Throughput Enhancement of Wireless Sensor Networks with IEEE 802.15.4 MAC based on Channel Allocation

Mini S. P.[1], S. Viswanatha Rao[2], Sakuntala S. Pillai[3]
Department of Electronics and Communication Engineering
Mar Baselios College of Engineering and Technology
`Trivandrum, India`

Abstract: *IEEE 802.15.4 standard was especially designed to provide specifications for simple, low data rate, ultra low power and economical wireless personal area networks (WPANs). By exploiting the 16 non-interfering channels supported by IEEE 802.15.4, we can improve the channel capacity of wireless sensor networks. This paper analyses the performance of a channel assignment method based on 3-hop neighborhood which enhances the throughput of 802.15.4 MAC by reducing the number of packets dropped. Simulation results using NS2 demonstrates improvement in throughput and reduction in average end to end delay.*

Keywords— *Wireless personal area network, IEEE 802.15.4, throughput, multi-channel MAC.*

I. INTRODUCTION

Recently, multi-channel MAC protocols have gained substantial attention of many researchers due to inevitability to enhance the network performance of wireless sensor networks (WSNs). Wireless sensor networks are widely used in environmental monitoring, structural and health monitoring, security systems, industrial and military applications. They are made up of small low power sensor nodes located at different places to collect information [1]. These sensor nodes consist of sensing, processing and communication units. Communication unit/ transceiver controlled by MAC protocol is the major power consuming unit of a sensor node. So design of MAC protocol is the vital part of wireless sensor networks [2].

Medium access control (MAC) layer is the part of data link layer in the open system interconnection (OSI) layer model and is responsible for proper communication through the channel. Majority of existing MAC protocols stick on single channel communication. In single channel MAC communication any node within the range can interfere with the ongoing transmission. This may leads to collision and packet loss. In a multi-hop wireless sensor network a successful packet transmission occurs after several retransmissions due to packet collisions. This degrades the network performance.

Multi-channel MAC protocol supports parallel transmissions. Simultaneous multiple channel transmission reduces number of retransmissions. This leads to reduction in packet loss and hence the network performance increases [3].

This paper evaluates a channel allocation method which improves the network performance of IEEE 802.15.4 MAC [4]. The IEEE 802.15.4 MAC standard is especially designed for low data rate Wireless Personal Area Networks (WPANs). This standard supports simple, ultra low power and low cost applications. As a result, the IEEE 802.15.4 MAC has been widely used in WSNs employed in low data rate applications. IEEE 802.15.4 MAC supports 16 non-interfering channels within the Industrial, Scientific and Medical (ISM) band.

The simulations of this channel allocation method has been done using NS-2 simulator. The performance of WSNs with IEEE 802.15.4 MAC has been analysed based on the packet arrival rate. The variations in average end-to-end delay, number of lost packets and the network throughput, with respect to the packet arrival rate, have been studied and the results have been plotted. The results show that channel allocation method improves the performance of the network, by increasing the throughput and reducing the packet loss and latency.

The rest of the paper is organized as follows: Section II gives a brief overview of the IEEE 802.15.4 MAC operation. The related works on performance analysis of WSNs employing IEEE 802.15.4 MAC have been discussed in Section III. The simulation scenario and simulation results have been explained in detail in Sections IV and V respectively. Section VI concludes the paper.

II. OVERVIEW OF IEEE 802.15.4

IEEE 802.15.4 standard provides physical and MAC layer specification for low rate wireless personal area networks. IEEE 802.15.4 standard was intended to enable simple, ultra low power and low data rate wireless connectivity among various devices.

A. Physical Layer Characteristics

Physical layer is the base layer of OSI model. It provides the data transmission service. Networks based on IEEE 802.15.4 operate on three RF bands: 868, 915 and 2450 MHz bands. Last band does not require licensing and it is known as Industrial, Scientific and Medical (ISM) band. According to the original standard (IEEE 2003b), 868 and 915 MHz frequency bands utilized Direct Sequence Spread Spectrum (DSSS) with data rates of 20 kbps and 40kbps respectively. Data rate of ISM band is 250 kbps. Revised standard IEEE 2006 allows data rate up to 250 kbps for 868and 915 MHz bands.

All three bands together provide 27 channels. 868 MHz band provides a single channel at 868.3 MHz frequency. 915 MHz band provides 10 channels with 2 MHz bandwidth between 906 to 924 MHz. ISM band supports 16 non-interfering channels having 5 MHz bandwidth between frequencies 2405 to 2485 MHz.

Physical layer can operate data packets with a maximum payload of 127 bytes. This standard has ability to adjust the transmitting power, ability to measure the strength/ quality of received signal and the ability to check for the activity on the medium.

***1) Network Model*:** In IEEE 802.15.4 network, the PAN coordinator is the controller device and it can build a network with other devices. Two types of devices are used in 802.15.4 networks. Full function device (FFD) can act as a PAN coordinator and/or an ordinary device. FFD can talk to any device in the network. Reduced function device (RFD) acts as an ordinary device. It can only talk to an FFD.

***2) Topologies*:** This standard supports two topologies: Star topology and peer-to-peer topology. In a star topology all communications must go through the PAN coordinator. In peer-to-peer topology, devices can communicate with each other directly with or without a PAN coordinator.

B. MAC Layer Characteristics

The Medium Access Control (MAC) supports the transmission of MAC frames through the physical channel. MAC layer itself manages physical channel access and network beaconing. It also controls validation of frames, guarantees time slots and node associations. Two operating modes in this standard are beacon enabled mode and non-beacon enabled mode.

In beacon enabled mode the coordinator periodically emits a special frame known as beacon. Super frame/beacon interval is the time gap between two beacon frames. It can be divided into two: an active period and an inactive period. All communications are carried during the active period. Active period is subdivided into Contention Access Period (CAP) and Contention Free Period (CFP). Each sub section contains a number of slots having same size. PAN coordinator sends beacon frames at the beginning of slot0 and it is followed by CAP. During CAP channel access is done based on CSMA/CA mechanism. In CFP, devices can access the channel by using Guaranteed Time Slots (GTSs). Inactive period is used for power saving by turning off the transceiver or moving into low power mode. Two MAC layer attributes; Beacon Order (BO) and Superframe Order (SO) controls the duration of beacon interval and active part of superframe respectively with a condition that it must satisfy the limit $0 \leq SO \leq BO \leq 15$. This mode utilizes slotted CSMA/CA mechanism to access the medium.

Non-beacon enabled mode does not support the superframe. In which values of (BO) and (SO) set are to 15. In this mode coordinator does not emit beacons unless a device particularly request to do so. Due to the absence of beacon frames, devices can transmit data at any time. In this mode each node can communicate with any other device directly, without the help of a coordinator. This mode uses Un-slotted CSMA/CA technique to access the channel.

1) Uplink Communication in Beacon Enabled Mode

Uplink communication is the data transfer from node to the coordinator as shown in Fig.1. This follows CSMA/CA algorithm. First step in slotted CSMA/CA algorithm is to set initial values for the state variables. i.e, the contention window (CW) is set to 2, the number of backoff stages (NB) is set to zero and the backoff exponent (BE) is set to macMinBE(default value is 3). Then a backoff timer is initialized using a random backoff time within the interval $[0,(2^{BE} - 1)]$, distributed according to the uniform distribution.

When the backoff timer reaches zero, algorithm performs the Clear Channel Assessment (CCA) operation. If the channel is free for data transmission after the first CCA operation, then CW is decremented by 1 and a second CCA is carried out and the process is repeated until the value of CW becomes zero. The packet is transmitted only if the value of CW equals zero. Otherwise, if the channel is found to be busy, then the state variables are updated, and this continues till the maximum limit of NB is reached. In this case, the data frame transmission is dropped. After receiving the data packet, the coordinator sends an optional acknowledgement. If the acknowledgement packet is not received within the time limit sender node initiates retransmission.

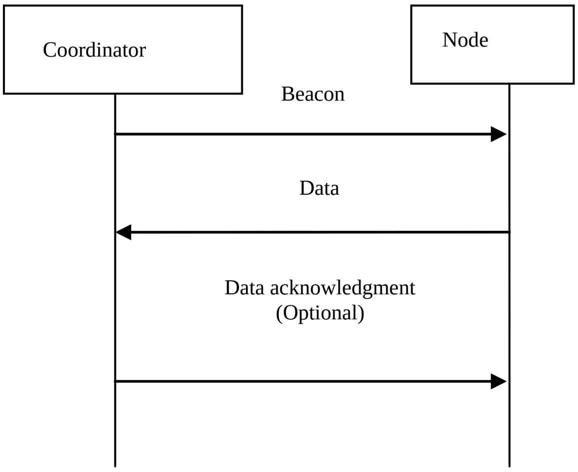

Fig. 1 Uplink data transmission

2) Downlink Communication in Beacon Enabled Mode

As shown in Fig.2, data transfer from the coordinator to a node is termed as downlink communication. After receiving a downlink packet by the coordinator, it sends beacon frame which contains list of nodes that have pending downlink packets. Upon receiving this beacon destination node becomes aware of a data packet to be received. To receive this data packet, destination node transmits a data request packet to the coordinator. Then the coordinator transmits an acknowledgement packet to the destination node. Destination node listens for a period of aMacFrameResponseTime, after receiving the acknowledgement. During this period the coordinator send the data packet. After the successful reception of data packet, destination node sends an optional acknowledgement.

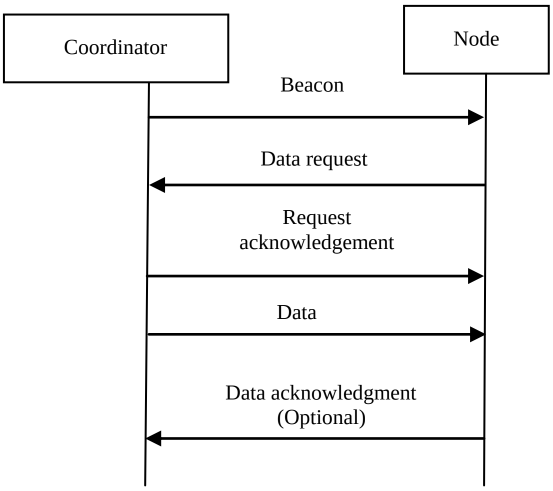

Fig.2 Downlink data transmission

III. RELATED WORKS

Many researchers evaluated the performance of IEEE 802.15.4 MAC protocol under various scenarios. V.Kumar *et al.* [5] studied the performance of beacon enabled IEEE 802.15.4 MAC by using a cross layer approach for clustered wireless sensor networks. For the performance evaluation, they used Low energy adaptive clustering hierarchy protocol (LEACH) as clustering protocol and Dynamic MANET on-demand (DYMO) as routing protocol. The authors show that the clustered wireless sensor networks give better performance over non-clustered wireless sensor networks in terms of average jitter and end to end delay. They also prove that this clustered method degrades the performance of network by reducing throughput and increasing the energy consumption.

In [6] authors propose the circularity principle to improve the performance of IEEE 802.15.4 MAC. This method minimizes the number of data packet collision by modifying the data transmission from each node. Evaluation is done using AODV protocol by varying the number of nodes. They show that this method improves the throughput by reducing the number of dropped packets.

Shih, Bih-Yaw *et al.* [7] suggest two channel selection methods to enhance the performance of IEEE 802.15.4 MAC. They used a hybrid channel selection method based on hashing technique. Proposed method improves the performance of a wireless sensor network with star topology. They showed the performance improvement by measuring throughput, delay, channel utilization and average delay.

Authors in [8], improve the performance of IEEE 802.15.4 MAC with the help of practical service differentiation mechanisms. They ensure backward compatibility with the standard by making minor changes from the original protocol. The proposed differentiated service scheme mainly focused on improving the performance of time-sensitive messages. They also analysed the performance of data frames in terms of average delay and probability of success.

IV. SIMULATION SCENARIO

We analyse IEEE 802.15.4 MAC performance using a channel allocation method based on 3-hop neighbourhood. 3-hop neighborhood channel allocation method reuses the same frequency only in its 3-hop neighborhood. The interference rate of all the nodes in a network with channel allocation technique based on 3-hop method is comparatively very less than that of 1-hop and 2-hop method [9]. A cluster-tree type beacon-enabled network topology is selected to make the system energy efficient.

The network model with 20 nodes is shown in Fig. 3. Each node in this network model represents a Full Function Device (FFD) with single half-duplex transceiver. The depth of the network is five. Node 0 in depth 0 acts as a PAN coordinator. All other nodes are coordinators. Each node in the network transmits data packets to the PAN coordinator (uplink transmission). The PAN coordinator broadcasts downlink beacon frames to all nodes in the network to update the information about all nodes.

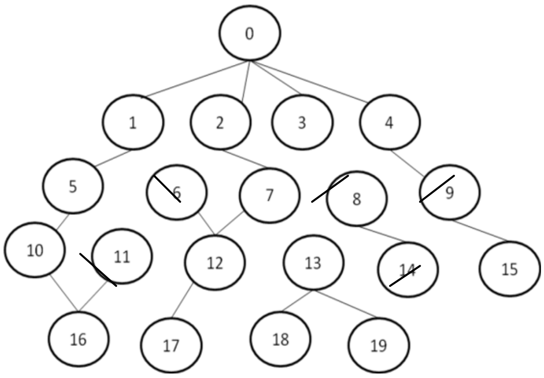

Fig. 3 Network Model

During initial stage, each coordinator performs a passive scan for collecting information about neighbouring nodes. A node finds its1-hop neighbor from the source address of received beacon frame. Each node forms its 1-hop neighbors list by using the source address of received beacon frames. 2-hop neighbour's list can be formed with the help of 1-hop neighbor's list and the 1-hop and 2-hop neighbor's list together helps to build the 3-hop neighbor's list. According to this list, available channels are allocated to all nodes in the network. Nodes in the 3-hop neighbour's list select the channel first according to the priority based on the address of each node. Priority is in increasing order of node's address .i.e., highest priority goes to node with smallest address. In 3-hop method same channel is reused only in the 3-hop neighbourhood, when all the channels are already allocated node select one of the least chosen channel.

All the simulations have been carried out in the Network Simulator NS-2 [10]. The traffic in the network is assumed to be Constant Bit Rate (CBR). The protocol used in the transport layer is the Transmission Control Protocol (TCP), since it ensures high reliability in packet transmission. The data rate is assumed to be 250 kbps and the total simulation time is 60 seconds.

The initial energy of each node is assumed to be 50 J. The values of the power consumptions during the transmit, receive, idle and sleep states of the nodes have been taken from the datasheets of commercial sensor nodes. Table 1 represents the simulation parameters.

In the simulation, we have considered four different traffic flows. The graphs in Section V show the variation in number of dropped packets, average end-to-end delay and throughput in the network, with the packet arrival rate. In this paper packet arrival rate is considered as the number of AGT packets arrived per simulation time. The packet arrival rate has been varied between 100 packets/min and 190 packets/min. Each point in the graph has been obtained by averaging over a large number of iterations.

TABLE1. SIMULATION PARAMETERS

Parameter	**Value**
Simulation area	120 m x 120 m
Simulation time	60 seconds
Packet size	50 bytes
Antenna	Omni-directional
Transmission frequency	2.4 GHz
Traffic	CBR
Routing protocol	AODV
MAC protocol	IEEE 802.15.4
Initial energy	50 J
Channel spacing	5 MHz

V. SIMULATION SCENARIO

In this section we evaluate the performance of channel allocation method based on 3-hop method and compare it with other methods. Parameters used for evaluation are number of dropped packets, average end to end delay and throughput.

Fig. 4 shows the variation in number of dropped packets with packet arrival rate, for various channel allocation methods. During the initial stage packet arrival rate is less. In this state, the traffic density is low i.e. less number of packets will be generated. Hence, the probability of occurrence of collisions is considerably small which leads to less number of packet drops. As the packet arrival rate increases, the traffic density increases, leading to a higher number of packets generation. Hence, higher number of packets will be dropped due to increase in number of collisions. This causes an increase in the number of dropped packets with increase in packet arrival rate. Considering the effect of channel allocation methods on the variation in number of dropped packets, it can be observed from Fig. 4 that the number of dropped packets is considerably reduced in 3-hop method, for the same packet arrival rate. This is because of the fact that in 3-hop method, frequency assigned for a particular node is reused only in its 3-hop neighborhood. So the number of collisions is very less in 3-hop method compared to the other two methods.

The average end-to-end delay of the network is the average time taken for a data packet to reach the destination node from the source node which generates it. Fig.5, shows that the average end-to-end delay increases with increasing packet arrival rate. Traffic density is low when the packet arrival rate is less, which means the number of packets generated will be small, which leads to less number of collisions. The number of retransmissions becomes very less in this situation. So the average end-to-end delay is also less. When the packet arrival rate increases, traffic density also increases, this in turn leads to a rapid increase in the number of collisions. This demands the retransmission of packets and thereby increasing the time required for successful delivery of packets which increases the average end-to-end delay. 3-hop method provides lowest average end to end delay among the three methods.

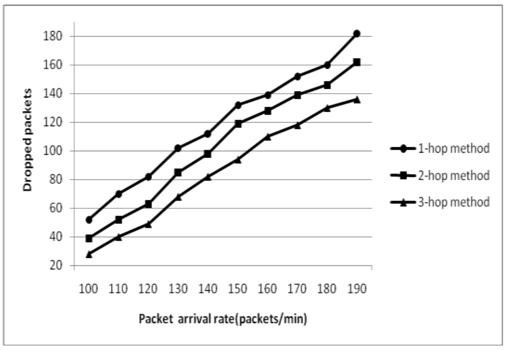

Fig.4 Number of dropped packets

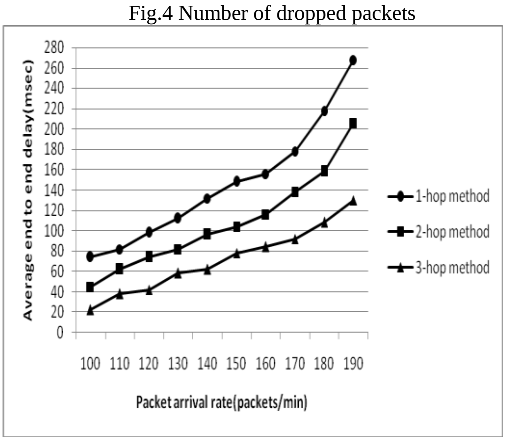

Fig.5 Average end to end delay

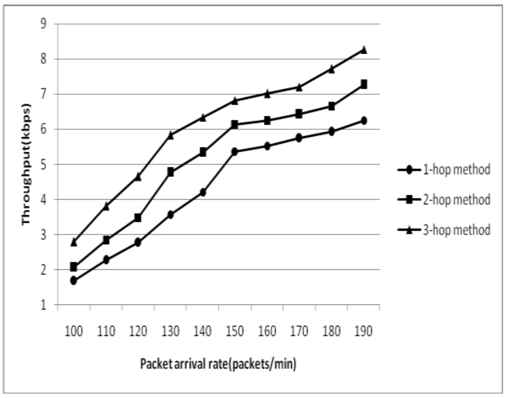

Fig.6 Throughput

Fig.6 shows enhancement in network throughput of 3-hop method compared to 1-hop and 2-hop methods corresponding to packet arrival rate. Throughput increases with increase in packet arrival rate, since number of packets generated increases with increase in packet arrival rate. 3-hop method achieves highest throughput among the three methods. This is because 3-hop method has least number of dropped packets.

VI. CONCLUSION

This paper evaluates the performance of 802.15.4 MAC using a channel allocation technique based on 3-hop neighborhood method. This analysis showed that channel allocation based on 3-hop method enhances the network throughput by decreasing the number of dropped packets.

In the future work we would like to incorporate traffic density while allocating channels based on 3-hop method.

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