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Multihop Multi-Channel Distributed QOS Scheduling MAC Scheme for Wireless Sensor Networks

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Abstract: *In this paper, we propose a* Multihop Multi-Channel Distributed QoS Scheduling MAC scheme *(MMDQS-MAC) to improve the network performance of WSNs, which selects the best channel for an individual wireless sensor node. MMDQS-MAC supports dynamic channel assignment mechanism where each sensor node is equipped with a directional antennas. The proposed protocol helps to decrease the probability of collision, interferences and improves the overall network performance of Wireless Sensor Networks (WSNs). The protocol is most suitable for short packet transmission under low traffic networks and has ability to utilize parallel transmission among neighboring nodes and achieves increased energy efficiency when multi-channels are available. Simulation result shows that the proposed protocol improves the performance of aggregate throughput, probability of successful transmission, packet delivery ratio, energy consumption and average end-to-end delay.*

Keywords: *Medium Access Control (MAC); Quality of Service (QoS); Wireless Sensor Networks (WSNs); Multi-Channel (MC)*

I. Introduction

Wireless Sensor Networks (WSNs) has low-cost, low-power transceivers, processors and multifunctional sensor nodes, that are small in size and communicate over short distances with capability of sensing various types of physical and environmental conditions. These tiny sensors have sensing, data processing and communication devices, which are capable to communicate over wireless on multihops with their neighbouring sensor nodes [1]. WSNs are being designed and developed for specific purpose which depends on a variety of different applications including military, environment monitoring, health, surveillance, industry, smart buildings, medical care and home applications [2].

Due to the half-duplex property of the sensor radio and the broadcast nature of wireless medium, limited bandwidth remains a issue for Wireless Sensor Networks. MAC protocols have direct impact on the utilization of channels, Quality of Service (QoS) of the entire network and node battery life. The bandwidth problem is more serious for multihop WSNs due to interference between successive hops on the same path as well as the neighboring paths. As a result, conventional single channel Medium Access Protocol (MAC) protocol cannot adequately support the bandwidth requirements.

In this paper, we design the use of multi-channel MAC protocols to improve the achievable throughput of WSNs. The typical WSNs radio operate on a limited bandwidth, the operating frequency of the radio can be adjusted over different channels. Once different channels are assigned to contending links, more parallel transmissions can take place and more data can be delivered to the sink node in shorter intervals [3] such as home applications, military, industrial and health care. The primary goal of this work is to reduce the channel access time of a sensor node when the medium is busy, utilize the available multi-channels as much as possible and improve the overall network performance.

Motivation

In this paper, we have a concept of Multi-channel MAC schemes for a potential of increasing the capacity of wireless access control mechanisms. In multi-channel access mechanism wireless links occupied by different transmissions can maintain active at the same time without collision. This mechanism assigns each channel a pre-determined and fixed length of the wireless bandwidth resource. Such multi-channel scheduling MAC assignment can eliminate the interference among different channels and therefore, no collision in the

MAC layer. With this each node can only transmit at the pre-assigned set of slots. The collision avoidance is the improvement of effective channel utilization, packet delivery ratio, saving energy and average end-to-end delay.

Contribution

We present a MMDQS-MAC multi-channel protocol with a fully distributed scheduling mechanism that does not require a centralized scheduler. The protocol is a multi-channel MAC protocol specially designed for WSNs, in which each sensor node is equipped with a directional antennas and the MAC layer packet size is very small. The main contribution of the proposed protocol is that it successfully exploits multi-channels to improve WSNs performance in terms of aggregate throughput, packet delivery ratio, probability of successful transmission, energy consumption and average end-to-end delay.

Organization

The organization of this paper is as follows. Related Work is discussed in Section II, while Background is reviewed in Section III. Problem is defined in Section IV and System Model is described in Section V. Mathematical Model is derived in Section VI and Performance Evaluation is analyzed in Section VII. Conclusions are presented in Section VIII.

II. Related Work

Ye et al., [4] designed a static-scheduling based energy saving S-MAC protocol that allows neighboring nodes to sleep for long periods and wake up in sensor networks. It uses periodic listen and sleep, the collision avoidance facilities of 802.11 and over-hearing avoidance to reduce energy consumption. Cuomo et al., [5] provide contention minimized random access that combine CSMA with any multiple access scheme such as frequency division multiple access (FDMA), code division multiple access (CDMA), TDMA. Jain et al., [6] proposed a multi-channel MAC protocols; the multiple orthogonal channels are provided by frequency division and develop a suite of protocols to exploit channel diversity to achieve higher throughput.Wu et al., [7] described the effective use of multiple channels by having a separate channel for reservation. This extends the idea of using short slots in contention mode to reserve longer non-contending slots for the data.

Garces et al., [8] presented a model where a mobile host can only access one channel at a time. This is not necessarily equivalent to the single-channel model, because the transceiver is still capable of switching from one channel to another. The transceiver can be simplex or duplex. Wu et al., [9] proposed a multi-channel MAC protocol called Dynamic Channel Assignment (DCA), which is degree independent and does not require any form of clock synchronization among mobile hosts. Chen et al., [10] presented a Multi-channel Access Protocol (MAP) as an example of channel hopping, in which time is slotted and nodes hop through all the channels following a common schedule or their respective pseudo random schedules. If a node wants to communicate they successfully exchange control information and stay on that channel to complete the data transfer.

Yang et al., [11] proposed Contention-Aware Admission Control (CACP) Protocol that considers the contention among flows within a node's interference range and uses on-demand resource discovery-based scheme to provide QoS assurances. Chakeres et al., [12] addressed the Perceptive Admission Control (PAC) admission control problem by monitoring the wireless channel using channel busy time and dynamically adapting admission control decisions to enable high network utilization while preventing congestion. However, this protocol does not consider intra-flow interference when making admission decisions. Dapeng Wu et al., [13] guarantees a QoS of data rate, error rate and delay bound for delay sensitive applications. The effective capacity (EC) is a promising technique for analyzing the statistical QoS performance of wireless networks where the service process is regarded as a time-varying wireless channel. A pure queuing model was considered, assuming ideal rate adaptive channel codes achieving the instantaneous Shannon capacity, where the effect of channel variations on link performance was captured by a single function called Effective Capacity. In reality, one needs to consider not only the ideal queuing model, but also an explicit physical layer model for channel coding.

Cho et al., [14] proposed a variable bandwidth allocation scheme using time-frequency slot allocation to reduce the energy consumption of a collaborative sensor network. Chen et al., [15] designed a Coordinator-based Multi-Channel MAC (MCMAC) that assumes nodes belonging the same cluster are synchronized. In addition, a cluster comprises not more than 64 sensor nodes. Cluster Heads (CHs) can communicate with each other at stronger power, where one of the available channels is used as control channel; the control channel can be operated to exchange the control packets and data packets. Salajegheh et al., [16] focused on Hybrid MAC protocol, to provide high throughput and small bounded end-to-end delay for the packets exchanged between each node and the sink. HyMAC is a combination of TDMA and FDMA protocols in which data gathered by sensor nodes has to be delivered to at least one sink node in a timely manner. Le et al., [17] proposed the general-purpose Multi-channel that assigns a home frequency to each node such that network throughput is maximized.

Wu et al., [18] is a Tree-based Multi-Channel Protocol TMCP for data collection applications in WSNs. The main idea of TMCP protocol is to partition the whole network into multiple vertex-disjoint sub-trees rooted at the base station. Different channels are allocated to each subtree and each flow is forwarded only along its corresponding sub-tree. TMCP tries to keep away from complex coordination methods by reducing channel switching and communication among the nodes. Chen et al., [19] proposed a Multipath Fairness Solution (MFS) that redistributes network bandwidth from high rate data sources to low-rate sources as long as they share common routing paths. MFS is easy to implement, which is advantageous in a resource scarce sensor network. More importantly, it achieves much higher network throughput and better fairness among the flows.

Yang et al., [20] designed a Tree-based MAC protocol for Reliable Data Collection in WSNs in scenarios with Radio Frequency (RF) interference. It uses local TDMA and Frequency Hopping Spread Spectrum (FHSS) together. The FHSS scheme is used to decrease collisions, enhance throughput and avoid RF interference. In this scheme every hopping sequence is obtained by cyclic shifting a standard hopping sequence that is generated by interleaving a normal sequence with a S-random interleaver. Lohier et al., [21] proposed a Multichannel Access for Sensor Networks (MASN) protocol that improves the global throughput to satisfy high bandwidth requirements for applications like monitoring or traffic control. It uses multiple channels on current low-cost, low-energy radio transceivers to increase the number of parallel transmissions between different pairs of transceivers. It improves the global throughput depending on the scenario compared to the distributed channel allocation. Hung et al., [22] proposed a multihop MAC protocol called Bandwidth Utilization and Fairness Enhancements Medium Access Control (BUFE MAC), which increases the bandwidth utilization, maintaining fairness and avoiding collision. The performance of the proposed MAC protocol not only avoids the collision but improves the end-to-end throughput.

III. Background

Zhou et al., [23] designed a Multi-Frequency Media Access Control (MMSN) for WSNs. It is a slotted CSMA protocol in which at the beginning of each time slot, nodes need to contend for the medium before they can transmit. MMSN assigns channels to the receivers; when a node intends to transmit a packet it has to listen for the incoming packets both on its own frequency and the destinations frequency. MMSN uses a special broadcast channel for the broadcast traffic and the beginning of each time slot is reserved for broadcasts, which requires a dedicated broadcast channel.

Satish et al., [24] proposed an Opportunistic Multi-Channel MAC (OMC-MAC) protocol for distributed Cognitive Radio (CR) networks that provide a QoS assurance to the prioritized Secondary Users (SUs) such as SU with delay sensitive applications in a highly dynamic CR environment. Incel et al., [25] proposed Multi-Channel Lightweight MAC protocol (MC-LMAC), that uses a semi-dynamic channel assignment approach for channel allocation. The proposed protocol overhead is significantly high. MC-LMAC achieves interference free and collision-free parallel transmissions over multi-channels. Time is slotted; each node is assigned the control over a time slot to transmit on a particular channel. The performance of MC-LMAC provide a high throughput and high delivery ratio by coordinating multi-channel transmissions.

IV. Problem Definition

The proposed protocol MMDQS-MAC is a schedule-based multi-channel MAC protocol with minimum communication overhead. The sensor nodes and sink node are all equipped with directional antennas. Each timeslot is designed to accommodate data to transmit in multihop and receive by sink node in WSNs. Hence, the allocation of timeslots directly influences the network performance. The maximum throughput can reach only if the sink node is busy with receiving packets and if the schedules of all nodes are aligned for interference-free communication when several transmissions run simultaneously for the given network topology. Multi-channel allows parallel transmissions within a sensor network, which results in increased throughput, decreased collision probability and improves energy efficiency. The main objectives of the proposed work is to

1. Maximize the aggregate throughput.
2. Align the nodes for interference-free communication.
3. Guarantee QoS.

A. Assumptions

i. All sensor nodes are equipped with a directional antennas.
ii. All sensor nodes are stationary.
iii. Sensor nodes can choose an arbitrary transmit power for each data transmission.

V. System Model

In Figure 1, we consider a multi-channel static Wireless Sensor Network, where each sensor node is equipped with a directional antennas and a data collection sink node. There are S non-overlapping channels having the same bandwidth in WSNs and transmit data packet on one of these channels at a time. Each sensor node in WSNs use the same fixed transmission range and a fixed interference range. In this section, we analyse the MMDQS-MAC protocol, that carefully schedules packet transmissions to avoid collisions at the MAC layer and utilize the multi-channels to maximize parallel transmission among neighboring sensor nodes in multihop. Each sensor node initially operates on the default channel to allow initial synchronization and discovery of neighbours. Time synchronization is performed periodically by generating beacon frames. The beacon frames are broadcast during the Contention Period (CP). The frame format of MMDQS-MAC protocol is divided into two time periods as shown in Figure 2.

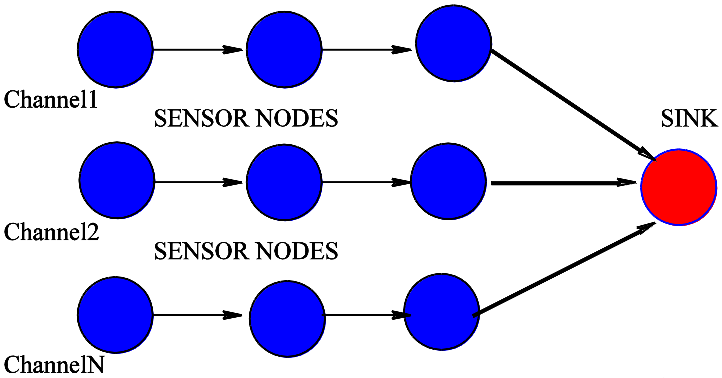

Fig. 1. Sensor Nodes and a Sink Node are Scheduling using Multi-Channel for Data Collections

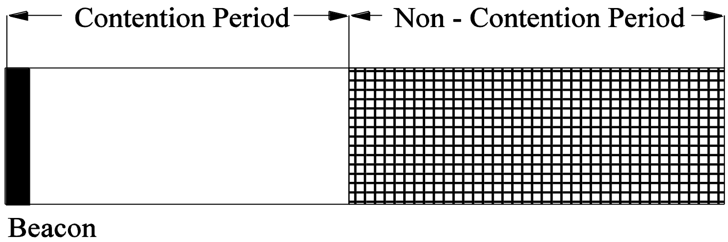

Fig. 2. The Frame Structure of MMDQS-MAC Protocol

The proposed protocol is based on a combination of Contention Period (CP) and Non Contention Period (NCP) based techniques. In the MMDQS-MAC protocol, the CP is of fixed length frames composed of a specified number of time slots and the period of NCP is dependent on the contention resolution of CP. All deployed sensor nodes are enforced to listen to the results of contentions in CP to provide collision-free operation. Excellent energy efficiency is achieved due to the minimization of idle listening and overhearing. The schedule of each sensor node is traffic adaptive and contend for channel access when they have packets in their queue. The sending source node stays on the contention channel during a CP time. When a source node wants to access the medium, it must receive the beacon frame before contending medium access channel. The purpose of the contending channel is to resolve the contention of data channels and assign data channels to sensor nodes.

VI. Mathematical Model

In this paper, we analyse the MMDQS-MAC protocol for multichannel WSNs performance. The notations are defined in Table I. Let T_{suc} denote the time period of successful transmission, consisting of time period of RTS/CTS/SIFS packet, a data packet (t_D) followed by the propagation delay (δ) across the channel. Therefore,

$$T_{suc} = t_{RTS} + t_{SIFS} + t_{CTS} + t_D + 2\,\delta \qquad (1)$$

Let T_{fail} an unsuccessful transmission time period consists of RTS packet delay, propagation delay due to collision. Therefore, the duration of the average failed transmission time period is,

$$T_{fail} = t_{RTS} + \delta \qquad (2)$$

We assume that the packet arrival time at a queue in each node is a Poisson process. Under this assumption, Poisson statistics state that the probability $P_{suc}(t)$ of exactly y packets arriving in a time period t per each node is given by

$$P_{suc}(t) = (\lambda t)^y\, e^{(-\lambda t)} / y! \qquad (3)$$

where λ represents the mean packet arrival rate of a sensor node. Let $P_{chI}(t)$ denote the probability of a node successfully sensing a channel idle in time interval t. In other words, the $P_{chI}(t)$ is the probability that a node detects that no other node is transmitting data in the network during the observing time interval t and can be derived as

$$P_{chI}(t) = e^{(-\beta t)} \quad (4)$$

where $\beta = N\lambda$ is the total packet arrival rate in the network. By considering the propagation delay, the channel capacity wasted (CH_{wa}) due to collision of two RTS control packets that are partially overlapping with each other can be derived by the following equation:

$$CH_{wa} = \delta - (1 - e^{-\beta\delta})/\beta \quad (5)$$

Therefore, the average channel busy time CH_{avgB} in a CP is given by

$$CH_{avgB} = CH_{wa} + T_{fail}\,(1 - P_{chI}(t)) + T_{suc}\,P_{chI}(t) \quad (6)$$

The expected duration of idle time between two consecutive busy time is 1/ β. Once a sensor node has a packet to transmit, it first senses the idle channel for a Distributed Coordination Function Inter Frame Space (DIFS) period and then chooses a random backoff time for counting down. The random backoff probability P_{AB} equation can be expressed as

$$P_{AB} = CH_{avgB} * [1/\beta + CH_{avgB} + DIFS + BW/2]^{-1} \quad (7)$$

where BW/2 is the mean value of the first backoff countdown. where BW/2 is the mean value of the first backoff countdown. In this work, we assume the minimum backoff window size BW = 32α and the maximum window size of 1024α, where α is the time allocation of a slot (20µs).

The P_{wp} is the probability that there are no arrivals during the waiting time. The length of an average waiting time is η seconds, expressed as

$$P_{wp} = e^{-\beta\eta} \quad (8)$$

When a sensor node completes its backoff countdown, it transmits without any delay sending the RTS packet. P_{suc} is the successful probability of a node which has transmitted data in time T_{suc}. The probability $(1-P_{suc})$ is the transmitting node failure time T_{fail} in the backoff period. The probability P_{suc} of a sensor node that sends RTS packet successfuly without colliding with any other neighbors within δ seconds can be expressed as

$$P_{suc} = e^{-\beta\delta} \quad (9)$$

(i) Average delay: We can compute the expected average contention delay of a RTS/CTS handshake protocol. We can obtain an expression for the average contention access MAC delay T_{Delay} as given below

$$T_{Delay} = P_{AB}\,(CH_{avgB} / 2) + (1 - P_{AB})\,(DIFS + BW/2) \quad (10)$$

(ii) Aggregate Throughput: The aggregate throughput of proposed protocol MMDQS-MAC can be computed as follows. From the results of the derived contention delay, the number of successful reservations (R_{suc}) in a given CP is as follows

$$R_{suc} = CP/ T_{Delay} \quad (11)$$

Based on value R_{suc}, we can estimate the network throughput N_T, which is defined as the total quantity of successfully transmitted data over the capacity of all channels within the T_{period}. Let L be the mean length of the data frame. Then, the total quantity of transmitted data in the NCP is given by R_{suc} * L and the throughput is obtained as given below

$$N_T = (R_{suc} * L / T_{period} * S) * d \quad (12)$$

In MMDQS-MAC, the T_{period} consists of the CP and NCP periods and d is the data rate, since they are non-overlapping and hence T_{period} = CP + NCP. Assuming all successful reservations are arranged of all channels ideally, the length of NCP in MMDQS-MAC is

$$NCP = (R_{suc} /S) * T_{aP} \quad (13)$$

Where T_{aP} is the average transmission period of a request and is equal to (l + 2δ + SIFS + ACK).

Table :1 Notations

Symbols	Meaning
CP	Contention Period
NCP	Non Contention Period
T_{suc}	Time period of successful transmission
t_D	Time period of data packet
S	Number of non-overlapping channels
y	Packets arriving in a time period t
d	Data rate

Symbols	Meaning
δ	Propagation delay
T_{fail}	Time period of unsuccessful transmission
P_{suc}	Successful probability of a node
T_{Delay}	Average contention access MAC delay
t_{RTS}	Time period of Request-To-Send
t_{CTS}	Time period of Clear-To-Send
t_{SIFS}	Time period of Short Inter-Frame Space
CH_{avgB}	Average channel busy time

VII. Performance Evaluation

A. Simulation Setup

The performance of MMDQS-MAC protocol was evaluated by conducting simulations on the NS2 simulator comparing with MC-LMAC and MMSN. We consider five important performance metrics: (i) aggregate throughput, (ii) probability of successful transmission, (iii) packet delivery ratio, (iv) energy consumption and (v) average end-to-end delay. We compare our MMDQS-MAC protocols results with the MC-LMAC and MMSN protocols. In our simulation model, we assume a multi-hop network environment, where 100 sensor nodes are randomly distributed over a 200m x 200m terrain size and simulation run for 900 sec. We assume that network topology is static and the radio range of all sensor nodes are same. A free space propagation channel model is assumed with the capacity set to 250 Kbps.

It is observed in Figure 3, that the aggregate throughput increases from 1100 bytes to a maximum of 1655 bytes with the increase in contention length period from 4 to 24. Our protocol gives an throughput of 10% greater than MCLMAC and MMSN. This is an account of efficient allocation of channels and minimization of contention period. Beyond the contention length of 24, the aggregate output of all the channels decrease. This is due to the non optimal allocation of channels as well as the increase in the overhead of the contention length period.

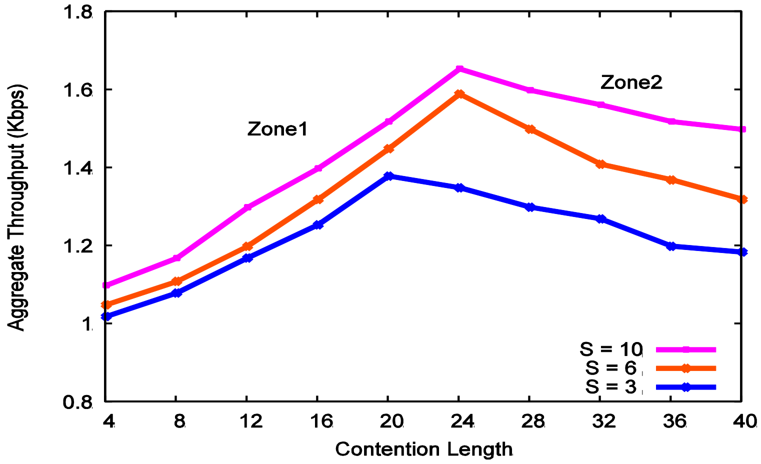

Fig. 3. Aggregate Throughput (kbps) with Number of Contention Length for different S Channels

Simulation results of successful transmission rate is shown in Figure 4 for varying number of channels S. The packet transmission rate increases with increase in the number of channels. The packet transmission rate decreases with the increase in the packet arrival rate, though there is a slight increase with larger number of available channels. We plot the probability of successful transmission of an arriving packet for S = 3, 6 and 10 channels versus packet arrival rate, under ideal carrier sensing conditions, the probability of successful transmission access is available for any one of S channels. However, the rate of improvement reduces when S is large. The accurate calculation of the probability of successful transmission depend on the available channel selection used in the sensor network.

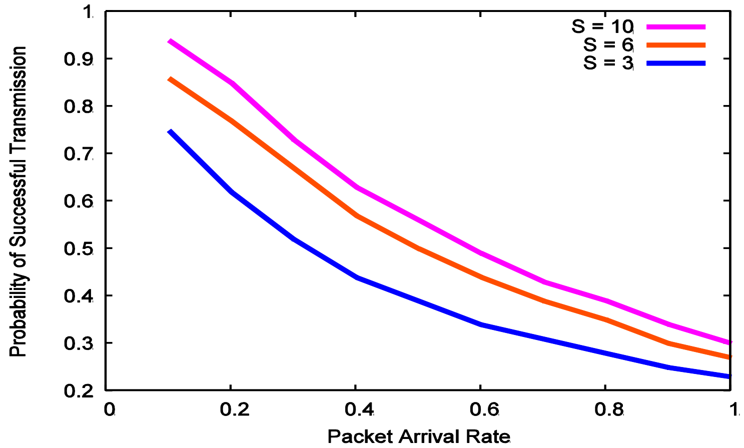

Fig. 4. Simulation results of Probability of Successful Transmission with Packet Arrival Rate (packets/sec) for different S Available Channels

Figure 5 shows the aggregate throughput with respect to the number of available channels. Output in MMDQS-MAC is much higher than MC-LMAC and MMSN. Initially, at lower number of channels, the MMDQS-MAC utilizes the channel much more efficiently reducing multihop collision and guaranteeing network connectivity. As the number of channels increase, channels may not be utilized completely, though there is increase in output. In MMDQS-MAC, the output is better due to contention based channel allocation in conjunction with channel load distribution. The output is 1655 bytes at the sink while it 1500 bytes in MC-LMAC and 1180 bytes in MMSN.

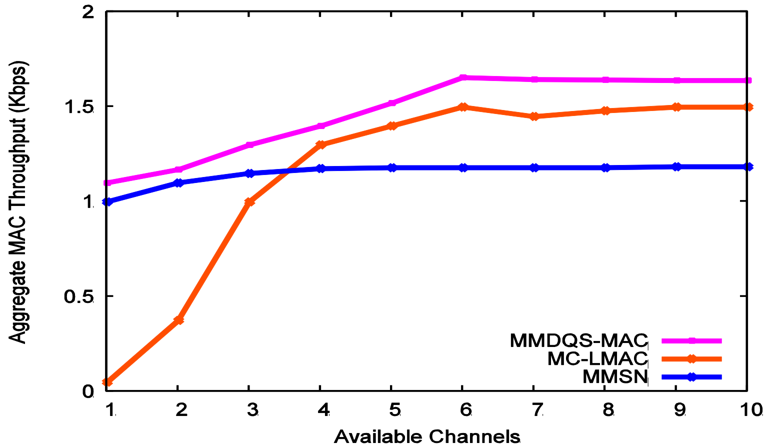

Fig. 5. Aggregate Throughput (kbps) with different Number of Available Channels

Figure 6 shows the results of packet delivery ratio with available channels, which is the ratio between the number of packets received at the sink and total number of packets generated by the sensor nodes. With sufficient data channels, MMDQS-MAC delivers on the average 99% of the packets. As we mentioned, the small percentage of losses is due to the collision. However, with a smaller number of data channels, the packet delivery ratio is rather limited since most of the nodes do not get a free timeslot. On the other hand, contention based MMSN protocol saturates around 70% packet delivery ratio with the increasing number of data channels.

Figure 7 shows the average end-to-end packet delay which is the time between the transmission of a packet at the source node and reception at the sink node. Our proposed MMDQS-MAC protocol achieves much lower delay than the MC-LMAC and MMSN protocol. Unlike the MC-LMAC, our protocol has decreasing end-to-end delay with the increase in number of data channels. This is because the average delay from source to the sink is influenced by the size of a frame in MMDQS-MAC protocol. Furthermore, decreasing the frame size does not reduce the delay since the number of packets that can be delivered per timeslot also decreases as the packets are buffered and transmitted later. As observed in Figure 7, there is a huge improvement in delay between our protocol and MC-LMAC.

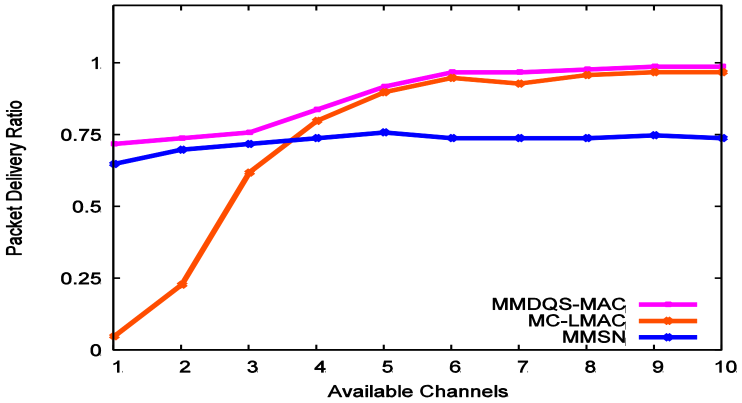

Fig. 6. Packet Delivery Ratio with different Number of Available Channels

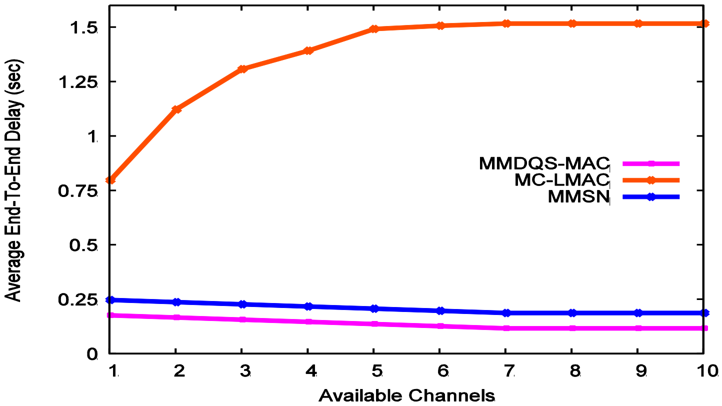

Fig. 7. End-to-End Packet Delay with different Number of Available Channels

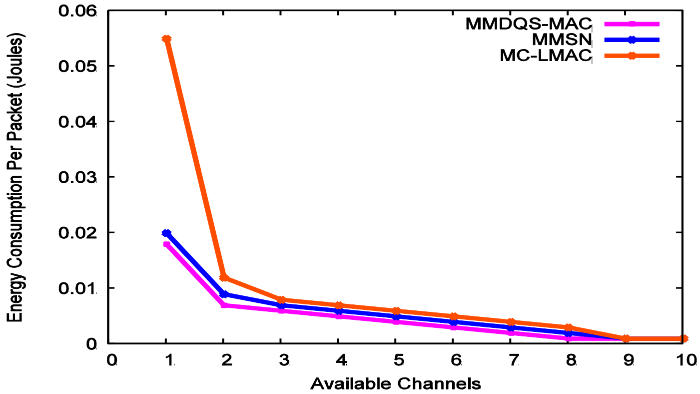

Fig. 8. Energy Consumption per Successfully Delivered Packet with different Numbers of Available Channels

Figure 8 shows the results of energy-efficiency per successfully delivered packet. We consider both the energy spent to receive and transmit as well as the energy spent for relaying the packet towards the sink node. Energy spent per delivered packet is quite high with MC-LMAC when there is only a single channel. This is due to the very low delivery rate. As the number of data channels increase, the proposed MMDQS-MAC protocol spends much less energy than other protocols i.e., MC-LMAC and MMSN. Although MMSN consumes much lower energy when compared to MC-LMAC protocol in the case of first and second channels, our protocol is more energy efficient than other two protocols. This is because our protocol has much lower collisions compared to the existing ones and excellent energy efficiency is achieved due to the minimization of idle listening and overhearing. As the number of channels increase and with low load, packet contention reduces rapidly and therefore energy consumption almost remains the same in all the scheme.

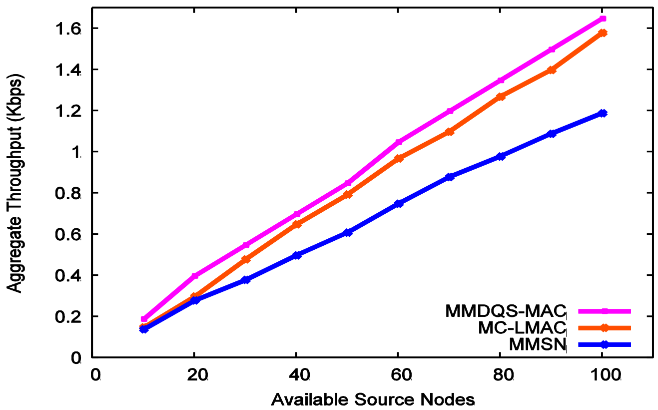

Fig. 9. Aggregate Throughput (kbps) with different Number of Sources Nodes

As shown in Figure 9, the use of 10 multi-channels achieves higher throughput. The number of sensor nodes are varied from 10 to 100. The MMDQS-MAC protocol allocates small slots to all the sensor nodes; hence there is maximum aggregate throughput due to large number of sensor nodes participation in scheduling mechanism in comparison with MC-LMAC and MMSN.

Figure 10 compares channel utilizations of MMDQS-MAC, MC-LMAC and MMSN, with varying the number of available channels. The channel utilization is higher for MMDQS-MAC than for the other protocols. The Proposed protocol MMDQS-MAC utilizes all ten channels, for the given traffic load. While, MMSN has peak utilization at four channels and MC-LMAC reaches maximum utilization at six channels.

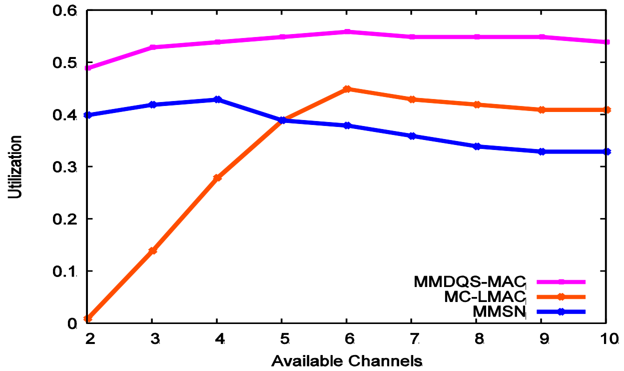

Fig. 10. Channel Utilization with Number of Available Channels

In Figures 11, we have analyzed the performance of the channel access delay with number of available channels. In the MMDQS-MAC protocol, nodes only transmit to neighboring nodes within range. This comparison is aimed at determining the efficiency in relation to channel access delay based on distance between nodes and varying data rates. We observe that channel access delay of MMDQS-MAC is much better than MC-LMAC and MMSN. When the number of available channels increase from 1 to 10, the average channel access delay in MMDQS-MAC decreases from 0.05s to 0.012s. The channel access delay decreases from 0.08s to 0.015s in MMSN protocol and it is still higher than our protocol. The MMDQS-MAC uses a small packet size of 32 to 50 bytes, which contributes to improved performance and hence outperforms the other two protocols.

VIII. Conclusions

In this paper, we have designed MMDQS-MAC for efficient QoS Multi-Channel Scheduling protocol for WSNs that carefully schedules message transmission to avoid collisions at the MAC layer. The MMDQS-MAC takes advantage of control slot in Contention Period (CP) and groups data transmission in Non-Contention Period (NCP) to maximize the simultaneous transmission among neighboring sensor nodes without collision. The sender node sends a beacon message to the schedule system requesting for transmitting data packet in parallel on different channels without disturbing other data transmission. Simulation results show that MMDQS-MAC successfully exploits multi-channels to improve overall network performance in terms of aggregate throughput, channels access, packet delivery ratio, average delay and energy consumption over MC-LMAC and MMSN in WSNs. The work can be extended with different node densities in WSNs.

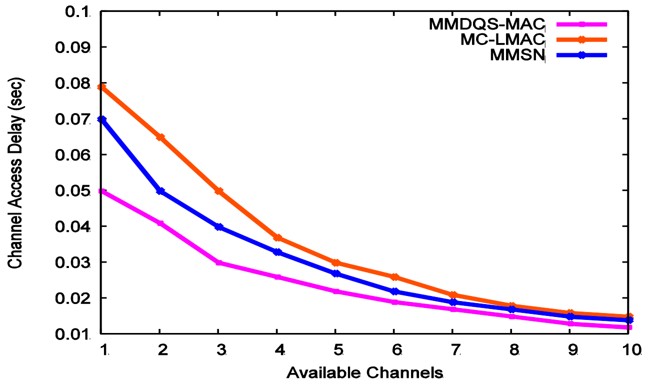

Fig. 11. Average Channel Access Delay

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