A Comparative Study on Improving Quality of Service in Networks Carrying Multi-Service Level Data over Resource-Limited Multi-Hop Wireless Networks

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Abstract —Multi-hop Wireless Networks (MWNs) based on Single-Radio Single-Channel (SRSC) networks will likely attract more deployments if the required Quality of Service (QoS) can be provided. Carrier sense multiple access with collision avoidance (CSMA/CA) in MWNs faces an increase in packet loss and contention with an increase in the number of hops to reach the destination. This results in an increase in collisions and a wastage of bandwidth. The Distributed Coordination Function (DCF) treats all data the same, while the Enhanced Distributed Channel Access (EDCA) method was mainly designed for delay-sensitive applications to provide multi-service differentiation. EDCA is known to provide unfairness, where higher-priority data can starve low-priority data under high loads. We have shown that Schedule-Before-Contention (SBC) packet scheduling strategies can address the limitation of EDCA, but it is still unclear which SBC strategy provides the best performance in distributed networks. Good scheduling mechanisms can reduce packet loss to the maximum, as well as avoid unnecessary delay. In this paper, we assert that the queue selection mechanism plays a critical role in the achievable Quality of Service (QoS). A comparative analysis of four SBC mechanisms is carried out and it is found that the transmission of lower-priority data helps lower packet loss, as this uses larger contention window ranges for back-off.

Index Terms—Data service management, distributed management, protocols, simulation

I. INTRODUCTION

Current trends in improving performance in Multi-Hop Wireless Networks (MWNs) include using multiple channels [1], [2]; using non-interfering channel assignments [3], and routing to consider other link quantities such as load and link quality [4]. In MWNs, for data packets to reach the destination from the source, more than one possible route that can be used, as well as more than one hop [5].

The IEEE 802.11 standard has become the most widely used standard for MWNs [6]**.** Although contention-free strategies such as Time Division Multiple Access (TDMA) improve performance in networks that access the channel using a central controller, the situation is different in MWNs, where scheduling is coordinated without a controller. For contention-free scheduling to operate correctly, perfect time synchronisation is required among all devices. In MWNs, on the other hand, the devices are distributed and there is no central controller, making contention-based strategies more suitable [7].

The key challenges in applying Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to MWNs with Single-Radio Single-Channel (SRSC) networks, is improving Quality of Service (QoS) by reducing collisions, reducing packet loss [8]–[12], and improving intra-node fairness under heavy load scenarios [13]–[15]. In this paper, the term *heavy load* is used to refer to the network conditions when packets start to form a queue in the node.

Limited work has been done to address performance in SRSC multi-hop networks. SCRC is among the more promising deployment technologies in rural telemetry and IoT applications due to its lower cost compared to Single-Radio Multi-Channel (SRMC) and Multi-Radio Multi-Channel (MRMC) technologies. The internet bandwidth in rural areas is usually very limited by cost [16], [17]. Collisions result in the wastage of bandwidth, as lost packets must be retransmitted. A reduction in collisions and packet loss will therefore allow the bandwidth to be utilised more efficiently.

The main role of a scheduling algorithm is to enable the sharing of resources and to provide QoS by choosing the next packet for transmission [18]. Fair scheduling can be classified into different categories such as hard fairness, max-min fairness, proportional fairness, mixed-biased fairness and maximum throughput [19], [20]. The type of fairness studied in this paper refers to accessing the channel fairly between the different priority queues in a node to maximise throughput and to prevent the starvation of lower-priority data, but at the same time to give higher-priority data a higher probability to access the medium.

With the application of CSMA/CA to MWNs, an increase in collision probability due to an increase in contention for a channel is experienced [8], [9]. The enhanced distributed channel access (EDCA) strategy is a contention-based strategy. EDCA places packets in different priority queues, known as Access Categories (ACs), and then provides medium access based on the parameters assigned to the different queues [21]. These

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parameters are the arbitration interframe spacing (AIFS) and the Contention Window (CW) size range for the back-off. The higher-priority traffic is assigned smaller parameter values compared to the lower-priority traffic, giving the higher-priority traffic a higher probability to transmit. An internal contention mechanism is present within the EDCA structure to handle contention for the medium by these different queues within a node.

In this paper, heavy load scenarios refer to cases that result in the queuing of packets. Under heavy loads, if contentions by two ACs finish at the same time, an internal collision takes place. This collision is handled by the virtual collision handler, which allows the higher-priority traffic to transmit, while the lower-priority traffic has to contend for the medium again by exponentially increasing its CW range, resulting in starvation [22]-[24]. If a node manages to transmit successfully, it sets its CW to the initial value. This gives the remaining packets in its queue an even higher chance to be transmitted, which results in the unfairness problem that is central to this paper [8].

In our work in [25] and [26], a summary was presented of the existing research that addresses the problems of packet loss, collision and unfairness in MWNs. A number of publications have also addressed the routing issues in MWNs and packet loss by considering channel and load conditions. To reduce the number of collisions or the extent of packet loss, some studies such as in [27]-[47] have focused on developing routing metrics that choose routing paths with better link qualities (less congestion or less interference) for data to travel over from the source to the destination. The disadvantage here is that these techniques either introduce more overhead into the medium and network, or require more buffer memory to store additional information in their routing tables. This is not suitable for rural smart applications, in which memory is a critical factor in hardware due to the need to keep costs down.

Numerous studies have addressed the starvation problem in IEEE 802.11e EDCA contention-based single-hop WLANs [21], [48], [49]. Multi-hop networks are subjected to more contention and collisions than single-hop networks, which affects their performance considerably. Limited work has been done on intra-node fairness and collision increase problems in multi-hop networks. In EDCA, differentiated services are provided by assigning different parameter values, such as CW_{min}, CW_{max}, AIFS and TXOP, to the different priorities of queues. Previous studies have proposed solutions that focus on varying these parameters to address the starvation and collision problems in multi-hop networks. Studies that have investigated the effect of changing the priority of the messages include [8], [50]–[53]. The use of weighted queues to address the unfairness problem has been investigated in [14], [21] and [48].

The first problem with these techniques is that for their successful operation, they require information from the network and other layers, such as load level, numbers of hops left, or acknowledgements. The second problem is that the priority of a packet keeps changing across the network, which means that the packet requires extra header fields to store the information on its priority (called the end-to-end delay information). This introduces additional overhead into the network. Thirdly, the techniques mentioned so far were mainly developed for multimedia applications, where end-to-end delay is critical. This is not the case with rural smart applications, which are non-delay-sensitive (elastic) and require a high degree of reliability (i.e. less packet loss) over delay.

For resource-constrained telemetry networks, strategies that reduce collisions without introducing more overhead into the network will be more suitable. The strategies based on different scheduling mechanisms that are proposed in this paper do not introduce more overhead into the network, and perform decentralised resource sharing to provide access to the medium. As mentioned before, the resulting reduction in collisions will assist in utilising the available bandwidth more efficiently.

Scheduling-Before-Contention (SBC) strategies have been proposed in our previous work in [25] and [26] to improve QoS by reducing packet loss, reducing collisions and improving fairness to prevent starvation in low-cost SRSC MWNs. These scheduling strategies first select a packet for transmission from one of the priority queues and then perform the contention period to gain access to the channel and transmit the data. The different priority data queues in a node therefore do not contend for the medium at the same time, as is the case in EDCA, and as a result these strategies do not have an internal contention-handling mechanism.

SBC strategies are applicable to smart applications that require higher reliability and that have data of different priority levels. These applications include smart grid, smart health, water utilities, gas utilities, smart agriculture and smart buildings. In this paper, data is classified into one of three categories, namely High Priority (HP), Medium Priority (MP) and Low Priority (LP) [54]. These heterogeneous data have different priority levels depending on the application, but the Distributed Coordination Function (DCF) in CSMA/CA treats all data equally. It is unclear which SBC mechanism gives the best performance in MWNs. The performance of four Medium Access Control (MAC) layer SBC mechanisms is investigated and compared in this paper. These mechanisms are Adaptive Weighted Round Robin (AWRR) [25], a deterministic mechanism; Roulette Wheel Sampling (RWS), a probabilistic mechanism; RWS-AGE, an age counter; and Congestion Control and Fairness Scheduling (CCFS) [26], which sets a maximum queue length.

II. How Schedule-Before-Contention Strategies Work

Before the scheduling mechanism can be applied in any of the SBC strategies, the packets need to be classified into the respective class queues. In all four of the proposed strategies, when data arrives at the MAC layer, it is placed into one of the three priority data class queues depending on the application from which the data originates. The classes used in the proposed schemes are high-priority data, medium-priority data, and low-priority data. Different applications use different transport layer protocols, such as the transmission control protocol (TCP) or the User Datagram Protocol (UDP), which have different port numbers. The port number in the header of the frame is what is used to classify a packet. After classification, a packet from the head of line (HOL) is selected. The medium is then monitored for the AIFS and back-off period to determine if it is still idle, after which the packet is transmitted over the channel.

The scheduling packet selection mechanisms for each strategy are presented here. The back-off values for the Contention Window (CW) used for the different priority packets in all the SBC strategies are provided in Table I.

TABLE I: BACK-OFF CONTENTION WINDOW RANGES

Priority Class	Minimum CWvalue	Maximum CWvalue
Low Priority	31	1023
Medium Priority	15	31
High Priority	1	15

A. *Adaptive Weighted Round Robin (AWRR) Scheduling Strategy*

The AWRR scheduling strategy aims at reducing packet loss as well as preventing starvation by increasing the number of lower-priority packets that gain access to the channel compared to EDCA under heavy loads. This is expected to reduce packet loss, as lower-priority data have larger CW sizes, and therefore a lower collision probability, than higher-priority data. Weighted Round Robin (WRR), a deterministic packet selection mechanism, is used in this strategy. A wheel is used which cycles from queue to queue depending on the number of slots allocated. This ensures that, after a certain number of high- and medium-priority data packets have been transmitted, lower-priority data is also given access to the medium. The WRR is a common CPU scheduling technique and appears in wireless standards such as in WiMax in [55], as well as in single-hop WLANs using IEEE802.11 in [14], [21] and [48], but never before in multi-hop wireless networks.

In the proposed AWRR strategy, weights (i.e. numbers of slots) are assigned to the different queues based on their priority requirements. The queues that are empty are skipped. Under heavy loads, when more than one queue has data, the order in which the packets from the different queues are transmitted is fixed, with high-priority data transmitting first, then medium-priority data and lastly low-priority data, after which the cycle is repeated. AWRR implicitly implements an age counter, as each priority queue cannot consecutively transmit more packets than its assigned transmission slots. The AWRR scheduling strategy is shown in Fig. 1.

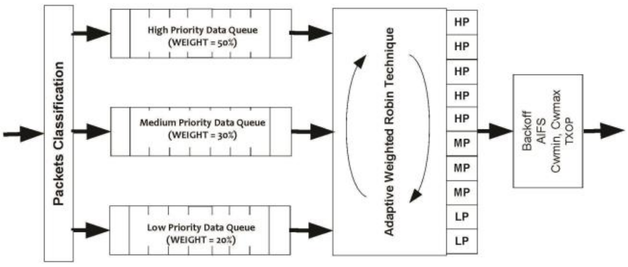


Fig. 1. Operation of the AWRR scheduling strategy

B. *Roulette-Wheel Sampling (RWS) Scheduling Strategy*

The same principle of reducing packet loss is applied in the Roulette-Wheel Sampling (RWS) scheduling strategy, which also attempts to reduce packet loss and prevent starvation by increasing the number of lower-priority packets that are transmitted under heavy loads. This is done by using a probabilistic packet selection mechanism to allow packets from different priority queues and multiple nodes to simultaneously gain access to a channel.

Let us consider N priority classes, each characterised by their weight $w_i > 0 \ (i = 1, 2, \dots, N)$. The selection probability of the i-th priority class is given in Equation 1.

$$\mathrm{p_i} = \frac{w_i}{\sum_{i=0}^{N} w_i} (i = 1, 2, \dots, N) \tag{1}$$

$$\sum_{i=0}^{N} p_i = 1$$

The priority classes are mapped onto a continuous segment of a line, such that each priority class segment is equal in size to its selection probability. A number (r) is then randomly chosen, and the AC sector that r points to, is selected for the transmission of the data (provided that its transmission queue is not empty).

As shown in Fig. 2, the stages of RWS scheduling are as follows:

1. Assign a probability selection weight to each data priority queue.
2. The strategy then determines the size of the individual queues. If all the queues have data, the original assigned weights are used. If all the queues do not contain data, then the weight of the queues with data are normalised and assigned new weights. The queues with no data are assigned a weight of zero. This allows the strategy to be adaptive to whichever queues have data.
3. The range of values for each of the priority data classes is assigned on a scale.
4. A random number is generated between 0 and the maximum scale value. A packet is chosen for transmission from a queue containing this random number.

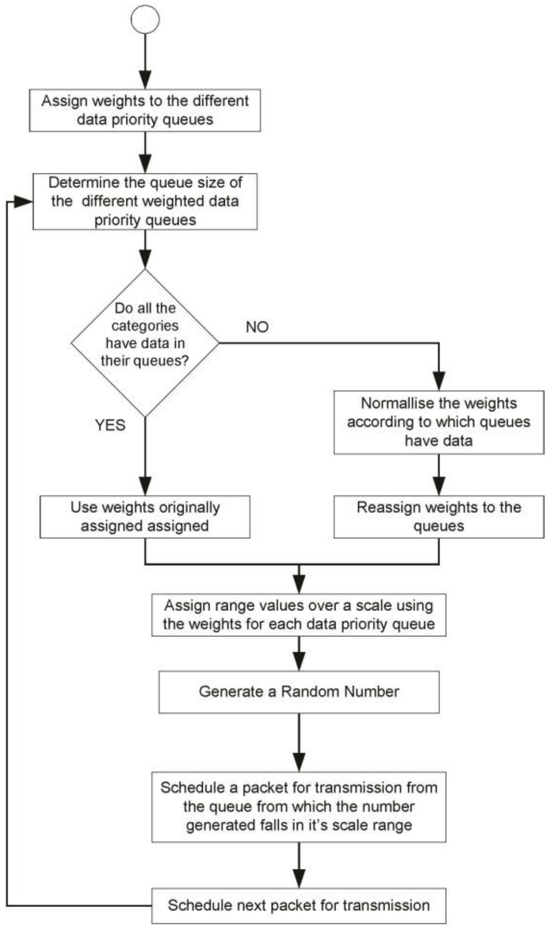


Fig. 2. Operation of the RWS scheduling strategy

In the RWS strategy, packets are transmitted based on probabilistic selection, offering a better chance for packets that have different CW ranges and are contending for the medium at a specific instant in time compared to AWRR. However, RWS does not transmit a fixed number of packets from each queue in a certain order under heavy loads, even when more than one queue has data. Thus RWS is expected to reduce packet loss, since packets have different CW sizes when contending for access to the channel.

C. ARWS-AGE Scheduling Strategy

The RWS-AGE strategy incorporates an age counter into the probabilistic packet selection mechanism. The age counter is used to determine how many consecutive packets of the same class of data are transmitted. This counter prevents more than a predetermined number of packets from the same priority queue to be consecutively transmitted. The starvation counter also maintains the weight transmission probabilities assigned to the different queues and ensures that, in the worst-case scenario, starvation does not occur.

D. Congestion Control and Fairness Scheduling (CCFS) Strategy

If data in a priority queue start to increase and the packets are not given access to the channel more quickly, there is a possibility of starvation. To address such cases, the congestion control and fairness scheduling (CCFS) strategy consists of a queue length mechanism added to the AWRR mechanism. With CCFS, the number of slots assigned to each priority queue is adaptive depending on the load level in each queue. Fewer transmission slots are assigned to each priority queue than for AWRR. This is done to allow other queues to more quickly gain access to the medium. The stages of CCFS operation are as follows:

1. The technique firstly determines which priority queues have data by checking the queue lengths.
2. If only one queue has data, data is scheduled from that queue. If more than one queue has data, one of four flows is followed (see Fig. 3), depending on which queues have data. In the case where only the medium-priority (MP) queue and the low-priority (LP) queue have data, flow 3*a* is used. If the high-priority (HP) and the low-priority queues have data, flow 3*b* is used. If the high-priority and the medium-priority queues have data, flow 3*c* is used. If all the priority queues have data, flow 3*d* is used.
3. The load threshold value for all the queues is set to two, as having three packets waiting in the queue for transmission gives an indication that the queue has started to build up.
4. If only the medium-priority and low-priority queues have data, the queue length of the low-priority queue is determined. If the load level is greater than the threshold, then the medium-priority transmission slots are set to two; otherwise they are set to three. For every consecutive medium-priority data transmitted, the MP age counter value is incremented by one. If the maximum medium-priority age value is reached, then a low-priority packet is immediately scheduled for transmission, and the counter value is reset to zero.
5. The remaining flows are interpreted in a similar way. The counter values are chosen such that higher-priority data can be sent out in preference to lower-priority data.

III. Comparing the Proposed Schedule-Before-Contention Mechanisms

The scheduling strategies that are proposed here deviate from EDCA in that only one packet queue is chosen for each transmission, from all the priority queues contending for the medium. DCF implicitly performs schedule-before-contention as it only has one queue. With the proposed strategies, no internal collisions take place as only one packet from each of the queues is scheduled at a time, whereas with EDCA, internal collisions do take place since each queue behaves as a virtually separate node. This contention is performed separately, in parallel.

The proposed strategies discard the internal collision-handling mechanism, as the data from the different priorities of queues are not contending for the medium at the same time. The advantage of removing the internal contention-handling mechanism is that this prevents internal collisions and the starvation of lower-priority data. The AWRR, RWS-AGE and CCFS strategies also maintain an additional measure to avoid starvation, namely an age counter to detect the transmission of consecutive data from the priority class.

Table II presents a comparison of the proposed scheduling strategies and the baseline contention-based strategies (EDCA and DCF). The four proposed strategies all perform classification of data into different queues, and all consider which queues have data.

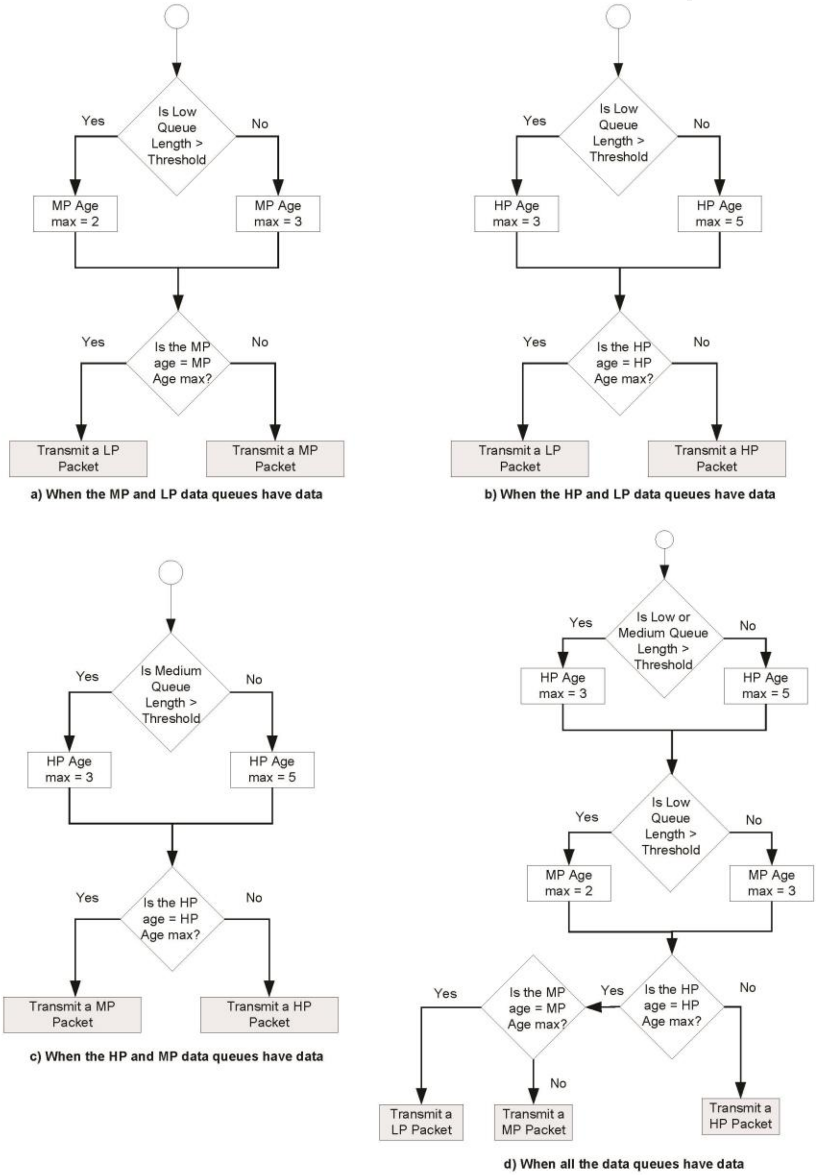


Fig 3. Flows for CCFS packet selection operation.

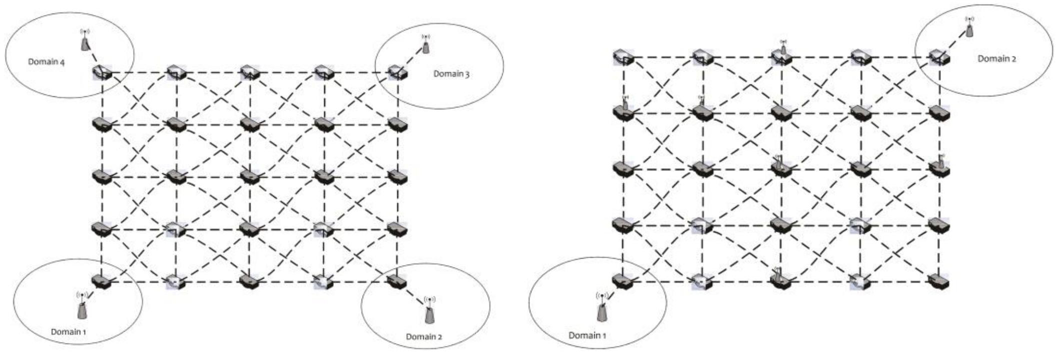
TABLE II: COMPARISON BETWEEN THE SCHEDULING STRATEGIES

	EDCA	DCF	AWRR	RWS	RWS-AGE	CCFS
Data differentiation	YES	NO	YES	YES	YES	YES
Considers the load level?	NO	NO	NO	NO	NO	YES
Considers the age of packets?	NO	NO	YES	NO	YES	YES
Adaptive to which queues have data?	YES	NO	YES	YES	YES	YES
Parameters that can be adjusted to different application needs	None	None	Round robin slots assigned to each priority category	Weights assigned to each priority data queu	Weights assigned to each priority data queue, age	Queues threshold values, age
Scheduling	Contention-based	FIFO	Weighted round robin: Deterministic	Random	Random	Predefined flow-based: Deterministic

IV. A Simulation-based Performance Analysis of the Strategies

To carry out a performance analysis between the different scheduling mechanisms, simulations were performed using OMNeT++. The OMNeT++ discrete event simulator was used with the INETMANET framework, as it allows the use and modification of already available code. The combination of OMNeT++ and the INETMANET framework has been used in many EDCA-based studies before, such as in [56].

[57], [58] and [59] have all proposed the suitability of grid topologies for the testing of MWN protocols. Grid topologies also provide up to eight possible mesh links, resulting in high contention. Grid topologies were therefore used in these simulations. Two MWN topologies (shown in Fig. 4) were used to compare the performance of the four scheduling strategies. All the nodes forward incoming data in addition to generating and transmitting their own data. Every node in these topologies can communicate with its neighbours provided that the neighbours fall within the coverage range of their omni-directional antennas.



(a) Topology 1: 5x5 grid (b) Topology 2: 5x5 grid with randomly selected sending nodes

Fig. 4. Topologies used in the simulations.

Access points (AP) generate the data that flows in the network, and receive the data sent for testing the scheduling strategies. In Topology 1, Domain 1 sends data to Domain 3, and Domain 2 sends data to Domain 4. In Topology 2, Domain 1 sends data to Domain 2, while three other random nodes also send data to other selected random nodes in the network. The results in this paper were obtained by measuring the data received at the destination nodes.

TABLE III: SIMULATION ENVIRONMENT

Network Setup	
Simulation Time	300sec
Propagation Model	Two Ray Ground Model
Routing Protocol	OLSR
Channel Capacity Data Rate	54Mbps
Basic Rate	6 Mbps
Transport Protocol	UDP Packets
Application Data	High Priority (HP), Medium Priority (MP) and Low Priority (LP)
Packet Size	512bytes
Confidence Interval	95%
Seeding	100000

Table III presents the simulation setup. All the nodes were configured with the IEEE 802.11g standard at the MAC and physical layer, with nodes transmitting the MAC service data units (MSDU) at 54Mbps and operating in the 2.4 GHz band. The same parameters as EDCA were used for the priority queues. In telemetry networks, packet sizes are usually small (between 60 and 600 bytes) instead of a single large packet (e.g. one kilobyte) [60], [61], [62]. The reason for this is that the information carried in telemetry packets is small compared to that in multimedia packets. Smaller packets are less prone to collisions [63]. Each simulation was repeated five times, each time using a different seed number generated by the random number function in OMNeT++. For each mean of the results presented here, the 95% confidence interval is shown.

TABLE IV: DIFFERENT LOAD LEVEL TEST SCENARIOS

Load level	Normalised offered load
Low	0.3
Medium	0.6
High	0.9

Different data transmission rate test cases were run on these topologies by applying the different scheduling strategies as given in Table IV. These different test cases caused different load levels for the different data priorities in the network, thus serving as an assessment of the performance of the different strategies over differing load levels. The normalised load used for the testing was between 0.3 and 0.9. The normalised load was calculated by dividing the absolute load by the channel capacity. With a value of 0.5 of normalised load, there is always a packet in the collision domain, either in the queue or being processed for transmission. With a load greater than 0.9 of normalised load, the system becomes unstable and experiences a loss in performance that is due to the network condition and not the scheduling strategy.

A value of five packets was chosen for the age counter, which meant that more than five packets from the same priority queue could not be transmitted consecutively. For

AWRR, transmission slots for the high-priority (HP), medium-priority (MP) and low-priority (LP) queues were in a ratio of 5:3:2. For CCFS transmission, slots were assigned to each priority queue in the ratio of 3:2:1 for a total of six transmission slots per cycle.

V. Performance Analysis based on Simulation Results

The comparison in performance was made in terms of number of collisions, packet loss, end-to-end delay, and Jain's fairness index. There are many metrics proposed in literature to measure fairness. These among others include Min-Max, Entropy, and Jain's Fairness Index (JFI). The most common fairness measure metric found in literature for measuring fairness in communication networks is the JFI which is regarded as the de facto standard in communications. It measures how fair or unfair the resources are shared among the competing hosts by giving a value between 0 and 1. Since the strategies aim at preventing starvation, which will directly improve fairness, the JFI metric will be a good measure to determine if the fairness is improved or not. With JFI, a value between 0 and 1 is always obtained. A value close to 1 indicates the highest fairness while those close to 0 indicate the most unfair [64].

A. Collisions

The total number of collisions in the network is shown in Fig. 5 (for Topology 1) and Fig. 6 (for Topology 2), where HL, ML and LL respectively refer to high load, medium load and low load. For all the test topologies, EDCA experienced the most number of collisions under low, medium and high loads, except that CCFS experienced the most collisions under high loads in Topology 1. DCF experienced the least number of collisions under all loads in all the tested topologies. The AWRR, RWS and RWS-AGE mechanisms experienced fewer collisions than EDCA and CCFS, but on average more than DCF.

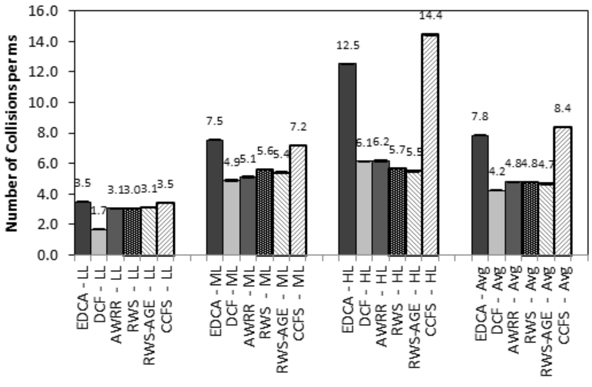


Fig 5. Average number of collisions with the different scheduling strategies in Topology 1.

We noted that having larger CW value ranges for the back-off process reduced the collision probability. When a number is selected over a larger range by two nodes, the chances are lower of them selecting the same back-off number than when the range is smaller. For all the priority classes, DCF used a larger CW range for the back-off (CW_{min} = 31 and CW_{max} = 1023) compared to AWRR, RWS, RWS-AGE, EDCA and CCFS, which use the values presented in Table I. Increasing the number of lower-priority data packets (or other packets) with larger CW ranges results in a decrease in packet loss. Lower collisions overall help to utilise channel bandwidth more efficiently. Therefore, the AWRR, RWS and RWS-AGE scheduling mechanisms on average utilise bandwidth more efficiently for heterogeneous data priority scheduling. On average, the RWS-AGE mechanism experienced lower collisions than AWRR and RWS.

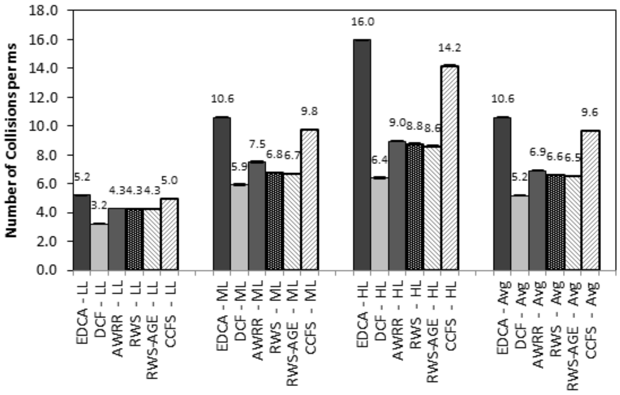


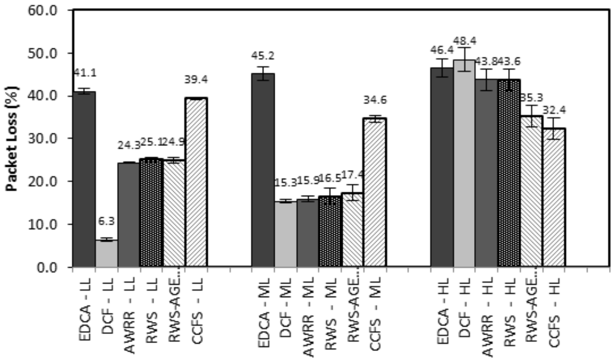
Fig 6. Average number of collisions with the different scheduling strategies in Topology 2.

B. Packet Loss

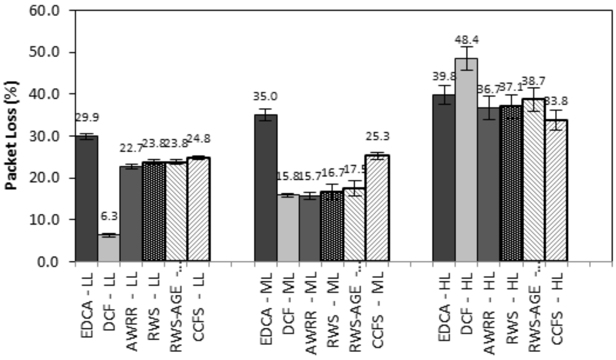
As can be seen in Fig. 7 to Fig. 10, DCF experienced less packet loss than EDCA for low- and medium-load scenarios in all the test topologies. In high-load scenarios, the packet loss with DCF was higher than with EDCA. DCF used larger CW range values, which reduces collision probability. EDCA on average experienced high packet loss under all load scenarios.

In the proposed scheduling strategies, one packet at a time is scheduled for transmission depending on the selection mechanism. With EDCA, if two or more queues have data to transmit, the AIFS and back-off periods are performed concurrently. If two data packets from different queues finish this period at the same time, the result is an internal collision, which starves the lower-priority data. In the proposed strategies, there are no internal collisions, therefore the lower-priority data is not at a disadvantage, although it is dependent on the scheduling mechanism. We noted that with all topologies, the AWRR, RWS and RWS-AGE mechanisms experienced the least packet loss, with only slight variations between them. Their packet losses were lower than those of DCF, EDCA and CCFS under medium and heavy loads. For low loads, DCF experienced the least packet loss.

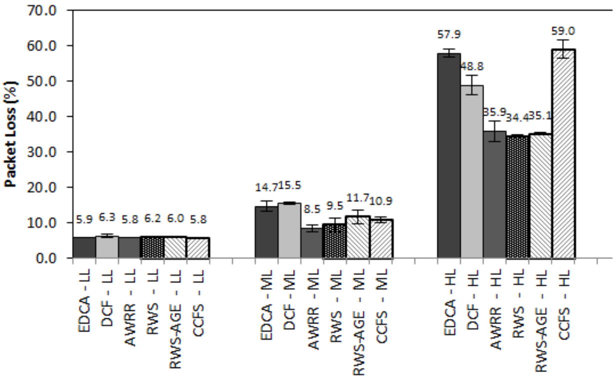
The CCFS mechanism experienced higher packet loss than the AWRR, RWS and RWS-AGE mechanisms under heavy load scenarios. The CCFS strategy changes the number of slots assigned to the different queues when the load exceeds the threshold value in any queue in the mechanism. This ends up lowering the overall transmission probability of the lower-priority data, resulting in the starvation of the lower-priority data. Although it was expected that reducing the transmission wheel size by assigning fewer slots when the load increases would help with transmitting packets faster from the queue that is becoming longer, the performance test showed that this led to more starvation of lower-priority data. If, for example, there are HP and LP data packets in a node and the queue length of the LP data is more than the threshold, this will imply that after this detection, a further three HP packets could be transmitted before the LP data is given a chance to transmit. On average, CCFS experienced less packet loss than EDCA. Throughout a network, more lower-priority packets will be in transmission if using CCFS than if using EDCA, which lowers the collision probability on the network. The lowering of the collision probability is a result of the wider CW ranges used for lower-priority data.



(a) High-Priority Data



(b) Medium-Priority Data



(c) Low-Priority Data

Fig. 7. Packet loss with the different scheduling strategies in Topology 1.

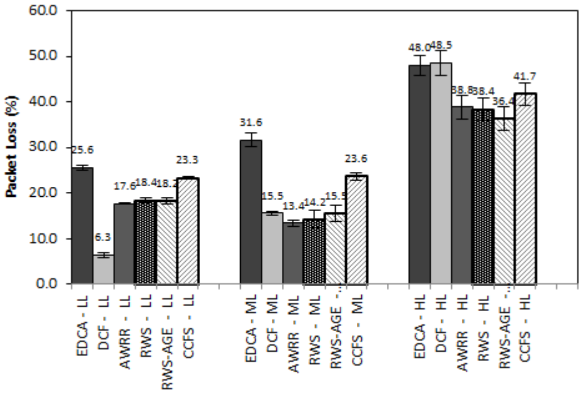
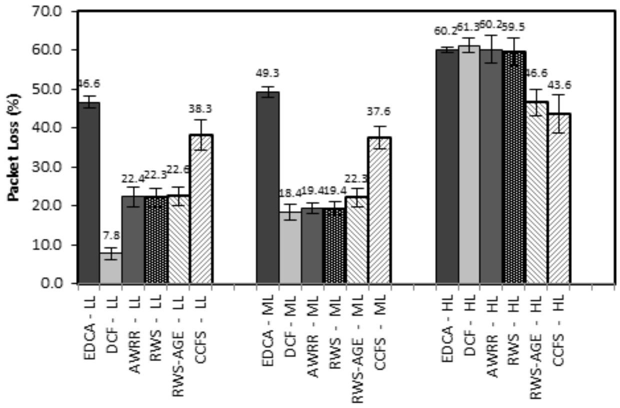
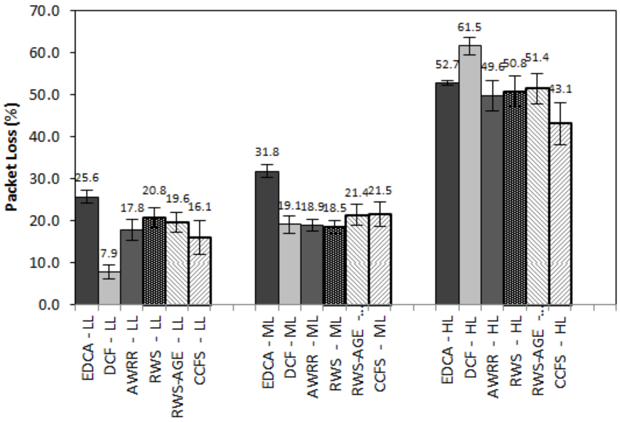


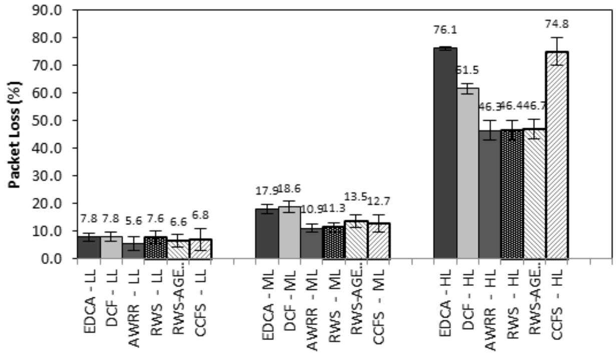
Fig 8. Average packet loss with the different scheduling strategies in Topology 1.



(a) High-Priority Data



(b) Medium-Priority Data



(c) Low-Priority Data

Fig 9. Packet loss with the different scheduling strategies in Topology 2.

On average, over all the test topologies and load levels, lower packet loss was observed with the SBC mechanisms than with EDCA. Some mechanisms do starve lower-priority data under heavy loads, but the loss experienced is on average no more than that which is experienced with EDCA.

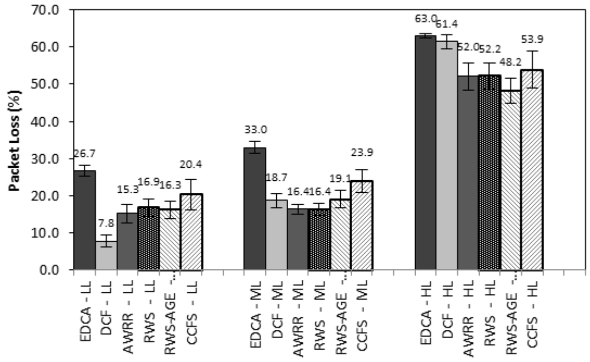


Fig 10. Average packet loss with the different scheduling strategies in Topology 2.

The results in this section have shown that the design of the scheduling strategy can have a significant impact on the QoS that is achievable in terms of packet loss in MWNs. This supports our hypothesis that the scheduling algorithm has a global effect on the achievable QoS. We found that CCFS tends to starve lower-priority data, even though there is no internal contention mechanism. In CCFS, a threshold value for queue length is used such that the age counter is made smaller if the lower-priority queue is lower than this threshold value. Higher-priority packets than the number of the age counter can still be transmitted after the queue length of the lower-priority packets has been detected to be higher than the threshold.

The AWRR, RWS and RWS-AGE scheduling mechanisms are adaptive and change the number of slots or weights for each priority class depending on which queues have data. The channel access probabilities are only proportional to which queues have data, and not to queue load. On average, the RWS-AGE mechanism experienced lower packet loss than the RWS mechanism in Topologies 1 and 2 under high loads.

The RWS-AGE mechanism has an additional age counter. This ensures that, under all conditions, if any other queue has data, and if five packets from any one queue are transmitted, another queue is given the opportunity to transmit. Increasing the transmission of lower-priority data reduces packet loss due to the fact that the lower-priority data have larger CW sizes. Overall, the RWS-AGE mechanism experiences less packet loss than AWRR under high loads for all test topologies.

With AWRR, only the number of packets equivalent to the number of slots assigned to each priority category can be transmitted consecutively if another priority queue has data. This strategy therefore also behaves as if it has a default counter. To determine if RWS-AGE statically performs better than AWRR, a paired T-test was carried out in the heavy load cases, under the null hypothesis that the means are the same and the alternative hypothesis that the means are different. The calculated T value was 11.03, which was greater than the T critical value of 2.77 for high-priority data in Topology 2. We therefore rejected the null hypothesis and showed that on average RWS-AGE experiences lower packet loss than AWRR. The application of RWS-AGE on average results in the least packet loss with a 95% confidence level. The probability-based selection mechanism with an age counter thus performs better than a weighted round robin wheel in the transmission of heterogeneous data.

C. End-to-End Delay

As can be seen in Fig. 11-Fig. 14, the lowest average end-to-end delay was experienced with the use of EDCA for high- and medium-priority data, as the higher-priority data packets have the shortest back-off time periods; and overall the higher-priority data have a higher probability to access the channel. With DCF, all the data priorities have the same DIFS and back-off time periods (the back-off time depends on the random number selected). For high- and medium-priority data, DCF experienced the longest end-to-end delay.

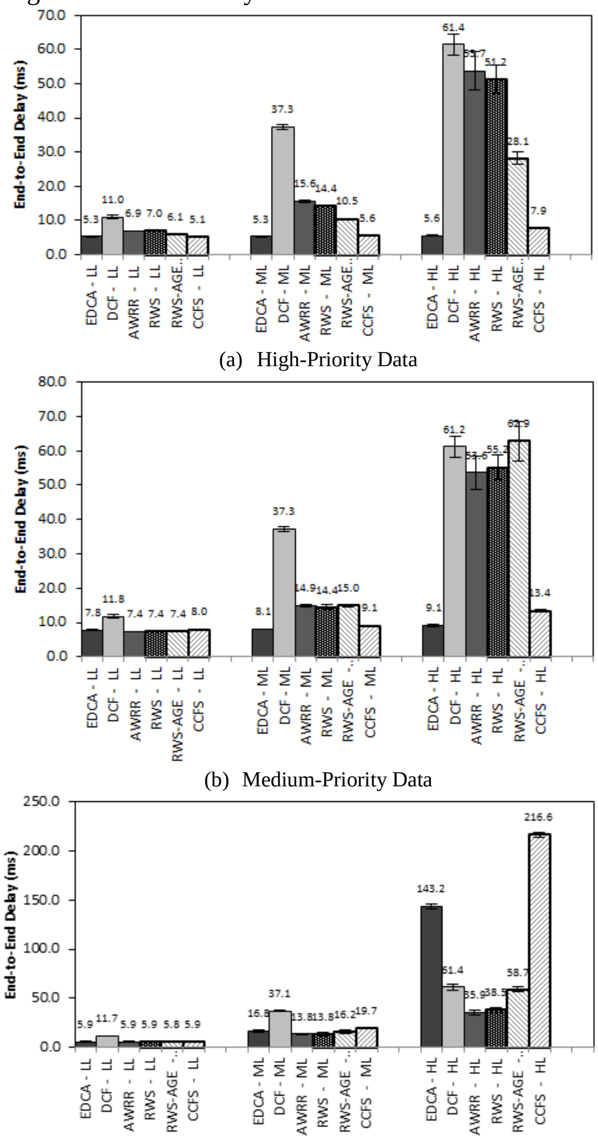


Fig. 11. End-to-end delay with the different scheduling strategies in Topology 1.

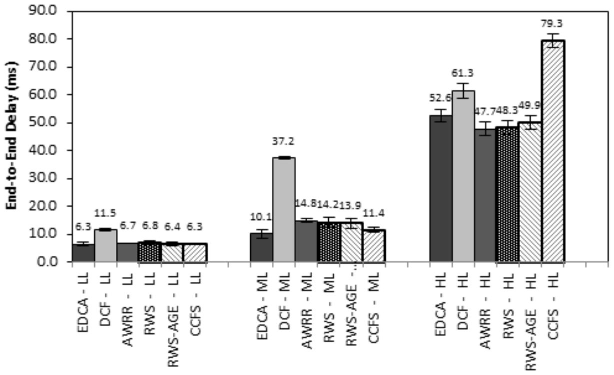
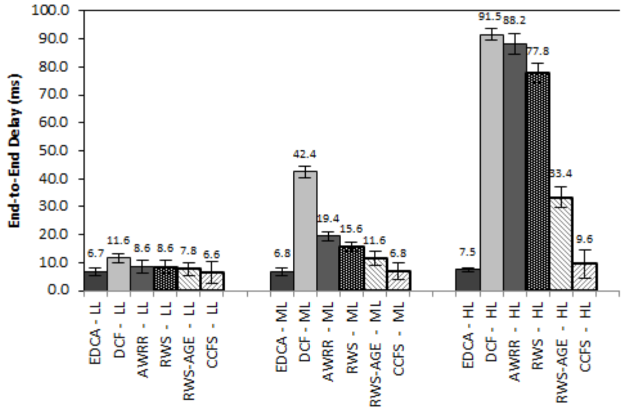
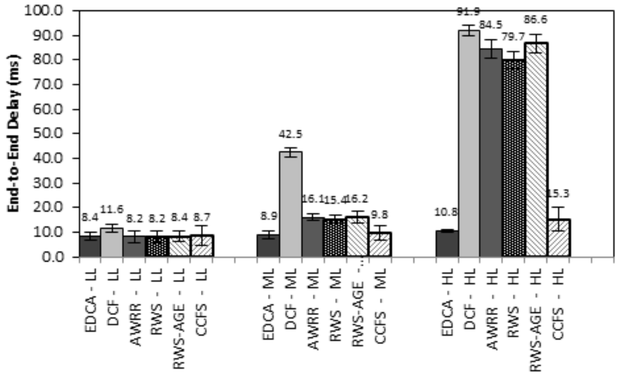


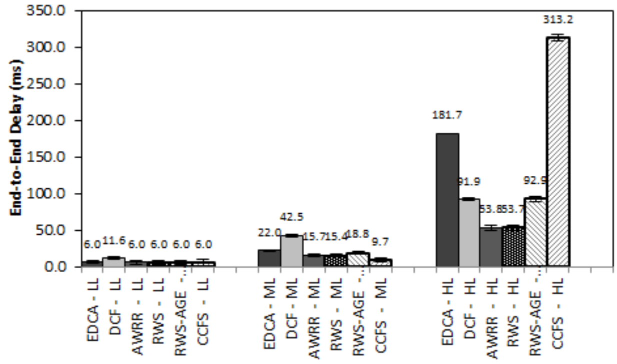
Fig. 12. Average end-to-end delay with the different scheduling strategies in Topology 1.



(a) High-Priority Data



(b) Medium-Priority Data



(c) Low-Priority Data

Fig. 13. End-to-end delay with the different scheduling strategies in Topology 2.

For high-and medium-priority data under all load levels, the AWRR, RWS, RWS-AGE and CCFS scheduling mechanisms experienced lower end-to-end delay than DCF, but higher end-to-end delay than EDCA. For low-priority data under all load levels, the AWRR, RWS and RWS-AGE scheduling mechanisms all experienced lower end-to-end delay than DCF and EDCA, while CCFS experienced more delay than EDCA. With DCF, roughly the same average end-to-end delay is experienced for high-, medium and low-priority data as the packets are all treated with equal priority in a FIFO fashion. It was observed that with the RWS and AWRR scheduling mechanisms, low-priority data experienced a lower end-to-end delay than high- and medium-priority data. This is because of the increase in the chances of lower-priority data gaining access to the channel and transmitting their data. With the RWS-AGE mechanism, lower end-to-end delay was experienced for high-priority data than for medium- and low-priority data in all test topologies and load levels. Lower priority data have a larger contention window size compared to high and medium priority data which reduces the chances of collision.

The number of collisions has a significant effect on the achievable end-to-end delay. Between AWRR, RWS and RWS-AGE, RWS-AGE experienced lower end-to-end delay for high-priority data, while for medium- and low-priority data, it experienced higher end-to-end delay.

The application of RWS-AGE to high-priority data resulted in the lowest end-to-end delay out of all the SBC mechanisms investigated with a 95% confidence level, except with CCFS, which starves low-priority data.

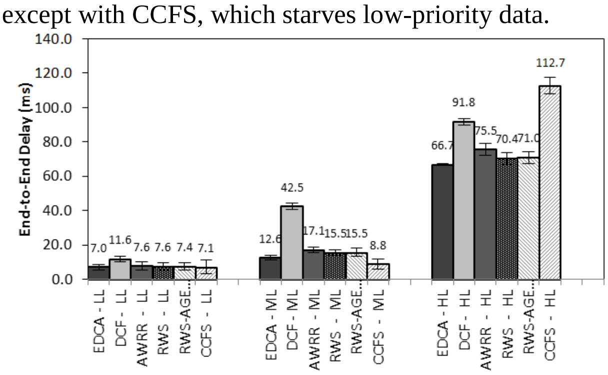


Fig. 14. Average end-to-end delay with the different scheduling strategies in Topology 2.

D. Jain's Fairness Index

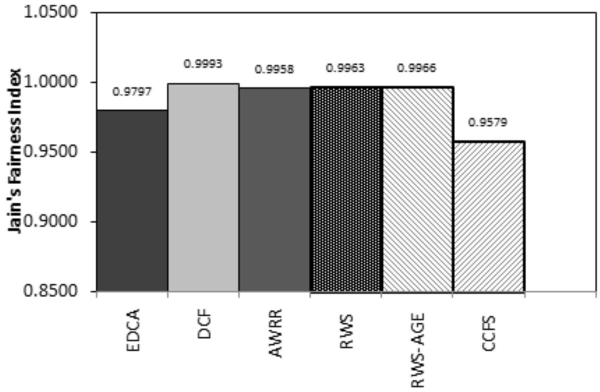


Fig. 15. Fairness under heavy loads with the different scheduling strategies in Topology 1.

As can be noted in Fig. 15 and Fig. 16, for all the topologies, EDCA and CCFS provided the least fairness and DCF the highest fairness. With AWRR, RWS and RWS-AGE, fairness was considerably better than with EDCA. AWRR, RWS and RWS-AGE improve fairness by not starving low priority compared to EDCA. CCFS had lower fairness than EDCA, DCF, AWRR, RWS and RWS-AGE in both Topologies 1 and 2. The results show that the CCFS mechanism starves lower-priority data under heavy loads, and thus the starvation problem is still present in the CCFS SBC mechanism.

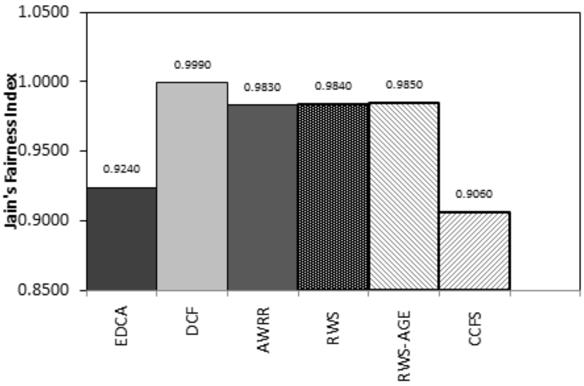


Fig. 16. Fairness under heavy loads with the different scheduling strategies in Topology 2

VI. Conclusions

The scheduling-before-contention (SBC) strategies introduced in our previous research have shown performance improvements in terms of collision reduction, reduction of packet loss and improvement of fairness over EDCA in multi-hop networks. One of the unanswered questions that remained was which SBC scheduling mechanism gives the best performance or is the most efficient under heavy loads. To answer this question, four MAC-layer SBC strategies were investigated.

The CCFS strategy changes the number of slots assigned to the different queues when the load exceeds the threshold value in any queue in the mechanism. This ends up lowering the overall transmission probability of the lower-priority data, and therefore results in the starvation of the lower-priority data. The AWRR, RWS and RWS-AGE scheduling mechanisms are adaptive and change the number of slots or weights for each priority class depending on which queues have data. These mechanisms have shown to reduce collisions and packet loss to a greater extent than EDCA does.

On average over all the test topologies, the RWS-AGE mechanism experienced lower packet loss and collisions than the RWS and AWRR mechanisms. The random probability weight assigned selection mechanism with an age counter (RWS-AGE) performed better than the mechanism without an age counter (RWS). RWS-AGE also performed better than a weighted round robin (AWRR) wheel for the transmission of heterogeneous data. Although a reduction in packet loss compared to EDCA and DCF was observed with AWRR, RWS and RWS-AGE, the end-to-end delay was higher for high- and medium-priority data compared to EDCA. However, the end-to-end delay was lower than with DCF. With RWS-AGE, the high-priority data end-to-end delay was lower than with the AWRR and RWS mechanisms.

Our conclusion was that RWS-AGE utilises bandwidth most efficiently for heterogeneous data over multi-hop networks. The RWS-AGE mechanism is therefore suitable for use in smart application networks with elastic heterogeneous traffic, where all the nodes are configured with the same scheduling strategy.

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