The Impact of Transmission Opportunity (TXOP) on the Performance of Priority based Contention based Scheduling Strategies in Multi-hop Mesh Networks

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Abstract: Wireless Mesh Networks (WMNs) face multiple problems. An increase in the number of hops for packets to reach the destination results in an increase in contention for the medium which also results in an increase in the collision rates. The enhanced distributed channel access (EDCA) mechanism was developed to provide differentiated services to data with different priority levels in the IEEE 802.11e standard. The EDCA is a distributed, contention-based channel access mechanism of the hybrid coordination function (HCF) which results in an unfairness problem where higher priority data can starve lower priority data. We adopt the EDCA architecture for heterogeneous data in telemetry and IoT applications to address these problems of EDCA in multi-hop mesh networks. An adaptive weighted round robin (AWRR) scheduling strategy has been proposed and tested on multi-hop networks in our previous work. With the AWRR strategy, although packet loss is reduced, the end-to-end delay increases with high and medium priority data compared to EDCA in WMNs. In this paper we investigate the effect of the Transmission Opportunity (TXOP) bursting on the global performance in a WMN through setting up simulations in OMNeT++ using the INETMANET framework. Simulation results have shown that using TXOP–bursting in the priority based scheduling which follows the concept of schedule before backup helps reduce packet loss as well as reduce the end-to-end delay. TXOP further optimizes the performance of AWRR.

1 INTRODUCTION

Wireless Mesh Networks (WMNs) have been viewed as a promising technology for low cost deployments for telemetry networks in rural areas as well as for extending network coverage compared to other solutions such as fiber optic, cellular networks, Wi-Max or VSATs (iDirect 2009; Hammond and Paul, 2006). WMNs have also attracted deployment in many applications due to their self healing properties where data can use an alternate route to send data to the destination in the event when a link becoming faulty (Akyildiz et al., 2005). Despite these advantages, WMNs experience some performance limitations. As stated in (Akyildiz et al., 2005; Sheikh et al., 2015 and Pathak and Dutta, 2011) some of the main challenges are (1) the drop in throughput with an increase in the number of hops for data to reach the destination, (2) an increase in the contention for the medium which results in an increase in the collision rates and (3) a starvation problem (fairness) affecting lower priority data with the use of the enhanced distributed channel access (EDCA) scheduling mechanism. Data that traverses multiple hops to reach the destination usually experience more contention to access the medium compared to nodes closer to the destination (Denko and Obaidat, 2009). The unfairness problem takes place as the nodes closer to the receiver are given a higher chance to transmit their data than those progressively further way (Denko and Obaidat, 2009). EDCA has an internal node contention mechanism such that when two data packets try to transmit data on the medium at the same time, the higher priority data is given access to the medium and the lower priority data behaves as if a collision occurred on the medium and exponentially increases it's contention window size resulting in starvation for lower priority data (Chen, 2011 and Telenor et al., 2005).

In many implementations and research, WMNs usually use the EDCA scheduling strategy which enhances the popular carrier sense multiple access

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with collision avoidance (CSMA/CA) for data of different priority levels. The original CSMA/CA was designed for wireless local area networks (WLANs) based on signal-hop networks (Denko and Obaidat, 2009). To address the fairness and contention increase problems in WMNs, a novel distributed contention based mechanism called adaptive weighted round robin (AWRR) in (Sheikh et al., 2015) was proposed. Weighted round robin (WRR) scheduling had been applied before for WiMax scheduling as in (Guesmi and Maaloul, 2013), for single hop WLANs IEEE802.11 based networks in (Kuppa and Prakash, 2004; Farn and Chang, 2005 and Lee et al., 2005, but not for multi-hop WMNs. With this proposed scheme, packet loss is reduced as well as improvement in fairness to address starvation as the internal collisions mechanism is removed. With this strategy different nodes might be transmitting data from a different queue as there are guaranteed slots for different queues which results in an increase in end-to-end delay for high and medium priority data and a reduction for low priority data.

EDCA contains a contention free period known as Transmission Opportunity (TXOP). When one of the priority classes gain access to the channel to send data, multiple frames can be transmitted in the duration of the TXOP without the need to sense the channel again and perform the back-off period (Inan et al., 2007; Suzuki et al., 2006 and Min et al., 2008. This condition is only valid as long as the duration does not exceed the TXOP limit set. Each packet transmission in the TXOP duration is separated by Short Inter-frame Spacing (SIFS). If the TXOP limit is set to 0, only one frame can be sent when the priority class gains access to the channel (Inan et al., 2007). Transmitting of multiple frames during the TXOP is also referred to bursting as many packets are transmitted continuously (Suzuki et al., 2006).

In the study in (Hu et al., 2012), it is shown that TXOP with Quality of Service (QoS) differentiation helps improve the system performance. The AWRR strategy has been tested without focus on the integration of TXOP. In this paper, we carry out a comparative analysis of EDCA and AWRR with and without the implementation of TXOP bursting in multi-hop mesh networks. In (Reddy et al., 2007), the proposed strategy focuses on dynamically changing the TXOP limit values. In (Reddy et al., 2007), an Adaptive-TXOP (A-TXOP) is proposed where the TXOP interval is dynamically adjusted based on the packets in the queue. The TXOP in our understanding also contributes to a form of unfairness as it allows multiple consecutive packets to be transmitted of the same priority class. Therefore, if high priority data is starving lower priority data; it is expected than TXOP will result in further unfairness.

EDCA was mainly designed for multimedia applications such as voice and video which can tolerate small amounts of packet loss but require less end-to-end delay (Gao et al., 2005). There are many non-delay sensitive applications that require a high degree of reliability (less packet loss) QoS over delay. This is to say that they can tolerate slightly more delay provided it is within the tolerable ranges. Examples of these applications are smart rural applications such as smart grid, smart buildings, smart farming and smart health (Sheikh et al., 2015). These applications carry heterogeneous type of data having different priority levels running on the same communication network. In (Sheikh et al., 2015), the requirements of these applications have been classified into three categories, namely high, medium and low priority. For EDCA to be used in these applications to carry data of different priority levels, it will have to be able to provide a high degree of reliability as well as provide end-to-end delay within tolerable ranges.

The novel contribution of this paper is that we investigate the impact of TXOP (also know as bursting) on the performance of EDCA and AWRR. With EDCA packets from the different queues concurrently try to access the medium by performing their back-off countdown in parallel. With AWRR, the packets only perform back-off after they have been selected for transmissions. The rest of this paper is organised as follows. Section 2 presents an overview of EDCA which is a contention based strategy in the IEEE802.11e standard. In section 3, we present an overview of the AWRR scheduling strategy. In section 4, an overview of the simulation setup and performance metrics used for the analysis are presented. In Section 5, the results and presented and in section 6, the paper is concluded.

2 PRIORITY SCHEDULING IN THE IEEE802.11E STANDARD

In this section we present a brief overview of the EDCA scheduling strategy which is used as the baseline strategy in this paper. EDCA is an enhancement of CSMA/CA which is widely used in many WMNs implementations.

In the IEEE802.11 standard, the Medium Access Control (MAC) layer has two access mechanisms, namely the contention based method called distributed coordination function (DCF) and the contention–free method called point coordination function (PCF) (Maamar et al., 2011). The PCF is the infrastructure based technique while DCF is the distributed technique where the devices content for the medium (Kaveh Pahlavan, 2002). The PCF is used less in WMNs implementations due to the difficulty of achieving time synchronisation globally within a network.

With DCF, data of different priority is treated equally and in a first in first out (FIFO) transmission queue scheduling strategy. To provide differentiated services the IEEE802.11e standard was proposed. The IEEE 802.11e standard is based on both the centrally-controlled and contention based medium access mechanism (Kaveh Pahlavan, 2002). The hybrid coordination function (HCF) is used in IEEE 802.11e which combines the aspects of DCF and PCF with enhanced QoS mechanisms to provide service differentiation providing both distributed and centrally controlled channel access mechanisms. EDCA is the distributed, contention-based channel access mechanism of HCF (Poonguzhali, 2014).

Table 1: EDCA parameters.

AC	Traffic Type	AIFS No.	CW_{min}	CW_{max}	TXOP limit 802.11a PHY	TXOP limit 802.11b PHY
AC[3]	Background	7	31	1023	0	0
AC[2]	Best Effort	3	31	1023	0	0
AC[1]	Video	2	15	31	3.008ms	6.016ms
AC[0]	Voice	2	7	15	1.504ms	3.264ms

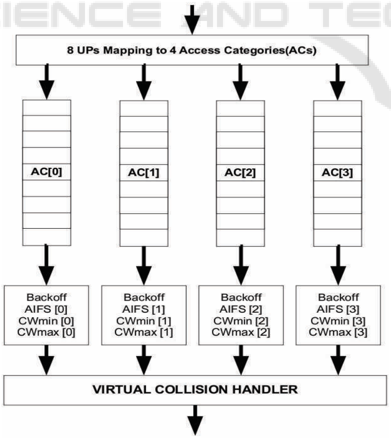


Figure 1: Reference EDCA implementation model for IEEE802.11e (Sheikh et al., 2015).

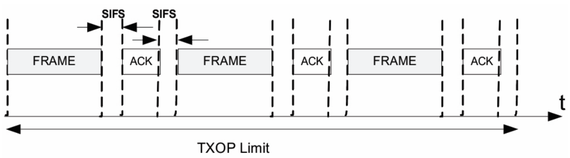


Figure 2: TXOP Limit.

EDCA consists of more than one queue for data of different priority levels known as access categories (ACs). Each one of these ACs has specific parameters associated with it as shown in table 1. These parameters are designed such that high priority data have smaller values than lower priority, giving the higher priority data a higher chance to access the channel (Pan et al., 2009).

Data is mapped at the MAC layer into the corresponding AC. EDCA introduces a new interframe spacing called Arbitration IFS (AIFS). AIFS is the minimum time period for which the medium must be sensed idle before an Enhanced Distributed Channel Access Function (EDCAF) may start transmission or back-off. The period is depended on the AIFSN, CWmin and CWmax values as shown in table 1. The higher priority ACs have smaller CWmin and CWmax values compared to lower priority ACs (Poonguzhali, 2014). For each of the ACs, the corresponding AIFSN, CW values and TXOP limit values are also shown in table 1. Figure 1 shows the implementation scheduling structure of EDCA. If any queue has data, data is scheduled after sensing the medium to be idle for the AIFS period and CW backoff period depending on the priority class.

TXOP is a time interval during which a station can send multiple frames one after the other separated by a SIFS period as shown in figure 2. In the EDCA standard, the TXOP limit is set to 3.264 ms for voice data and 6.016 ms for video data if the IEEE 802.11b standard is used and to 1.504ms for voice data and 3.008ms for video data if the IEEE 802.11a standard is used. For data, the TXOP–bursting is set to 0 (Suzuki et al., 2006). These TXOP limit values have been setup to suit voice and video QoS required and packet sizes.

3 ADAPTIVE WEIGHTED ROUND ROBIN (AWRR) SCHEDULING STRATEGY

In this section we briefly explain how the AWRR scheduling strategy works. To this AWRR strategy we integrate a TXOP mechanism and test this strategy with different TXOP limit values for data. With AWRR, information from the header on the type of application the packet is coming from is used to classify and place the frames in the different priority queues at the MAC layer. Weights are assigned to the different priority queues. In our case we have assigned 50% for high priority data, 30%

for medium priority data and 20% for low priority data. Based on these weights, we assign 10 slots to these queues. The numbers of slots assigned to the different queues can be changed. They are application dependent and are dependent on how much transmission probability chance you want to assign to the different queues (Sheikh et al., 2015). Table 2 presents the slots assigned to the different queues depending on which queues have data. The weights only apply if all the queues have data. Figure 3 shows the complete overview of the AWRR strategy. The frame only gets transmitted after performing the AIFS and back-off according to the priority data (Sheikh et al., 2015).

With the AWRR scheduling strategy, only one frame gets scheduled at a time as compared to EDCA where the frames from the different queues contend for the medium. After the scheduling process, the AIFS period and back off are carried out before transmission on the medium takes place. There is no internal contention mechanism in AWRR. To perform the investigations in the paper, the TXOP limit mechanism is added after the back-off period.

Table 2: Queue slots assigned (Sheikh et al., 2015).

Does queue have data?			Adaptive Queue Weights Assigned		
High	***Medium***	***Low***	***High***	***Medium***	***Low***
No	No	Yes	0	0	1
No	Yes	No	0	1	0
Yes	No	No	1	0	0
No	Yes	Yes	0	3	2
Yes	No	Yes	5	0	2
Yes	Yes	No	5	3	0
Yes	Yes	Yes	5	3	2

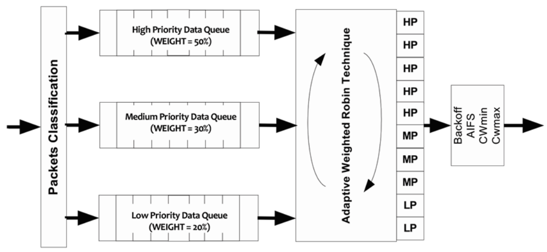


Figure 3: AWRR scheduling strategy (Sheikh et al., 2015).

4 SIMULATION SETUP

Many telemetry and Internet of Things (IoT) applications such as smart grid, home-automation, health-care monitoring are characterized as consisting of heterogeneous data in the network. These heterogeneous data have different priority levels depending on the applications. To investigate the effect of TXOP on EDCA and the AWRR scheduling strategy for data, simulations were setup in OMNeT++ using the INETMANET framework. Table 3 presents the simulation parameters. The standard IEEE802.11e model with AC[0] for high priority data, AC[1] for medium priority data and AC[2] for low priority data was used. The traffic types are heterogeneous with different priority levels. The two ray ground propagation model was used to represent the physical environment as the main focus of testing these strategies are for rural smart applications. Usually the numbers of obstacles or buildings are less in most rural areas in Africa. The two ray model was used as in rural areas, predominantly these two rays exist, i.e. direct rays and the reflected rays due to less development in rural areas. Shadowing models are more suitable for more developed areas with more obstacles. User Data Protocol (UDP) packets at the transport layer having sizes of 512 bytes were used as UDP applications such as Trivial File Transfer Protocol (TFTP) and Domain Name Systems (DNS) use a default packet size of 512 bytes. UDP was used as it does not establish connections between the source and destinations (connectionless) and also there is no retransmission of lost packets [40]. The use of UDP packets helps to determine the unreliability of the network at the lower layers through packet loss measures. On the other hand, Transmission Control Protocol (TCP) is connection oriented and also feedback is received for delivered packets (Xylomenos and Polyzos, 1999).

A 5x5 square grid topology was used for the investigation with measurements being done at the source and sink nodes being the furthest apart in the network as shown in figure 4. Source 1 and Sink 1 are other nodes also in communication to have a scenario with data links also in communication. The transmission range of each node is set such that each node can only communicate with its adjacent nodes. Square grid topologies present higher contention levels with a high number of neighbouring nodes. This helps to access the performance in extreme cases.

Five test cases with different TXOP limit values were setup with EDCA and AWRR as shown in table 4. For each of these test cases, the performance was tested over different data transmission rates with constant bit rate (CBR) data as shown in table 5. Each test with each test case and each data transmission date rate was repeated 10 times with different seed numbers generated by the random number generator utility in OMNeT++. Each seed number was 10000 apart. The errors bars show the

95% confidence level.

The performance metrics used in this paper are:

1. *Number of Collisions*: There are two types of collisions that can take place with the EDCA. These are internal and external collisions. Internal collisions take place in the node if EDCA is used. In AWRR no internal collisions take place. External collisions take place on the channel when packets collide physically. The total number of collisions is calculated as:

$$\text{Total number of Collisions per second} = \frac{\text{External collisions} + \text{Internal collisions}}{\text{simulation time in seconds}} \quad (1)$$

2. *End-to-end Delay:* This is the average time delay by a packet to arrive at the destination from the source.
3. *Percentage Packet Loss (%):* This is the measure of the percentage of packets lost from the source to the destination. This value was measured at the destination as (Periyasamy and Karthikeyan, 2014):

$$\text{Packet Loss (\%)} = \frac{(\text{\# of Packets transmitted} - \text{\# of packets recieved}) * 100}{\text{\# of Packets transmitted}} \quad (2)$$

4. *Jain Fairness Index (JFI):* It measures how fairly or unfairly the resources are shared among the nodes. Equation 3 presents the JFI value where x_i is the normalized throughput of station i, and n is the number of flows in the WMN. A JFI of 1 indicates absolute fairness and a JFI of 0 absolute unfair resource distribution (Deng and Han, 2009). In our case n=3 as we investigate the fairness for 3 data classes namely for high, medium and low priority classes.

$$f(x_0, x_1, x_2, \ldots, x_n) = \frac{(\sum_{i=0}^{n} x_i)^2}{n \sum_{i=0}^{n} x_i^{\,2}} \quad (3)$$
$$where\ 0 \le f(x_0, x_1, x_2, \ldots, x_n) \le 1$$

5 RESULTS

Figure 5 presents the number of collisions that took place in the network with EDCA and AWRR with the different TXOP test cases. In the TXOP tests, the value for the low priority data TXOP is kept smaller than the TXOP limit values for high and medium priority data as normally the higher priority data need to be transmitted with higher importance. For AWRR in TXOP test cases 1 to 5, the number of collisions per millisecond starts at 4.12 per ms with case 1 and reduces to 3.87 per ms in case 4. With EDCA, the numbers of collisions stay approximately the same, despite using TXOP, due to the internal collision mechanism being present which starves lower priority data. The higher priority data have a smaller collision window range and hence the chances of collisions are high. With AWRR, the reduction in collision with higher TXOP values is observed since when a higher priority data gains access to the medium, more higher priority data can be transmitted without having to contend for the medium as they have a higher collision possibility. AWRR also allows more packets from other classes to be transmitted on the medium compared to EDCA.

For brevity, the consolidated average packet loss over all the data transmission data rates with the different TXOP test cases are presented in figures 6 to 8. From figure 6, we can observe that for high priority data using EDCA, there is a packet loss of 50.8% in case 1 (No TXOP) and this reduces to

Table 3: Simulation Parameters.

Network Setup	
Topology type	5 by 5 Grid Topology
Terrain Area	2.2km x 2.2km = 4.84km^2
IEEE Standard	IEEE 802.11g
Propagation Model	Two Ray Ground Model
Routing Protocol	OLSR
Data rate	54Mbits/s
Transport Protocol	UDP Packets
Packet Size	512bytes

Table 4: TXOP test cases.

	Case 1	Case 2	Case 3	Case 4	Case 5
High Priority Data	No TXOP	1ms	2ms	3ms	4ms
Medium Priority Data	No TXOP	0.5ms	1.5ms	2.5ms	3.5ms
Low Priority Data	No TXOP	0	1ms	1ms	1ms

Table 5: Data transmission test cases.

	High Priority Data (Packets/sec)	Medium Priority Data (Packets/sec)	Low Priority Data (Packets /sec)
Data Case 1	50	50	50
Data Case 2	50	50	100
Data Case 3	50	100	50
Data Case 4	50	100	100
Data Case 5	100	50	50
Data Case 6	100	50	100
Data Case 7	100	100	50
Data Case 8	100	100	100

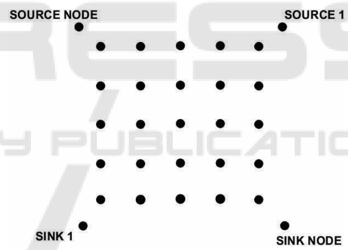


Figure 4: Test Topology.

50.4% until TXOP case 3. For high priority data using AWRR, there is a packet loss of 44.8% in case 1 (No TXOP) and this reduces to 37.6% until TXOP case 3. Therefore, a further packet loss reduction of 7% with AWRR for high priority data is observed. From figure 7, we can observe that for medium priority data using EDCA, there is a packet loss of 45.5% in case 1 and this reduces to 44.5% until TXOP case 3. For medium priority data using AWRR, there is a packet loss of 42.5% in case 1 and this reduces to 36.6% until TXOP case 3. Therefore, a further packet loss reduction of 1% for EDCA and 5.9% with AWRR for medium priority data is observed. From figure 8, we can observe that for low priority data using EDCA, there is a packet loss of 40.5% in case 1 and this reduces to 36.9% until TXOP case 3. For low priority data using AWRR, there is a packet loss of 39.1% in case 1 (No TXOP) and this reduces to 33% until TXOP case 3. Therefore, a further packet loss reduction of 1% for EDCA and 6.1% with AWRR for low priority data is observed. It is observed that increasing TXOP beyond case 3 does not affect packet loss any further for either EDCA or AWRR.

It is observed that TXOP does not significantly affect packet loss in EDCA, but does significantly reduce the packet loss in AWRR. The TXOP limit allows multiple frames to be transmitted in this TXOP duration without the need to contend for the medium for each frame in the queue. The TXOP only comes into play when more than one frame is present in the queue. During the TXOP the medium is sensed as being busy by the other nodes contending for the medium and therefore, this results in fewer collisions for the extra frames transmitted during this period. The packet loss is reduced until a point and further increasing the TXOP has no effect on the performance. This is as a result that there are no packets queued up further for the longer TXOP to come into play.

With AWRR, the back-off countdown is started only after scheduling a packet, while with EDCA, the packets in the different queues in a node perform the count down simultaneously. After a transmission takes place, the queues that were already counting down for back-off start from where they left off, while with AWRR a new back-off is started. This

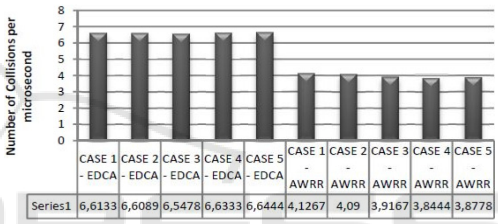


Figure 5: Number of Collisions.

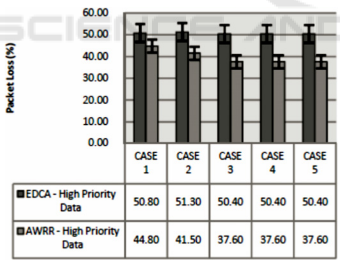


Figure 6: Average packet loss for high priority data in all TXOP test cases.

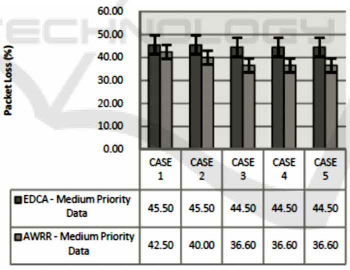


Figure 7: Average packet loss for medium priority data in all TXOP test cases.

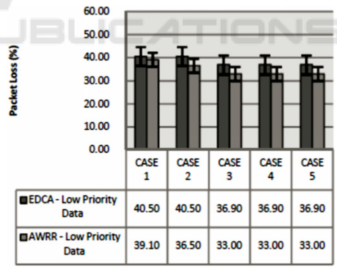


Figure 8: Average packet loss for low priority data in all TXOP test cases.

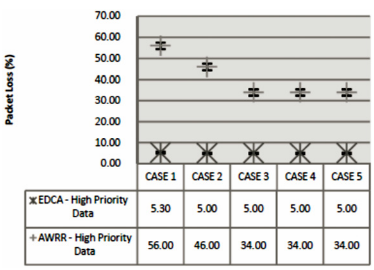


Figure 9: Average end-to-end delay for high priority data in all TXOP test cases.

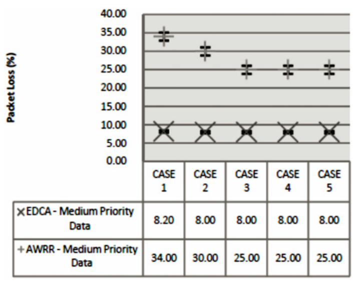


Figure 10: Average end-to-end delay for medium priority data in all TXOP test cases.

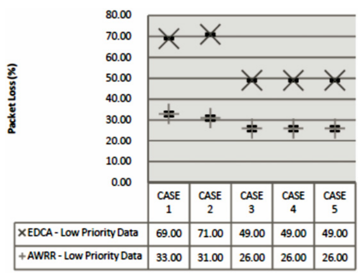


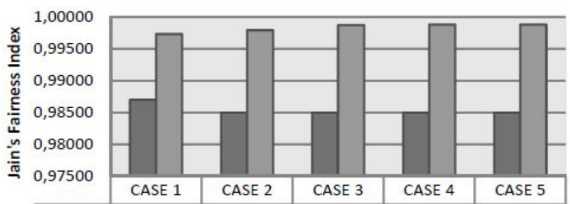
Figure 11: Average end-to-end delay for low priority data in all TXOP test cases.

increases the chances of collision on the medium with EDCA.

The consolidated average end-to-end over all the data transmission test cases for the different TXOP test cases are shown in figures 9 to 11. From figure 9 we observe an end-to-end delay of 5.3ms for high priority data and 56ms for AWRR in case 1. The end-to-end delay drops to 5ms with EDCA until case 3 and drops to 34ms for AWRR. A reduction in the end-to-end delay of 23ms is observed with AWRR. From figure 10 for case 1, we observe an end-to-end delay of 8.2ms with EDCA and 34ms with AWRR. The end-to-end delay drops to 8ms with EDCA until case 3 and drops to 25ms for AWRR. A reduction in the end-to-end delay of 9ms is observed with AWRR. From figure 11 for case 1 it is observed that EDCA has an end-to-end of 69ms and 33ms for AWRR. The end-to-end delay drops to 49ms with EDCA until case 3 and drops to 26ms for AWRR. A reduction in the end-to-end delay of 7ms is observed with AWRR and 20ms with EDCA. Higher end-to-end delay reductions are observed with AWRR as AWRR does not starve lower priority data and gives a higher chance for data from other classes to be transmitted as mentioned earlier.

The Jain's fairness index values are presented in figure 12. No significant change in fairness is observed. Since the internal collision mechanism is absent in AWRR, AWRR has a higher fairness than EDCA. Application of TXOP with AWRR is expected to improve fairness at higher loads as lower priority data are given a fair opportunity and are not being starved.

It must be noted that these strategies have a retry limit of 7. The packets that collide increase the end-to-end delay. These results are for heavy load scenarios. With low loads, performance is better.



	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
EDCA	0,98700	0,98500	0,98500	0,98500	0,98500
AWRR	0,99730	0,99790	0,99870	0,99880	0,99880

Figure 12: Jain's Fairness Index in all TXOP test cases.

6 CONCLUSIONS

The problem with contention based scheduling strategies is that they require monitoring of the channel before data can be transmitted. The advantage of TXOP is that multiple packets from the same queue can be transmitted without the need of continuously performing the contention period. With AWRR using TXOP, a reduction in collisions has been shown as the channel is sensed as being busy by the other nodes during the TXOP period and the other packets within the TXOP period of the same data class can successful transmit. Retransmission of collided packets waste channel bandwidth and reduce the overall performance of the network. Bandwidth is a critical factor in rural telemetry networks.

In this study, we have observed that with the application of TXOP to the AWRR, packet loss for high priority data can be reduced by 7%, 5.9% for medium priority data and 6.1% for low priority data. The AWRR strategy does not have an internal collision mechanism in the nodes and also the nodes only contend for the medium after it is decided which device will access the medium. Little, if any improvement with EDCA is observed with EDCA in WMNs due to the starvation and internal contention mechanism present. However, TXOP application to AWRR has shown significant packet loss and end-to-end delay reduction for all data priority classes.

With AWRR a high increase in end-to-end delay for high and medium priority packet is observed compared to EDCA as AWRR gives higher chances for packets from other priority data classes to be transmitted on the medium. In a multi-hop scenario, this results in the end-to-end delay increase for high and medium priority data only. The TXOP period helps lower this delay by a significant amount. A delay reduction of 23ms for high priority, 9ms for medium and 7ms for low priority data are observed.

This paper has shown that the performance of AWRR can be further improved and optimised by the use of TXOP limit values. In EDCA, back-off is performed concurrently between the parallel queues, while with AWRR, it is performed after the packet is selected for scheduling which shows more positive results with the use of TXOP.

Simulation results show an improvement in performance in terms of reliability, end-to-end delay and fairness. The proposed strategy, AWRR with TXOP is a promising technique for implementation in smart rural applications such as smart grid, smart buildings, smart health and smart agriculture as a low cost option to build and extent networks as observed through simulation results.

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