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Performance Characterization of IEEE 802.11s Compatible MAC Protocols

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Abstract: ***Wireless Mesh Network (WMN)*** **[1]** ***deployment based on IEEE 802.11s*** **[2]** ***standard is a popular choice in setting up cost-efficient alternative to support broadband internet services to a larger population. They can provide network connectivity over large geography when compared to WLANs. WMN makes use of Distributed Coordination Function (DCF) Medium Access Control (MAC) protocol with Binary Exponential Backoff (BEB) algorithm to avoid collision due to simultaneous transmissions by more than one user at the same time. These collisions bring the network performance drastically down if not handled properly. Thus this work tries to evaluate the suitability of the better efficient CA algorithms (EIED, EILD, MILD, PB, CCW, EBO, HBA…) which can replace BEB to support higher throughput for IEEE 802.11s networks (WMNs). The NS-3*** **[3]** ***simulation results indicate that Polynomial Backoff (PB) performs better than others against the BEB algorithm in about 52 % of network scenarios and it is suggested to operate with TWO radios enabled with all access points.***

Keywords: IEEE 802.11s, WMN, BEB, MAC, HWMP, MRMC

I. INTRODUCTION

WMNs have been projected as the most preferred alternative for next-generation wireless networks with least cost last-mile connectivity. WMNs essentially make use of multi-hop communication to support wireless services over a large area. At the heart, the Mesh Router provides internet access to the Mesh Clients. A Mesh Router can be built out of general-purpose computing devices like, laptops, desktops, or on dedicated systems. The simplicity in adding the new routers make WMNs as the preferred technology for applications viz., Advanced Metering Infrastructure (AMI), intrusion detection systems, remote video surveillance, smart grids, environmental monitoring. In many applications, WMNs are expected to support internet services to heterogeneous clients over a large area.

Figure 1. Depicts the need to adopt multi radio multi channel features on Mesh Router to achieve maximum throughput, but is not required for mesh clients to achieve the best results from WMNs.

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The WLAN standard was originally designed to support best-effort services, in providing high throughput and fairness in resource allocation.

Increased demand for wireless Internet access has led to rapid growth in WLANs in recent years. The lion's share of this burgeoning market has been captured by products based on the IEEE 802.11 family of standards. Most of the traffic carried on a typical WLAN is made up of non-real-time applications such as web browsing and email. WMN is advancement over WLAN, which can provide wireless connectivity over a relatively large geography when compared to WLAN. WMNs are undergoing rapid progress

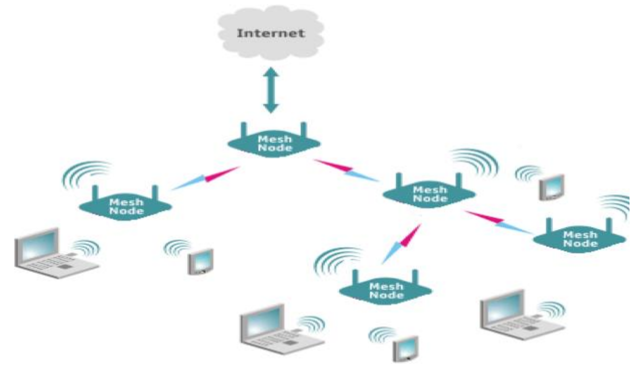

Figure 1. Multi-radio wireless mesh network [1]

and inspiring numerous applications due to their enhanced capability against WLANs. However, many technical issues still exist in WMNs.

Some of the common sets of problem areas, which needs to be handled in order to achieve better WMN performance are (a) choosing the most efficient backoff algorithm which has been developed for WLAN instead of the default BEB algorithm, (b) choosing the most efficient routing protocol which can work with complex meshed connections which makes wireless connectivity more and more complex to manage and support user data transmission, (c) multi radio devices can support better throughput but there is not much literature has been published on multi radio backoff schemes, which needs a serious deliberation on suitability of multi radio (MR) backoff (BO) schemes instead of single radio BO schemes. Randomized BEB plays a pivotal role in coordinating medium access by multiple devices to a shared communication medium. On the contrary BEB is expected to underperform, when the traffic is "bursty". Also there are huge effort has gone into designing newer back off BO algorithms for various wireless standards. There raises a question, Is BEB still a best choice for wireless networks. In [4] authors have inferred that newer BO algorithms significantly underperform in many network setups.

They have also inferred that number of collisions is not the only root cause for underperformance. Thus this work tries to evaluate the BEB's suitability for WMN setups.

The main practical problem of random multiple accesses in a wireless channel is the collision of transmitted packets.

The collisions can degrade the throughput and fairness efficiency of WLAN / WMN. Backoff algorithm is an important component which can be enhanced to reduce the collision probability. One of the simplest ways to reduce the collision problem is the usage of a sampling random-time to delay the next retransmission packet. Significantly, a key concept of designing back-off algorithms is how to select an optimum contention window size for the maximum throughput, fairness index and smallest packet delay.

II. RELATED WORK

Substantial research has gone into evaluating the performance of WMNs with different network densities (grid sizes). In [5] , authors have evaluated the performance of 802.11s in comparison with 802.11g/b/a type of nodes. They have found that multi-hop communication substantially reduces the performance of IEEE 802.11n. They have also found that WMN with layer-3 routing (ex. AODV) results in better performance when compared to layer-2 routing protocols (ex. HWMP, PMP). Also they have observed that the 802.11n with multi-hop communication perform poorly when compared to single-hop communication. This necessitates identification of a backoff scheme instead of BEB which works well with WMN implementations.

BEB is the earliest MAC protocol used in CSMA protocols to reschedule packets after a collision. In BEB, a node attempts to transmit a packet following a backoff interval that is randomly selected from a backoff window; in response to a collision the window is multiplied by a factor of TWO in order to reduce the probability of collision during the next transmission. There are quite a few enhancements proposed in the literature viz., EIED, EILD, DIDD, MILD, QB, LB mechanisms (broadly classified as exponential, linear and polynomial backoff schemes). But there is not much work has been published specifically suited for wireless mesh networks (WMN). In this work we propose an analysis of backoff algorithms suitable for WMNs. In this work we assume WMN setup based on IEEE 802.11s standard, which in turn uses HWMP and PMP protocols for link scheduling and routing operations.

Linear backoff scheme [6]

$$W_i = \begin{cases} \langle(\beta i + 1)W_0\rangle, & \text{for } i = 0, \ldots, m-1, \\ \langle(\beta m + 1)W_0\rangle. & \text{for } i = m, \ldots, R-1, \end{cases}$$

Exponential backoff scheme [6]

$$W_i = \begin{cases} \langle\beta^i W_0\rangle, & \text{for } i = 0, \ldots, m-1, \\ \langle\beta^m W_0\rangle. & \text{for } i = m, \ldots, R-1, \end{cases}$$

Polynomial backoff scheme [6]

$$W_i = \begin{cases} \langle(i+1)^\beta W_0\rangle, & \text{for } i = 0, \ldots, m-1, \\ \langle(m+1)^\beta W_0\rangle. & \text{for } i = m, \ldots, R-1. \end{cases}$$

Jesada Sartthong et.al, [7] proposed a new backoff algorithm named *half binary exponential Increase and Double Decrement (HBEIDD)* which perform better throughput than BEB, EIED [8], DIDD [9], BEIHD [10], RIBED under heavily loaded WLANs. But there is no guarantee on its suitability for WMNs.

Zygmunt J. Haas et.al, [11] have found that the optimum BO interval should be FOUR times the transmission time of a packet when the random access channel operates under a pure ALOHA scheme. They have observed that the BO algorithms which select the CW based on the node density can perform better than BEB in WLAN setup

On the same lines, Nataraju A.B. et.al, [12] observed that the network performance can be enhanced if the medium access protocol based its operation on network node density.

Sakurai et.al, [13] observed that the BEB mechanism induces a heavy-tailed delay distribution in case of unlimited retransmissions. Also they have inferred that DCF is prone to long delays and not suited to carry delay-sensitive data.

Anderton et.al, [4] have observed BEB may not be a best medium allocation algorithm under many of the application scenarios. Thus the work carried out in this work finds a greater significance for WMN throughput enhancement.

B. Nithya et.al, [14] proposed an Integer Sequences based Backoff Algorithm (ISBA) which exploits cubic, exponential, jacobsthal and catalan integer sequences to estimate the proper Contention Window (CW) size. Based upon backoff stages and failure count of acknowledgments, these integer sequences are used to accomplish the adequate growth rate of CW. This leads to relatively efficient medium access to curtail end-to-end delay and collisions among contending stations.

Srikrishna Sridhar et.al, [15] have proposed a channel to radio mapping scheme in MRMC based WMNs. They have constructed a model for channel assignment as an optimization problem with the goal of minimizing the overall network interference. The problem has been proven to be NP-Hard. Through extensive simulations they have demonstrated that the distributed algorithm performs competitively and can serve as a practical and scalable solution to the channel assignment problem.

Xinghua Sun et.al, [16] observed that the BEB may not provide best performance in WLAN environment when compared to other backoff algorithms. They have also observed that BEB can achieve the theoretical limit of throughput when the initial backoff window size is properly selected. It, however, suffers from significant delay degradation when the network becomes saturated. They have also inferred that polynomial backoff support better throughput compared to exponential backoff schemes. They have also inferred that the polynomial backoff with degree (x=2) support the better performance when compared with higher order polynomial, x = 3, 4, 5.

Suzhi et.al, [17] have observed that the BEB mechanism, the key collision avoidance scheme in DCF of 802.11, is fundamentally defected in inducing divergent moments of medium access delay. The delay variance can easily approach infinity with pragmatic system configurations, which translates into service starvation for some users and eventually leads to severe service inequality among users.

The authors have shown that the application of power law delay can be mitigated by swapping BEB with polynomial back-off (PB). They have found, through a rigorous analysis, that all delay moments are finite with polynomial backoff, and thus fundamentally fix the problem of starvation and inequality. In addition, PB yields higher throughput with a practical network size when the order of the polynomial backoff function is set reasonably

Balador et.al, [18] inferred that the network performance can be improved when the multiple channels are used simultaneously over multi radios using different frequency bands. But for this mechanism to work properly the channels shall be separated spatially far apart to avoid any interference to communications over other channels at the same time. It is also observed the channels (1, 6, 11, and 14) or (2, 7, 12) or (3, 8, 13) can be used by routers / nodes simultaneously over different logical or physical radios. Supporting multiple simultaneous communications over channels separated in frequency domain is called as multi-radio / multi-interface based communication. The multi radio feature can supported over existing 802.11b/g/n hardware with software update or with brand new hardware to support the multi-radio functionality over multiple antennas.

Ruopeng Wang et.al, [19] proposed a modification to DCF with constant contention window which is dependent upon scale of network to obtain the maximum throughput where the user density is fixed for a given application scenario.

In [20], the authors have proposed an Enhanced BO (EBO) algorithm with different contention intervals dependent upon back off stage. The proposed hybrid algorithm is dynamic in nature and found to absorb the collisions more efficiently than BEB and other older variants of backoff algorithms.

III. PROBLEM FORMULATION & METHODOLOGY USED

The main goal of this work is to identify the optimal number of radio interfaces, packet size; and backoff algorithm to achieve peak throughput performance for WMNs.

Methodology for performance characterization

Initialization:

gridSize = 3x3, 4x4, 5x5, 6x6, 7x7;
nInternfaces = 1, 2, 3;
packetSize = 400, 600, 800, 1000, 1200, 1400, 1500, 1600, 1800, 2000;
RngRun = 11, 22, 33, 44, 55, 66, 77, 88, 99, 101, 111, 122, 133, 144, 155, 166, 177, 199, 201, 211; // 20 values

Methodology:

1: *Repeat for all gridSize, // realized by* `m_xSize & m_ySize`
2: *Repeat for all nInternfaces, // realized by* `m_nIfaces`
3: *Repeat for all packetSize // realized by* `m_packetSize`
4: *Repeat NS-3 simulation with different RngRun*
5: *Run the NS-3 simulation with specific gridSize, packetSize interfaces, and Random Seed number(RngRun)*
6: `./waf --command-template="%s --m_xSize=3 --m_ySize=3 --m_packetSize=400 --m_nIfaces=1 --m_step=170 --RngRun=11" --run scratch/HwmpGrid`
7: ***→ This statement simulate 3x3 grid, nInterfaces = 1, PacketSize = 400;***
8: *Save the results; // → result-1, 2, 3,....20*
9: *End - Repeat NS-3 simulation*
10: *Find the median of these 20 iterations and tabulate for analysis/characterization.*
11: *End - Repeat for all packetSize*
12: *End - Repeat for all nInternfaces*
13: *End - Repeat for all gridSize*
14: *Repeat the above steps 1-13 for different MAC CA algorithms viz., BEB, DIDD, EIED, EBO, HBO, PB, CCW, ...*
15: *Compare the Throughput from BEB with other algorithms. The differential values are tabulated in Table 2 - Table 11.*

For instance, Table 2 : indicates difference in Throughput from EIED and BEB algorithms → TH_{EIED} - TH_{BEB}
Similarly, Table 3 : indicates difference in Throughput from EIED and BEB algorithms → TH_{DIDD} - TH_{BEB}.
Continue similarly for other CA algorithms as well for performance characterization.
The following section discuss the experimental results obtained using the methodology mentioned and inferences drawn accordingly.

IV. EXPERIMENTAL SETUP FOR CONTENTION AVOIDANCE ALGORITHM TEST

The following results have been observed from the extensive simulations using NS-3 simulator and the inferences have been drawn accordingly. The set of configurations considered in these simulations are listed in

Table 1.

Table 1- Simulation parameters [21]

Parameter	Values
Computing environment and Operating System	Ubuntu 16.04 LTS HP Compaq 8200 Elite MicroTower - 4GM RAM, 500GB HDD Core-i5, 3.09GHz processor.
Grid size (P x Q)	3x3, 4x4, 5x5, 6x6, 7x7
Step size (metre)	170
Radio Propagation Model	ns3::ConstantSpeedPropagationDelayModel
Propagation Loss Model	ns3::LogDistancePropagationLossModel
Payload size (bytes)	0,4, 0.6, 0.8, ... 2.0 KB
Simulation time (sec)	175
No of simulation scenarios (driven by different random seed numbers, RngRun = 11, 22, 33, 44, 55, 66, 77, 88, 99, 101, 111, 122, 133, 144, 155, 166, 177, 188, 199, 211)	20
Topology	Grid
Routing protocols considered	HWMP+PMP (IEEE 802.11s)
Number of radio interfaces (channel no. – 0, 5, 10)	1 / 2 / 3
Number of nodes = MxN	9 / 16 / 25 / 36 / 49
No. of Connections / flows	9 / 16 / 25 / 36 / 49
EnergyDetectionThreshold	-89.0 dbm
CcaMode1Threshold	-62.0 dbm
WifiPhyStandard	WIFI_PHY_STANDARD_80211b
RtsCtsThreshold	2200 (Disabled)
User application	ns3::OnOffApplication
Application data rate	150kbps

Channel allocation schemes considered.	BEB, EIED, EILD, DIDD, PB(2), CCW, EBO, HBO

HWMP protocol performance has been analyzed against the system Throughput parameter, which is defined as:

Throughput *(bps): it is a measure of number of application data bytes received by the receiver in one unit of time.*

$$\text{Throughput} = \frac{\sum \text{Total no. of app data bytes received}}{\sum \text{Total simulation time}}$$

Contention window ranges for different MAC protocols are set as follows.

1) BEB – Binary Exponential Backoff *[22]*

The contention window range is doubled after each failure and reset to minimum value upon successful transmission.

$$CW = \begin{cases} \min(2 * CW, CWmax) & on\ collision \\ CWmin & on\ success \end{cases}$$

Backoff range {0, CW}

*Backoff Timer ← Rand(0,CW) * slotTime;*

2) EIED – Exponential Increase Exponential Decrease

The contention window range is doubled after each failure and reset by a factor of $\sqrt{2}$ upon successful transmission [8].

$$CW = \begin{cases} \min(2 * CW, CWmax) & on\ collision \\ \max\left(\frac{CW}{\sqrt{2}}, CWmin\right) & on\ success \end{cases}$$

Backoff range {0, CW}

*Backoff Timer ← Rand(0,CW) * slotTime;*

3) DIDD – Double Increase Double Decrease *[9]*

$$CW = \begin{cases} \min(2 * CW, CWmax) & on\ collision \\ \max(CW/2, CWmin) & on\ success \end{cases}$$

Backoff range {0, CW}

*Backoff Timer ← Rand(0,CW) * slotTime;*

4) MILD – Multiplicative Increase and Linear Decrease

$$CW = \begin{cases} \min(CW * 1.5, CWmax) & on\ collision \\ \max(CW - x, CWmin) & on\ success \end{cases}$$

Backoff range {0, CW}, and x = 32 .

*Backoff Timer ← Rand(0,CW) * slotTime;* [22]

5) EILD – Exponential Increase Linear Decrease *[22]*

$$CW = \begin{cases} \min(2 * CW, CWmax) & on\ collision \\ \max(CW - x, CWmin) & on\ success \end{cases}$$

Backoff range {0,CW}, x = 32 or 64.

*Backoff Timer ← Rand(0,CW) * slotTime;*

6) EBO – Enhanced Backoff algorithm *[23]*

slot_lb[N] = {0, 32, 96, 224, 480, 992}

slot_ub[N]={32, 96, 224, 480, 992, 1023}

$$boStage = \begin{cases} boStage = 0; & on\ success \\ boStage++; & on\ collision \end{cases}$$

Backoff range { slot_lb[boStage], slot_ub[boStage] }

*Backoff Timer ← Rand (slot_lb[boStage], slot_ub[boStage]) * slotTime;*

7) PB – Polynomial Backoff (PB_PAPER_2) *[17]*

β = 2;

$$boStage = \begin{cases} boStage = 0; & on\ success \\ boStage++; & on\ collision \end{cases}$$

$CW_{boStage} = (1+\beta)^{boStage} * W_0$

Backoff range $\{0, CW_{boStage}\}$

Backoff Timer ← Rand(0, $CW_{boStage}$*) * slotTime;*

8) HBO – Hybrid BackOff algorithm *[20]*

m1=2, m2=8, a=240, W_0=cmMin(31)

$$boStage = \begin{cases} boStage = 0; & on\ success \\ boStage++; & on\ collision \end{cases}$$

$CW_i = 2^{boStage} * W_0 \qquad 0 \le boStage \le m1$

$CW_i = 2^{m1} * W_0 + a * (boStage - m1) \qquad m1 < boStage \le m2$

$CW_i = 2^{m1} * W_0 + a * (m2 - m1) \qquad boStage > m2$

Backoff range {0, CWi}

*Backoff Timer ← Rand(0, CWi) * slotTime;*

9) CCW –Constant Contention Window algorithm *[19]*

Contention window remains same irrespective of success or failure in communication (CW_{fixed}=300 or 400).

$$CW = \begin{cases} CWfixed & on\ collision \\ CWfixed & on\ success \end{cases}$$

Backoff range {0, CW}

*Backoff Timer ← Rand(0,CW) * slotTime;*

V. Results Analysis & Discussion

In this section, we present the results obtained and inferences are drawn accordingly.

Note for decoding labels used in Table 2 - Table 11

3x3_2 ➔ grid size = 3x3, number of Interfaces = 2

7x7_3 ➔ grid size = 7x7, number of Interfaces = 3 …

SIZE ➔ Packet SIZE

Each cell value indicates Throughput with row indicating packet size and column indicating node density, & No. of interfaces enabled with mesh router.

A cell in the table with green/gray shade indicates BEB underperform when compared to other MAC protocol. Table 2 - Table 11, list out the difference in throughput from two different CA algorithms.

For instance, when $\mathbf{TH_{(EIED\ 3x3\_i1)}}$ > $\mathbf{TH_{(BEB\ 3x3\_i1)}}$ leads to positive value (gray shaded cell).

Table 2 - Differential throughput (EIED, BEB)

$\mathbf{TH_{EIED}}$ - $\mathbf{TH_{BEB}}$																
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3

400	-29.69	-14.60	-18.65	-87.69	23.74	-5.18	-193.12	-181.81	-11.61	-516.65	-152.04	-237.34	-800.60	-483.97	-267.89
600	-10.58	-3.77	-24.50	-8.29	-32.40	-18.16	-104.02	-54.95	-34.12	-372.03	-211.94	-180.11	-775.10	-509.04	-261.62
800	-34.40	-4.97	2.63	-54.66	-46.15	24.17	-267.23	66.46	51.70	-344.52	-143.03	-34.25	-565.19	-248.74	-119.74
1000	-0.44	7.73	-8.23	38.38	-68.76	-100.19	30.35	62.63	-45.30	-287.44	-30.84	8.78	-322.98	-62.94	-42.53
1200	3.65	16.16	-4.36	-13.83	55.20	-27.21	-126.65	-63.53	-33.77	-195.45	-18.28	23.87	-600.19	-254.18	-115.23
1400	3.88	2.93	-6.51	24.47	-94.75	-6.97	78.18	-38.58	24.54	1.30	-66.36	-121.51	-218.78	-83.28	-32.49
1500	15.71	9.32	19.28	18.41	-46.16	3.03	-63.93	44.54	-4.46	-252.76	12.67	-60.20	-260.90	98.93	-206.56
1600	31.15	7.22	21.08	11.87	12.91	8.23	-57.88	18.35	-45.82	-222.84	26.12	-74.58	-209.60	24.87	-6.85
1800	-30.77	-14.04	-2.74	-64.05	28.84	37.89	-130.60	117.61	104.74	-242.35	232.48	44.18	-234.52	-37.89	-26.85
2000	-7.19	8.16	-5.87	67.65	-0.06	-45.61	-21.32	112.20	85.82	31.98	166.14	-26.25	-23.06	-200.33	162.56

Inference-1: It can be inferred from Table 2 that EIED with packet sizes 1200 to 2000 bytes performs better with lesser radio interfaces when compared with BEB. (Refer. Columns 3x3_p – 5x5_p, where p=1/2/3)
Inference-2: With highly dense networks the performance is always observed to be to poorer when compared with BEB (Refer columns 7x7_1, 7x7_2, 7x7_3)

Table 3- Differential throughput (DIDD, BEB)

TH_{DIDD} - TH_{BEB}															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	-5.71	16.62	3.23	-70.69	57.14	-13.60	-108.93	-62.11	68.10	-286.34	-43.45	-61.92	-417.39	-81.31	-3.02
600	-4.76	-6.17	-3.49	34.97	-64.63	4.21	41.75	-20.53	-20.46	-248.90	-140.46	-122.09	-345.72	-281.50	-209.35
800	-18.06	7.66	4.92	-33.97	-9.96	40.69	-128.94	49.23	81.73	-174.01	-68.85	33.98	-184.82	-59.00	193.75
1000	-7.15	4.51	-13.18	-16.11	-98.19	-35.85	85.78	-9.32	-36.46	-39.54	37.02	117.47	-22.93	-109.51	-75.89
1200	-2.96	12.75	9.35	-35.78	20.40	28.09	-27.24	-73.16	-76.89	8.95	57.88	144.06	-268.19	-119.84	8.46
1400	1.97	4.70	-6.48	4.07	7.03	-29.65	60.16	-46.26	-51.65	33.69	-35.11	-202.91	-96.83	90.44	-0.27
1500	24.33	9.39	7.89	28.73	-51.19	-15.34	-24.33	-1.24	26.31	-117.47	192.24	12.98	-259.83	152.70	-157.67
1600	10.61	0.60	-7.66	-9.93	111.90	-17.82	-61.38	-34.60	-29.19	-53.55	5.49	79.25	13.57	217.26	242.06
1800	-29.66	-0.17	-2.21	-72.55	15.61	81.44	-81.90	7.17	87.77	-114.43	336.08	60.02	-123.38	55.83	-6.77
2000	-15.17	6.22	-11.93	6.91	-64.16	-47.92	-76.35	54.65	21.31	2.47	47.98	-157.46	159.86	113.19	158.85

Inference-1: It is suggested to use DIDD with packet sizes between 1200 and 1800 bytes with TWO or THREE number of interfaces. But with single interface, it performs poorly when compared to BEB. Refer Columns AAxAA_1 (where AA = 3, 4, 5, 6, 7)
Inference-2: DIDD perform better than BEB with THREE radio interfaces irrespective of the size of packets, whereas with ONE / TWO radios, it is suggested to operate with packet sizes between 1200 and 2000 bytes.

Table 4 - Differential throughput (MILD, BEB)

TH_{MILD} - TH_{BEB}															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	-66.94	-55.71	-72.42	-270.82	-97.12	-11.80	-496.73	-345.71	-112.10	-879.08	-587.82	-687.56	-1400.16	-1100.32	-1101.29
600	-58.71	-16.18	-81.96	-162.34	-97.96	-2.91	-414.22	-97.80	-216.30	-906.18	-633.84	-555.11	-1362.04	-1061.81	-794.82
800	-51.55	-44.21	-16.29	-134.60	-84.89	-26.63	-408.99	-60.04	-85.81	-769.91	-528.53	-392.28	-985.77	-795.70	-443.05
1000	-18.16	-20.07	-13.07	-50.73	-102.04	-123.10	-49.10	-38.57	-126.57	-499.26	-314.36	-164.73	-923.78	-791.78	-434.61
1200	24.77	13.85	-3.50	-52.56	-15.56	27.93	-287.85	-205.33	-148.85	-451.39	-119.79	-254.52	-965.72	-504.80	-391.17
1400	-10.04	7.55	0.33	-10.16	-75.02	-29.62	-7.77	-71.56	-116.19	-227.86	-195.88	-310.46	-594.07	-499.84	-430.97
1500	17.18	4.79	16.23	-18.38	-94.41	28.25	-160.70	17.71	-64.51	-424.92	-30.84	-194.15	-581.85	-200.78	-488.82
1600	21.41	6.06	10.58	-23.26	24.18	-1.84	-81.95	-133.06	-70.56	-525.31	-285.19	-341.38	-393.18	-177.28	-535.21
1800	-16.67	14.04	0.88	-108.35	-46.27	56.80	-75.67	62.60	28.13	-188.53	83.54	-187.79	-678.63	-250.06	-487.02
2000	4.07	11.79	-0.40	-3.56	-45.84	-25.98	-53.69	83.64	108.86	-335.59	55.43	-177.17	-235.06	-428.68	-119.06

Inference-1: It can be inferred that MILD perform very poorly when compared to BEB with smaller sized packets (less than 1.2KB).

Inference-2: It is suited for lightly dense networks (3x3_1, 3x3_2, 3x3_3) with packet size between 1200 and 2000 bytes.

Table 5 - Differential throughput (EILD_32, BEB)

$TH_{EILD\_32} - TH_{BEB}$															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	-118.62	-59.30	-107.34	-263.31	-102.30	-146.14	-712.05	-519.12	-212.63	-1125.33	-957.55	-712.09	-1583.63	-1543.52	-1251.82
600	-72.38	-67.31	-85.35	-258.91	-124.15	-90.44	-488.74	-283.56	-151.12	-1022.09	-745.18	-535.47	-1527.99	-1170.90	-919.99
800	-76.44	-12.01	-40.10	-160.11	-54.95	-44.51	-448.84	-64.34	-143.50	-802.80	-501.80	-405.79	-1302.13	-839.03	-579.35
1000	-28.25	-2.48	-28.52	-65.38	-121.78	-107.98	-170.76	-104.49	-197.80	-654.47	-287.54	-264.66	-1103.00	-729.16	-629.36
1200	-4.42	14.07	1.85	-92.79	8.09	-15.00	-291.36	-169.66	-53.99	-490.78	-243.77	-297.88	-1071.01	-684.15	-456.11
1400	-12.53	16.54	3.73	-38.27	-114.64	-24.50	-38.12	-56.00	-80.00	-262.24	-258.68	-348.32	-663.85	-508.70	-557.97
1500	0.45	18.73	6.46	-15.14	-55.61	12.09	-190.13	44.82	-90.76	-557.63	-133.96	-335.37	-678.15	-235.43	-504.58
1600	5.92	10.61	19.74	-54.17	19.23	10.07	-124.95	-93.47	-60.10	-361.75	-138.32	-180.74	-570.01	-287.97	-383.23
1800	-19.49	19.32	17.78	-102.76	60.36	87.05	-233.84	24.84	94.03	-387.07	157.39	-87.44	-598.90	-156.66	-439.98
2000	3.30	15.54	8.52	36.69	-17.10	17.72	-165.82	29.26	58.78	-275.85	54.70	-5.65	-418.26	-501.05	-47.28

Inference-1: It can be inferred that EILD_32 perform very poorly when compared to BEB with smaller sized packets (less than 1.2KB).
Inference-2: It is suited for lightly dense networks with packet size between 1200 and 2000 bytes.

Table 6 - Differential throughput (EILD_64, BEB)

$TH_{EILD\_64} - TH_{BEB}$															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	-68.90	-64.53	-2.78	-190.67	-44.56	-33.90	-437.80	-243.89	-73.15	-809.48	-532.14	-291.52	-1241.09	-883.26	-800.69
600	-54.23	-105.88	-31.50	-143.79	-61.19	-16.12	-314.65	-102.51	-193.96	-731.92	-491.96	-326.49	-1122.56	-997.95	-673.45
800	-60.43	-16.41	-22.13	-96.28	-89.47	14.84	-377.17	-50.10	-33.98	-636.13	-363.48	-176.71	-940.41	-462.99	-271.08
1000	-1.84	19.22	-27.34	-29.21	-151.30	-19.26	-161.54	31.53	-115.54	-498.37	-222.50	-193.34	-688.25	-529.83	-467.88
1200	-2.02	26.16	2.11	-45.37	-3.18	2.38	-303.00	-101.02	-101.73	-312.51	-121.18	17.76	-764.29	-458.05	-321.02
1400	0.60	12.72	8.84	7.71	-65.45	6.65	-37.41	65.66	-41.49	-233.49	-276.27	-291.09	-530.60	-441.51	-346.67
1500	4.61	7.32	9.01	-11.65	-48.96	25.80	-119.22	-18.11	12.77	-389.96	12.65	-296.66	-576.14	-53.81	-301.26
1600	15.78	9.16	15.51	-37.44	36.60	-7.51	-81.97	7.83	-51.16	-269.61	-244.40	-252.15	-564.97	-188.20	-242.23
1800	-27.96	5.01	8.60	-92.28	-30.64	70.39	-117.22	93.86	19.75	-341.62	174.04	-78.94	-458.80	-160.00	-335.80
2000	15.21	-4.57	-8.56	64.87	-111.22	-20.18	-100.50	145.57	110.36	-100.99	40.84	-38.79	-299.20	-293.78	-76.89

Inference-1: It can be inferred that EILD_64 perform very poorly when compared to BEB with smaller sized packets (Rows1-4 – 400, 600, 800, and 1000).

Inference-2: It is suited for lightly dense networks with packet size between 1.2KB and 2.0KB.
Inference-3: It can be inferred from Table 5 -
Table 6 that EILD_64 works better than EILD_32.

Table 7- – Differential throughput (DCF_CCW_300, BEB)

$TH_{DCF\_CCW\_300} - TH_{BEB}$															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	-50.52	-39.83	-42.43	-136.22	-47.11	-65.71	-266.16	-214.82	-116.97	-495.04	-268.01	-344.48	-666.89	-604.25	-648.04
600	-45.74	-30.13	-30.77	-61.04	-79.69	-26.91	-36.16	-41.49	-120.82	-284.53	-312.34	-231.41	-558.10	-398.94	-324.80
800	-8.88	-14.87	-5.92	-34.70	-42.09	-23.49	-76.25	18.90	-1.79	-263.23	-123.15	-212.76	-339.37	-294.31	80.74

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1000	3.10	-5.37	-11.06	11.33	-21.73	-89.43	59.26	-82.38	-56.78	-74.88	-86.64	1.84	-24.52	-164.08	-90.27
1200	7.52	4.66	3.22	-27.19	23.14	-10.89	-108.54	-115.79	-165.80	-2.35	-1.85	-58.39	-264.24	-199.98	-150.89
1400	3.21	-1.45	-6.23	24.41	-126.78	-36.81	137.67	-76.17	-143.27	32.72	-97.44	-307.90	1.14	-43.02	-195.58
1500	13.09	1.79	11.52	47.01	-68.52	-49.21	-95.49	-17.61	-34.41	-106.94	5.08	-278.21	-27.25	-168.21	-280.62
1600	19.44	-3.91	16.96	18.18	91.65	0.17	-22.06	-117.34	-113.55	-14.71	-132.42	-220.51	-46.08	105.22	-97.90
1800	-31.39	-5.78	0.23	-64.72	45.35	54.21	-100.57	47.28	8.69	-141.12	177.42	-187.01	-84.85	-64.84	-144.67
2000	2.13	2.18	-1.03	34.03	-74.94	-49.97	-124.21	-30.44	-38.37	57.02	43.67	-99.54	165.82	-263.14	107.85

Inference-1: It can be inferred that DCF with CCW (cw=300) mostly underperform with packets less than 1KB. Otherwise it works better than BEB for most of the network configurations.
Inference-2: It can be inferred that DCF with CCW (cw=300) mostly works better with lesser dense networks.

Table 8- Differential throughput (DCF CCW (w=400), BEB)

$TH_{DCF\_CCW\_400}$ - TH_{BEB}															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	-62.49	-81.51	-63.73	-213.28	-139.04	-117.60	-349.42	-315.04	-201.86	-637.89	-464.17	-511.31	-1070.51	-885.90	-748.67
600	-37.13	-70.15	-48.13	-91.24	-75.72	-49.31	-166.58	-68.08	-124.83	-455.66	-259.20	-226.93	-582.77	-589.74	-295.28
800	-36.75	-22.97	-7.58	-79.11	-67.39	-25.00	-175.20	13.73	-29.05	-225.52	-109.56	-109.07	-340.73	-264.77	-70.91
1000	-13.91	3.49	-9.75	3.05	-121.41	-25.15	41.92	-1.16	-80.28	-60.45	-29.43	20.51	-71.79	-160.35	-120.81
1200	-11.85	11.36	0.13	-31.39	-21.69	4.60	-115.33	-157.70	-77.26	-140.11	-101.67	-106.84	-118.95	-161.36	-10.50
1400	7.40	-4.24	-15.80	-2.84	-81.27	-30.64	102.12	-1.17	11.60	-1.35	-166.69	-221.88	-9.79	94.45	-85.92
1500	12.92	-2.05	1.74	-7.21	-27.00	40.86	24.94	53.54	-33.83	-83.61	73.37	-129.23	-38.64	109.79	-273.20
1600	17.97	-11.20	24.71	3.33	138.74	-33.36	14.50	-19.39	-81.21	-70.53	-127.95	-38.10	60.72	18.78	4.46
1800	11.16	17.45	-4.92	-33.25	-40.52	58.33	-10.57	50.47	50.16	-118.98	156.55	11.12	-129.21	258.03	-118.81
2000	32.44	6.27	-19.61	20.54	-39.48	-73.14	-60.87	73.49	49.60	62.52	36.32	-130.81	244.72	-121.05	262.53

Inference-1: It can be inferred that DCF with CCW (cw=400) mostly underperform with packets less than 1.2KB. Otherwise it works better than BEB most of the network configurations.
Inference-2: It can be inferred that DCF with CCW (cw=400) mostly works better with lesser dense networks.

Table 9 - Differential throughput (PB_PAPER_2, BEB)

$TH_{PB\_PAPER\_2}$ - TH_{BEB}															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	5.15	8.74	5.85	48.03	25.78	17.44	18.41	-79.13	131.58	-73.10	-72.46	-32.57	-175.87	-77.20	7.83
600	-0.43	-8.33	-9.37	23.35	-15.05	28.18	51.42	-27.70	22.49	-67.97	-71.70	-45.71	5.84	-169.71	-37.35
800	-21.84	4.99	1.93	-50.58	-39.70	52.08	-7.12	67.95	-18.67	-151.74	-51.56	47.08	-156.04	95.70	117.55
1000	0.53	-2.16	-4.18	31.30	-86.32	-35.50	113.41	16.81	72.07	-62.58	68.70	87.82	98.53	99.31	94.07
1200	-1.27	11.04	-0.60	9.81	20.40	23.43	-85.91	-101.41	3.67	118.16	105.46	-17.47	-432.38	-108.66	-29.81
1400	46.53	1.27	9.29	5.44	-93.56	0.83	211.40	16.86	-27.30	91.28	-141.39	-196.96	-103.04	52.62	-114.93
1500	13.29	-4.85	8.91	37.70	21.29	9.23	6.21	35.33	-30.64	-51.74	189.76	-52.32	-24.51	157.03	-278.52
1600	26.15	-7.43	2.85	17.39	51.08	-82.87	-68.83	-8.39	38.38	-73.09	62.62	-107.01	62.50	101.78	137.15
1800	-44.48	6.05	-3.77	-96.72	-54.41	58.08	-59.32	-35.48	102.65	-159.47	199.10	-130.45	-127.78	154.18	-229.68
2000	-1.33	8.87	-5.16	33.56	-46.42	-33.04	-60.44	37.82	42.49	23.03	140.42	78.50	198.30	-218.59	111.18

Inference-1: It can be inferred that Polynomial backoff (PB) works well when compared to BEB, Irrespective of number of interfaces, node density, packet sizes.
Inference-2: It can be inferred that with 3 radio interfaces (3x3_3, 4x4_3, 5x5_3, 6x6_3. 7x7_3), PB works better than BEB.

Table 10 - Differential throughput (EBO, BEB)

THEBO - THBEB															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	11.03	30.26	7.08	-96.40	8.40	-10.30	-281.37	-60.96	42.54	-514.13	-17.69	-208.49	-630.07	-272.59	-263.31
600	-1.41	-31.22	-32.57	-51.46	-16.66	20.47	-181.10	-26.88	-18.19	-403.21	-103.53	-128.85	-709.32	-378.73	-281.96
800	-13.72	11.83	3.83	1.35	-78.16	-7.79	-161.16	107.11	1.82	-291.20	-163.00	-90.96	-310.10	-34.09	-45.54
1000	2.34	1.41	-20.14	4.10	-11.77	-31.60	-35.51	71.81	-46.04	-227.11	-5.27	-41.32	-365.09	-193.49	-250.05
1200	-2.75	9.10	-18.08	-43.89	63.60	8.28	-82.78	-102.71	-47.64	-108.52	99.75	1.66	-474.30	-190.01	240.29
1400	1.16	9.41	2.48	-8.89	-52.15	-17.94	18.72	-48.48	-56.89	-10.20	-104.00	-107.44	-167.86	-167.16	-127.14
1500	14.26	-10.85	1.40	18.23	-92.86	26.70	8.92	56.63	-75.76	28.31	27.06	-10.03	-195.44	102.10	-53.48
1600	16.93	11.72	11.61	10.77	-29.89	5.30	-60.64	-48.02	-95.82	-181.24	-1.67	-159.00	-192.15	8.17	-95.35
1800	-29.68	2.73	5.73	-100.40	80.26	67.57	-119.12	41.52	93.13	-231.84	155.88	-107.47	-172.75	-20.00	19.47
2000	12.02	4.67	-6.48	29.20	-150.26	-8.27	-131.73	85.00	17.18	-38.76	28.49	-107.88	-1.33	15.57	339.56

Inference-1: It is observed that EBO works well with small network sizes irrespective of number of interfaces supported by the Mesh router (Refer Columns –

Table 10 , 3x3_1, 4x4_1, 3x3_2, 4x4_2, 3x3_3, 4x4_3)
Inference-2: With larger network sizes irrespective of number of interfaces supported by the Mesh router the performance is not better than BEB (Refer Columns –

Table 10 , 5x5_q, 6x6_q, 7x7_q, where q=1, 2, 3)

Table 11 - Differential throughput (HBO, BEB)

THHBO - THBEB															
SIZE	3x3_1	3x3_2	3x3_3	4x4_1	4x4_2	4x4_3	5x5_1	5x5_2	5x5_3	6x6_1	6x6_2	6x6_3	7x7_1	7x7_2	7x7_3
400	10.22	-2.59	16.43	46.29	62.34	-27.51	-6.92	-82.10	48.05	93.03	-37.16	87.07	-131.90	-15.73	12.44
600	7.49	-12.18	-11.74	-38.12	-41.82	-3.94	74.31	-39.29	-47.24	-20.70	-60.05	-105.37	-74.66	-134.91	-142.67
800	-10.01	-5.02	-5.80	-20.72	-26.45	6.99	-24.99	31.23	69.34	-46.06	-42.65	-88.71	-184.94	51.76	302.60
1000	-4.51	8.78	-4.91	5.71	-117.92	-65.48	100.30	0.50	-58.15	11.60	29.63	87.80	18.28	-14.18	-40.04
1200	0.29	19.16	1.59	0.18	160.08	-48.90	11.10	-58.28	-87.18	13.38	96.46	25.67	-207.87	-163.26	0.17
1400	-1.69	-4.25	2.57	2.51	-45.61	-17.42	67.14	-71.40	-2.07	51.96	-115.36	-264.72	92.90	231.45	-28.39
1500	9.13	4.60	0.57	75.92	-9.97	-21.89	-62.06	43.23	60.04	-142.90	-39.44	-38.19	72.11	11.83	-148.93
1600	15.56	-12.52	11.10	57.04	58.30	-33.33	36.09	-71.88	-5.37	-218.02	50.59	-98.66	65.33	254.60	-123.16
1800	-32.73	2.84	5.82	-69.59	6.16	-4.99	-77.81	15.73	6.10	-89.60	142.82	-6.15	-179.85	1.56	-297.42
2000	1.40	2.35	0.26	2.96	-22.82	-84.54	-122.91	35.00	-32.58	176.32	-145.15	17.43	251.59	-240.97	-50.06

Inference-1: It is observed that HBO works well with majority of the scenarios but consistency is not guaranteed.
Inference-2: It is observed that HBO with THREE interfaces does not guarantee throughput enhancement (Refer Columns – Table 11, ZxZ_3, where Z=4, 6, 7).

Overall inference:

1. It is inferred that BEB algorithm may not be the best choice for mesh routers in WMNs.
2. It is inferred that the WMNs shall be operated with packet sizes in between 1KB and 2KB to achieve better throughput performance.
3. Considering Columns (3x3_3, 4x4_3, 5x5_3, 6x6_3, 7x7_3) from Table 2 - Table 11, it can be inferred that PB is the best choice to obtain higher throughput.
4. For a given router, MAC protocol implementation cannot be changed at run time depending upon the node density. Thus a MAC protocol which works well with almost all the network configurations shall be selected for a given Mesh router implementation. Among various MAC protocols considered in this work, polynomial backoff (PB) algorithm appears to be a better choice for WMN installations. [24]

VI. CONCLUSION

In this paper, we have presented the NS3 simulation results with BEB and its enhanced variant of CA algorithms *(EIED, EILD, MILD, PB, CCW, EBO, HBA…)* to evaluate their suitability for WMNs.

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The performance has been compared and contrasted in terms of packet size, grid size, number of radio interfaces. It is observed that polynomial backoff (PB) algorithm appears to be a better choice for WMNs instead of de-facto MAC CA algorithm (BEB) with few limitations.

Next alternate choices for WMN performance enhancement are EBO, HBO, EIED, and/or DIDD algorithms. Also enabling TWO radios on each of the mesh router helps to achieve better throughput performance.
Thus in future we plan to enhance polynomial backoff algorithm or combination of these algorithms to support higher throughput for WMNs.

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