An Adaptive Congestion Control and Fairness Scheduling Strategy for Wireless Mesh Networks

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Abstract— **Wireless mesh networks (WMNs) are a promising technology for low cost deployments for telemetry networks in rural areas. The popular contention based carrier sense multiple access with collision avoidance (CSMA/CA) technique is widely used in WMN implementations as it does not require time synchronization compared to time division multiple access (TDMA). The IEEE 802.11e standard was introduced to provide data differentiation services to data on a network with data of different priority. With this standard, the enhanced distributed channel access (EDCA) technique for contention based services experiences a fairness problem where high data can starve lower priority data. CSMA/CA was originally developed for single-hop networks. Collisions tend to increase in multi-hop networks as the contention for the medium increases. To address the fairness and performance degradation with an increase in contention in multi-hop network problems, a novel adaptive congestion control and fairness scheduling (CCFS) strategy is proposed in this paper. The proposed strategy is simulated in OMNeT++ using the INETMANET library to ascertain the performance of the strategy. The strategy was compared with EDCA in terms of end-to-end latency, packet loss percentage and Jain's fairness index. The proposed adaptive strategy is shown to reduce packet loss in most test cases as well as provide an overall more fair system with data of different priority when compared to EDCA.**

I. Introduction

Smart Rural Areas is a new concept for the development of rural areas. It is hypothesized that Internet of Things (IoT) can help develop rural areas by providing better services as well as eradicate poverty. These services include diverse applications such as (1) public safety and security systems such as video surveillance and access control; (2) smart grids and telemetry networks for automated meter reading and monitoring networks; (3) Wi-fi access to increase coverage and community mesh networks; (4) enterprise networking; and (5) building automation [1, 2]. IoT networking environments are strongly characterized by the heterogeneity of data in the network with multiple applications running on the same network. Data in the network have different priority levels depending on the applications. Network traffic can be categorized into two main classes, namely elastic and non-elastic. Throughput and delay tolerant traffic is known as elastic traffic and the inelastic traffic is for bandwidth and delay sensitive (real-time) traffic [3].

However, rural areas of Sub-Saharan Africa have limited internet connectively, and therefore limited internet use is observed. Most of the internet users in Sub-Saharan Africa are usually found in the urban areas which creates a digital divide [4]. A rural village is usually up to a thousand kilometres away from urban areas with villages being widely scattered [4]. Cost plays a major role in these rural areas and hence, internet bandwidth in these rural areas is also very limited [5, 6,7]. Many rural areas deploy expensive satellite links to provide internet access [8,9]. Wireless Mesh Networks (WMNs) are known to reduce deployment cost and extend network coverage as compared to other solutions such as fiber optic, cellular networks, Wi-Max or VSATs [8,9]. WMNs also have self healing capabilities where data can be rerouted through other functional links to reach the destination in the event that a node becomes dysfunctional [1]. Although WMNs hold a great promise, there are two still main challenges to address, namely the increase in contention in multi-hop networks and the fairness problem.

WMNs typically use the IEEE802.11e standard for communication which uses the popular carrier sense multiple access with collision avoidance (CSMA/CA) to allow multiple nodes to share the communication medium. The original CSMA/CA was designed for signal-hop networks [10], however in multi-hop networks the destination can be a few hops away. Transmitted data that traverse multiple hops to reach its destination usually experience more contention to access the medium compared to data from nodes that are closer to the destination [10]. This causes additional contention in the shared medium resulting in a decrease in network capacity, throughput and an increase in packet loss. As a result, the end-to-end latency becomes large in multi-hop networks, and collisions increase as the contention for the medium increases with neighbouring nodes on the same communication channel [11,12].

The IoT networking environment has to support network traffic with different priority levels. The original distributed coordination function (DCF) that is used by CSMA/CA does not provide differentiated services to data of different priority. The IEEE802.11e standard was developed for data differentiation to provide QoS at the medium access control (MAC) layer. This standard is based both on centrally-controlled and contention-based channel access [13]. In this

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paper we focus on the contention-based channel mechanism called EDCA, which classifies data into access categories (ACs) depending on the priority level. The two main problems with EDCA are the fairness problem and the inability to adapt to changing network conditions. Each of the ACs has predefined parameter values that determines the AC's ability to gain access to the medium [13]. This results in the fairness problem as higher priority data is given more opportunities to access the medium [14–16]. This can result in the lower priority data never receiving an opportunity to gain access to the medium. The AC specific parameters can provide differentiated services for QoS, however the values cannot be adapted to the network conditions [17].

The focus of this paper is to address the fairness and collision increase in multi-hop networks problems. Few studies address the fairness problem and the collision increase in multi-hop WMNs. Most of the proposed strategies address the fairness problem between the uplink and the downlink by using the parameter settings of EDCA [11,18,19]. Many of the studies address the fairness problem in the contexts of Wireless Local Area Networks (WLANs) and not in terms of multi-hop wireless networks [13,15,19–26]. The fairness problem in IEEE 802.11e has been addressed in literature using fuzzy logic as in [27,28]; using weighted queue techniques as in [13,15,24]; using scheduling with the packet queues as well as adjusting the CW values as in [15]; fair queuing as in [22, 23]; and adaptive queuing as in [26]. It was realized that the fairness and contention increase problems have not been addressed specifically for multi-hop networks such as WMNs with static nodes as well as for low cost networks.

To address these problems we propose a novel adaptive strategy which uses CSMA/CA called congestion control and fairness scheduling (CCFS). The strategy is based on a deterministic scheduling mechanism where a packet from the head of a queue of either one of the different priority queues is selected for transmission. The selection process considers the queue length and also the age of the packet. After this process, a backoff process is followed before data can be transmitted on the medium. The range of values for the contention window (CW) of the backoff procedure is adapted depending on the load level in the node. We compare the proposed strategy with the contention-based channel access mechanism, EDCA. Our contribution is that we address the fairness and collision increase problems by using adaptive CW values and by using deterministic scheduling of data in the contexts of static WMNs using single radio and single channel.

The rest of this paper is organized as follows. In section 2, we present the application domains of the proposed scheduling strategy for rural low cost networks. Section 3 presents a detailed overview of the EDCA technique in the IEEE802.11e standard and how the fairness problem arises. Section 4 presents the proposed CCFS scheduling strategy. Section 5 presents an overview of the simulation setup, the topology test cases and the performance metrics used for the evaluation. Section 6 presents the results of the proposed strategy compared to EDCA in the different test case topologies. Section 7 concludes the paper and discusses future work.

II. Background

In this paper, six different IoT smart rural application domain areas have been briefly highlighted as possible application areas of the proposed scheduling strategy presented in this paper. The traffic types considered are both elastic and non-elastic data. These application domains are the smart grid which includes energy; smart transport which includes transportation, traffic and parking; smart education which include networks for educational use; smart health; smart farming which include both horticulture and livestock farming; and smart buildings. Smart operations are made possible in networks through the use of intelligent sensors and actuators, two-way communication, control and monitoring mechanism, information and communication technology (ICT) and the internet. Each of these application domains carry traffic of different priority. We have classified the data into three categories, namely high, medium and low priority. The strategy we develop in this paper is therefore, based on these three data priority classes (high, medium and low) to provide improved QoS service in terms of reliability and fairness. Table 1 gives a summary classification of priority data for these different application domains for smart rural areas.

Having discussed the limitations and requirements in rural areas for telemetry networks, the proposed technique developed in this paper is designed to work on low cost rural WMNs. The WMNs are referred to as having low cost as the scheme is simulated with devices having a single radio and use the unlicensed Industrial, Scientific and Medical (ISM)

TABLE I. Data priority classification for Different smart Rural application domains

	High Priority Data	**Medium Priority Data**	**Low Priority Data**
Smart Grid	Emergency Response	Automated Demand Response (ADR)	Advanced Metering Infrastructure (AMI)
	Fault Detection	Transformer Monitoring	Remote Connect/Disconnect
	Supervisory control and data acquisition (SCADA)	Direct Load Control	Voltage and Current Monitoring
Smart Education	Online tests	Audio Conferencing	Web Browsing
	Exams		Emails
	Video Conferencing		Online Libraries
Smart Buildings	Air-conditioning (HVAC) systems	Access control systems	Web Browsing
	Video Surveillance, Safety Alarms		Internet Access
	Fire protection systems		Smart Lighting Designs
Smart Transport	Ticketing	Digital Signage	Sensor Object Detection for Parking
	Payments	Transport Logistic	
Smart Farming	Renewable energy sources	Tracking of livestock	Sensor readings such as temperature, feed level, soil moisture, Access to stock level for suppliers
Smart Health	Tele-monitoring - remote health monitoring of patients	Mobile Assistance	Office based applications, medicine use intake by patient, messages to patients

band. The cost is therefore, lower than using a licensed spectrum and devices with multi-radios.

III. Distributed Priority Services in IEEE 802.11e

This section presents a brief overview of IEEE802.11e EDCA and how the fairness problem occurs. The MAC layer has two access mechanisms, namely the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). The PCF uses a centrally controlled method to support synchronous data transmission mainly for real-time traffic [29]. The DCF technique is a distributed technique where access to the wireless medium is performed by all the nodes [30]. CSMA/CA is a popular contention based scheme which uses the distributed coordination function (DCF) where the node first senses the medium to determine if any other communication is in process or not. If no communication in process is sensed, then it can transmit the data.

The DCF includes the carrier sensing mechanisms, inter-frame spacing (IFS) and binary exponential backoff (BEB) timers. If a node has data to send, it first senses the medium. If the medium is sensed to have been idle for a time period greater than the DCF Interframe Space (DIFS), the node immediately transmits its data. If the medium has not been idle for a time duration greater than DIFS, it first senses the medium for this DIFS period. If the medium is still idle, the node than performs the BEB procedure where a number is generated randomly in the interval of [0, contention window (CW) -1] where CW is set to CW_{min} and the backoff time calculated. For any unsuccessful transmission that might occur (due to a collision), the CW_{min} value is doubled. The value can only be doubled up to the value for CW_{max}. The value of CW_{max} is reset to the minimum value after a successful transmission takes place. The default value for CW_{min} in DCF is 31 and CW_{max} is 1023. After this backoff period, if the medium is found idle, transmission takes place. If the medium is sensed to be busy, the node then waits for the channel to become idle again for the DIFS period and then the BEB procedure is restarted [31].

Many networks carry heterogeneous data of different priority levels as highlighted in the background section of this paper. The aim of the IEEE 802.11e standard is to provide QoS to differentiated data types by enhancing the MAC layer. It uses a modified version of the DCF called Hybrid Coordination Function (HCF). The HCF implements both contention-based channel access method, called EDCA and centrally controlled channel access, called HCF Controlled Channel Access (HCCA). The HCCA can only be used in infrastructure-based networks which have a Hybrid Coordinator (HC) setup for coordinating access to the medium. In WMNs, no infrastructure is available to perform this coordination, thus EDCA is used [11].

The EDCA is an extension of DCF and provides differentiated medium access to the data with different priority levels by using different parameters. The EDCA introduces the concept of Access Category (AC) for different data types, and consists of 4 ACs. Each AC has specific parameters associated to its priority class. The parameters are designed such that the higher probabilities ACs have a higher probability of medium access compared to the lower ACs

TABLE II. Parameter Values of EDCA Assigned to the Different AC categories

	AC Type	Traffic Type	AIFSN	CW_{min}	CW_{max}
AC[3]	AC_BK	Background	7	31	1023
AC[2]	AC_BE	Best Effort	3	31	1023
AC[1]	AC_VI	Video	2	15	31
AC[0]	AC_VO	Voice	2	7	15

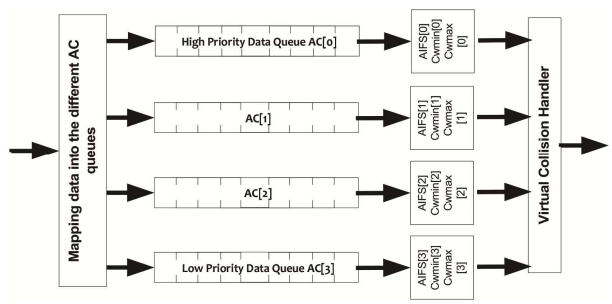

Fig. 1. Scheduling in EDCA for the different AC category data.

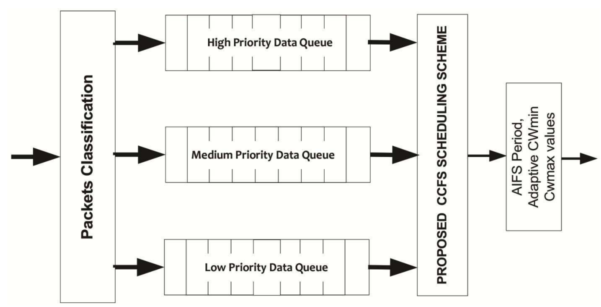

Fig. 2. The proposed CCFS strategy.

[17]. Data is mapped at the MAC layer into the corresponding AC. The four ACs are Background (BK), Best-effort (BE), Video (VI) and Voice (VO). The EDCA introduces a new interframe spacing called Arbitration IFS (AIFS). For each of the ACs, the corresponding CW and AIFSN values are shown in Table 2. Fig. 1 shows the implementation scheduling structure of EDCA. The length of the AIFS for the different priority AC data is calculated using equation 1 with values in table 2. The arbitration Slot Time (aSlot-Time) and the arbitration SIFS Time (aSIFSTime) values are dependent on the physical properties and are standard depending on the IEEE 802.11 standard used. AIFSN[AC] is the number of AIFS slots.

$$AIFS[N] = AIFSN\,[AC].aSlotTime + aSIFSTime \quad (1)$$

Two types of collisions can take place in EDCA namely, the physical collision on the medium or the internal collision in the EDCA contention mechanism within the node. When data arrives at the node, it is placed in one of the four AC queues. When the node wants to send out its data, it first senses the medium. If the medium is idle, it than performs the AIFS and BEB periods. Within a node, if two queues want to send data, they perform their AIFS and BEB procedures. If this period ends for two packets at the same time, an internal collision occurs. This internal collision is resolved by the virtual collision handler shown in Fig. 1. The virtual collision handler gives the higher priority data access to the medium, while the lower priority data behaves as if a real collision on the medium occurred and doubles its CW_{min} value [33]. This is how the starvation and fairness problem occurs for lower priority data with the higher priority data having higher chances to access the medium [32, 34].

IV. Proposed Scheduling Strategy

The working principles of the proposed CCFS strategy are explained in this section, as well as the differences between CCFS and EDCA. With CCFS, when data arrives at the MAC layer, the data is placed into one of the three priority data queues (high, medium or low) depending on the application the data is coming from. In our case, we use port numbers in the header of the frame to classify these packets. After that, one packet at a time is selected for transmission on the medium following the deterministic scheduling selection process. After the packet is selected for it to be transmitted on the medium, the medium is monitored for the AIFS and BEB period to determine if it is still idle and then the packet is transmitted. The CW values are adaptive in this CCFS strategy. The model of this strategy is shown in Fig. 2 consisting of the packet classification module, packet queues for each data category, the deterministic scheduling selection process module and lastly the adaptive CW BEB module stage.

Basically EDCA regards each AC as a virtual separate node that contends for the medium if it has data to transmit. All these virtual AC nodes perform separate AIFS and BEB periods. The CW ranges in EDCA are fixed and smaller for higher priority data. With the proposed CCFS only one queue contends for the medium (i.e. the queue chosen by the deterministic scheduling selection process). This deterministic scheduling process is designed to address the fairness problem by picking packets from the different queues in such a way that all queues get a chance to access the medium. The strategy considers age of the packets waiting in the queue as well as queue length. Once a packet has been selected for transmission, only one BEB period is performed. With CCFS, the CW values adapt to the nodes load level (i.e. queue length) such that if the load level is high, higher range values are used. Higher CW range values are used if the load level is high to reduce the collision probability in CCFS as it is used as an indication of the congestion on the network.

This section now looks into the details of the CCFS deterministic scheduling and adaptive CW process.

A. Deterministic Scheduling Selection Process Stage

This selection process is predefined and the selection algorithm process is explained. The basic design principle followed in the development of the predefined flow charts was to give priority to higher priority data, but to assign an age counter value depending on the load level in the other queues. The age counter ensures that lower priority data does not get starved as well as frequent chances are given to data queues that have a higher priority level. The working principle of CCFS is as follows:

i. The scheme first determines which queues (high, medium and low) have data in them.

ii. If only one of the queues has data, it then schedules a packet from the queue with data. If more than one queue has data in it, then depending on which queues have data, one of the four flow charts as shown in Fig. 3 is followed for the selection of the packet for transmission. If the medium priority data and the low priority data queues have data, than flowchart *a* is followed (i.e. Fig. 3a). If the high priority data and the low priority data queues have data, than flowchart *b* is followed (i.e. Fig. 3b). If the high priority data and the medium priority data queues have data, than flowchart *c* is followed (i.e. Fig. 3c). If all the data queues have data, than flowchart *d* is followed (i.e. Fig. 3d).

iii. In our strategy, the load threshold values for all the queues were set to 2 as having 2 packets already in the queue indicates that more than one packet is queued waiting to be transmitted and the queue has started building up.

iv. If only the medium priority (MP) and low priority (LP) data queues have data, (flowchart from Fig. 3a) the load length of the queue of the low priority queue is determined. If the load level is greater than the threshold, then the MP age counter maximum value is set to 2. If the load level of the LP queue is less than the threshold, the MP age counter maximum value is set to 4. Every time a consecutive MP packet is transmitted, the MP age counter value is incremented. If the MP age max is reached, then a LP packet is scheduled for transmission and the counter values are reset to 0. The flow charts for Fig.s 3b, 3c and 3d can be interpreted in a similar way with the information provided in the respective flowcharts depending on which queues have data. The HP max age, MP age max and LP max age default counter values are set such that the higher priority data have a higher value then the lower priority data allowing more frequent transmission of the higher priority data. In the case that the lower priority data queue has data greater than the threshold, then the default counter values are lowered to allow data to also be transmitted from the other queue to prevent congestion as well as starvation. This is the logic that was applied to assign our default values of 5 for HP Age max and 4 to MP Age max in the case when the other queue has less data than the threshold.

These deterministic scheduling strategies are designed such that starvation is prevented from taking place. If a packet transmission of the same priority class is continuously taking place, the counter values forces a packet from another queue to also be transmitted. If much higher values than the default HP Age max and MP Age max are assigned than it result in starvation as well as more data building up in the other queue(s).

B. Assigning CW values stage

The selection of the CW range values of $CW_{minCCFS}$ and $CW_{maxCCFS}$ are carried out adaptively in our proposed strategy as follows:

i. The load level of each of the queues is determined.

ii. If either of the queues have a load level greater than he threshold value, than the $CW_{minCCFS}$ value is set to 31 and

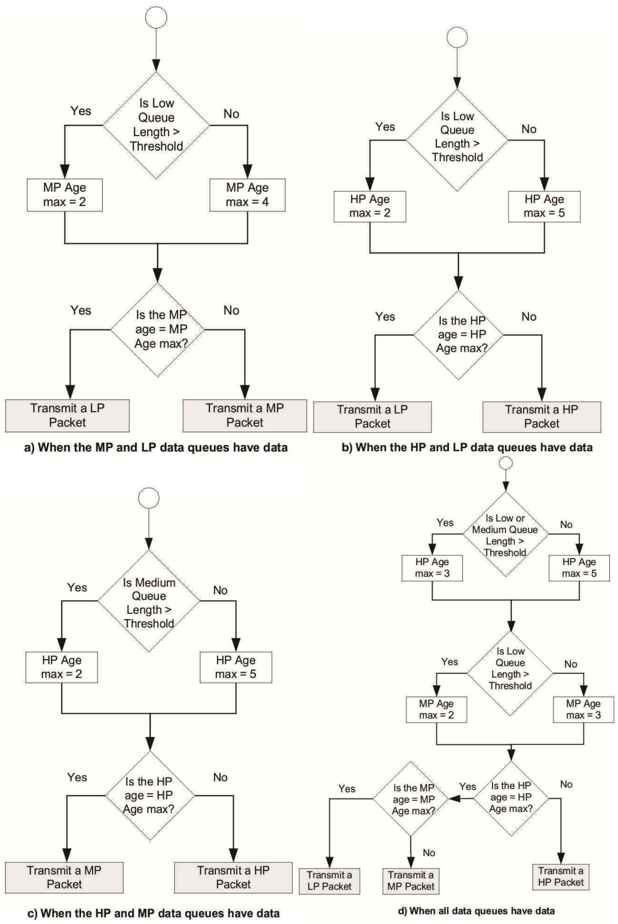

Fig. 3. Flowcharts for data Scheduling.

TABLE 3: SIMULATION ENVIRONMENT

Network Setup	
Simulation Time	100 seconds
Topologies	Square Grid and Triangular Topologies
Terrain Area	2.2km x 2.2km = 4.84km^2
Propagation Model	Two Ray Ground Model
Routing Protocol	OLSR
Application Data	UDP Packets
Data Categories	3 categories of Data - Low, Medium and High Priority
Packet Size	512bytes

TABLE 4: DATA RATES IN THE TOPOLOGY TEST CASES

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

$CW_{maxCCFS}$ value is set to 1023 for all the data priority types as can been seen in the cost functions in equations 2 and 3.

iii. If none of the queues in the node have a load greater than the threshold, then the $CW_{minCCFS}$ value is set to 15 and $CW_{maxCCFS}$ value is set to 31 for all the data priority data types as can been seen in the cost functions in equations 2 and 3.

$$CW_{minCCFS} = \begin{cases} CW_{min} & queuelenth > threshold \\ \frac{(CW_{min}+1)}{2} - 1 & queuelenth < threshold \end{cases} \quad (2)$$

$$CW_{maxCCFS} = \begin{cases} CW_{max} & queuelenth > threshold \\ CW_{min} & queuelenth < threshold \end{cases} \quad (3)$$

In the EDCA strategy, the CW_{min} and CW_{max} values for the high priority data class are 7 and 15. In our design, we do not use this small range as with small CW values, the collision probability is high and there is a high chance of collision.

V. SIMULATIONS SETUP

In order to determine the performance of the strategy, extensive simulations were carried out. The simulations were setup in OMNeT++ using the INETMANET framework. OMNeT++ is a discrete event simulator designed for simulation computer networks. The INETMANET library offers detailed modeling of radio propagation, implementation of various protocols of wireless network from the different OSI layers and applications making it possible to simulate WMNs [35].

Tables 3 presents the common simulation settings used for all the test cases. Simulations were carried out for wireless mesh backbone networks. The two ray ground propagation model was used to represent the physical environment which uses the delay speed to be equal to the delay between the line-of-site (LOS) ray and the reflected ray. The two ray model was used as in rural areas, predominantly these two rays exist, i.e. direct rays and the reflected rays. The 2.4GHz ISM band was used in our simulations with a channel capacity of 54Mbps. Three types of UDP heterogeneous traffic was used for the data priority classes of high, medium and low priority having different port numbers. UDP packets were used in our simulations as UDP operates as a connectionless protocol and does not retransmit any lost packets. This helps to expose any unreliability in any of the underlying layers. UDP packet sizes of 512Bytes were used as most UDP applications such as Trivial File Transfer Protocol (TFTP) and Domain Name Systems (DNS) use a default packet size of 512Bytes.

Simulations were conducted on 3 square grid topologies and 3 triangular topologies with 25 nodes. Square and triangular topologies were used to test the performance of our proposed scheme based on the following reasons: 1. Every node can communicate with their neighbours provided omni-directional antennas are used and also the neighbours are in their coverage range. Square grid topologies provide 8 possible neighbours and triangular topologies provide 6 neighbours. This provides a higher number of alternate (mesh) routes, as well as creates more contention for the medium between the neighbours; 2. With more mesh routes available, more overhead is created in the network which helps in assessing the performance with these overheads. The theme of the paper is WMNs and hence the strategy was not analyzed in line topologies which do not have mesh links. In random topologies set, some nodes will not have coverage to their neighbours while others will be able to communicate directly with their 1 hop away nodes depending on the coverage area. Grid and triangular topologies provide symmetry and are well balanced. A terrain area of 2.2km by 2.2km was used as many rural villages in Botswana such as Gumare, Jwaneng, Kang, Nokaneng and Tshootsha cover an approximate area to that size taken from Google Earth. In these networks, different nodes were selected randomly to transmit data to different nodes making the simulations more realistic to real life networks as other nodes are also simultaneously communicating in a network. 16% of the nodes were set to be sending data making it a total of 40% of the nodes in the network communicating. Fig. 4 shows an example of the square grid topology and triangular topology. Cases 1, 2 and 3 were setup for square grid topologies with data being transmitted at different rates as shown in table 4. Cases 4, 5 and 6 were setup for triangular topologies. Cases 2 and 4 were tested as all the data rates are high and this helps to expose the starvation problem for low priority data in EDCA. The other test cases tested in this paper hypothesize that in most time situations the high priority data rate will not be higher than medium and low priority data transmissions. Each simulation was run 5 times with different simulation seeds. The error bars indicate the 95% confidence interval. For each of the test cases, the performance of both the proposed CCFS scheduling strategy and the standard EDCA (baseline strategy) were obtained and a comparison conducted. The results obtained were compared with EDCA AC[0] for high priority data, EDCA AC[1] for medium priority data and EDCA AC[2] for low priority data. The EDCA technique already consists in the INETMANET library developed for OMNeT++.

For each of the test cases, the data transmitted from the source node was measured at the sink node to determine how many packets were received and the end-to-end delay. The source and sink nodes used for the measures were set to be the furthest away to allow multi-hop communication. The arrow lines in the diagrams represent others nodes also transmitting data in the network from the source (start of arrow) to the destination (head of arrow position). The coverage area for each node to transmit data to its neighbors is shown with the big circle in Fig. 4 for the centre node.

The performance metrics used in this paper were the end-to-end latency, packet loss (%) and Jain's Fairness Index.

1. *End-to-end latency:* This is the measure of the average time it takes a data packet to arrive at the destination from the source. The value includes all the delay experienced from the source to the destination which includes data queuing, packet transmission, channel access delay, contention and back-off period [36].
2. *Packet Loss:* This is a measure in terms of percentage of the number of packets lost from the sender to reach the destination. This value was calculated as [37]:

$$Packet\ Loss\ (\%) = \frac{(Packet\ transmitted - packets\ received) * 100}{Packets\ Transmitted} \qquad (4)$$

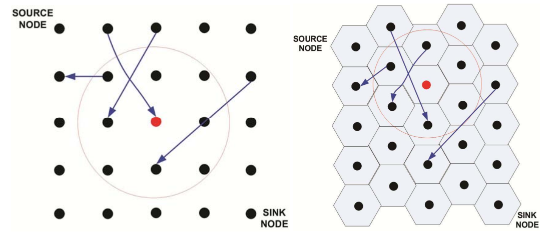

Fig. 4. Square grid and triangular topology setup.

3. *Jain Fairness Index (JFI):* To calculate the fairness of the schemes, the JFI index was used. This is a measure of how fairly or unfairly the resources are shared between the different nodes. Equation 5 is used to calculate fairness where x_i is the normalized throughput of station i, and n is the number of flows in the WMN. A JFI has values between 0 and 1 and indicates a very fair system for values close to 1 and very unfair system for values close to 0 [38]. In our case n=3 as we investigate the fairness for 3 data classes namely for high, medium and low priority classes.

$$f(x_0, x_1, x_2, \dots, x_n) = \frac{(\sum_{i=0}^{n} x_i)^2}{n \sum_{i=0}^{n} {x_i}^2} \qquad (5)$$

$$where\ 0 \le f(x_0, x_1, x_2, \dots, x_n) \le 1$$

VI. Results

The results of our CCFS strategy when applied to WMNs are presented in this section. A comparison is also made with the standard EDCA scheme. Figs. 6 to 8 present the packet loss percentage experienced in the different test cases. It can be noticed that for high priority data (Fig. 6); for medium priority (Fig. 7) data for all the test cases except 3 and 6; and for low priority data (Fig. 8) in all the test cases a reduction in packet loss was observed with the new CCFS scheme compared to EDCA in both the square grid and triangular topologies. A packet loss reduction of up to 7% for high and medium priority data and 6% for low priority data is observed. A packet loss reduction is observed due to a reduction in collisions. With the proposed new CCFS scheme, no internal collisions also take place as one packet is scheduled at a time as well as higher CW values on the medium reduce the collision probability.

In Figs. 9 to 11, the end-to-end latency for the different data priority types is presented. It can be observed for all high, medium and low priority data (Figs. 9, 10 and 11), the end-to-end latency is increased in all the cases with the new CCFS scheme compared to EDCA. Higher increase in observed in the cases where all the data is transmitted at high transmission rates i.e. cases 2 and 5. Our scheme uses adaptive CW range values such that for low loads, CW_{min} = 15 and CW_{max} = 31 and in high loads, the CW values become CW_{min} = 31 and CW_{max} =1023. These larger range values reduce the collision probability in high loads as compared to the original EDCA, however, they increase the end-to-end latency as in EDCA for high priority data, CW_{min} = 7 and CW_{max} = 15 which is much smaller. The increase in latency could also be caused by the fact that at different nodes, there is a higher chance of packets being transmitted with different priority queues as the scheme uses a deterministic scheduling approach. CCFS gives the

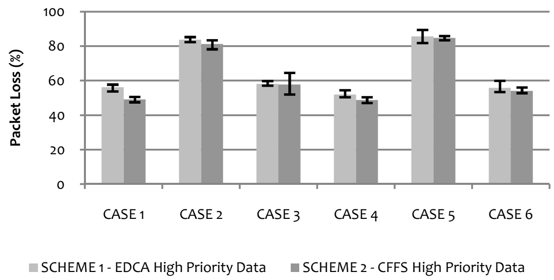

Fig. 6. Packet Loss for High Priority Data experienced in the different test cases.

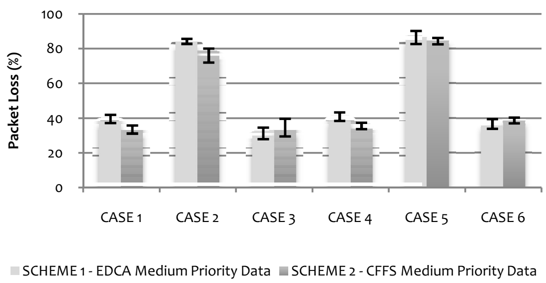

Fig. 7. Packet Loss for Medium Priority Data experienced in the different test cases.

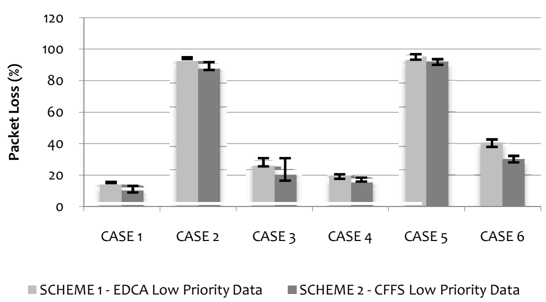

Fig. 8. Packet Loss for Low Priority Data experienced in the different test cases.

lower different priority categories a higher chance of being transmitted compared to EDCA.

The Jain's fairness index was calculated for each of the test cases and is shown in Fig. 12. It can be observed that the fairness is improved with the proposed CCFSs scheme compared to EDCA for all the test cases, except in cases 3 and 6. With the higher loaded networks (cases 2 and 5), more fairness is observed. Overall, the scheme is shown to be more fair than EDCA. The fairness is improved as the higher priority data cannot starve the lower priority data with this CCFS scheme and also collisions are reduced.

VII. Conclusion

In this paper, a novel congestion control and fair scheduling strategy was proposed. This strategy consists of two main components: a deterministic scheduling module and to adaptively select CW values based on the load level of the node. The scheme was developed to address the fairness problem and to reduce data collisions in WMNs that use EDCA.

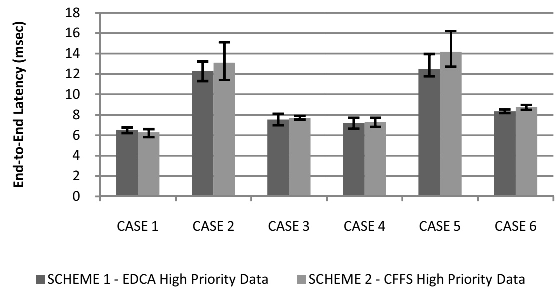

Fig. 5. End-to-End Latency for High Priority Data experienced in the different test cases.

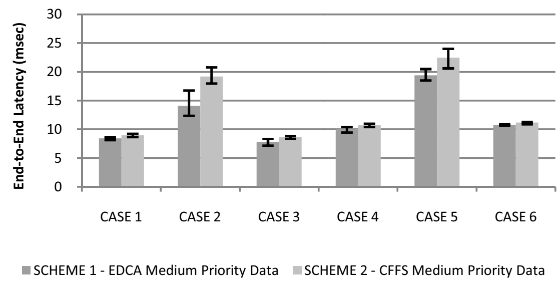

Fig. 10. End-to-End Latency for Medium Priority Data experienced in the different test cases.

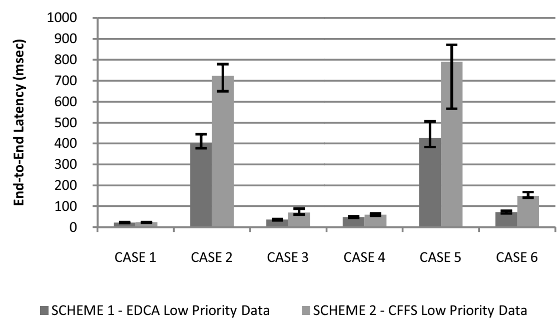

Fig. 11. End-to-End Latency for Low Priority Data experienced in the different test cases.

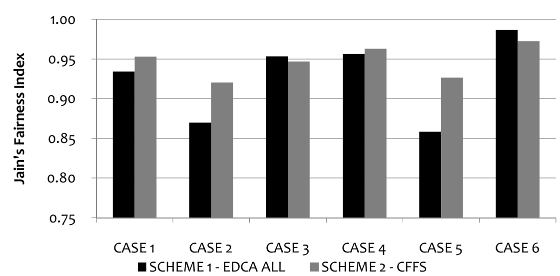

Fig. 12. Jain's Fairness index calculated for the different test cases.

Simulation results show a reduction in packet loss in most cases with the new proposed scheme. Despite this reduction in packet loss, the end-to-end latency increases slightly for the different data priority types. However, the proposed scheme shows to be more fair than the original EDCA technique in high loaded scenarios. With the proposed scheme, a reduction in collisions is observed. The strategy also discards the internal collision mechanism present in EDCA. The proposed strategy is a promising technique for implementation in smart rural applications as a low cost option as simulation results conducted on single channel networks show performance improvement. CCFS is designed to provide differentiated services to data by classifying data into one of three priority queues (high, medium and low) for the smart rural application networks such as the smart grid, smart education, smart farming, smart health and smart buildings.

Although it was expected that the collisions will be reduced considerably by the CW range values being made adaptive according to the load in the node, the results did not show much improvement. Strategies that reduce collisions as well as provide fairness still require further investigation. The outcomes of this paper will be valuable to our future work in designing other strategies to address the fairness and collision problems in both IEEE802.11 WMNs and IEEE802.15.4 wireless sensor networks.

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