SPB: Scalable Polynomial Backoff Algorithm For IEEE 802.11s Networks

A.B Nataraju, S.A Hariprasad

Abstract : Wireless Mesh Network (WMN) [1] is a popular choice in setting up cost-efficient alternative to provide broadband internet services to a larger geography. The performance of WMN is greatly impacted by the collision due to simultaneous transmissions by many users at the same time. This problem has been addressed by MAC layer using BEB [2] collision avoidance (CA) algorithm. There are many CA algorithms (EIED, EILD, MILD, PB, ISBA, EBO, HBA, etc.,) published in the recent past to reduce the collisions. These algorithms works better than BEB in specific network configurations (such as higher node density, delay sensitive data transmission …), otherwise they underperform when compared to BEB. This work proposes Scalable Polynomial Backoff (SPB) algorithm using fast decrease mechanism (after successful transmission) to support better throughput under varied node densities (grid sizes), and varied number of radio interfaces (1/2/3). The new algorithm has been tested for its performance using NS3 simulator [3]. The results show the SPB algorithm performs better than BEB in about 93% of network configurations against BEB and better than PB[4] algorithm in about 73% of network configurations (with application packet Size set to 1500 bytes).

Keywords : WMN, BEB, MAC, HWMP, MRMC, CA

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1. INTRODUCTION

WMNs have been projected as the most preferred alternative for next-generation wireless networks with cost effective last-mile connectivity. They essentially make use of multi-hop communication to support wireless services over a large geographical 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, 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 through inter network. 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 IEEE 802.11 (WLAN) family of products. Most of the traffic carried on a typical WLAN is made up of non-real-time applications such as web browsing, email etc; WMN [5] is advancement over WLAN, which can provide wireless connectivity over a relatively large geography. In our previous work [6] , it was found that multiple radios in mesh routers provide better throughput performance. Still WMNs are undergoing rapid progress 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(SR) BO schemes. The following section discusses different works on CA algorithms for WLAN and WMN.

2. RELATED WORK

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 significantly. 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. Substantial research has gone into evaluating the performance of WMNs [5] with different network densities (grid sizes). In [7], 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). Nataraju A.B. et.al, [8] observed that the network performance can be enhanced if the medium access protocol based its operation on network node density. Xinghua Sun et.al, [9] 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 2nd order polynomial backoff support better throughput compared to exponential backoff schemes. Sakurai et.al, [10] 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, [11] 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, [12] 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. Suzhi et.al, [4] 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 reasonablyBalador et.al, [13] 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. In [14], 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. In our previous work [15], it is observed that Polynomial backoff (PB) is relatively better candidate for modification to support better WMN performance. This work tries enhancing PB to support higher throughput for WMNs. The following section tries explaining the test setup used for performance evaluation of SPB against BEB and PB algorithms.

3. PROBLEM FORMULATION, ALGORITHM & 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. The CA algorithms in consideration are BEB, PB, and proposed algorithm (SPB).

The algorithm for SPB is as follows:

Algorithm – 1: Scalable Polynomial Backoff (SPB) Algorithm

```
Initialization of Parameters used:
$\sigma = 2$;  $boStage = 0$; $CW_{min} = 31$, $CW_{max} = 1023$; $W_0 = CW_{min}$;
$CW_{boStage} = W_0$; slotTime =72µs
Backoff procedure after each collision:
    $boStage$ ++ ;
    $CW_{boStage} = (1+\sigma)^{boStage} * W_0$ ;
    $CW_{boStage} = \min(CW_{boStage}, CW_{MAX})$
    BackoffTimer ← Random(0, $CW_{boStage}$ ) * slotTime;
    SEND THE PACKET out after the BackoffTimer times out

Backoff procedure after each successful data transmission:
    $if\ (boStage > 0)$
        $boStage = boStage / 3$; // Reduce the back off stages by a factor for THREE
    else
        $boStage = 0$;

    $CW_{boStage} = (1+\sigma)^{boStage} * W_0$
    $CW_{boStage} = \max(CW_{boStage}, CW_{MIN})$
    BackoffTimer ← Random(0, $CW_{boStage}$ ) * slotTime;
    SEND THE PACKET out after the BackoffTimer times out
```

The methodology to obtain the test results is as follows:

Algorithm – 2 : Methodology for performance evaluation [15]

```
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:
Repeat for all packetSize // realized by m_packetSize
  Repeat for all  nInternfaces, // realized by m_nIfaces
    Repeat for all gridSize, // realized by m_xSize & m_ySize
      Repeat NS-3 simulation with different RngRun
        Run the NS-3 simulation with specific gridSize, packetSize interfaces, and Random Seed number(RngRun)
          ./waf --command-template="%s --m_xSize=4
          --m_ySize=4 --m_packetSize=1400
          --m_nIfaces=2 --m_step=170 --RngRun=22"
          --run scratch/HwmpGrid
          → This statement simulate 4x4 grid, nInterfaces = 2, PacketSize = 1400;
          Save the results; // → result-1, 2, 3,….20
      End - Repeat NS-3 simulation
      Find the median of these 20 iterations and tabulate for analysis/characterization.
    End - Repeat for all gridSize
```

12: End - Repeat for all nInternfaces
13: End - Repeat for all packetSize
14: Repeat the above steps 1-13 for different MAC CA algorithms viz., BEB, PB, and SPB.
15: Compare the Throughput from BEB with other algorithms. The differential values are tabulated in Table 7, Table 8, and Table 9.

For instance, Table 7: indicates difference in Throughput from PB and BEB algorithms → TH_{PB} - TH_{BEB}
Similarly, Table 8 : indicates difference in Throughput from SPB and BEB algorithms → TH_{SPB} - TH_{BEB}.
The following section discusses the experimental results obtained using the methodology mentioned above and inferences are drawn accordingly.

4. 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 [6][15]*

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, PB
Channels used in MR setup	1, 6, 11

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) PB – Polynomial Backoff (PB_PAPER_2) [4]
$\beta = 2$;
$$boStage = \begin{Bmatrix} boStage = 0; & on\ success \\ boStage++; & on\ collision \end{Bmatrix}$$
$CW_{boStage} = (1+\beta)^{boStage} * W_0$
Backoff range $\{0, CW_{boStage}\}$
Backoff Timer ← Random(0, $CW_{boStage}$) * slotTime;
Send the packet after BackoffTimer Expires.

2) BEB – Binary Exponential Backoff [2]
$$CW = \begin{Bmatrix} \min(2 * CW, CWmax) & on\ collision \\ CWmin & on\ success \end{Bmatrix}$$
Backoff range $\{0, CW\}$
Backoff Timer ← Random (0,CW) * slotTime;
Send the packet after BackoffTimer Expires.

3) SPB – Scalable Polynomial Backoff
$\beta = 2$;
$$boStage = \begin{Bmatrix} boStage /= 3; & on\ success \\ boStage++; & on\ collision \end{Bmatrix}$$
$CW_{boStage} = (1+\beta)^{boStage} * W_0$
Backoff range $\{0, CW_{boStage}\}$
Backoff Timer ← Random (0, $CW_{boStage}$) * slotTime;
Send the packet after BackoffTimer Expires.

II. RESULTS ANALYSIS & DISCUSSION

In this section, we present the results obtained using NS-3 simulator and inferences are drawn accordingly.

Note for decoding
Table *2* - Table 9.
4x4_1 ➔ grid size = 4x4, number of Interfaces = 1
6x6_2 ➔ grid size = 6x6, number of Interfaces = 2 …
SIZE ➔ Packet SIZE
Each cell value indicates Throughput with row indicating packet size and column indicating node density, and No. of interfaces enabled with mesh router

Table *2* - Table 5, list out the throughput (in kbps) with BEB, PB, and SPB algorithms.

***Table 2** – Throughput (kbps) - (BEB)*

Algorithm – 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	1161.35	1162.04	1165.74	2118.20	2183.42	2301.53	3239.60	3569.59	3422.76	4427.78	4921.48	4984.18	5810.75	6525.98	6896.29
600	1213.93	1216.29	1215.79	2222.04	2288.43	2362.13	3435.84	3662.47	3629.67	4826.96	5336.07	5253.05	6415.49	7121.34	7254.07
800	1246.97	1228.06	1226.36	2302.80	2337.31	2423.46	3674.58	3730.73	3686.08	5047.28	5459.10	5386.31	6715.52	7222.58	7365.16
1000	1245.96	1240.01	1250.65	2306.77	2437.24	2521.21	3619.89	3824.90	3827.13	5175.59	5532.75	5481.64	6854.76	7502.61	7697.23
1200	1258.88	1240.99	1252.28	2366.10	2343.60	2495.34	3857.69	4009.10	3920.76	5260.96	5604.71	5703.20	7233.34	7695.77	7847.47
1400	1268.42	1260.42	1263.26	2381.33	2485.36	2544.74	3755.57	4009.13	3961.10	5351.90	5863.01	5981.69	7230.72	7753.16	8104.65
1500	1266.61	1267.04	1261.69	2381.69	2493.78	2544.66	3896.76	3964.42	3944.26	5517.97	5753.46	5954.98	7405.08	7778.23	8313.34
1600	1266.85	1274.16	1265.45	2413.06	2413.45	2575.83	3887.91	4076.20	4041.46	5550.02	5901.56	6002.81	7424.27	7796.40	8268.23
1800	1327.10	1283.60	1284.45	2517.68	2507.10	2530.84	3978.27	4051.82	3950.72	5680.89	5773.33	6073.41	7633.75	7956.68	8557.23
2000	1309.66	1289.66	1299.35	2449.70	2586.00	2650.30	4067.98	4105.54	4053.70	5624.28	5993.13	6153.78	7526.26	8259.65	8379.65

The Table *2*, list out the throughput (kbps) by WMN with Binary Exponential Backoff (BEB) CA algorithm

***Table 3 –** Throughput (kbps) - (PB_PAPER_2)*

Algorithm – PB (PB_PAPER_2)															
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	1166.49	1170.79	1171.59	2166.23	2209.19	2318.97	3258.01	3490.46	3554.33	4354.68	4849.01	4951.61	5634.88	6448.78	6904.13
600	1213.50	1207.97	1206.42	2245.39	2273.38	2390.31	3487.26	3634.77	3652.16	4758.99	5264.37	5207.34	6421.33	6951.63	7216.72
800	1225.13	1233.05	1228.29	2252.21	2297.61	2475.54	3667.47	3798.69	3667.41	4895.54	5407.54	5433.39	6559.48	7318.28	7482.71
1000	1246.48	1237.85	1246.46	2338.07	2350.93	2485.71	3733.29	3841.71	3899.20	5113.01	5601.45	5569.46	6953.29	7601.92	7791.30
1200	1257.60	1252.03	1251.67	2375.91	2364.00	2518.77	3771.78	3907.69	3924.43	5379.11	5710.16	5685.73	6800.97	7587.11	7817.66
1400	1314.95	1261.69	1272.55	2386.77	2391.80	2545.57	3966.97	4025.98	3933.80	5443.18	5721.62	5784.73	7127.68	7805.78	7989.72
1500	1279.90	1262.18	1270.60	2419.39	2515.07	2553.89	3902.97	3999.74	3913.63	5466.23	5943.22	5902.66	7380.57	7935.26	8034.82
1600	1293.00	1266.73	1268.30	2430.45	2464.53	2492.96	3819.08	4067.80	4079.84	5476.93	5964.18	5895.80	7486.77	7898.18	8405.39
1800	1282.62	1289.65	1280.68	2420.96	2452.69	2588.93	3918.95	4016.34	4053.37	5521.42	5972.43	5942.96	7505.97	8110.86	8327.55
2000	1308.33	1298.53	1294.18	2483.26	2539.58	2617.26	4007.54	4143.36	4096.19	5647.31	6133.55	6232.28	7724.57	8041.06	8490.83

The Table 3, list out the throughput (kbps) by WMN with polynomial backoff (PB) CA algorithm

***Table 4** - Throughput (kbps) - (SPB)*

Algorithm – SPB (PB_PAPER_2_BY3)															
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	1168.63	1163.65	1164.05	2100.77	2217.60	2333.60	3273.25	3498.90	3517.99	4318.46	4919.14	4931.05	5676.38	6487.42	7013.64
600	1207.07	1212.51	1202.79	2222.48	2277.02	2395.98	3489.58	3648.85	3606.36	4719.21	5270.51	5277.81	6083.47	6965.66	7473.21
800	1240.16	1240.52	1231.69	2349.86	2369.71	2409.51	3663.14	3809.56	3682.48	4992.12	5376.13	5353.07	6584.43	7193.44	7457.01
1000	1247.92	1243.20	1241.82	2283.72	2403.06	2465.78	3681.20	3805.95	3836.50	5117.14	5622.58	5434.27	6744.45	7447.86	7688.52
1200	1260.23	1236.98	1252.19	2372.73	2466.08	2543.78	3828.69	3889.60	3908.08	5278.08	5643.92	5809.72	7012.27	7628.63	7994.73
1400	1263.79	1253.59	1269.66	2408.53	2443.06	2571.80	3836.24	3929.31	3995.47	5530.45	5955.43	5715.87	7437.58	7801.82	8064.76
1500	1280.15	1277.55	1279.98	2406.38	2522.65	2555.82	3979.49	3999.63	4028.62	5511.34	5763.76	5955.13	7469.24	7833.74	8365.07
1600	1286.37	1270.62	1277.42	2447.98	2520.77	2541.60	3907.47	3976.19	3993.09	5484.71	5854.04	5910.47	7364.69	8100.19	8352.54
1800	1297.73	1274.14	1287.22	2493.98	2527.32	2583.03	3920.46	4090.69	4049.58	5529.55	6014.68	6023.19	7526.05	8017.21	8399.88
2000	1300.84	1295.35	1296.39	2465.13	2559.78	2694.20	3989.91	4048.32	4039.56	5752.17	6043.01	6250.81	7712.20	8316.15	8682.84

The Table 4, list out the throughput (kbps) by WMN with scalable polynomial backoff (SPB) CA algorithm

***Table 5 –** Throughput (kbps) - BEB, PB and SPB with packetSize – 1500 bytes*

Algorithm – BEB, PB, SPB (Refer Table 2 , Table 3, Table 4)															
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
BEB	1266.61	1267.04	1261.69	2381.69	2493.78	2544.66	3896.76	3964.42	3944.26	5517.97	5753.46	5954.98	7405.08	7778.23	8313.34
PB	1279.90	1262.18	1270.60	2419.39	2515.07	2553.89	3902.97	3999.74	3913.63	5466.23	5943.22	5902.66	7380.57	7935.26	8034.82
SPB	1280.15	1277.55	1279.98	2406.38	2522.65	2555.82	3979.49	3999.63	4028.62	5511.34	5763.76	5955.13	7469.24	7833.74	8365.07

***Note:** The Table 5, (Row-1500 extracted from Table 2, Table 3, Table 4) plots the throughput with BEB, PB, SPB algorithms with different grid size (3x3, 4x4, 5x5, 6x6, 7x7), number of interfaces (1/2/3), and application packetSize = 1500 bytes.*

Inference-1: (refer Table 5) SPB consistently perform better than BEB (row-1, androw-3) in 14/15 (93%) cases
Inference-1: SPB perform better than PB (row-2, androw-3) in 11/15 (73%) cases

***Table 6 -** Differential throughput (kbps) - BEB, PB and SPB with packetSize – 1500 bytes*

$TH_{PB(PB\_\_PAPER\_2)}$ - TH_{BEB} (Refer Table 5)															
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
TH_{PB} - TH_{BEB}	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
TH_{SPB} - TH_{BEB}	13.53	10.51	18.29	24.69	28.86	11.16	82.73	35.21	84.36	-6.63	10.30	0.15	64.16	55.51	51.73
TH_{SPB} - TH_{PB}	0.24	15.36	9.39	-13.01	7.57	1.93	76.52	-0.12	114.99	45.10	-179.46	52.47	88.66	-101.52	330.25

Inference-1: (refer Table 6) in 09/15 (60%) network configurations PB performs better than BEB (Refer row-1, PB, BEB). Also PB performs better than BEB when enabled with TWO radios. Also perform enhancement is not guaranteed with ONE / THREE radio interfaces (few negative values).

Inference-2: In 11/15 (73%) network configurations SPB performs better than PB (Refer row-3, SPB, PB)

Inference-3: In 14/15(93%) network configurations SPB performs better than BEB (Refer row-2, SPB, BEB). This indicates SPB is a better choice to replace BEB with better throughput than BEB irrespective of number of radio interfaces (1/2/3) enabled with the mesh router. Thus SPB is a better scalable algorithm than PB to replace BEB algorithm in WMN setup.

Inference-4: On an average 1% throughput enhancement by SPB against BEB (Refer row-2, SPB, BEB)

The following tables Table 7, Table 8, Table 9, list out the differential throughput between (PB, BEB), (SPB, BEB), (SPB, PB) respectively. A cell in these tables with green/gray shade indicates BEB underperform when compared to other CA algorithm.

For instance, when TH $_{(PB\ 3x3\_i1)}$ > TH $_{(BEB\ 3x3\_i1)}$ leads to positive value (gray shaded cell).

***Table 7** - Differential throughput (PB_PAPER_2, BEB)*

$TH_{PB(PB\_\_PAPER\_2)}$ - TH_{BEB} (Refer Table 2, Table 3)															
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: (refer Table 7) 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 PB with 2 or 3 radio interfaces (refer columns -- AxA_q, where A=3, 4, 5, 6, 7 and q = 2, 3), works well than BEB. In, 54% network configurations, PB work better than BEB.

Inference-3: It can also be inferred that PB works better than BEB when TWO / THREE radio interfaces are enabled on mesh routers. Relatively MR with TWO radios provides better results (consistently) than ONE / THREE radios.

Inference-4: In (09/15) 60% of network configurations, PB perform better than BEB (packet size = 1500 bytes)

Table 8 *- Differential throughput (SPB, BEB)*

TH_{SPB} - TH_{BEB} (Refer Table 2, Table 4)															
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	7.28	1.60	-1.69	-17.44	34.18	32.07	33.65	-70.69	95.24	-109.32	-2.34	-53.13	-134.4	-38.56	117.35
600	-6.86	-3.78	-13.00	0.44	-11.41	33.85	53.75	-13.62	-23.31	-107.75	-65.56	24.75	-332.03	-155.68	219.14
800	-6.81	12.46	5.33	47.07	32.40	-13.95	-11.45	78.82	-3.60	-55.16	-82.97	-33.24	-131.09	-29.14	91.85
1000	1.97	3.20	-8.83	-23.05	-34.18	-55.43	61.31	-18.95	9.38	-58.45	89.83	-47.37	-110.31	-54.75	-8.71
1200	1.36	-4.01	-0.09	6.63	122.47	48.44	-29.00	-119.50	-12.68	17.12	39.21	106.53	-221.07	-67.14	147.26
1400	-4.63	-6.83	6.40	27.20	-42.30	27.06	80.67	-79.82	34.37	178.55	92.43	-265.82	206.86	48.66	-39.89
1500	13.53	10.51	18.29	24.69	28.86	11.16	82.73	35.21	84.36	-6.63	10.30	0.15	64.16	55.51	51.73
1600	19.52	-3.54	11.98	34.93	107.31	-34.23	19.57	-100.01	-48.37	-65.31	-47.51	-92.34	-59.58	303.79	84.31
1800	-29.36	-9.46	2.77	-23.70	20.22	52.18	-57.81	38.87	98.86	-151.34	241.35	-50.22	-107.70	60.53	-157.35
2000	-8.82	5.69	-2.96	15.43	-26.22	43.90	-78.07	-57.21	-14.14	127.89	49.89	97.03	185.94	56.50	303.20

Inference-1: (refer Table 8) in 93% of configurations, SPB perform better than BEB (packet size = 1500 bytes)

Inference-2: In about 56% cases SPB perform better than BEB with ONE/TWO/THREE radios enabled with mesh routers. SPB support more consistent enhanced performance when compared to PB. We can't observe this consistency with PB algorithm.

Table 9 *- Differential Throughput (SPB, PB)*

TH_{SPB} - TH_{PB}(PB_PAPER_2) (Refer Table 4, Table 3)															
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	2.14	-7.14	-7.54	-65.46	8.41	14.63	15.24	8.43	-36.34	-36.22	70.13	-20.56	41.5	38.64	109.51
600	-6.43	4.55	-3.62	-22.91	3.64	5.67	2.33	14.08	-45.80	-39.77	6.14	70.47	-337.86	14.03	256.49
800	15.03	7.47	3.40	97.65	72.10	-66.03	-4.33	10.87	15.07	96.58	-31.41	-80.32	24.95	-124.83	-25.70
1000	1.44	5.35	-4.65	-54.35	52.13	-19.93	-52.09	-35.76	-62.70	4.13	21.13	-135.19	-208.84	-154.06	-102.78
1200	2.63	-15.05	0.52	-3.18	102.08	25.01	56.91	-18.09	-16.35	-101.03	-66.24	123.99	211.31	41.52	177.07
1400	-51.16	-8.10	-2.89	21.76	51.26	26.24	-130.73	-96.68	61.67	87.26	233.81	-68.86	309.90	-3.96	75.03
1500	0.24	15.36	9.39	-13.01	7.57	1.93	76.52	-0.12	114.99	45.10	-179.46	52.47	88.66	-101.52	330.25
1600	-6.63	3.89	9.13	17.54	56.23	48.64	88.39	-91.62	-86.75	7.77	-110.14	14.67	-122.08	202.01	-52.85
1800	15.11	-15.51	6.54	73.02	74.63	-5.90	1.51	74.35	-3.79	8.13	42.25	80.23	20.07	-93.65	72.33
2000	-7.49	-3.18	2.21	-18.12	20.19	76.94	-17.62	-95.04	-56.63	104.86	-90.53	18.53	-12.37	275.09	192.02

Inference-1: (refer Table 9), in about 73% network configurations, SPB perform better than PB. SPB algorithm consistently outperforms PB under varied network configurations. In high density scenarios the 7x7_p (p=1/2/3) the throughput enhancement is more compared to low density scenarios.

Overall inference:

1. It is inferred that BEB algorithm may not be the best choice for mesh routers in WMNs. With varied network configurations, BEB does not seem to work well. Same is true with other algorithms as well.
2. It can be inferred that SPB perform better than BEB more consistently than PB. Thus SPB is suitable for working varied network configurations and hence suitable for scalable WMNs.
3. From the results we can infer that SPB does not put any restriction on number of radio interfaces enabled on each of the MRs to support higher throughput. Thus SPB is better scalable than PB / BEB algorithms.

CONCLUSION

In this work, we have proposed Scalable Polynomial Backoff (SPB) algorithm based on fast decrease mechanism to support higher throughput for WMNs. The SPB algorithm has been compared against PB and BEB algorithms using NS3 simulation results. The performance has been compared and contrasted in terms of packet size, grid size, number of radio interfaces. It is observed that SPB algorithm provide better throughput for WMNs when compared with PB and BEB algorithms. The SPB performance is consistent irrespective of the number of radio interfaces enabled on mesh routers. In about 93% of network configurations SPB perform better than BEB and in about 73% network configurations it performs better than PB (when packet size is set to 1500 bytes). In future we have plans to enhance SPB's performance for varied WMN setups.

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AUTHORS' PROFILE

Mr. Nataraju A.B, Research Scholar, Jain University, and Assistant Professor, Dept. of ECE, Acharya Institute of Technology, Bangalore, completed his M.E degree from UVCE, Bangalore. He has work experience of over 9 years in the Information Technology Industry (Huawei Technologies, Kodiak Networks, Sonus Networks…) and over 10 years in academia. +He is good with Computer Networking, VoIP, Internet Protocols, and Multimedia Communication. His research interest includes Wireless Networking, WMN performance enhancement, and wide-area networking using WMNs. He has published about 10+ Conference/Journal publications. He is a member of IEEE, IAENG, and CSI".

Dr. Hariprasad S.A, Director, School of Engineering and Technology, Jain University, Bangalore. He has work Experience of 25+ years (RVCE, BMSIT, DSU...) and guiding 8 research scholars. 3 PhD scholars have been awarded with Ph.D. He is an expert in the field of Microcontrollers, Field theory, embedded systems. His Research Areas include Micro Controller, embedded system design, Machine learning etc., He has published more than 95 international Journal/Conference publications, and has got research fund of 5 Lakhs.