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Analytical Analysis of IEEE 802.11 MAC

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Abstract*: The most important parameters of the IEEE 802.11 MAC protocol, which can help to improve its performance, are collision time, idle time, and number of collisions. In this paper we try to find the contention window size that will make the WLAN operate in the steady state. We find the optimal contention window (CW) only via mathematical equations. It is observed that by proper selection of the contention window size, the network performance can be improved as the network load increases.*

Keywords*:* Poisson distribution, Backoff Tuned channel access mechanism, collision time, idle time

1. Introduction

The operation of the IEEE 802.11 MAC protocol may be found in [10], [11] and, [12]. Here we briefly describe the protocol and its functioning. Wireless local area network operates in two modes; adhoc mode and infrastructure mode. While some unique features of the infrastructure mode of operation can be used to gain high performance in this mode, it may result in losing the generality of the access mechanism, whereas our algorithm can be applied to both infrastructure and adhoc modes of operation without losing the generality of the access mechanism. However, we focus on Adhoc mode of operation for experimental purposes. Basics of the wireless networks, physical layer (wireless channel) and MAC layer can be found in [15].

IEEE 802.11 MAC protocol has three commonly used access mechanisms namely Distributed Coordination Function (DCF also known as the basic access method), DCF with RTS-CTS (Request to send, clear to send) and Point Coordination Function (PCF built over DCF access method). Of all three methods, DCF access method is mandatory and is very widely used. Hence we will explain the protocol and our work with reference to this access method. We plot the results for DCF access methods.

In DCF access method all stations wait for a Differentiated InterFrame Space (DIFS) time interval, defined by the physical layer implementation, before actually contending for the channel. After a DIFS interval each station generates (slotted) backoff time. A station has to countdown the backoff time to zero before accessing the channel to send a packet. From the past work done in this field ([2] [5] [6] [8] [9]), it can be easily seen that this is one of the most important factor responsible for optimal or non-optimal performance of the IEEE 802.11 MAC protocol. This is a prime parameter, which can make a WLAN operate in the steady state [In steady state, the channel idle time is equal to the collision time]. Cali et al. ([3] and [7]) presents a method to control this parameter to achieve maximum protocol capacity.

We know that backoff time is uniformly taken from the contention window size. Hence our problem now becomes, finding the optimal contention window size.

Rest of the paper is organized as follows. Section 2 describes mathematical model for analysis and controlling the backoff window. Section 3 presents results and analysis, we provide our conclusion in section 4 followed by appendix.

2. Mathematical Model

The shared medium (wireless channel) transmits only one packet from a source to a destination during a successful transmission. When more than one packet is assigned to the wireless channel for transmission, collision occurs. Number of packets originating from a set of wireless devices can be inherently modeled as Poisson distribution. The length of the packets generated can also be modeled as Poisson distribution [16]. A packet may undergo multiple collisions before being successfully transmitted. The time interval between two consecutive successful packet transmissions is known as the virtual transmission time. Fig. 1 shows a typical virtual transmission time.

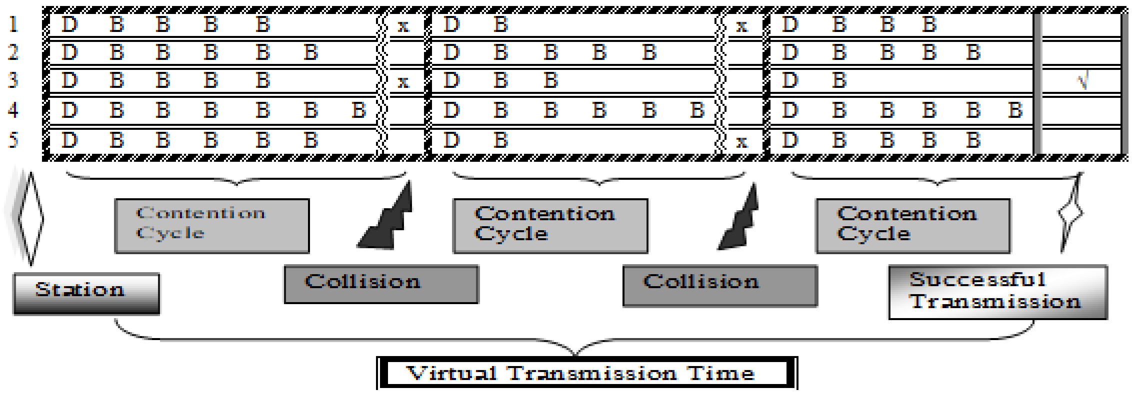

Figure 1: A typical virtual transmission time structure

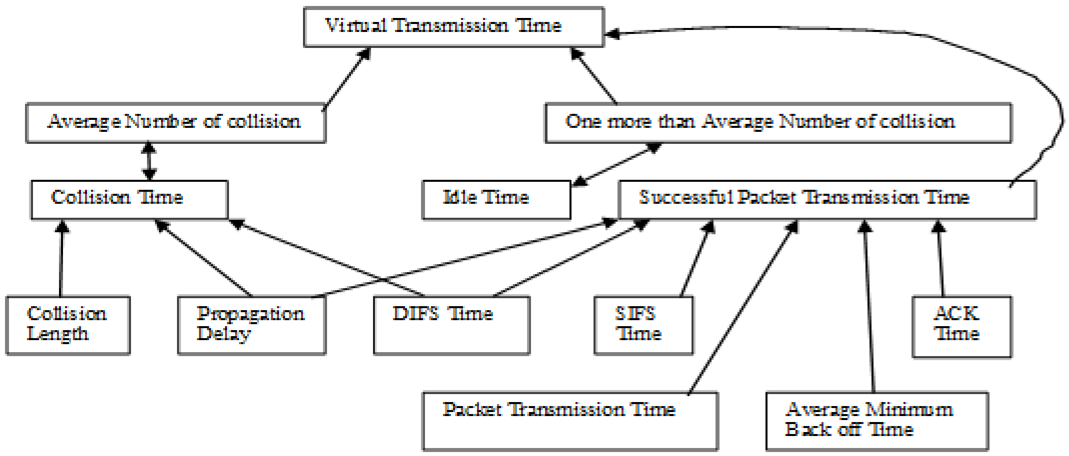

Fig. 2: Break up of virtual transmission time

The tree structure of fig. 2 will explain the breakup of virtual transmission time. A simple convention may be followed to interpret fig. 2. The two objects (text boxes) connected by an arrow with double head is to be multiplied. For an arrow with single head, the object present at the tail of the arrow is to be added into the object present at the head of the arrow. The tree will result in the virtual transmission time (in a different perception) to be the same as given by Cali et al. This leads us to the following formula for the virtual transmission time:

$$T_V = E[Nc](DIFS + \tau + COLL) + (E[Nc] + 1)(IdleTime) + E[S] \quad (1)$$

$$E[S] = DIFS + \overline{m} + SIFS + ACK + 2\tau + E[B1] \quad (2)$$

$$E[B_1] = (CW\min - 1)/2 \quad (3)$$

Here E [B_1] is the average backoff time for the single [By single station we mean only one station is contending and transmitting during that period] station [A station is a wireless device acting as a node in the network. It is also known as node, wireless station] case. For MAC and physical parameters used in our model, we consider the MAC card to be a Lucent Wavelan DSSS radio interface operating at 914 MHz [13]. Table I gives the parameters of the radio interface and its values. This is the basic WLAN configuration used by our model.

Since we model the packet transmission process as Poisson distributed, all wireless devices will take its backoff time from this distribution with parameter α, where $\alpha = 1/(E[B]+1)$ and E [B] is the average backoff time. The probability that k packets will be given to the wireless channel for transmission during a contention cycle is:

$$P(packets = k) = e^{-\alpha_m}(\alpha_m)^k / k! \quad (4)$$

Where $\alpha_m = M \times P_{T_c}$, M = Number of wireless devices and P_{T_c} = Probability of transmission in the current contention cycle. The probability of transmission in the current contention cycle depends on the backoff time. From the above assumption it follows that $\alpha = 2/(E[CW]+1)$

Table 1: WLAN configuration based on Lucent Wavelan DSSS radio interface at 914 Mhz

Parameter	Values	Parameter	Values
SIFS μsec	10	CWmin	16
DIFS μsec	50	CWmax	1023
ACK μsec	112	CSThreshold (dBm)	-74,-66
Backoff slot length μsec	20	RxThreshold (dBm)	-64,-66
Bit rate	1 Mbps	CS Range (meter)	550,250
Propagation delay μsec	2	Rx Range (meter)	550,250

2.1 Analytical estimation of average contention window size

We estimate the average contention window size with IEEE 802.11 MAC protocol as the reference protocol. For estimating the contention window size we focus on a tagged station.

We follow the iterative algorithm of Cali et al., for the estimation. To this effect, the probability of collision experienced by the tagged station is:

$$P_{coll} = 1 - (e^{-M\alpha} + M\alpha e^{-M\alpha}) \qquad (1)$$

We know that before successfully transmitting a packet, a station will undergo ‘h’ collisions. Thus, the probability of a station experiencing ‘h’ collisions is derived as follows:

$$P\left(N_{coll}^{i+1} = h\right) = e^{-\alpha_c} \alpha_c^{\,h} / h! \qquad (2)$$

Where α_c = (number of contention cycles for which packets will be contending to access the channel) x (probability of collision during each contention cycle)

To find α_c consider the scenario of table II. It is very obvious that, when channel is idle (i.e. no transmission is going on), collision cannot occur and hence its probability is zero. But if a packet is sent into the air, it may collide with another packet. The probability of this collision is $P_{collision}$. Hence $\alpha_c = P_{collision}$ As the packet will take (h+1) contention windows for a successful transmission, we have probability for ‘h’ collisions as:

$$P_{N_{coll}}(h) = e^{-P_{collision}} \left(P_{collision}^{\ \ h}\right) / h! \qquad (3)$$

Let E_h denote the set of contention windows used by the tagged station when it experiences ‘h’ collisions. From this, the average contention window size for the next iteration can be computed from the following expression.

$$P\left[CW = CW_j\right] = \begin{cases} (1-\alpha) & j = 0 \\ (1-\alpha)\left(1 - e^{-\alpha}\left(\sum_{k=0}^{j} \alpha^k / k!\right)\right) & j = 1,2,3,4,5 \end{cases} \qquad (4)$$

Table 2: Collision status of a tagged station during a virtual transmission time

Contention Cycle	Transmitted	Before Tx Collision	Contention Window used	After Tx Collision
1	Y	0	16	1
2	N	1	32	1
3	Y	1	64	2
……	……	……	……	……
c-1	Y	h-1	512 , h-1>5	h
c	Y	h	512 , h > 5	--

Table 3: Contention Window size values used by the protocol

J	0	1	2	3	4	5
CWj	16	32	64	128	256	512

Equation (8) is obtained as shown below:

$$p\left(CW^{(i+1)} = x\right) = \sum_{h=0}^{\infty} \left(P\left(CW^{(i+1)} = x \,\middle|\, CW^{(i+1)} \in E_h\right) \cdot P\left(CW^{(i+1)} \in E_h\right) \right) \qquad (5)$$

Where $P\left(CW^{(i+1)} = x \,\middle|\, CW^{(i+1)} \in E_h\right)$ is obtained by considering the backoff algorithm of the IEEE 802.11 MAC protocol and is given in table IV below. Following the lines of Cali et al. the probability for the contention window size can be given as:

$$P\left(CW^{(i+1)} = x\right) = \sum_{h=0}^{\infty} \left(P\left(CW^{(i+1)} = x \,\middle|\, CW^{(i+1)} \in E_h\right) \cdot \left(e^{-P_{collision}^{i+1}} \left(P_{collision}^{i+1}\right)^h / h! \right) \right)$$

Solving for individual contention window sizes, we get

$$P\left(CW = CW_0\right) = (1-\alpha)e^{-\alpha}\left[1 + \alpha + \alpha^2/2! + \cdots\infty\right]$$
$$= (1-\alpha)e^{-\alpha}e^{\alpha} = 1-\alpha$$
$$P\left(CW = CW_1\right) = (1-\alpha)e^{-\alpha}\left[\alpha + \alpha^2/2! + \cdots\infty\right]$$
$$= (1-\alpha)e^{-\alpha}\left(e^{\alpha} - 1\right)$$
$$= (1-\alpha)\left(1 - e^{-\alpha}\right)$$

Table 4: Probability of the contention window size (=x) belonging to the contention window set.

$P\left(CW^{(i+1)} = x \,\middle|\, CW^{(i+1)} \in E_h\right)$	E_h the contention window set					
	h=0	h=1	h=2	h=3	h=4	h=j-1,j≥6
x = 16	1	½	1/3	¼	1/5	1/j
x = 32	0	½	1/3	¼	1/5	1/j
x = 64	0	0	1/3	¼	1/5	1/j
x = 128	0	0	0	¼	1/5	1/j
x = 256	0	0	0	0	1/5	1/j
x = 512	0	0	0	0	0	1/j

Similarly, probability, for other contention window sizes can be found. This leads us to equation (8).

Next we find out the expressions for idle time, collision length and the number of collision. The expression for these parameters is given in (10) (11) (17) below. These expressions will help us find out the optimal contention window size (We have to find the optimal contention window size which will make the idle time equal to collision length and hence make WLAN to operate in steady state improving its performance over IEEE 802.11 MAC protocol). In what follows, we will be deriving various expressions that will lead us to estimating the contention window size.

To compute the average number of collision, average collision time and average idle time we consider an example scenario of table V. From the table it can be seen that, in a virtual transmission time, a contention cycle will either experience a collision or a successful transmission. Thus before a successful transmission the system will experience 'c' collision if there were (c+1) contention cycles in a virtual transmission time.

2.2 Expression for the average number of collision

If we denote by Pc the probability that a collision occurs conditioned to at least one transmission in the slot and with Ps the probability of a successful transmission, we get the distribution function for the number of collision in a virtual transmission time as:

$$p\left[N_c = i\right] = e^{-\alpha_{N_c}} \left(\alpha_{N_c}\right)^i \Big/ i! \quad ; where \quad \alpha_{N_c} = E\left[N_c\right]$$

Now consider a virtual transmission time which has (c+1) contention cycle with 'c' cycles experiencing collision and the last one is a successful transmission. Average number of collision is nothing but rate of collision into time over which the collision has been observed. Since we are finding the number of collision in a virtual transmission time, the time of observation will be 'c' contention cycles and the rate of collision is, the number of collision taking place for every successful transmission. Hence,

$$P\left(N = n \,\middle|\, rate\ of\ success = 1/Ps\right)$$

$$= e^{-Pc/Ps}\left(Pc/Ps\right)^n \Big/ n!$$

Where, the rate of success is 1 success for every 'n' collision.

$$Pc = P\left\{Transmitting\ Stations \geq 2 \,\middle|\, Transmitting\ Stations \geq 1\right\}$$

$$Ps = P\left\{Transmitting\ Stations = 1 \,\middle|\, Transmitting\ Stations \geq 1\right\}$$

From this we find the average number of collision experienced by the system as given by the following equation.

$$E\left[N_c\right] = \left(\left(1 - e^{-M\alpha}\right) \Big/ M\alpha e^{-M\alpha}\right) - 1 \tag{6}$$

2.3 Expression for the average idle time

Since a station can start transmission with probability α, we have:

$$P\left\{0\ Transmitting\ stations\ in\ a\ slot\right\} = e^{-M\alpha}$$

$$P\left\{atleast\ 1\ Transmitting\ stations\ in\ a\ slot\right\} = 1 - e^{-M\alpha}$$

Hence, the probability of 'x' continuous slots going idle given that the possibility of any slot going idle is P_0/P_1 is given as shown below.

$$P\left(idle\ slots = x \,\middle|\, any\ slot\ going\ idle = P_0/P_1\right) = e^{-P_0/P_1}\left(P_0/P_1\right)^x \Big/ x!$$

And the average idle time in a contention cycle is given by

$$E\left[Idle\right] = e^{-M\alpha} \Big/ 1 - e^{-M\alpha} \tag{7}$$

The total average time of the system for the complete run is given by

$$E\left[Idle\right] = \left(e^{-M\alpha} \Big/ 1 - e^{-M\alpha}\right) \cdot \left(E\left[N_c\right] + 1\right) \cdot T_{slot} \tag{8}$$

2.4 Average collision time expression

We need to find the average collision length, experienced by the system as a whole, taken over the complete observation time. To this effect we define the following set of random variables CL_1, CL_2 …CL_n to denote the collision length in the respective transmission period. The length is expressed in T_{slot} units.

$$Let\ CL = CL_1 + CL_2 + \cdots CL_n + \cdots \infty$$

The above series represents sum of non-negative independent identical random variables. Hence its conditional expectation is given by:

$$E\left[CL \,\middle|\, N = n\right] = \sum_{i=1}^{E[N_c]} E\left[CL_i\right] = nE\left[CL\right]$$

Using the theorem of total expectation we get,

$$E\left[CL\right] = \sum_n nE\left[CL\right] P_N(n) = E\left[CL\right] \sum_n nP_N(n) = E\left[CL\right] E\left[N_c\right]$$

The above expression gives the average collision length for the entire system observed over the time for which the algorithm will be run (In other words E[CL] is equal to, the average collision length in any virtual transmission time multiplied by the number of collisions in the system).

E [CL] is derived below.

$$E\left[CL\right] = T_{slot} \sum_{m=1}^{\infty} m \cdot \left[\sum_{n=2}^{M} P\left(Coll = m \,\middle|\, N_{cp} = n\right) \cdot P\left(N_{cp} = n \,\middle|\, N_{cp} > 1\right)\right] \tag{9}$$

$$P\left(N_{cp} = n \,\middle|\, N_{cp} > 1\right) = P\left(N_{cp} = n\ and\ N_{cp} > 1\right) \Big/ P\left(N_{cp} > 1\right)$$

$$P\left(N_{cp} = n \,\middle|\, N_{cp} > 1\right) = \left(e^{-M\alpha}\left(M\alpha\right)^n \Big/ n!\right) \cdot \left(1 \Big/ 1 - \left(e^{-M\alpha} + M\alpha e^{-M\alpha}\right)\right) \quad for\ n = 2, 3, \cdots \tag{10}$$

And,

$$P\left(Coll = m \,\middle|\, N_{cp} = n\right) = \frac{P\left(\left\{\max\left(PL1, PL2 \cdots PLn\right) = m\right\} and\ N_{cp} = n\right)}{P\left(N_{cp} = n\right)}$$

Since the two events (Coll=m) and (N_{cp} = n) are independent we have,

$$P\left(coll = m \mid N_{cp} = n\right) = P\left(\max\left\{PL_1, PL_2, \cdots PL_n\right\} = m\right)$$
$$= P\left(PL_1 \le m, PL_2 \le m, \cdots PL_n \le m\right)$$
$$- P\left(PL_1 \le m-1, PL_2 \le m, \cdots PL_n \le m\right)$$

Since the packet lengths are independent identical non-negative Poisson distributed we have,

$$P\left(coll = m \mid N_{cp} = n\right) = \left[PL(m)\right]^n - \left[PL(m-1)\right]^n$$

Solving the above equation and substituting the results in (13) above we get the expression for the average collision length as given in (15) below.

$$E\left[coll\right] = \sum_{h=0}^{\infty} h \cdot \left(\sum_{m=1}^{\infty} \left(m \cdot \sum_{n=2}^{M} \frac{e^{-M\alpha}\left(M\alpha\right)^n \left(e^{-m}\left(e-1\right)\left(P_{coll_{mn}}\right)\right)}{n!\left(1-\left(e^{-M\alpha}+M\alpha e^{-M\alpha}\right)\right)} \right) \right) \quad (11)$$

Where $P_{coll_{mn}} = \sum_{x=0}^{n} \left(1-e^{-m}\right)^{n-1-x} \left(1-e^{-(n-1)}\right)^x$

It can be easily seen that the average collision length computation is very complex and cannot be used at run time.

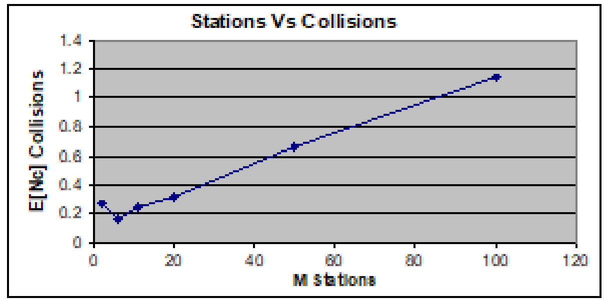

Figure 3: Average Number of collisions when IEEE 802.11 channel access is optimized

However, our assumption that the WLAN works best in steady state will simplify the equation. The steady state condition for WLAN channel utilization is given by (16).

Table 5: The following table gives an example scenario for the computation of average number of collision, average collision time and average idle time.

Contention cycle number	Stations Transmitting							Number of collision experienced by the station						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
1	N	Y	Y	N	Y	N	N	0	1	1	0	1	0	0
2	N	N	N	Y	Y	Y	N	0	1	1	1	2	1	0
3	Y	N	Y	N	N	N	Y	1	1	2	1	2	1	1
4	Y	N	Y	N	N	N	N	2	1	3	1	2	1	1
5	Y	Y	N	N	N	N	N	3	2	3	1	2	1	1
6	Y	N	N	N	Y	N	N	4	2	3	1	3	1	1
7	N	N	N	N	Y	Y	N	4	2	3	1	4	2	1
8	N	N	N	N	Y	N	Y	4	2	3	1	5	2	2
9	N	N	Y	Y	N	N	N	4	2	4	2	5	2	2
10	Y	N	N	Y	N	N	N	5	2	4	3	5	2	2
11 (Success)	Y	N	N	N	N	N	N	5	2	4	3	5	2	2

$$E\left[coll\right] \cdot E\left[N_c\right] = \left(E\left[coll\right]+1\right) \cdot E\left[Idle\right] \quad (12)$$

This leads us to the following expression for average collision length.

$$E\left[coll\right] = e^{-M\alpha} \Big/ \left(1-e^{-M\alpha}\right) \quad (13)$$

We find the theoretical capacity of the protocol that can be attained, by the proper selection of the contention window size, as follows.

$$\rho_{\max} = PS_{avg} \Big/ T_v \quad (14)$$

Where $PS_{avg} = T_{slot} / \lambda$, λ being the parameter of Poisson distribution for packet size and Tslot is the length of the slot in time units. T_v is given by (1).

3. Results and Analysis

We tabulate the results for average idle time, average collision length, average number of collision, average contention window size, average estimated α parameter, and average packet length.

Table VI (given in appendix B) gives the optimal values for the IEEE 802.11 MAC protocol. From table VI it can be seen that to reach the maximum protocol capacity the contention window size should be set as per the table. Also, we can see that it is not possible to reach the maximum protocol capacity of 1. This point can also be explained very obviously by considering the nature of MAC operation in the WLAN.

We also see that when the contention window size is selected based on table VI; we get the steady state condition of WLAN operation. If we compare the values of average idle time (E [Idle]) and average collision time (E [Coll]), we see the values to be almost same for a large network. Also the average virtual transmission time is very close to the successful transmission time for networks of all size. This strongly justifies the need for optimal selection of contention window, although the IEEE 802.11 MAC protocol performs well for networks containing less than 20 nodes.

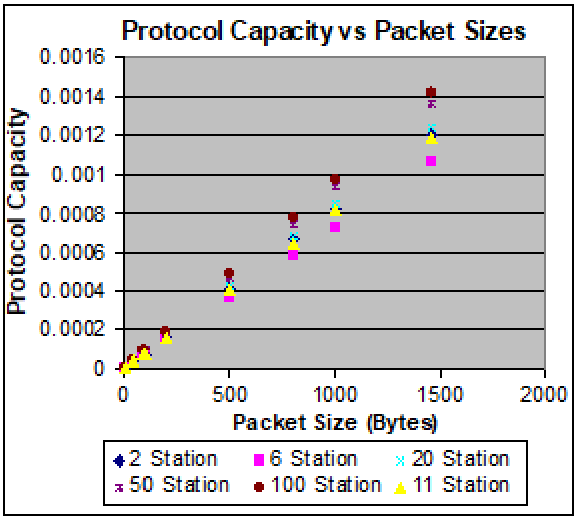

Figure 4: Capacity analysis of IEEE 802.11 channel access when the protocol is optimized by the mathematical model above

Fig. 3 clearly shows that the number of collision can be brought down to less than 2 if the contention window is selected properly. Finally fig. 4 gives the capacity that the standard protocol can reach on optimal selection of contention window. Fig. 4 shows the capacity against various packet sizes for different network configuration (i.e. for different M values).

From the graph of fig. 3 it is seen that as the number of stations increases, the number of collisions in the system also increases. This is quite obvious as more packets will be waiting for its turn to be delivered by the wireless channel to its destination.

Fig. 4, shows that the protocol capacity increases when the number of nodes packet size increases. This is quite obvious and can be deduced directly. However, if we observer carefully, the protocol capacity also increases when the number of nodes in the system increases. This is very difficult to grasp as, when the number of nodes increases, the number of collision should also increase and hence protocol capacity should decrease. If we look at it more closely (while keeping fig 3. in mind), we see that when the number of stations increases if the contention window is selected appropriately, there will be more successful transmissions, less waiting time, less number of collisions. However, the collision length may be more since it is dependent on the packet lengths. Hence, when the collision happens its cost may be more. But, we try to keep the number of collisions to minimum thus improving the system performance.

4. Conclusion

This paper gives the analytical limit for the IEEE 802.11 MAC protocol capacity. The results show that the IEEE 802.11 protocol can not reach a maximum capacity of 1. It is also supported by the general theory; to avoid collision the network should have a large average back off time and to avoid high delay the network should have a low average back off time. Hence, optimizing the protocol capacity involves a trade off between low collision lengths and low idle time. From the results we see that by optimizing the contention window size we can trade off collision time; doing so will result in less waiting time and number of collisions in a virtual transmission time will also be reduced. This is applicable even when the network is heavily loaded. In other network scenarios collision lengths are high but the number of collision is less. Thus we get better performance in all network configurations. Work is being carried out to support the analytical method with simulation results. This result can be used in conjunction with some novel ideas like in [1] [4] to get the best of the performances. Future work involves, reducing the computation complexity. Also integrating this method with the other methods will be a difficult task and can be taken up as a new research objective.

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Appendix: - A

M	=	Number of Stations in the system
α	=	Parameter of "Poisson distribution for Backoff time selection"
β	=	Smoothing factor to reduce errors
λ	=	Parameter of "Poisson distribution for Packet Lengths"
E[α]	=	Optimal or Expected value for the parameter a
E[CW]	=	Optimal or Expected value of the contention window
E[Idle]	=	Average idle time experienced by the system
E[Coll]	=	Average collision time experienced by the system
E[Nc]	=	Average number of collision experienced by the system
PS_{avg}	=	Average packet length for which the results are found
T_v	=	Virtual transmission time as defined in section II
ρ_{max}	=	Protocol Capacity; determines the effective utilization of the system
CW	=	Contention Window
WLAN	=	Wireless Local Area Network
MAC	=	Medium Access Control
DIFS	=	Differentiated Inter Frame Space time
SIFS	=	Short Inter Frame Space time
RTS	=	Request to Send
CTS	=	Clear to Send
DCF	=	Distributed Coordination Function
PCF	=	Point Coordination Function
Standard Protocol	=	IEEE 802.11 MAC Protocol
RTS Threshold	=	Packet size beyond which RTS-CTS mechanism should work (Valid range: 1 – 2304 Bytes [14])
e	=	2.718 (a constant)
P (x < a)	=	Distribution Function with 'x' as the variable.

Appendix: - B

Table 6: Optimal Values for Standard Protocol (E[S] = 7.508176)

Average Number of Stations (M)	λ	E[α]	E[CW]	E[Idle]	E[Coll]	E[Nc]	T_v	ρ_{max}
2	0.5	0.228996	7.73377701	1.721477489	8.136408129	0.2683548	9.6837179	4.1306E-06
2	0.25	0.228997	7.73373887	1.721468119	8.136331218	0.2683562	9.6837483	8.2613E-06
2	0.05	0.228998	7.73370073	1.721458749	8.136254308	0.2683575	9.6840588	4.1305E-05
2	0.025	0.228999	7.73366259	1.72144938	8.136177398	0.2683589	9.6844493	8.2607E-05
2	0.0125	0.229	7.73362445	1.72144001	8.13610049	0.2683603	9.6852397	0.0001652
2	0.005	0.229001	7.73358632	1.72143064	8.136023582	0.2683616	9.6876302	0.0004129
2	0.003125	0.229002	7.73354818	1.721421271	8.135946676	0.268363	9.6900207	0.00066047
2	0.0025	0.229003	7.73351004	1.721411902	8.135869771	0.2683644	9.6916111	0.00082546
2	0.001712329	0.229004	7.7334719	1.721402532	8.135792867	0.2683657	9.6952816	0.00120471
6	0.5	0.048701	40.0669185	2.94655913	21.19861134	0.1614371	10.922536	3.6622E-06
6	0.25	0.048601	40.1514166	2.95355085	21.29040508	0.1610718	10.929618	7.3196E-06
6	0.05	0.048501	40.2362632	2.960571606	21.3827769	0.1607067	10.937008	3.6573E-05
6	0.025	0.048401	40.3214603	2.967621577	21.47573164	0.1603417	10.944508	7.3096E-05
6	0.0125	0.048301	40.4070102	2.974700946	21.56927416	0.1599768	10.952438	0.00014609
6	0.005	0.048201	40.4929151	2.981809894	21.6634094	0.1596121	10.961996	0.0003649
6	0.003125	0.048101	40.5791771	2.988948608	21.75814232	0.1592476	10.971585	0.00058333
6	0.0025	0.048001	40.6657986	2.996117271	21.85347795	0.1588832	10.980404	0.00072857
6	0.001712329	0.047901	40.7527818	3.003316074	21.94942138	0.1585189	10.991332	0.00106266
11	0.5	0.039201	50.0191067	1.854873681	9.267044428	0.250247	9.8193257	4.0736E-06

Average Number of Stations (M)	λ	E[α]	E[CW]	E[Idle]	E[Coll]	E[Nc]	T_v	ρ_{max}
11	0.25	0.039101	50.149587	1.860713782	9.318173532	0.2495104	9.8252967	8.1422E-06
11	0.05	0.039001	50.2807364	1.866584292	9.369706635	0.2487743	9.8315781	4.0685E-05
11	0.025	0.038901	50.4125601	1.872485447	9.42164795	0.2480388	9.8379702	8.1318E-05
11	0.0125	0.038801	50.5450633	1.878417483	9.474001742	0.2473039	9.8447931	0.00016252
11	0.005	0.038701	50.6782512	1.884380641	9.526772335	0.2465695	9.8532472	0.00040596
11	0.003125	0.038601	50.8121292	1.890375161	9.579964107	0.2458357	9.8617327	0.00064897
11	0.0025	0.038501	50.9467027	1.896401288	9.633581494	0.2451024	9.8694497	0.00081058
11	0.001712329	0.038401	51.081977	1.90245927	9.68762899	0.2443697	9.8792786	0.00118227
20	0.5	0.026601	74.1851434	1.423755838	5.8703491	0.3201903	9.3798988	4.2644E-06
20	0.25	0.026501	74.4688502	1.430684166	5.919040981	0.3187546	9.3870316	8.5224E-06
20	0.05	0.026401	74.7547063	1.437666206	5.96830529	0.3173208	9.394498	4.2578E-05
20	0.025	0.026301	75.042736	1.444702573	6.018150885	0.3158891	9.4020988	8.5087E-05
20	0.0125	0.026201	75.3329644	1.451793888	6.068586797	0.3144594	9.4101546	0.00017003
20	0.005	0.026101	75.6254167	1.458940783	6.119622231	0.3130316	9.419866	0.00042463
20	0.003125	0.026001	75.9201185	1.466143899	6.171266573	0.3116059	9.4296336	0.00067871
20	0.0025	0.025901	76.2170959	1.473403889	6.223529389	0.3101821	9.4386581	0.00084758
20	0.001712329	0.025801	76.5163753	1.480721413	6.276420435	0.3087603	9.4498202	0.001236
50	0.5	0.019401	102.08747	0.610472152	1.496946917	0.6886515	8.5311471	4.6887E-06
50	0.25	0.019301	102.621574	0.61541533	1.515452541	0.6837665	8.536528	9.3715E-06
50	0.05	0.019201	103.161242	0.620413954	1.534266943	0.6788991	8.5422446	4.6826E-05
50	0.025	0.019101	103.70656	0.625468899	1.553396804	0.674049	8.5480976	9.3588E-05
50	0.0125	0.019001	104.257618	0.630581057	1.572848983	0.6692163	8.554408	0.00018704
50	0.005	0.018901	104.814507	0.635751341	1.592630523	0.6644008	8.5623768	0.00046716
50	0.003125	0.018801	105.37732	0.640980682	1.612748661	0.6596026	8.5704048	0.00074676
50	0.0025	0.018701	105.946153	0.646270031	1.633210828	0.6548215	8.577693	0.00093265
50	0.001712329	0.018601	106.521101	0.651620359	1.654024663	0.6500574	8.5871223	0.00136018
100	0.5	0.014101	140.833912	0.322959339	0.593026593	1.1958478	8.2094619	4.8724E-06
100	0.25	0.014001	141.84694	0.327267377	0.604045106	1.1824195	8.2145665	9.7388E-06
100	0.05	0.013901	142.874541	0.331647287	0.615327226	1.1690897	8.2200239	4.8662E-05
100	0.025	0.013801	143.917035	0.336100659	0.626880981	1.1558576	8.2256358	9.7257E-05
100	0.0125	0.013701	144.974746	0.340629127	0.638714702	1.1427226	8.2317238	0.00019437
100	0.005	0.013601	146.048011	0.345234375	0.650837034	1.1296838	8.2394895	0.00048547
100	0.003125	0.013501	147.137175	0.349918136	0.663256954	1.1167405	8.2473348	0.00077601
100	0.0025	0.013401	148.242594	0.354682195	0.675983783	1.1038918	8.2544613	0.00096917
100	0.001712329	0.013301	149.364634	0.359528391	0.689027202	1.0911371	8.2637509	0.0014134