiency metric.

Extensive research has been carried out in literature to analyze the performance of IEEE 802.11 MAC. This MAC protocol achieves lower throughput compared to the PHY transmission rate. This happens due to the overheads associated with the MAC and PHY headers, ACK transmissions and inter-frame spaces. These overheads are added up during the transmission of each frame, resulting in a lower throughput while transmitting short frames. [7] describes a frame aggregation scheme for enhancing the throughput of IEEE 802.11 MAC. This scheme aggregates multiple packets from higher layers into a single MAC frame, thereby reducing the overheads associated with the MAC protocol. In [8], the energy efficiency of 802.11 Distributed Coordination Function (DCF) has been analyzed by considering transmission errors, along with collisions. But it fails to consider the effect of packet size on the performance of the MAC. Here, an optimal contention window has been chosen to optimize the energy efficiency of 802.11 DCF. But this is not an effective scheme in a network with bad channel conditions.

The authors in [9] have studied the performance of a single TCP-Reno traffic connection over a lossy link, as a function of TCP packet size. The performance of TCP-Reno is found to be good for longer packets, in case of connections affected by link errors. The choice of packet size of the TCP connection is important because it affects the sender node's congestion window size. The performance variation with respect to end-to-end delay has also been analyzed using simulations. The studies show that the choice of packet size becomes relevant when the connection is dominated by link losses. In cases where the connection is dominated by congestion, the packet size factor does not play a significant role. In this scenario, short packets provide higher throughput compared to longer packets.

This paper studies the performance of IEEE 802.11 MAC based on variations in data packet sizes. This packet size optimization procedure is significant, so as to attain energy efficient WSNs, with low energy consumption and latency.

IV. Simulation Scenario

The simulation has been done on NS-2 [10]. The network model is shown in Fig. 2. A flat grid topology has been assumed for a network with 25 nodes and one sink. The sink acts as a receiver for the data packets generated by the different nodes. The source nodes are the nodes generating the data packets.

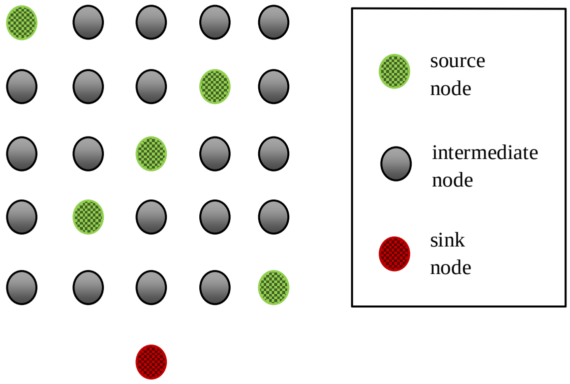

Figure 2. Network model.

IEEE 802.11 MAC has been chosen as the MAC protocol. The traffic is assumed to be Constant Bit Rate (CBR), attached to the TCP layer. The initial energy of each sensor node is assumed to be 1000 J. The power consumed by the nodes during different states of operation, like transmit, receive, idle and sleep states, have been taken from the specifications of commercially available sensor nodes. The entire simulation runs for 60 seconds.

The simulation results show the variation of PDR, average end-to-end delay and remaining energy of the weakest node in the network with the inter-arrival time. The weakest node in the network has been identified by calculating the consumed energy of each node in the network. The node with the highest consumed energy is considered to be the weakest node. The inter-arrival time gives an indication of traffic density. Larger inter-arrival time means lesser traffic, whereas smaller inter-arrival time indicates high density traffic.

In each graph, the data packet size has been varied as 128 bytes, 256 bytes, 512 bytes and 1024 bytes. The inter-arrival time has been varied from 5 seconds to 55 seconds, with an interval of 5 seconds. Each point in the graph has been obtained by averaging over a number of simulation runs. The parameter settings for the simulations have been summarized in TABLE 1.

Table 1. Simulation Parameters

Parameter	Value
Simulation area	180 m x 180 m
Simulation time	60 seconds
Maximum queue length	50 bytes
Traffic	CBR
MAC protocol	IEEE 802.11
Routing protocol	AODV
Initial energy	1000 J
Idle power	1.440 W
Transmit power	1.870 W
Receive power	1.620 W
Sleep power	0.910 W

V. Simulation Results

The variation in PDR with inter-arrival time for different packet sizes has been shown in Fig. 3. When the inter-arrival time is small, the number of packets generated by the nodes is higher and so there is a higher possibility of collision, leading to packet drop. Thus the PDR, which is calculated as the ratio of number of received packets to the number of sent packets, is smaller. As the inter-arrival time increases, the number of packets generated reduces, leading to lesser number of collisions, which in turn increases the PDR. Fig. 3 also shows that smaller the packet size, larger is the PDR. This is because the number of packets generated, and hence the number of packets received, will be higher for smaller packet sizes, with reduced number of collisions, compared to larger packet sizes. Also, at high traffic density, there is a significant variation in PDR among the different packet sizes, because of the large variation in number of dropped packets due to collisions. The variation in PDR becomes negligible at low traffic density. It can be seen that the PDR saturates as the inter-arrival time increases beyond a certain value, for all packet sizes. This is because as the inter-arrival time exceeds a certain limit, the number of packets generated and the number of packets received remain constant, thus bringing the PDR to a constant value. But even in this scenario, the PDR does not achieve the theoretical maximum of 100 %, since certain amount of collisions and transmission errors are present in the network, leading to packet drops.

The variation in average end-to-end delay with inter-arrival time for different packet sizes has been shown in Fig. 4. When the inter-arrival time is less, a large number of packets are generated by the nodes and so there is a higher possibility of collision, leading to higher number of retransmissions. Thus the average end-to-end delay, which is the time taken for a packet to reach the sink node from the sender node averaged over all the packets, is higher. When the inter-arrival time increases, the number of packets generated reduces, leading to lesser number of collisions and retransmissions, which in turn reduces the average end-to-end delay. Fig. 4 also shows that the average end-to-end delay increases with increasing packet sizes. This is because more time is taken for a longer packet to reach the sink node, compared to a shorter packet. The significant variation in average end-to-end delay among the different packet sizes, at high traffic density, can be attributed to the large variation in number of retransmissions, due to collisions. The variation in average end-to-end delay is very less at higher inter-arrival times. As in the case of PDR, the average end-to-end delay also tends to saturate after a certain value of inter-arrival time, due to the constant packet generation and reception rates. Here also, the end-to-end delay does not fall below a threshold value, since all packets generated will experience a certain amount of delay to reach the sink node, depending on the number of collisions and the wireless channel conditions.

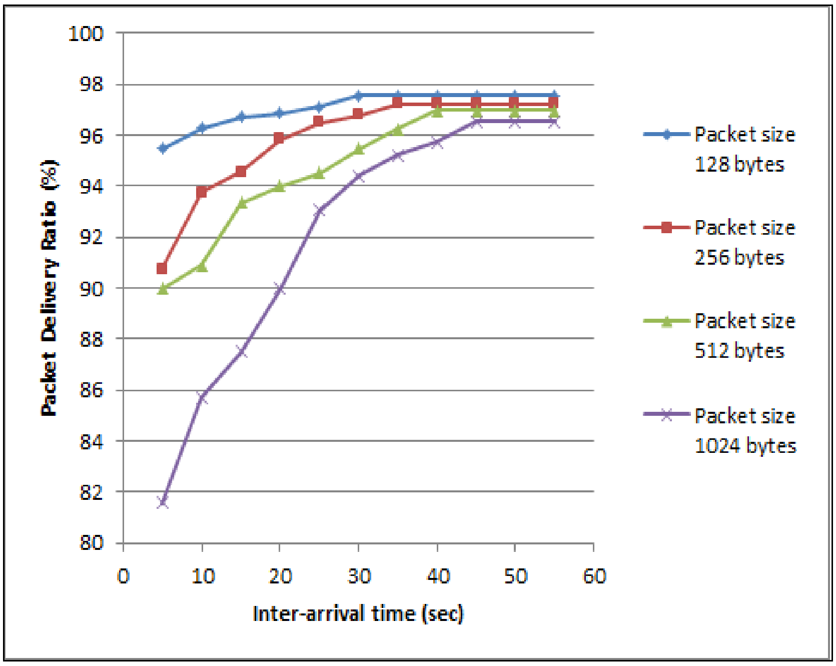

Figure 3. Packet delivery ratio.

Fig. 5 shows the variation in the remaining energy of a node in the network with inter-arrival time, for different packet sizes. Specifically, the graph corresponds to the node which consumes maximum amount of energy, referred to as the weakest node. This node has been identified because it will form the weakest link in the network, i.e. all other nodes will consume lesser energy than the weakest node. Thus analyzing the variation in remaining energy of the weakest node represents the worst case scenario.

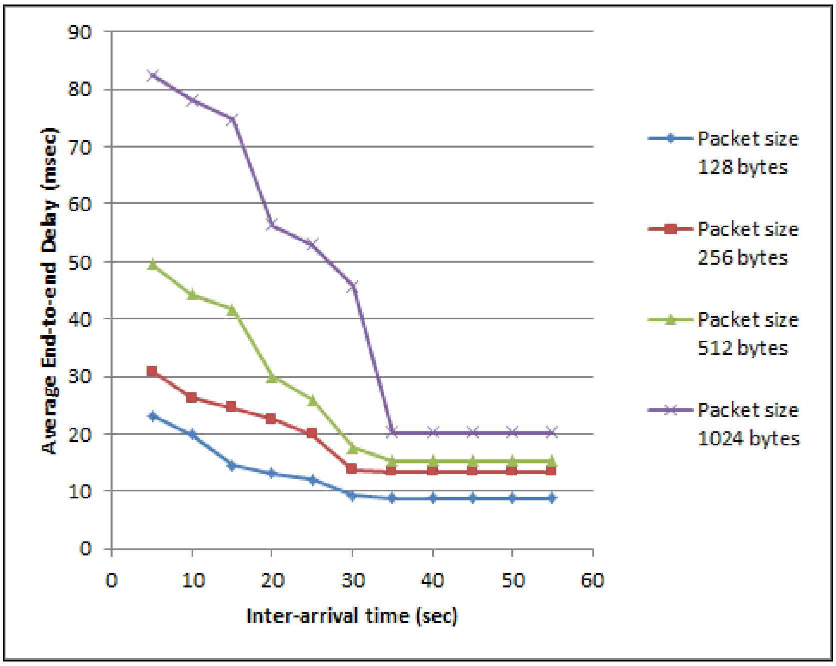

Figure 4. Average end-to-end delay.

Large number of packets generated by the nodes at lower inter-arrival times results in large number of collisions, which in turn leads to higher energy consumption. Thus the remaining energy will be low for lower inter-arrival times. When the inter-arrival time increases, the number of packets generated reduces, and so the number of collisions also reduces, thereby reducing the consumed energy. So the node will be having a higher remaining energy, as the inter-arrival time increases.

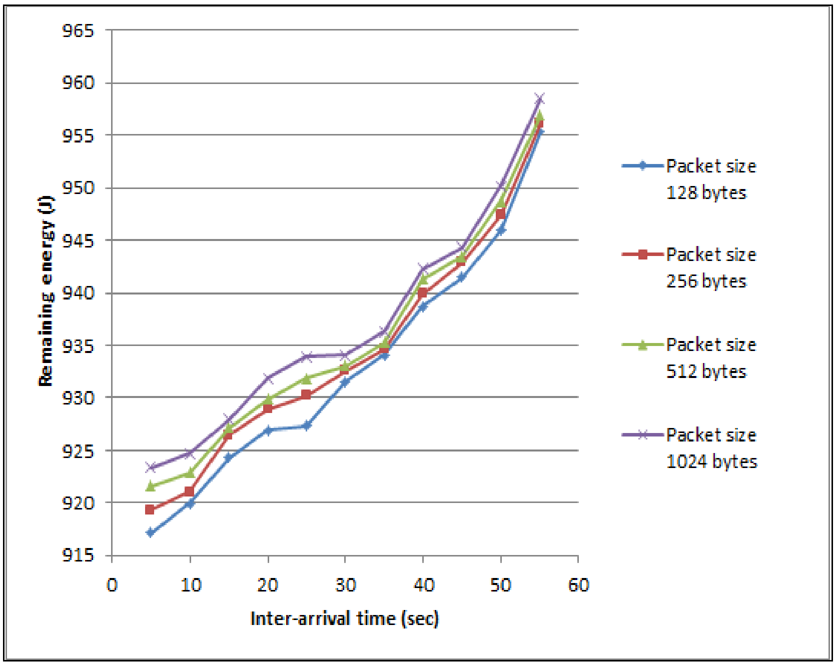

Figure 5. Remaining energy of a node.

From Fig. 5, it can also be observed that the remaining energy is higher for higher packet sizes. This is due to the fact that each packet generated leads to significant energy consumption, in terms of overhead associated with the packets. The number of packets generated decreases with increase in packet size, and so the energy consumed for generating smaller number of packets will be lower, leading to higher remaining energy. The higher variation in the remaining energy among the different packet sizes, at high traffic density, is due to the large amount of energy consumed as a result of collisions and overheads. The variation is negligible for lower traffic densities, i.e. higher inter-arrival times.

VI. Conclusion

MAC protocols in WSNs have been extensively researched upon, with an objective to increase the energy efficiency of the nodes. The IEEE 802.11 MAC is considered the default standard for wireless ad-hoc networks, and hence it has been used for analyzing the performance of WSN in this paper.

This paper investigates the impact of packet size on various parameters, like PDR, average end-to-end delay and the energy consumed. This analysis leads to the determination of an optimum packet size, which ensures a high PDR, reduced latency and low energy consumption. The packet size can be decided based on the application and the total size of the data to be transmitted. Typical usage of IEEE 802.11 MAC in WSN is relatively for applications requiring higher data rate of transmission and reception, such as those involving images or video. As a future work, similar studies can be done for low data rate applications using IEEE 802.15.4 MAC.

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