DCDS-MAC: A Dual-Channel Dual-Slot MAC Protocol for Delay Sensitive Wireless Sensor Network Applications

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Abstract —The application areas of Wireless Sensor Networks (WSNs) are expanding with time. Many of these applications demand a lower end-to-end delay, high throughput, and energy-efficient operations. The performance of these applications mostly relies on the performance of the MAC protocol. This paper presents a Dual-Channel Dual-Slot MAC (DCDS-MAC) protocol for WSNs, which significantly reduces the end-to-end delay and improves the throughput while ensuring energy-efficient operations. In the proposed protocol, the delay problem of existing Lightweight MAC (LMAC) and Multi-Channel LMAC (MC-LMAC) protocol has significantly improved by using suitable destination selection technique by data packet sending node and allowing a node to transmit its packet using a timeslot pair of a channel over two different channels. The timeslot pair is kept half of the frame time separated which is decided by an algorithm. Moreover, the schedule-based operations ensure an energy-efficient operation and use of two-channel results high throughput. Finally, extensive simulations are carried out in OMNeT++ to compare the performance of proposed DCDS-MAC protocol with the existing LMAC and MC-LMAC protocol, in terms of received packets, delay, energy consumption and network lifetime. Simulation results ensure that the proposed protocol performs a significant improvement in delay and throughput over existing protocols without consuming much energy.

Index Terms—Wireless sensor network, medium access control, schedule-based MAC protocol, energy-efficiency, end-to-end delay

I. Introduction

During the last few years, WSNs have introduced many new applications mostly deployed in remote or hazardous areas. WSNs are typically deploying with a *particular application* in mind [1]-[5]. Different performance criteria like delay, throughput, and fairness are necessary for different applications, whereas the issue of energy efficiency is common for almost all applications.

Like most networks, communication in WSNs also divided into several layers [6]. The basic task of any MAC layer protocol is to control the access of a node in a shared medium to meet the certain application-specific performance requirements. In contention-based protocols, collision, overhearing, and idle listening problems result in major energy wastes. On the contrary, schedule-based protocols suffer from high delay and low throughput. Authors of the article [7] have presented a short version of a new schedule-based Low Latency Multi-Channel MAC (LL-MCLMAC) protocol for WSNs. However, in LL-MCLMAC, extensive simulations were not carried out and the network lifetime was not calculated as well.

In this paper, we present schedule-based energy efficient DCDS-MAC protocol for delay sensitive and high throughput WSN applications. We evaluate the performance of proposed DCDS-MAC protocol by an extensive simulation work using Omnet++ [8] and MiXiM [9], which ensures a significant advancement in reducing end-to-end delay and a substantial improvement in throughput from existing schedule-based LMAC [10] and MC-LMAC [11] protocol.

The rest of the paper organized as follows: related research works explained in Section II. Section III includes the details of the proposed DCDS-MAC protocol. Performance of DCDS-MAC protocol has been evaluated in terms of different performance metrics and presented in Section IV. Finally, Section V concludes the paper.

II. Related Research Works

The invention of WSN opens the door for the researchers to continue study to offer a variety of new WSN applications with the solutions of different related issues. The performance of WSN mostly relies on the use of a suitable MAC protocol. For WSNs, recently, a large number of proposals have presented by the research community that utilizes the schedule-based medium access control technique to ensure an energy efficient operation by overcoming idle listening, collision and overhearing problem. However, most of these protocols experience low throughput and high delay due to the long waiting time.

In [12], the authors have introduced a low latency

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MAC protocol where asynchronous duty cycling concepts were used and based on the amount of received data a node can adjust the sleep time and hence to reduce end-to-end delay. However, a deviation of prediction mechanism, collision and protocol overhead consume significant energy and hence lessen the efficiency. In [13], a TDMA based low latency cross-layer MAC protocol presented where a node allows using a slot of another node if slot holder nodes do not have data to send. A low-latency protocol using joint optimization of MAC and routing strategy for target tracking in WSNs was introduced in [14], which incorporates a cluster working cycle synchronization process based routing algorithm and a new low duty-cycle MAC protocol. In [15], another multi-channel scheduling MAC protocol has proposed that uses a different algorithm for channel and timeslot assignment.

The authors of [16] have presented a duty cycle SR-MAC protocol for low latency and multi-packet transmission applications. SR-MAC protocol introduces a new scheduling mechanism to reduce latency and to promote the throughput by transmitting multiple packets over multiple hops in a cycle. However, SR-MAC protocol suffers from high protocol overhead and overhearing problem, which wastes significant energy. A duty cycle REA-MAC protocol for low latency applications was described in [17] where a sender node takes wakeup decision based on cross-layer routing information. A hybrid cluster based scheduling approach for mobile WSNs have presented in [18]. Still, this approach suffers from significant delay and energy consumption.

A Predictive Wakeup based Multi-channel MAC (PW-MMAC) protocol was proposed in [19] that incorporates the benefits of predictive wakeup mechanism and adaptive duty cycling over multiple channels. In [20], the authors have introduced an energy-efficient and low latency data collection MAC protocol for WSNs. However, in this protocol, extensive simulations were not done to ensure the latency minimization during data collection. In [21], a new distributed degree based scheduling approach for collision avoidance has introduced that result in minimizing the delay. But for high traffic condition, a significant delay will happen because here only one timeslot was assigned regardless of the transmission requirements of the node. A priority-based parallel schedule polling MAC protocol for WSN has proposed in [22], where most of the Quality of Service (QoS) parameters including end-to-end delay were not analyzed.

In [23], the authors have presented a connection-oriented TDMA based MAC protocol; where time divided into timeslot and each node allows to take control over a timeslot which it can use to send data with high latency without having competed for the medium. The authors have introduced a TDMA based self-organizing (since synchronization and timeslot assignment process performed in a distributed manner) MAC protocol and presented in [10]. In LMAC, a node can only use a timeslot of a frame to send its packet like Eyes MAC (EMAC) [23] without considering the amount of data will flow through it. So, extra packets containing nodes have to wait until the same numbered timeslot of consecutive frames for sending its subsequent packets which cause further delay and low network throughput as well. An improved version of the LMAC protocol named an Adaptive, Information-centric and Lightweight MAC (AI-LMAC) has proposed in [24]. In AI-LMAC protocol, if a node is expected to flow extra traffic, then it is allowed for this node to use more than one timeslots. Despite the benefits provided by AI-LMAC, in case of high dense WSNs, it becomes cumbersome for a node to own more free slots between two-hop neighbors by avoiding the well known hidden terminal problem. Therefore, timeslot shortage and a chance of timeslot conflict problems are present here.

MC-LMAC [11] is another schedule-based energy-efficient MAC protocol proposed with increased network throughput. In MC-LMAC, to send packets, a node can use a timeslot from more than one channel but can use only single timeslot in a frame like LMAC protocol. Therefore, the delay problem still exists there. In [25], the authors have suggested an improved version of Timeout MAC (T-MAC) protocol named Mobility-aware-Timeout-MAC (MT-MAC), which solves high packet loss ratio in T-MAC. However, the delay problem still has not been addressed. In [26], network throughput of 802.15.4 enabled WSN was analyzed. Again the delay problem was ignored. An energy efficient technique for data gathering in WSNs has introduced in [27] but not given enough attention to delay problem. The authors of [28] have demonstrated an energy-efficient cross-layer double cooperative MAC for WSN. Again the analysis of delay problem was overlooked. Survey paper [29-31], summarizes the characteristics of some of the schedule-based MAC protocols. Table I illustrates a comparison of proposed DCDS-MAC protocol with some existing protocols.

TABLE I: PROTOCOL COMPARISON

Parameter	EMAC	LMAC	MC-LMAC	Proposed DCDS-MAC
Medium Access	Scheduled	Scheduled	Scheduled	Scheduled
Channel Assignment	NA	NA	Sender	Sender
Channel Switching	NA	NA	Once per timeslot	Once per timeslot
Slot Assignment	Dynamic	Dynamic	Dynamic	Dynamic
Complexity	Low	Low	Moderate	Moderate
Throughput	Low	Low	Moderate	High
Delay	High	High	Moderate	Low
Network Lifetime	High	High	Low	Moderate

III. PROPOSED DCDS-MAC PROTOCOL

DCDS-MAC, a dual-channel dual-slot medium access control is a schedule-based MAC protocol proposed for delay sensitive and high throughput WSN applications while ensuring an energy efficient operation. DCDS-MAC protocol incorporates the idea from existing LMAC and MC-LMAC protocol. In DCDS-MAC protocol, each node assigned a half frame time separated dual timeslots of a channel which allows the node to send its packets by choosing the assigned channel's best timeslot between the pair. Unlike LL-MCLMAC protocol, the data packet sending node selects the next best hope destination for its packet routing towards the gateway node. Both the technique contributes to the reduction of end-to-end delay significantly. However, any node can receive packets at any time and through any channel by switching its radio interface between different channels.

A. Bit Vectors of Occupied Timeslots

To avoid timeslot conflict and collision problem, a node needs to choose timeslots that are not using in its two-hop neighbors. This is done by OR operation among the list of timeslots those have already assigned or free for its neighbors. This list of timeslots can be represented by bit vectors to separate used and unused timeslots. Fig. 1 shows a sample bit vector.

B. Channels and Timeslot Structure

The channel and timeslot structure of proposed DCDS-MAC protocol is almost uniform to that of the multi-channel MC-LMAC protocol. The default channels (usually 1) timeslot consist of some (equal to the number of channels) small Common Frequency (CF) period, a Control Message (CM) period and a Data Message (DM) period. Other channels consist of CM and DM period only. Communication during CF slots is also has based on scheduled operations. For simplicity Fig. 2 shows the channel and timeslot structure for two channels where a frame of each channel consist of m timeslots.

C. Network Setup

Initially, an unsynchronized node randomly chooses a channel and using Algorithm 1 [7], it selects two timeslots of that channel to take control and updates their local vector for that channel. To reduce the end-to-end delay; the algorithm tries to select two timeslots of a channel as they are half frame time separated.

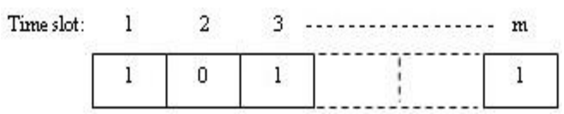

Fig. 1. Bit vector of occupied slots. '0' indicates free slot and '1' indicates used slot between its two-hop neighbors.

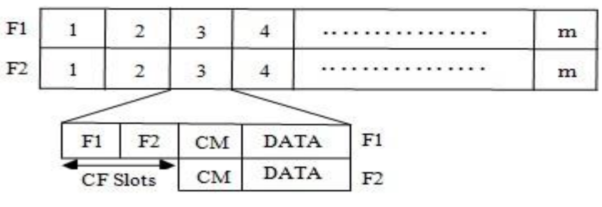

Fig. 2. DCDS-MAC channel and timeslot structure.

Algorithm 1. Initial Slot Selection

Input: Node_Id (ni), number of reserved slots (rs) and the total number of slots in a frame (ns).

Output: timeslot1 (S_1) and timeslot2 (S_2).

```
begin
    Initiate the parameters
    if ns > rs
        /* The slot can be assigned to the sensor node */
        if (ns - rs) >= 2 then
            /* Dual slot can be assigned to sensor node */
            S1 = ni % (ns - rs)
            S2 = (ni + floor((ns - rs)/2)) % (ns - rs)
        end
        if (ns - rs) = 1 then
            /* There is only one slot to assign to sensor node */
            S1 = 0
            S2 = -1
        end
    else
        /* There has no slot to assign to any node */
        S1 = -1
        S2 = -1
    end
end
```

To become synchronous with all other nodes in the network; the gateway (sink) node selects one of the timeslots between its owned timeslot pair. Then, using the default channels CF slot dedicated to its owned channel the gateway node broadcast initial CM. Then, the one-hop neighbors of the gateway node get informed that it has to switch its interface to the gateways (sender) controlled channel through which the gateway node will send the CM. After that, the gateway node broadcasts CM during the CM period; gateway's one-hop neighbors receive this CM to synchronizes themselves with the gateway. Moreover, the receiving nodes update their neighbor table, distance to the gateway and local vector for that channel to confirm that its selected channels selected timeslots are not using by any other nodes between its two-hop neighbors. If one or both of its selected channels timeslots used by any other nodes between its two-hop neighbors, then it chooses another one/two free timeslots by performing bitwise OR operation between it and its one-hop neighbor's local vector of that channel.

Then, one-hop neighbor nodes of the gateway follow the same procedure for sufficient duration to ensure for all nodes getting the free timeslots pair of a channel and become synchronous with others. During the network setup phase, nodes send only CM. After the end of setup phase, nodes can send CM and DM as well.

D. Distance to Gateway

When a node joins in the network for the first time or disconnected from the network, its distance to gateway value set to zero. The gateway (sink) node also set its distance to gateway value to zero. Then, when a node other than the sink node receives CM from other nodes of the network, it updates its distance to gateway value using the distance to gateway value of the sending node enclosed in the CM by that node. Thereafter the data packet sending nodes use this distance to gateway value to select the best next hop destination for its packet to route towards the gateway.

E. Channel and Timeslot Selection Procedure

Suppose, the node marked with '?' of Fig. 3 joins the network and is trying to own a channel with a pair of timeslots of that channel for its control. Other neighbor nodes marked with each channels local vector. For simplicity here we consider 2 channel with 8 timeslots for each channel. First, it chooses a channel randomly from the two. Suppose, it chooses channel F1. The "?" marked node get the local vector information from its neighbors during its neighbors controlled timeslots CM period. Then this node executes a bitwise OR operation on its neighbor's local vector (01000100 and 11001100) and updates its own local vector to find a pair of free timeslots of F1. The OR operation result is 11001100. So, this node select F1 channel's free timeslots 3 and 7 for its control. If there were no free slots in F1, then it will choose other channel and pair of free slots of that channel in the same way.

F. Scheduling Mechanism for Medium Access

Fig. 4 illustrates the scheduling mechanism of the proposed DCDS-MAC protocol. Here, each node chooses a channel with two timeslots. We refer to this channel as 'SelectedCh' and two timeslots as 'SelectedSlot1' and 'SelectedSlot2'. Since a frame consists of an integer number of timeslots and each node transmit packets in its selected timeslots and frame is repeated periodically. So to indicate the period of the timeslot in a frame, the variable CurrentSlot is introduced to indicate the current slot position in the frame.

G. Routing to Gateway Node

A simple routing to the gateway scenario shows in Fig. 5. When a node has to send a data packet to a designated gateway, it waits until any of its own timeslot starts. In LL-MCLMAC protocol, after receiving CM, probable destination nodes took the decision whether it will wait to receive the upcoming data packet or not based on its distance to gateway value, which may cause more nodes to wait unnecessarily for receiving the same data packet.

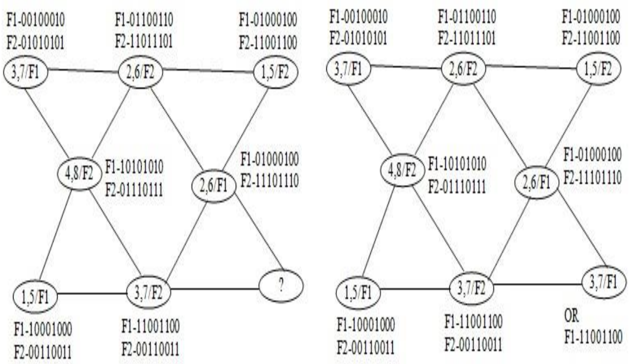

Fig. 3. Channel and timeslot selection procedure of DCDS-MAC.

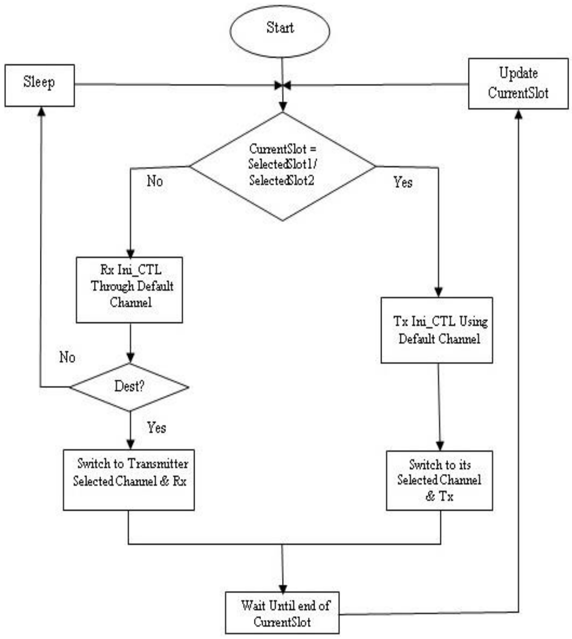

Fig. 4. Flowchart for medium access scheduling principle.

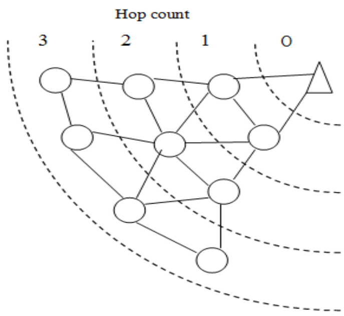

Fig. 5. Hop distance from sender nodes to the designated gateway (sink).

On the other hand, in DCDS-MAC protocol, for efficiently route the DM towards the gateway node, the sending node chooses its neighbor node which is closest to the gateway and set this node address as the destination address. Send this address through an initial_control message in its allocated CF slot of default channel F1 and switch its channel to its selected channel for further transmitting CM and DM. If initial_control message receiving node is the intended receiver switch its channel to senders associated channel; and waits to further receive CM and DM. Otherwise, it goes to sleep to conserve energy. After channel switching, the sender sends its CM and then DM through its selected channel and selected timeslot; and the intended receiver receives the CM and DM. Continue this process until the message arrives at the gateway.

IV. Performance Evaluation

A simulation model using OMNeT++ [8] and MiXiM [9] have designed to show the usefulness of the proposed DCDS-MAC protocol. To evaluate the capabilities of the proposed DCDS-MAC protocol, several experiments conducted and based on different parameters, results of

DCDS-MAC protocol has compared with existing single-channel LMAC and multi-channel MC-LMAC protocols.

A. Evaluation Metric

The main contribution of this proposed model is on exploiting the advantage of using two timeslots of two channels in DCDS-MAC protocol and selecting the most suitable receiver by the data sender. As a performance metric, here we used the number of received packets for throughput, end-to-end delay for latency, energy consumption and network lifetime.

1) Number of received packets

This performance metric used for throughput and has calculated by summing the received packets by sink node from other nodes of the network during total simulation time.

2) End-to-End delay

This metric is used to measure the data packets average end-to-end delay from any node in the network to the desired destination node. It is the average time difference between a packet initially sent by the source and successfully receiving the packet at the destination. Equation (1) used to calculate the average end-to-end delay.

$$d = \frac{\sum_{i=1}^{n}(R_i - S_i)}{n} \quad (1)$$

Here, d indicates the average end-to-end delay, n is the total number of successfully received packets by sink node, 'i' is the packet identifier, R_i is the time at which a packet 'i' is received and S_i is the time at which a packet 'i' is sent.

3) Energy consumption

Here this metric used to analyze the amount of average energy consumption by each node and calculated by taking into account Sleep Current, Rx Current and Tx Current etc. Equation (2) defines the energy consumption calculation.

$$E = P \times T \times 1000 \quad (2)$$

Here, E indicates the energy consumption in mJ, P is the power consumption in watt (W), T is the time in Second (s).

4) Network lifetime

There are many ways to calculate the network lifetime. In this research work, the maximum network lifetime (H) calculated from the duration between the network startup time and the time when all the networking nodes get die due to lack of energy. The equation shows in (3).

$$H = \frac{Total\_Energy(J)}{(P \times 60 \times 60)} \quad (3)$$

B. Simulation Environment

In our simulation setup, we selected a node as a sink node and placed it at the center of the simulation area; and other nodes are placed randomly in that area. In our experiment, all nodes can generate data except the sink node, which can only receive data. The same simulation parameters as shown in Table II had set for DCDS-MAC as in LMAC and MC-LMAC protocol. In our simulation, a physical layer energy model is also implemented to take into account the receiving, sending and sleeping energy consumptions of each node.

C. Simulation Parameters

For the performance evaluation of the proposed technique, we have simulated and defined our simulation model used the following simulation parameters presented in Table II.

TABLE II: SIMULATION PARAMETERS

Parameter	Value
Simulation Time	60 sec
Playground Size	500 x 500 x 500 m^3
Number of Nodes	25 to 200
Nodes Distribution	Randomly
Sensitivity	84 dBm
Data Rate	100 kbps
Transmission Power	100 mW
Carrier Frequency	2.4 GHz
Number of Channel	1/2
Number of Slot	16/32
Slot Duration	0.1 s
No. of Battery Per Node	1
Battery Capacity	1000 mAh
Tx Current	17 mA
Rx Current	16.4 mA
Sleep Current	0.02 mA
Data Packet Size	16 Bytes
Mobility Type	Stationary Mobility
Application Type	1 packet/sec

D. Simulation Results

The following subsection presents the simulation results. Here data calculated in the form of the number of received packets for throughput, end-to-end delay for the calculation of latency, average energy consumption by each node and network lifetime. The data collected for five different network topologies and averages the results. Performance analysis of the DCDS-MAC protocol, with the comparison of LMAC and MC-LMAC protocol for above-mentioned performance metrics, are given below.

1) Number of received packets

Fig. 6 shows the number of successfully received packets for the different number of nodes in the network throughout the full simulation time for 16 slots in a frame. The figure also represents that, when the number of nodes in the network area increased from 25 to 125, that means, with increasing the overall traffic load; the DCDS-MAC protocol provides significant improvement of throughput in terms of the number of received packets and maximum around 370 packets achieved at 125 nodes.

With further increasing the traffic loads, the number of received packets for proposed MAC protocol and also for LMAC and MCLMAC protocol decreases. This is because with the limited number of slots in a frame does not allow all nodes to get free slots in high traffic condition. However, the proposed DCDS-MAC protocol outdo the existing LMAC and MC-LMAC protocol throughout the experiment.

Fig. 7 presents that the number of received packets increased for all three protocols with increasing the number of nodes (from 25 nodes to 125 nodes) in the network. Maximum 338 packets received for proposed MAC protocol at 125 nodes, and then the number of received packets for all three protocols gradually decreasing with further increasing the number of nodes for the same reason of 16 slots in a frame. The figure also shows that, from the number of node 25 to 125, the number of received packets for LMAC always greater than MC-LMAC and lowering after 125 nodes. This is because now the number of slots in a frame is 32, and both LMAC and MC-LMAC protocol uses a single slot for transmitting. So for low dense networks, the chance of unavailable timeslot for sending is very low and for that reason sending packets over single-channel is quite enough. For that reason now MC-LMAC perform better than single-channel LMAC protocol. Again, the proposed DCDS-MAC protocol performs better than existing MC-LMAC and LMAC protocol as expected.

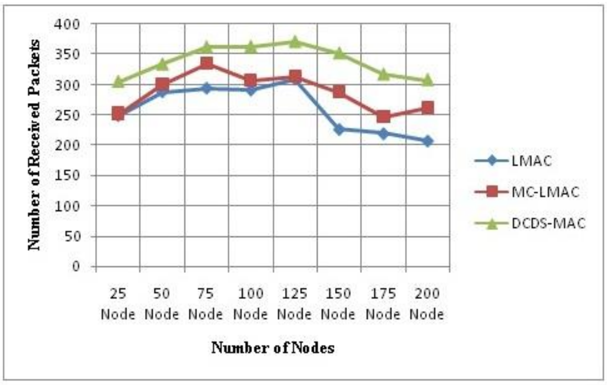

Fig. 6. The number of nodes vs. the number of received packets for 16 slots in a frame.

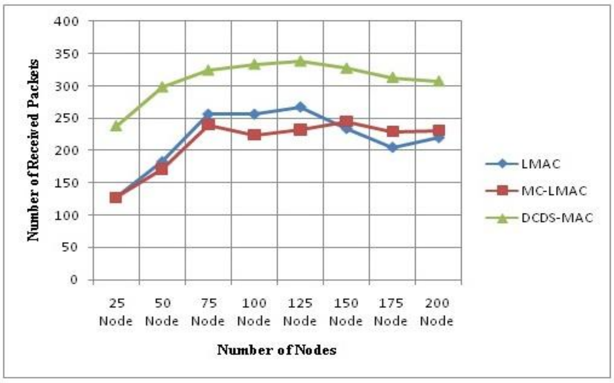

Fig. 7. The number of nodes vs. the number of received packets for 32 slots in a frame.

Fig. 8 represents that, number of received packets for both 16 slots and 32 slots increases for 25 nodes to 125 nodes and then gradually decreases for both types. Fig. 8 also reveals that the number of received packets for 16 slots in a frame always higher than the number of received packets for 32 slots in a frame. This is because for 32 slots in a frame sending nodes have to wait more time to send than 16 slots in a frame.

2) End-to-End delay

The performance result presented in Fig. 9 and Fig. 10 shows the effect of using two slots by each node with the intention to reduce end-to-end delay. Both figures for 16 slots and 32 slots in a frame confirm that after using the proposed DCDS-MAC protocol, the average end-to-end delay substantially reduced than the existing single-channel LMAC and multi-channel MC-LMAC protocols. Because, in the proposed DCDS-MAC protocol, a node can send packets using dual timeslots of a channel which results in less waiting time and hence less delay. However, with increasing the node density in the network area, there is a gradual rise in the end-to-end delay of proposed and existing protocols for the same reason as narrated in the prior section.

Finally, we can conclude that both figures confirm the proposed DCDS-MAC protocols consistent achievements in less end-to-end delay comparing with existing LMAC and MC-LMAC protocols.

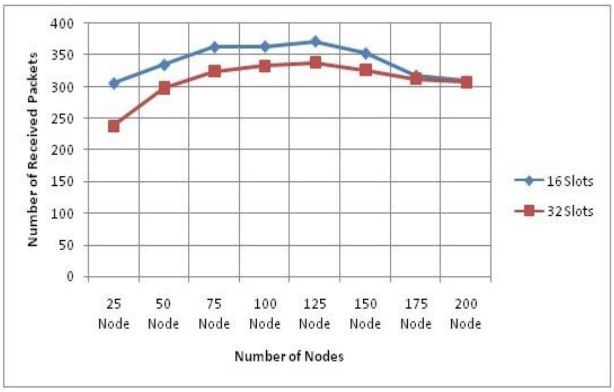

Fig. 8. The number of nodes vs. the number of received packets of DCDS-MAC protocol for 16 and 32 slots in a frame.

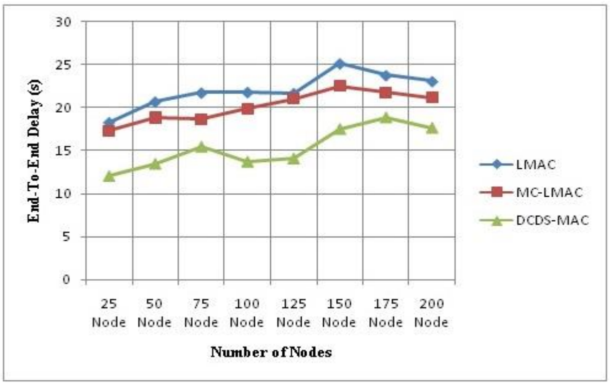

Fig. 9. The number of nodes vs. end-to-end delay for 16 slots in a frame.

Fig. 11 illustrates end-to-end packet delay of proposed DCDS-MAC protocol for both 16 slots and 32 slots in a frame. The figure confirms that end-to-end delay for 16 slots in a frame is enough lesser than 32 slots in a frame for the same reason as explained for Fig. 8.

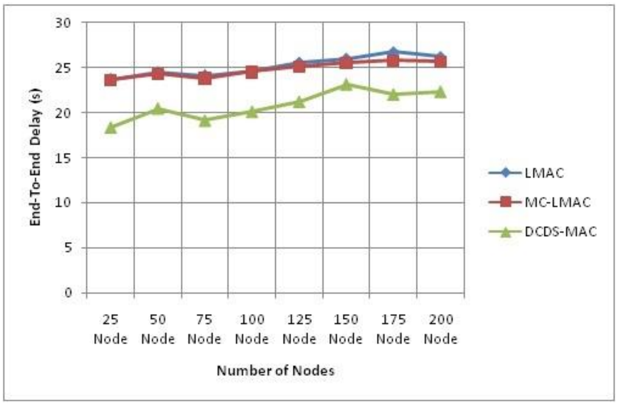

Fig. 10. The number of nodes vs. end-to-end delay for 32 slots in a frame.

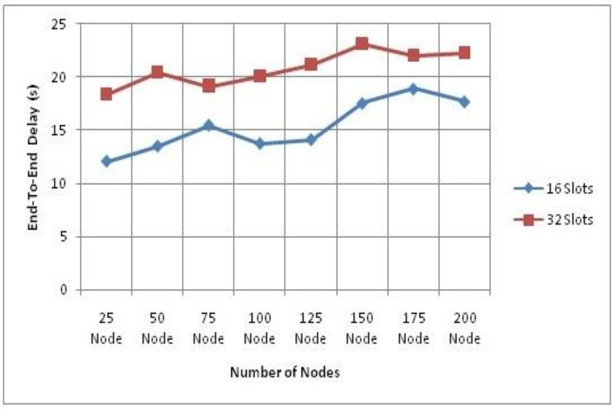

Fig. 11. The number of nodes vs. end-to-end delay of DCDS-MAC protocol for 16 and 32 slots in a frame.

3) Energy consumption

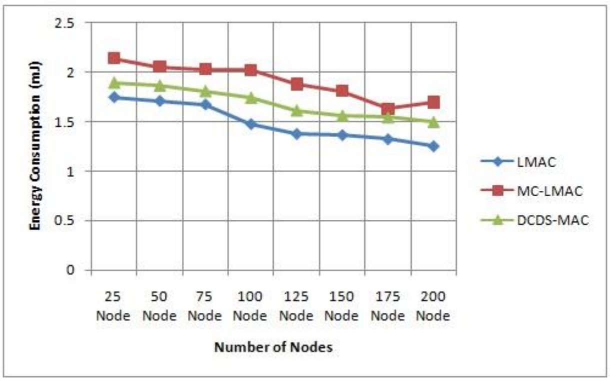

Fig. 12. The number of nodes vs. average energy consumption for 16 slots in a frame.

Fig. 12 and Fig. 13 illustrate that, while proposed DCDS-MAC protocol uses the concept of dual-channel dual-slot to further improve the throughput and delay performance, amalgamates a significant advancement in energy consumptions comparing with existing multi-channel MC-LMAC protocol for the whole experiment. However, the proposed protocol consumes more energy than the single-channel LMAC protocol because here the time and energy needed for channel switching are not required. The figure also reveals that the average energy consumption by each node gradually reduces with increasing the node density in the network which definitely reflects the reduction of the necessity of traffic transmission by each node.

Fig. 14. shows that energy consumption for 16 slots in a frame is less than 32 slots in a frame throughout the experiment. For 32 slots in a frame, a node has to wait more time than 16 slots in a frame; which incurs more energy consumption.

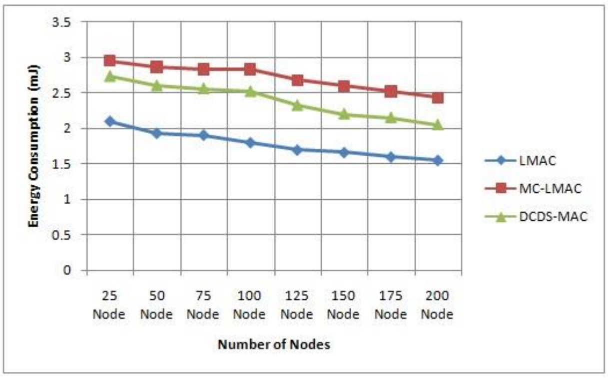

Fig. 13. The number of nodes vs. average energy consumption for 32 slots in a frame.

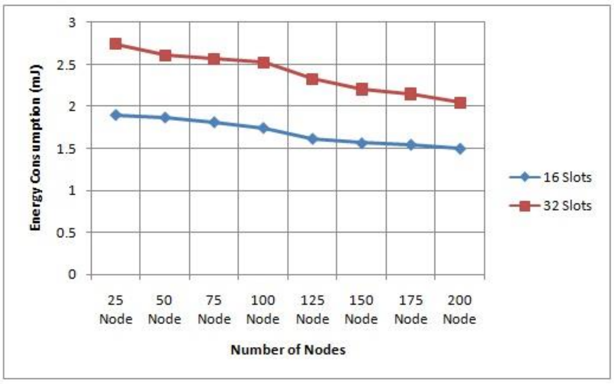

Fig. 14. The number of nodes vs. average energy consumption of DCDS-MAC protocol for 16 and 32 slots in a frame.

Again due to the reduction of the necessity of average traffic transmission by each node, the average energy consumption by each node gradually decreases with increasing the node density for both network types of using 16 and 32 slots in a frame.

4) *Network lifetime*

Fig. 15 and Fig. 16 (Fig. 15 for 16 slots in a frame and Fig. 16 for 32 slots in a frame) represent that, for single-channel LMAC protocol, the network lifetime is greater than multi-channel MC-LMAC and DCDS-MAC protocol. But in spite of utilizing the benefits of two slots per frame, in the proposed DCDS-MAC protocol, it consumes low energy than multi-channel MC-LMAC protocol. It is because; DCDS-MAC protocol ensures to receive packets within a short time than MC-LMAC protocol, which results in less energy consumption for DCDS-MAC protocol than MC-LMAC protocol. So the network lifetime of DCDS-MAC protocol is greater than the existing MC-LMAC protocol and less than existing single-channel LMAC protocol. Figures also show that, with increasing the node density, the network lifetime is gradually increased for all three protocols as expected.

Fig. 17 represents that, for same traffic load, the network lifetime for 16 slots per frame is always greater (because of less energy consumption and less end-to-end delay) than 32 slots per frame and the network lifetime is increasing with the increase of the number of nodes in the network for the same reason as explained before.

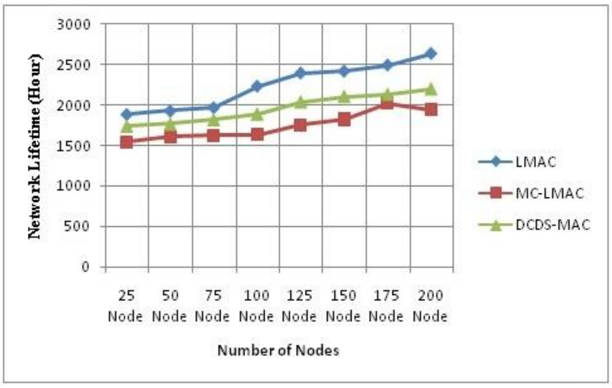

Fig. 15. The number of nodes vs. network lifetime for 16 slots in a frame.

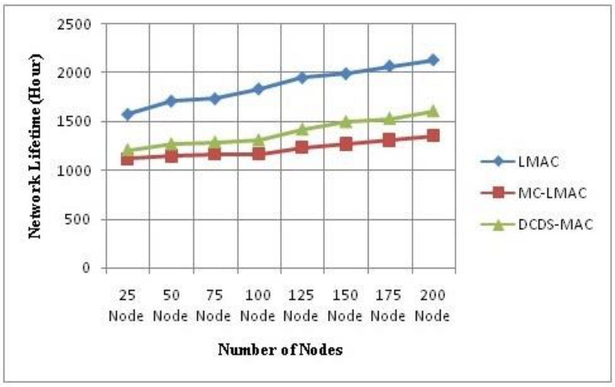

Fig. 16. The number of nodes vs. network lifetime for 32 slots in a frame.

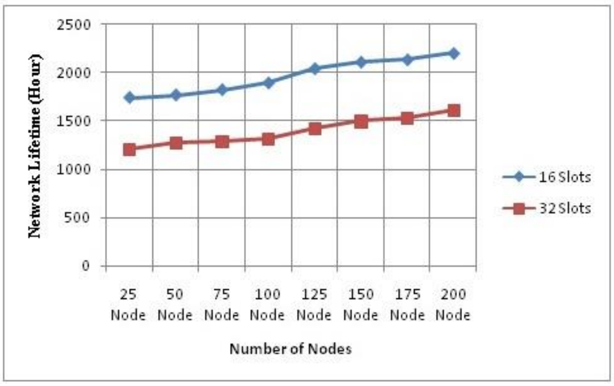

Fig. 17. The number of nodes vs. network lifetime of DCDS-MAC protocol for 16 and 32 slots in a frame.

V. Conclusions

In this research work DCDS-MAC, a Dual-Channel Dual-Slot MAC (DCDS-MAC) protocol for delay intolerable WSN applications presented. Proposed DCDS-MAC protocol utilize the concept of dual slots of a channel from dual channels and suitable destination selection technique to improve the performance of delay sensitive and high throughput required applications while ensuring an energy efficient operation. Since the proposed protocol based on LMAC and MC-LMAC protocol, using different performance parameters, the performance of the proposed DCDS-MAC protocol with the existing LMAC and MC-LMAC protocols have been analyzed in section 4.

Performance result confirms DCDS-MAC's consistency to improve latency and throughput performance compared to existing multi-channel MC-LMAC protocols and consumes more energy consumption than single-channel LMAC protocol. However, the network lifetime of the proposed protocol is less than the existing single-channel LMAC protocol but significantly greater than existing multi-channel MC-LMAC protocol. The incompetence of DCDS-MAC protocol may include highly application dependency. Moreover, the need for dual channel transceiver in each node may incur an additional price in each node.

Finally, we can conclude that the proposed DCDS-MAC protocol outperforms the existing LMAC and MC-LMAC protocols and will be well suited for high throughput and low latency WSN applications such as intrusion detection, security, and tactical surveillance application.

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