Dynamic Queue Utilization Based MAC for multi-hop Ad Hoc networks

MARCHANG, Jims <http://orcid.org/0000-0002-3700-6671>, GHITA, B. and LANCASTER, D.

Published version

MARCHANG, Jims, GHITA, B. and LANCASTER, D. (2015). Dynamic Queue Utilization Based MAC for multi-hop Ad Hoc networks. In: Proceedings of European Wireless 2015; 21th European Wireless Conference. IEEE, 25-32.

Dynamic Queue Utilization Based MAC for Multi-Hop Ad Hoc Networks

Jims Marchang, Bogdan Ghita, David Lancaster
Centre for Security, Communications and Network Research (CSCAN)
School of Computing and Mathematics
Plymouth University, United Kingdom
`{jims.marchang, bogdan.ghita, david.lancaster}@plymouth.ac.uk`

Abstract – **The end-to-end throughput in single flow multi-hop Ad Hoc networks decays rapidly with path length. Along the path, the success rate of delivering packets towards the destination decreases due to higher contention, interference, limited buffer size and limited shared bandwidth constraints. In such environments the queues fill up faster in nodes closer to the source than in the nodes nearer the destination. In order to reduce buffer overflow and improve throughput for a saturated network, this paper introduces a new MAC protocol named Dynamic Queue Utilization Based Medium Access Control (DQUB-MAC). The protocol aims to prioritise access to the channel for queues with higher utilization and helps in achieving higher throughput by rapidly draining packets towards the destination. The proposed MAC enhances the performance of an end-to-end data flow by up to 30% for a six hop transmission in a chain topology and is demonstrated to remain competitive for other network topologies and for a variety of packet sizes.**

Keywords – **Ad-Hoc, MAC, Queue, QoS, Network Saturation.**

I. INTRODUCTION

Quality of Service (QoS) provisioning in Ad Hoc networks remains a challenging issue despite substantial research undertaken over the past decade [1]-[5]. Seminal papers have considered the capacity of a wireless network subject to multiple flows [6] but in this paper attention is restricted to a single multi-hop flow in the saturated region (a point where increasing the input data rates in the network does not enhance the performance further). Even in this case, due to high interference and limited bandwidth, network environments self-generate bottlenecks along multi-hop paths. The network saturates rapidly and end-to-end throughput decays rapidly with path length [7]-[8].

For a single multi-hop flow in an Ad Hoc wireless network, a node is considered to be active if it is a source node, a relay node, or a receiving node. In standard IEEE 802.11DCF, all active nodes have equal probability of accessing the medium, and a node with i active nodes in its interference range may gain access to the medium with a probability of $1/i$. In a linear chain topology, per node access probability decreases as the hop count rises and the interfering nodes increases. For a long chain topology, the highest degree of interference occurs around the centre of the chain and is lower towards either the source or the destination ends of the chain. So, for a single flow along a chain, the queue utilization pattern will vary with the hop count. This motivates the design of a medium access mechanism that dynamically depends on the queue utilization of the participating nodes.

In the condition of network saturation, losses of data in the network are mainly due to the queue being full, no route availability or retry count exceeded. Other kinds of drops are due to collision and packet error, but such packets are retransmitted if the TTL (Time To Live) and retry count are still valid. Problems induced by physical limitations like bandwidth, transmission range and interference range cannot be resolved easily, but the MAC algorithm can be adjusted to control the access mechanism in such a way that overall packet drop is reduced and the network performance is elevated, which is the aim of this paper.

II. PERFORMANCE OPTIMIZATION IN AD HOC NETWORKS

In order to improve the performance of resource constrained Ad Hoc networks, a number of protocols have been proposed by different authors: challenges and prospects of bandwidth allocation are discussed in [9] and a method of predicting the available bandwidth for optimizing per node performance is proposed in [10].

Significant efforts have focused on optimizing the performance in multi-hop wireless Ad Hoc networks by controlling congestion and by designing efficient MAC protocols. The IEEE 802.11DCF specification provides fairness across the active contending nodes within its transmission range [11], but in order to differentiate services both in terms of throughput and delay and provide QoS, IEEE 802.11e was introduced with some variations in [12]-[14]. In order to enhance the performance of IEEE 802.11e, [15] discusses a technique to avoid unnecessary polling of a silent station which generates voice traffic. In order to elevate the end-to-end throughput, hop-by-hop congestion control is discussed in [16] and an end-to-end congestion control is also proposed in [17]. The authors of [18] describe a throughput-oriented MAC by controlling the transmitting power of the nodes based on game theory, to achieve concurrent transmission, [19] describes a method to optimize the sensing thresholds of the CSMA receiver and the transmitter by minimizing the outage probability by using SINR (Signal to Noise Ratio). A distributed contention window adaptation technique to adjust the incoming and the outgoing traffic is proposed in [20]. The authors of [21] describe an interesting MAC protocol that allows a concurrent transmission among the neighbours. In order to optimize the contention window usage, the authors of [22] also proposed a backoff generator based on contention level and the channel BER (Bit Error Rate) status.

The remainder of the paper is structured as follows. The proposed MAC is described in detail in Section III. Section IV provides the evaluation of the results, and then Section V concludes the paper by proposing a number of future directions.

III. PROPOSED MAC

A. Proposed Exponential Backoff Mechanism

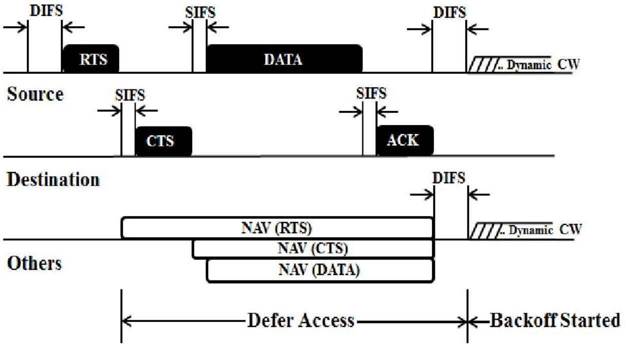

Figure 1 :Medium Access Control Operation

The proposed MAC, named Dynamic Queue Utilization Based MAC (DQUB-MAC), is derived from the original IEEE 802.11 specification and operates within the context of the RTS/CTS mechanism shown in figure 1. The new protocol dynamically adjusts the probability of accessing the medium according to the buffer utilisation of active nodes. It does this by varying the [CWMin; CWMax] interval used in the backoff phase of the IEEE 802.11 protocol. As such, this protocol is explicitly cross-layer and the information concerning the queue utilization is passed to the MAC layer with the help of a new 16-bit field in the IP packet header. Although not used in this paper, this information embedded in the packet header could also be useful at the next hop as it makes the node aware of the buffer status of the preceding node.

The DQUB-MAC assigns higher medium access probability to nodes with a higher queue utilisation. A node with full or already overflowing queue has the greatest likelihood of accessing the medium and a node with an almost empty queue has low probability of accessing the channel. This differentiation increases the probability of frames progressing to the next hop should that node have an emptier queue. This optimizes the utilization of the queues and reduces the packet drop along the path and leads to higher throughput.

A node running the DQUB-MAC protocol is initialised in the usual way with [*CWMin;CWMax*] =[0:8]. When the node becomes active either in sending, receiving or relaying, the CW range depends linearly on the remaining space in the queue according to (1).

$$[CWMin, CWMax] = \begin{cases} \left[2^{\alpha}\dfrac{\sigma-\pi}{\psi}; 2^{\alpha}(\dfrac{\sigma-\pi}{\psi}+1)\right], & r=0 \\ \left[2^{\alpha}\left(\dfrac{\sigma-\pi}{\psi}+1\right)(\gamma);\ 2^{\alpha}\left(\dfrac{\sigma-\pi}{\psi}+2\right)(\gamma)\right], & r>0 \end{cases} \tag{1}$$

In the formula, the queue size is denoted by σ, and the current utilization by π. There are two adjusting parameters, α and ψ. In the present work σ=100 and the parameters are set to α= 3 and ψ= 30. The retry count of a packet is denoted by r and when the data packet is to be retransmitted (r>0) then a new CW range interval is calculated as shown in (1). This depends linearly on the remaining number of retries given by γ, which is computed as the difference between the retry limit of retransmission, and the current retry number of retransmission. When multiple nodes with the same queue utilization compete to access the channel for retransmitting packets, the packet with higher number of retransmission attempts is preferred to that of a fresher one. The maximum number of retransmissions takes the same value as used in IEEE802.11 following the work of [23]. Since the queue size is 100, a parameter ψ= 30 is considered such that (1) generates four different levels of priority namely: low, fair, high and very high when the queue utilization is between 0-29%, 30-59%, 60-89% and >=90% respectively.

IV. EVALUATION

The new algorithm has been tested and benchmarked against both IEEE802.11 and IEEE802.11e standards in a variety of simulation environments. The purpose of the tests is to evaluate the efficiency in distributing the traffic and queue utilisation, as well as to determine the resulting packet loss in saturated network scenarios. Moreover, some tests of the robustness of the algorithm under less favourable circumstances are also performed.

All simulations are carried out with NS2, version 2.35. according to the network parameters listed in Table 1. Each simulation lasts for 800 seconds and each result is an average value of 10 rounds of simulations. The majority of simulations are performed using 1000 byte packet size.

A. Six-hop chain topology:

Most of the simulations use a regular chain topology based on the node arrangement shown in figure 2 and later a rigorous random topology simulations are considered to validate the testing. Different length chains will be considered but the first sets of simulations are based on a six hop chain. Node 0 and node 6 act as the source and the destination respectively for a UDP connection supporting a CBR application with a packet size of 1000 bytes.

Parameter	Value/protocol used
Grid Size	2000m x 2000m
Routing Protocol	DSDV
Queue Type	DropTail
Queue Size	100
Bandwidth	2Mbps
SIFS	10μs
DIFS	50μs
Length of Slot	20μs
Transmission Range	250m
CS Range	550m
Max$_{Retry}$	7
Simulation Time	800s
Traffic Type	CBR
Packet size	500, 1000, 1500 bytes

Table 1: Simulation Setup.

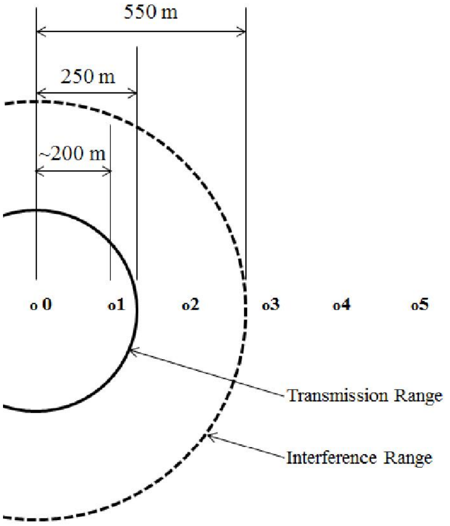

Figure 2: Chain Topology settings of the Ad Hoc Network

The first set of simulations measure the throughput as the offered load is increased on the 6-hop chain. Figures 3, 4, and 5 show the results for IEEE802.11 DCF, IEEE802.11e and DQUB-MAC respectively.

In the experiment of figure 3, using IEEE 802.11 DCF the MAC layer contention among the competing nodes is fair, but interference along the transiting path is different, and the incoming and the outgoing packets of an active node are not controlled. Consequently it is expected that the packet drop and queue utilization will not be uniform along the path. Figure 3 shows that end-to-end throughput starts to saturate when the source node generates data at approximately 290kb/s in IEEE802.11DCF. The performance deteriorates as the offered load increases, but stabilizes at around 400kb/s and upwards. The graph also shows the data rates in each node in order to display the bottlenecks. The graph confirms that loss of packets along the route is not uniform and neither is the utilization of each queue along the path. The end-to-end throughput at the point the network becomes saturated is approximately 200kb/s.

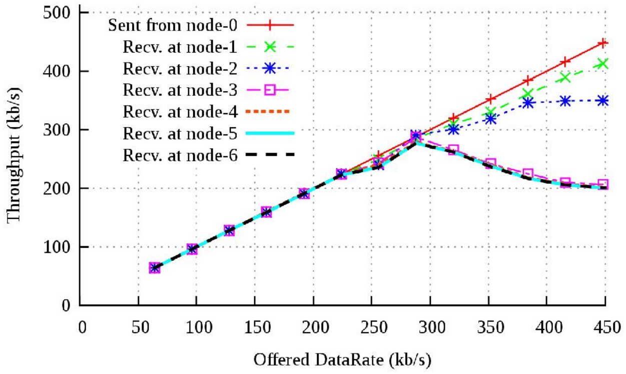

Figure 3: Throughput per Hop Vs Offered DataRate, IEEE802.11DCF on a 6-hop chain.

Figure 4 shows that the performance of IEEE 802.11e is worse than IEEE 802.11DCF despite setting the data flow to the highest priority. This is due to the fact that the CW window range for this highest priority is only (7,15) which is too narrow for a saturated network. The end-to-end throughput starts to saturate only at around 200kb/s, a traffic load much lower to that of IEEE802.11DCF. Since, the network becomes saturated much earlier, the experiment reveals that there is a heavy loss of packets in an around the source node. This result also shows that the distribution of the queue utilization is non-uniform along the high hop communicating path. The end-to-end throughput after network saturation is approximately 130kb/s, a value which is approximately 35% lower than IEEE 802.11DCF.

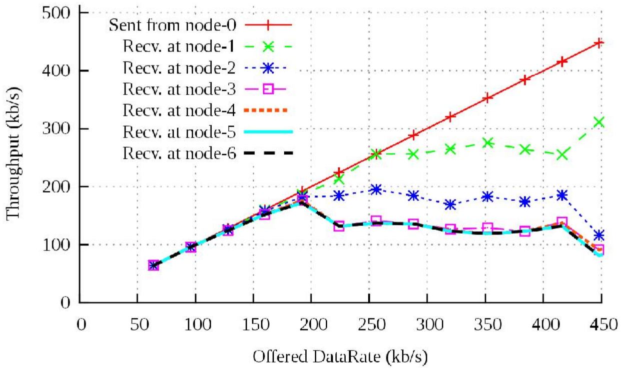

Figure 4: Throughput per Hop Vs Offered DataRate, IEEE802.11e on a 6-hop chain.

The experiment of figure 5 shows that the saturation point of the offered load of DQUB-MAC is similar to that of IEEE 802.11DCF protocol. However, as the offered load is further increased, the performance does not sink like IEEE 802.11DCF and IEEE802.11e. Instead, as the queue utilization along the path is distributed more uniformly in comparison with IEEE 802.11DCF or IEEE 802.11e, the resulting data rates continue to increase when the offered data rate increases. This is due to the fact that the nodes with heavily utilized queues are given higher probability to access the channel than the ones that are less utilized. As a queue fills up, more packets are forwarded towards the nodes with underutilised queues. Those nodes with similar queue utilization are hereby each share the same CW range. Nodes with fewer packets wait longer than the ones that are overflowing, therefore the overall packet drop is greatly reduced and in turn the network performance is enhanced. The network becomes saturated with a high end-to-end throughput of approximately 270kb/s. The end-to-end throughput of DQUB-MAC is approximately 35% and 107% higher than that of IEEE802.11DCF and IEEE802.11e respectively in network saturation.

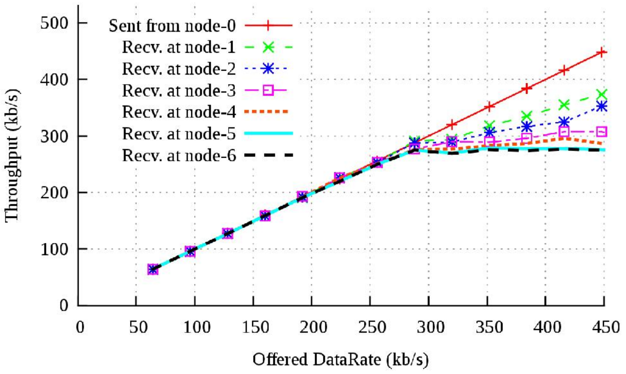

Figure 5: Throughput per Hop Vs Offered DataRate, DQUB-MAC on a 6-hop chain.

Figure 6 shows the throughput achieved per hop along with the error bar for a specific offered data rate of 416kb/s along the 6-hop chain. This represents the packet arrival rate at each intermediate node. In the case of IEEE 802.11DCF, the data rate is halved after three hops; IEEE 802.11e halves the data rate after only two hops from the source. In the case of DQUB-MAC, the overall arrival rate at each intermediate node is much higher than for the IEEE802.11 standards and the data rate never drops by half. This improvement is due to the fact that queues that are either full or highly utilised (in this case queues on the source and the following few nodes) will dynamically receive higher access probability compared to those nodes whose queues are less populated and are situated closer towards the destination. Since no priority of any form is assigned to IEEE 802.11 DCF, the impact of hidden nodes degrades the performance of the network after third hop and similar is the case for IEEE 802.11e.

The error bar is too small to be visible as shown in the Figure 6. During network saturation, the average delay between two successive packet arrivals of 1000KB at the destination when DQUB-MAC, IEEE 802.11 DCF, and IEEE 802.11e MAC are used are 28.8569ms, 29.3185ms and 60.411ms respectively, when the packet generating interval at the source is 19.2307ms. At a low data rate when packets of 1000KB are generated with an interval of 62.5ms at source i.e. unsaturated, average delay between two successive packet arrivals are 62.5131ms, 62.5046ms, and 64.102ms when used DQUB-MAC, IEEE 802.11 DCF, and IEEE 802.11e MAC respectively. During network saturation, the overall average arrival rate is higher for DQUB-MAC due to heavy loss of packets in other cases.

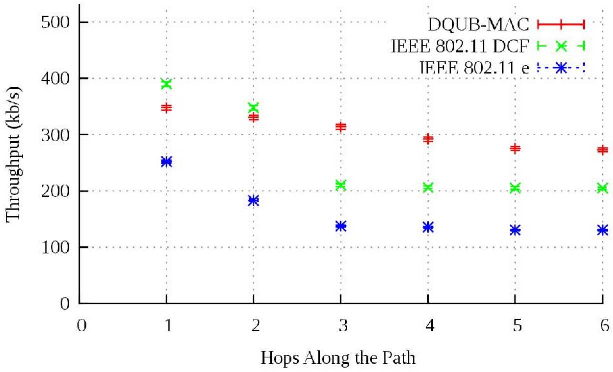

Figure 6: Avg. Throughput Vs Hops along the Path

The way in which DQUB-MAC improves the queue utilisation distribution is shown in figure 7 which presents the per-hop packet loss distribution with an offered load of 416kb/s. The maximum loss rate at any hop along the route for DQUB-MAC is only 15% whereas IEEE802.11DCF and IEEE802.11e have maximum loss rate approaching 40%. In DQUB-MAC, the loss rate is distributed uniformly along the route while IEEE 802.11DCF and IEEE 802.11e, display an irregular pattern of loss.

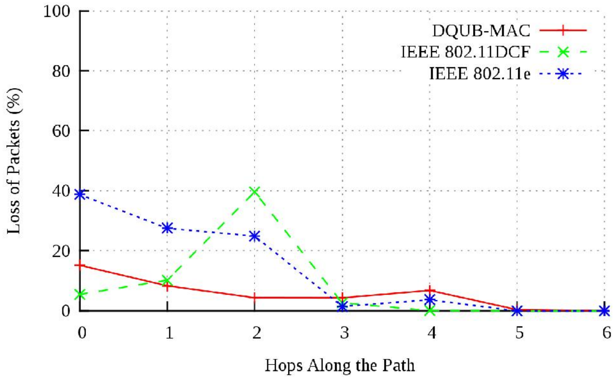

Figure 7: Per-hop packet loss distribution.

B. Shorter chains:

Since the end-to-end performance of IEEE 802.11e is not competitive, comparison of the proposed protocol is done only with IEEE 802.11DCF hereafter. Two-hop and four-hop chain topologies are tested and compared with the outcome scenario of the six-hop chain topology. In order to cause network saturation, the offered data rates are 768kb/s, 585kb/s and 416kb/s respectively.

Table 2 compares the three different scenarios and confirms that the longer the path length, the larger is the performance improvement from using the new algorithm. However, there is a discernable advantage even for short chains. The reason for small improvement for shorter chain in DQUB-MAC is due to similar queue utilization pattern (similar priority) among the nodes, since the nodes are exposed within the vicinity of each other's interference ranges. When the path length is high, the degree of contention and interference density vary, resulted in higher degree of variation in queue utilization pattern, highest around the source.

MAC Type	Chain throughput (kb/s)		
	2-hop	4-hop	6-hop
IEEE 802.11 DCF (A)	715	324	208
DQUB – MAC (B)	726	334	271
Percentage improvement	1.5%	3.1%	30.3%

Table 2: Saturation throughput of shorter chains.

C. Other packet sizes:

So far, all simulations have taken place with 1000 byte packets. Under the same network scenarios and the same network parameters, it is observed that for smaller 500 byte packets the performance gain is not as large. This is due to the fact that the control overhead (RTS-CTS-ACK) increases substantially. The gain of DQUB-MAC over IEEE802.11DCF for high hop count is approximately 16%. When the hop count between the communicating nodes is two and four, then the performance gain of DQUB-MAC over IEEE802.11DCF is approximately 2.5% and 3.2% respectively.

For larger packets, beyond the Maximum Transfer Unit (MTU) of a link, the packet is fragmented. However, even with a 1500 byte packet and 1000 byte MTU the performance gain of DQUB-MAC over IEEE802.11DCF over two hops, four hops and six hops is approximately 5.0%, 12.0% and 18.0% respectively.

D. Random topology:

In order to validate the results are not an artefact of artificially arranged networks, a random placement of 40 nodes is considered as shown in Figure 9, by dividing the area into three zones, namely AREA 1, AREA 2 and AREA 3. AREA 1, AREA 2 and AREA 3 are randomly placed with 10 nodes, 20 nodes and 10 nodes respectively. Sources and destinations are also randomly selected from AREA1 and AREA 3 respectively. Potential source zone and destination zone are separated by at least 1000m with a consideration that source and destination are at least multiple hops apart. A fixed data rate of 416kb/s is offered to the network and tested with 1000 byte packets. The same network parameters listed in Table 1 are used during the simulation. The actual path taken depends on the routing algorithm, DSDV. Two different sets of simulations are considered: firstly, with a single flow with a random selection of source from AREA 1 and a random selection of destination from AREA 3. Secondly, a case with a multiple flow (two flows in this case) with a random selection of distinct source and destination pairs from AREA 1 and AREA 3 respectively are considered. A total of 200 different random topologies are considered with a fresh random selection of source and a destination pair(s) at each turn in both the cases. Ignore all those simulations, if path could not be established between the source and destination pair.

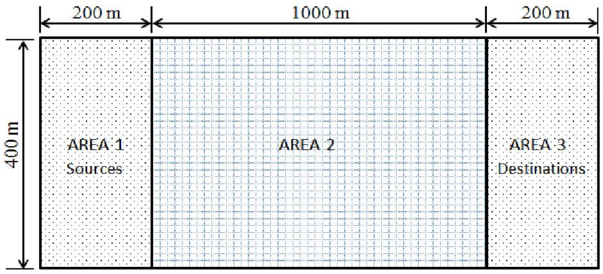

Figure 9: Random Topology

Since the node placement is defined and the simulation is ran extensively, an average value is considered for simplicity in analysis. In the first case with a single flow, the correlation coefficient of the end-to-end performance of IEEE 802.11 DCF and DQUB-MAC is +0.78, showing a strong uphill (positive) linear relationship. In this case DQUB-MAC yields a performance gain of approximately 22% over IEEE 802.11 DCF. The error bar of IEEE 802.11 DCF is 1.043 and that of DQUB-MAC is 1.127 which shows that both the protocols are consistent and performance does not fluctuate much. In a multiple flow scenarios, the total network performance gain of DQUB-MAC is approximately 20% over IEEE 802.11 DCF. The average degree of fairness among the flows in DQUB-MAC and IEEE 802.11 DCF are 97.51% and 97.60% respectively, using Jain's fairness index.

V. CONCLUSION AND FUTURE DIRECTION

This paper has proposed a new MAC protocol, called Dynamic Queue Utilization Based (DQUB) MAC, which adjusts the contention window range based on the current utilization of the queue. As a result, a node with higher utilisation queue will be prioritised over a node whose queue is less utilized. Moreover, during packet retransmission, the protocol also ensures that packets with higher retransmission count will take priority over packets with lower retransmission count.

In simulations using a long 6-hop chain topology, the proposed DQUB-MAC demonstrated a performance gain of up to 30% over IEEE 802.11DCF. Despite employing the highest priority, IEEE 802.11e performs even worse than IEEE 802.11DCF. Additional experiments also showed that these performance gains are robust with respect to varying the length of the chain, adjusting the packet size and considering a random topology. There is a high degree of stability and consistency in DQUB-MAC even with random topology. The degree of fairness of DQUB-MAC is equally compatible with the standard MAC with a higher degree of overall network performance gain.

Future work will be based on testing the protocol by introducing exponential back off when the packet retries so that the protocol can withstand and accommodate high degree of contention.

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