Analysis of Throughput and Energy Efficiency in the IEEE 802.11 Wireless Local Area Networks using Constant backoff Window Algorithm

T Madhavi
Assoc. Professor
ECE, GITAM University
Visakhapatnam, INDIA

G Sasi Bhushana Rao
Professor, ECE
Andhra Univ. Engg. College
Visakhapatnam, INDIA

M Rajan Babu
Assoc. Professor
ECE, Lendi Engg. college
Jonnada,Vizianagaram

K Sridevi
Assoc. Professor
ECE, GITAM University
Visakhapatnam, INDIA

ABSTRACT
The IEEE has standardized the 802.11 protocol for Wireless Local Area Networks. The primary medium access control (MAC) technique of 802.11 is called distributed coordination function (DCF). DCF is a carrier sense multiple access with collision avoidance (CSMA/CA) scheme with binary exponential backoff algorithm (BEB). DCF describes two techniques to employ for packet transmission: the two-way handshaking technique called basic access mechanism and an optional four way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS) mechanism. In wireless networks, the energy consumed to transmit bits across a wireless link, is a critical design parameter. The Constant backoff Window Algorithm (CWA) is the modification of the IEEE 802.11 BEB algorithm, which is used to control the contention window in the case of collisions, in order to provide a better Throughput and Energy efficiency. The new algorithm has been tested against the legacy IEEE 802.11 through matlab simulation. The tests have shown significant improvements in performance in throughput and energy efficiency using CWA compared to the original BEB algorithm.

Keywords
IEEE 802.11, Throughput, Energy efficiency, DCF.

1. INTRODUCTION
IEEE 802.11 [1] is the most popular standard used in Wireless Local Area Networks (WLANs). The IEEE 802.11 standard has defined two different access mechanisms in order to allow multiple users to access a common channel, the distributed coordination function (DCF) and a centrally controlled access mechanism called the point coordination function (PCF).

The basic access mechanism is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with BEB algorithm. In this mechanism, when a station listens to the medium before beginning its own transmission and detects an existing transmission in progress, the listening station enters a deferral period determined by the binary exponential backoff algorithm. It will also increment the appropriate retry counter associated with the frame [3]. The binary exponential backoff mechanism chooses a random number which represents the amount of time that must elapse while there are not any transmissions, i.e., the medium is idle before the listening station may attempt to begin its transmission again. The random number resulting from this algorithm is uniformly distributed in a range, called the contention window, the size of which doubles with every attempt to transmit that is deferred, until a maximum size is reached. Once the transmission is successful, the range reduced to its minimum value for the next transmission. Both the minimum and maximum values for the contention window range are fixed for a particular PHY.

In order to avoid collisions, the IEEE 802.11 MAC implements a network allocation vector (NAV) which is a virtual carrier sensing mechanism that indicates to a station the amount of time that remains before the medium will become available. By examining the NAV, a station may avoid transmitting, even when the medium does not appear to be carrying a transmission by the physical carrier sense. By combining the virtual carrier sensing mechanism with the physical carrier sensing mechanism, the MAC implements the collision avoidance portion of the CSMA/CA mechanism.

DCF describes two techniques to employ for packet transmission: the two-way handshaking technique called basic access mechanism and an optional four way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS) mechanism. The basic access mechanism consists of two frames, a frame sent from the source to the destination and an acknowledgement from the destination that the frame was received correctly. If the source does not receive the acknowledgment, the source will attempt to transmit the frame again, according to the rules of the basic access mechanism. This happens when the destination did not send the acknowledgement due to errors in the original frame or due to the corruption of acknowledgement. This retransmission of frames by the source effectively increases the bandwidth consumption.

In case of hidden nodes, the IEEE 802.11 MAC frame exchange protocol adds two additional frames RTS and CTS. The source sends a RTS frame to the destination. The destination returns a CTS frame to the source. Each of these frames contains information that allows other stations receiving them to be notified of the upcoming frame transmission and to delay any transmissions of their own. The RTS and CTS frames serve to announce to all stations in the neighborhood of both the source and destination the impending transmission from the source to the destination. When the source receives the CTS from the destination, the real frame that the source wants delivered to the destination is sent. If that frame is correctly received at the destination, the destination will return an acknowledgement, completing the frame exchange protocol. Depending on the configuration of a station and its determination of local conditions, a station may choose when to use the RTS and CTS frames.

The four frames in this protocol are an atomic unit of the MAC protocol and these cannot be interrupted by the transmissions of other stations. If this frame exchange fails at any point, the state of the exchange and the information carried in each of the frames allows the stations that have received these frames to recover and regain control of the medium in a minimal amount of time. A station in the neighborhood of the source station receiving the RTS frame will delay any transmissions of its own until it receives the frame announced by the RTS. If the announced frame is not detected, the station may use the medium. Similarly a station in the neighborhood of the destination station receiving the CTS frame will delay any transmission of its own until it receives the acknowledgement frame. If the acknowledgement frame is not detected, the station may use the medium. In the source station, a failure of the frame exchange protocol causes the frame to be retransmitted.

The modeling of 802.11 has been a research focus since the standards has been proposed. In papers [2-3], authors proposed a Markov chain model to estimate the throughput of 802.11 using binary exponential backoff by considering the frame retry limits. Instead of using binary exponential backoff (BEB), in papers [4-5] authors modified the markov chain to improve the performance of 802.11 DCF using the constant contention window. Energy efficiency is the amount of battery energy consumed in transmitting, receiving and in listening states across a wireless link. There has been extensive research in developing the analytical model to improve the energy efficiency of 802.11 DCF [6-8], using BEB. In this paper, a simple analysis is made to improve the energy efficiency of the 802.11 DCF by considering constant backoff window. The paper is organized as follows. In Section II we briefly review both basic access and RTS/CTS mechanisms of the DCF. A mathematical analysis to improve the energy efficiency for ideal channel conditions using constant backoff window is explained in section III. Throughput analysis is done in section IV. Analytical results are discussed in section V and Concluding remarks are given in Section VI.

2. OVERVIEW OF IEEE 802.11 DCF

The DCF defines two access mechanisms called basic access and RTS/CTS mechanisms.

2.1 Basic access mechanism

When the MAC receives a request to transmit a frame, a check is made of the physical and virtual carrier sensing mechanisms. If both mechanisms indicate that the medium is not in use for an interval of DIFS, the MAC transmits the frame. If either the physical or virtual carrier sense mechanisms indicate that the medium is in use during the DIFS interval, the MAC will select a backoff interval using the binary exponential backoff mechanism and increment the appropriate retry counter. The MAC will decrement the backoff value each time the medium is detected to be idle by both the physical and virtual carrier sense mechanisms for an interval of one slot time. Once the backoff interval has expired, the MAC begins the transmission. If the transmission is not successful, i.e., the acknowledgement is not received, a collision is considered to have occurred. In this case, the contention window is doubled, a new backoff interval is selected, and the backoff countdown is begun, again. This process will continue until the transmission is sent successfully or it is cancelled. Short Inter-frame Spacing (SIFS) is used to separate transmission belong to a single dialog. Each frame in IEEE 802.11 is composed of additional delay created by inter-frame spacing and back off period. The IEEE 802.11 MAC layer CSMA/CA operation is shown in Fig1.

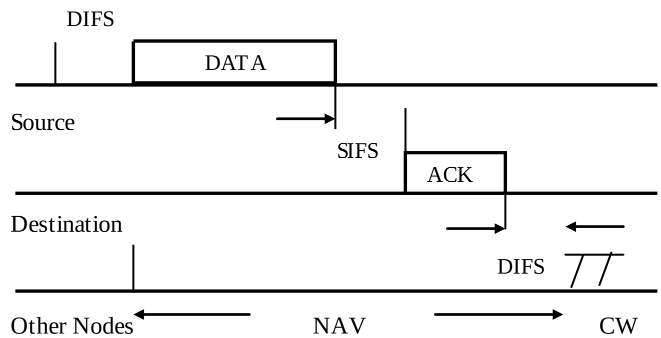

Fig 1: Basic access mechanism in DCF

Here, we denote $T_{success(basic)}$ as the duration of a successful transmission and $T_{collision(basic)}$ as the time consumed when a collision happens and δ is the propagation delay for basic access mechanism.

$$T_{success(basic)} = T_{DIFS} + T_{PACKET} + \delta + T_{SIFS} + T_{ACK} + \delta \quad (1)$$

$$T_{collision(basic)} = T_{DIFS} + T_{PACKET} + \delta + T_{SIFS} + T_{ACK} \quad (2)$$

2.2 RTS/CTS mechanism

The standard defines an additional mechanism of four way handshaking to be optionally used in the case a packet exceeds a specified length, to improve the system throughput by shortening the duration of the collisions. This mechanism requires the transmission of special short *request to send* (RTS) and *clear to send* (CTS) frames prior to the transmission of the actual data frame [2]. The RTS/CTS access mechanism is shown in the Fig.2. A station that wants to transmit a packet, waits until the channel is sensed idle for a DIFS, follows the backoff rules explained above, and then, instead of the packet, preliminarily transmits a special short frame called request to send (RTS). When the destination detects an RTS frame, it responds, after a SIFS, with a CTS frame. The source station is thus allowed to transmit its packet only if it correctly receives the CTS frame. Moreover, the frames RTS and CTS carry the information of the length of the packet to be transmitted. This information can be read by each station, which is then able to update a *network allocation vector* (NAV) containing the information of the period of time in which the channel will remain busy. When a station is hidden from either the transmitting or the receiving station, by detecting just one frame among the RTS and CTS frames, it can suitably delay further transmission, and thus avoid collision. If a collision occurs with two or more RTS frames, much less bandwidth is wasted when compared with the situations where larger data frames in collision [9].

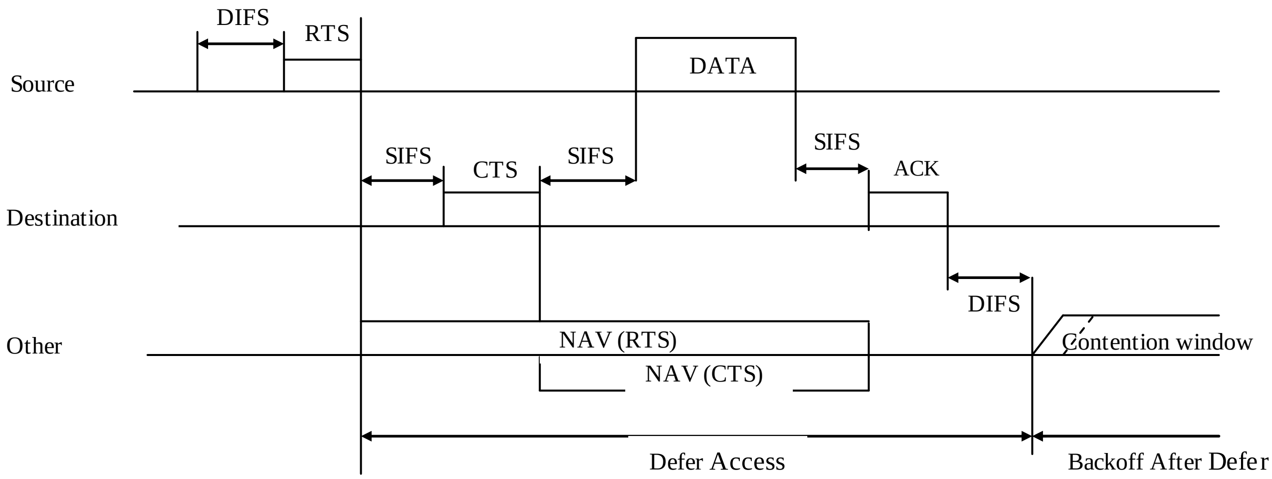

Fig 2: RTS/CTS mechanism in DCF

Here, we denote $T_{success}$ as the duration of a successful transmission and $T_{collision}$ as the time consumed when a collision happens and δ is the propagation delay for RTS/CTS access mechanism.

$$T_{success} = T_{DIFS} + T_{RTS} + \delta + T_{SIFS} + T_{CTS} + \delta + T_{SIFS} + T_{PACKET} + \delta + T_{SIFS} + T_{ACK} + \delta \quad (3)$$

$$T_{collision} = T_{DIFS} + T_{RTS} + \delta + T_{SIFS} + T_{CTS} + \delta + T_{SIFS} \quad (4)$$

3. ENERGY EFFICIENCY ANALYSIS

The main idea of this paper is to analyze the Energy Efficiency and Throughput of IEEE 802.11 DCF under ideal channel conditions using CW and BEB algorithms. Energy efficiency analysis is done in this section and throughput analysis in the next section. In the analysis, we assume a fixed number of stations and each station always has a packet available for transmission i.e., the transmission queue of each station is assumed to be always nonempty. In this analysis, first we consider the behavior of a single station with a Markov model, and we obtain the stationary probability that the station transmits a packet in a randomly chosen backoff slot from a constant contention window. This probability is same for both Basic access and RTS/CTS mechanisms. Then, by studying the probability of success and probability of collision within a generic slot time, the energy efficiency of both Basic and RTS/CTS access methods is analyzed for ideal channel.

3.1 Packet Transmission Probability

Consider *n*, the fixed number of contending stations in saturation conditions. Each station always has a packet available for transmission, and each packet needs to wait for a random backoff time before transmitting. Let *b(t)* be the stochastic process representing the backoff timer for a given station. A discrete and integer time scale is adopted: *t* and *t+1* corresponding to the beginning of the two consecutive slot times, and the backoff time counter of each station decrements at the beginning of each slot time.

When the channel is sensed busy, the backoff time decrement is stopped and thus the time interval between two consecutive slot time beginnings may be much longer than the slot time, as it may include a packet transmission.

In BEB [3], when collision occurs, the backoff stage increments, the contention window size doubles and the station selects a new backoff interval from the contention window. But here, it is assumed that the contention window is constant for all stations and no concept of backoff stage. Each station selects a backoff timer between 0 and (CW-1).
Let *b(t)* be the stochastic process representing the backoff timer for a given slot. The Markov Chain model [4] is shown in Fig 3. The backoff slot is always randomly selected from (0, CW-1) for each packet (just arriving or retransmitted). When the channel is sensed idle, the backoff timer value decrements and when it becomes zero, the station transmits the packet. The packet is discarded when the retry limit reaches its maximum value [5].

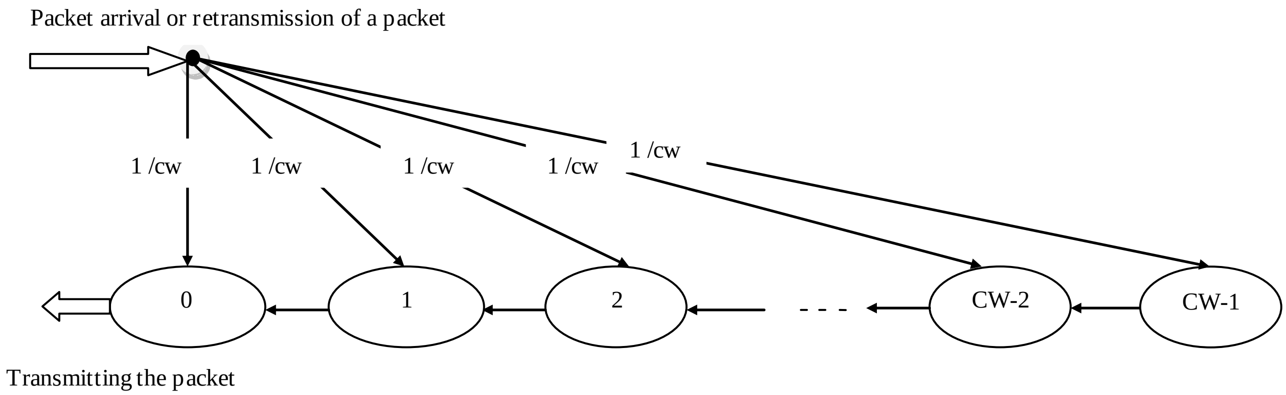

Fig 3: Markov chain model for the Backoff window size using CWA

In this Markov chain, the only one-step transition probabilities are

$$\begin{cases} P\{b(t+1)=k \mid b(t)=k+1\}=1 & k \in (0, CW-2) \\ P\{b(t+1)=k \mid b(t)=0\}=1/CW & k \in (0, CW-1) \end{cases} \quad (5)$$

The first equation in (5) accounts for the fact that, at the beginning of each slot time, the backoff time is decremented. The second equation accounts for the fact that in case of a new packet or retransmitted packet, the transmission starts with a backoff slot uniformly chosen in the range (0, CW-1).

Let b_k be the stationary distribution of the chain and is given as

$$b_k = \lim_{t\to\infty} p\{b(t)=k\}, k \in (0, CW-1) \quad (6)$$

$$b_k = \frac{CW-k}{CW} b_0, k \in (0, CW-1) \quad (7)$$

In the equation (7), all values of b_k are expressed as function of the value b_0.

$$1 = \sum_{k=0}^{CW-1} b_k = \sum_{k=0}^{CW-1} b_0 . \frac{CW-k}{CW} = b_0 \sum_{k=0}^{CW-1} \left(1 - \frac{k}{CW}\right)$$
$$= b_0 . \frac{CW+1}{2} \quad (8)$$

As any transmission occurs when the backoff time counter is equal to zero, according to Bianchi [3] and Xiangyi zou [4], we can now express the probability τ that a station transmits in a randomly chosen slot time as:

$$\tau = b_0 = \frac{2}{CW+1} \quad (9)$$

3.2 Energy Efficiency analysis for ideal channel

In ideal channel conditions, the energy consumed [6]

(i) when the station is in backoff time
(ii) when the station listens to other stations transmissions
(iii) when the station transmits the packet successfully
(iv) during collision

To find energy efficiency of 802.11 using constant backoff window, first let us see the probability that a station transmits the packets, probability of collision and probability of transmitting the packets successfully in a random slot time.

Let *n* be the fixed number of contending stations and τ be the probability that a station transmits the packets. Then the probability that there is no transmission in a given slot time is:

$$P_n = (1-\tau)^n \quad (10)$$

Collision occurs to packets transmitted by station X when any one of the *n*-1 stations transmit. Now the probability of collision P_c or the probability of any one of the n-1 nodes transmitting a packet P_{tr} in an idle time can be expressed as

$$P_c = P_{tr} = 1 - (1-\tau)^{n-1} \quad (11)$$

Given the values of contention window *CW* and the number of stations *n*, we can compute the values of P_c and τ.

Using BEB algorithm, the transmission probability τ can be expressed as

$$\tau = \frac{2(1-2P_{tr})}{(1-2P_{tr})(CW+1) + P_{tr} * CW(1-(2P_{tr})^m)} \quad (12)$$

Let P_s be the probability that any one of the *n*-1 nodes other than node X successfully transmits a packet. This happens when only one station transmits a packet and none of the other *n*-2 stations transmit. Therefore, P_s can be expressed as:

$$P_s = \frac{(n-1)\tau(1-\tau)^{n-2}}{P_{tr}} = \frac{(n-1)\tau(1-\tau)^{n-2}}{1-(1-\tau)^{n-1}} \quad (13)$$

As P_{tr} is the transmission probability, the total number of transmission attemts is $1/P_{tr}$. Therefore the average number of collisions N_c before the packet transmitted successfully is given by

$$N_c = \frac{1}{1-P_{tr}} - 1 \quad (14)$$

Let $E_{backoff}$ is the energy consumed when the station is in its backoff timer, E_{listen} is the energy consumed when the station overhears others transmissions, $E_{collision}$ is the energy consumed in collision and $E_{success}$ is the energy consumed for successful transmission. Here we consider three power levels, $P_{transmit}$, $P_{receive}$ and P_{idle}. We assume that a station consumes power $P_{transmit}$ for transmitting, $P_{receive}$ for receiving and P_{idle} when it is in idle state.
The total energy consumed to transmit a packet, E_{total} is given by

$$E_{total} = E_{backoff} + E_{listen} + E_{collision} + E_{success} \quad (15)$$

The energy efficiency η, the energy required to successfully transmit the data is given by [7]

$$\eta = \frac{L*8}{E_{total}} \quad (16)$$

Where L is the length of the data in bytes and

$$L = length\ of\ the\ packet - PHYheader - MACheader \quad (17)$$

***E*$_{backoff}$**

The station is in backoff for the number of transmission attempts i.e. $1/P_{tr}$. The time that the node spends in backoff is:

$$T_{backoff} = \left(\frac{1}{1-P_{tr}}\right) CW * slot\ time \quad (18)$$

Therefore the energy consumed in its backoff time, $E_{backoff}$ is given by

$$E_{backoff} = T_{backoff} * P_{idle} \quad (19)$$

***E*$_{collision}$**

The energy consumed when the packet transmitted by node X collides,

$$E_{collision(RTS/CTS)} = N_c[P_{transmit}T_{RTS} + P_{receive}T_{CTS} + P_{idle}(T_{DIFS} + 2T_{SIFS} + 2\delta)] \quad (20)$$

$$E_{collision(basic)} = N_c[P_{transmit}T_{packet} + P_{idle}(T_{DIFS} + T_{SIFS} + 2\delta)] \quad (21)$$

***E*$_{listen}$**

when node X is in backoff, it overhears the transmissions from other nodes. In these, P_s of them are successful and 1- P_s are unsuccessful. Therefore the energy consumed in overhearing other nodes transmissions, E_{listen} is given as

$$E_{listen} = CW * [P_s T_s + (1 - P_s)T_c]P_{idle} \quad (22)$$

***E*$_{success}$**

The energy consumed in transmitting the packet successfully is given by

$$E_{success(RTS/CTS)} = P_{transmit}(T_{RTS} + T_{packet}) + P_{receive}(T_{CTS} + +T_{ACK}) + P_{idle}(T_{DIFS} + 3T_{SIFS} + 4\delta) \quad (23)$$

$$E_{success(basic)} = P_{transmit}T_{packet} + P_{receive}T_{ACK} + P_{idle}(T_{DIFS} + T_{SIFS} + 2\delta) \quad (24)$$

The Energy Efficiency is calculated using the equation (16). The system parameters used for simulation are listed in the table 1.

Channel bit rate	1, 5.5 and 11 Mbps
PHY header	24 bytes
MAC header	28 bytes
RTS	44 bytes
CTS	38 bytes
ACK	38 bytes
DIFS	50 μs
SIFS	10 μs
Slot Time	20 μs
Propagation delay, δ	2 μs
$P_{transmit}$	1 watt
$P_{receive}$	0.8 watt
P_{idle}	0.8 watt

Table 1. System Parameters

4. THROUGHPUT ANALYSIS

Let S be the normalized system throughput, defied as the fraction of time the channel is used to successfully transmit MAC frame [4].

$$S = \frac{E[time\ used\ for\ successful\ transmission\ in\ an\ interval]}{E[length\ between\ two\ consecutive\ transmissions]}$$

$$= \frac{P_{tr}P_s E[P]}{P_{tr}P_s T_{success} + P_{tr}(1 - P_s)T_{collision} + (1 - P_{tr}) * slottime} \quad (25)$$

Where E[P] is the average packet payload size. The average payload information successfully transmitted in a slot time is $P_{tr}P_s E[P]$ since a successful transmission occurs in a slot time with probability $P_{tr}P_s$. The slot is empty with probability $1 - P_{tr}$. The packet is transmitted successfully with probability $P_{tr}P_s$ and collision probability is $P_{tr}(1 - P_s)$. Using equations (3), (4), (11), (12), (13) and (25) we get the throughput of RTS/ CTS mechanisms.

5. RESULTS AND DISCUSSION

In this section the Throughput and Energy efficiency analysis of 802.11 DCF using CWA and BEB algorithms for ideal channel conditions are discussed. All simulations are carried out in Matlab. In this simulation the energy efficiency and Throughput are analyzed in terms of contention window and number of active nodes. Here, the performance of CWA is compared with that of original backoff scheme in IEEE 802.11.

Fig. 4 and Fig. 5 shows the variation of Energy efficiency with number of active nodes for both basic and RTS/CTS access mechanisms. Here the packet size is fixed at 1000 bytes. As the number of contending stations increases, the energy efficiency decreases because the collision increases. From Fig 6 and Fig 7, it is observed that the energy efficiency decreases with increase in contention window size. The number of nodes fixed at 25. Fig. 8 and Fig.9 shows the variation of Energy efficiency and it increases with the Packet size and decreases with the number of nodes. In this, the contention window is fixed at 32.

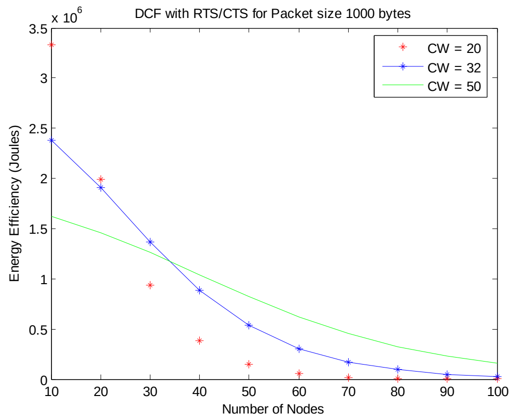

Fig 4: Energy Efficiency of Basic access with number of nodes

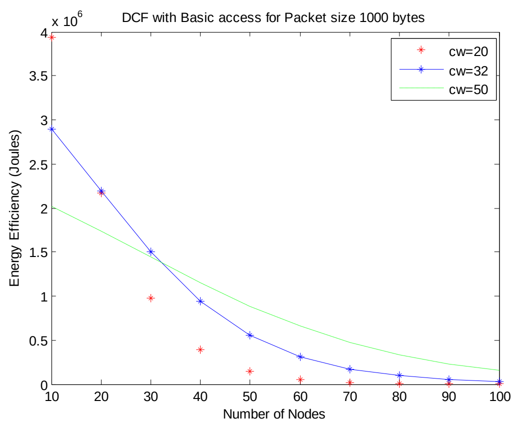

Fig 5: Energy Efficiency of RTS/CTS with number of nodes

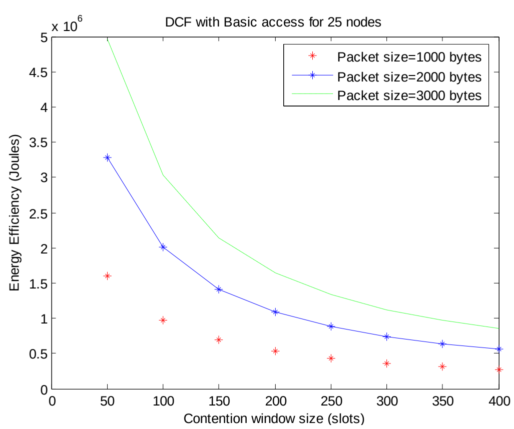

Fig 6: Energy Efficiency of Basic access with Contention window for 25 nodes

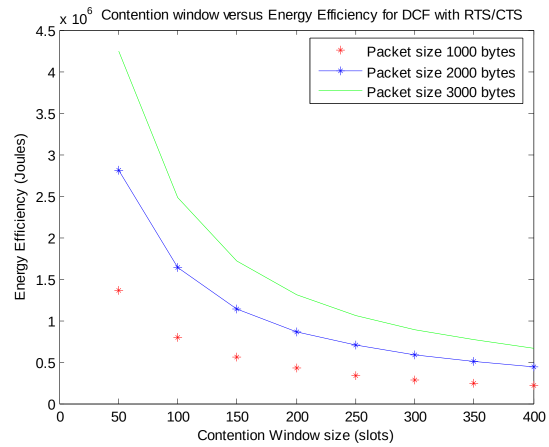

Fig 7: Energy Efficiency of RTS/CTS with contention window for 25 nodes

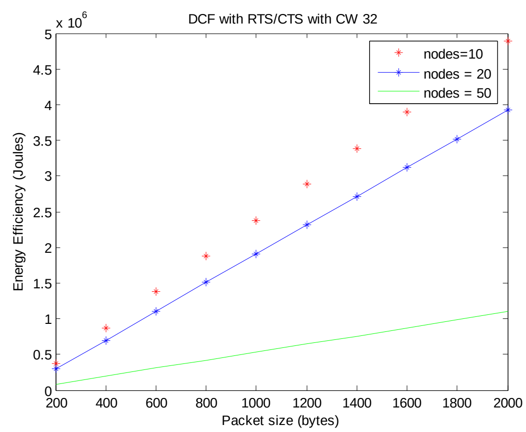

Fig 8: Energy Efficiency of Basic access with Packet size for CW=32

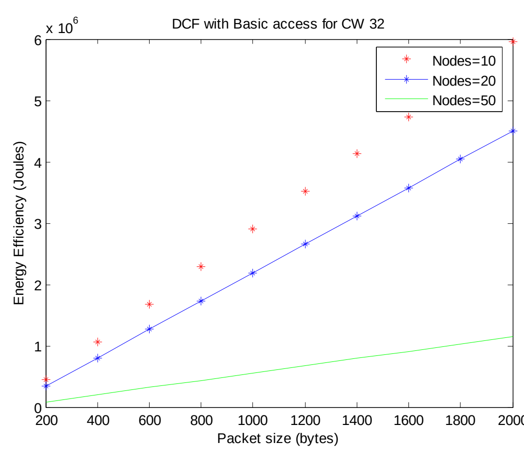

Fig 9: Energy Efficiency of RTS/CTS with Packet size for CW=32

Fig.10 shows the energy efficiency variation with the number of active nodes at different backoff stages for RTS/CTS mechanism using CWA and BEB algorithms. Here, m stands for the number of the backoff stage and CW stands for the initial backoff window size. From this figure it is observed that the CWA has a higher efficiency compared to BEB when the contending nodes are less. When the number of nodes are more than 30, BEB performs better. But the energy efficiency decreases with increase in backoff stage.

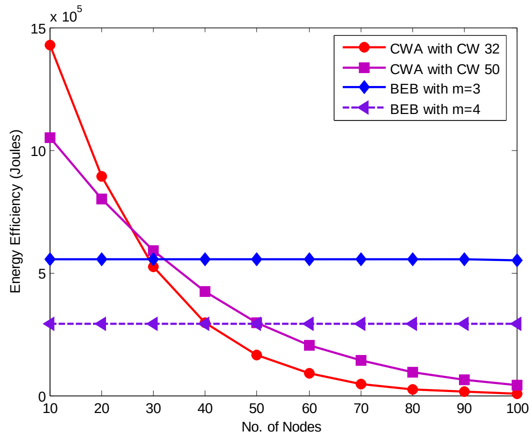

Fig 10: Energy Efficiency of RTS/CTS for CWA and BEB algorithms

Fig. 11 illustrates the variation of saturation throughput with contending nodes for different backoff stages. The increase of backoff stage results in increase in contention window size there by reducing the collisions. Here, CWA improves the throughput compared to BEB algorithm particularly when large number of stations used. From Fig 12, it is seen that as the value of CW increases, the throughput firstly increases and then decreases. Hence the maximum throughput can be obtained if the size of contention window is properly selected.

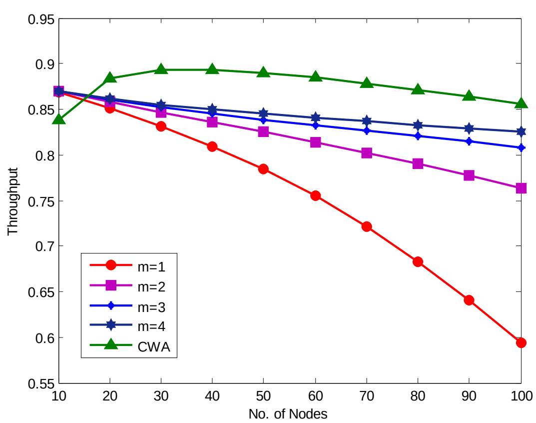

Fig 11: Saturation throughput for various retry limits

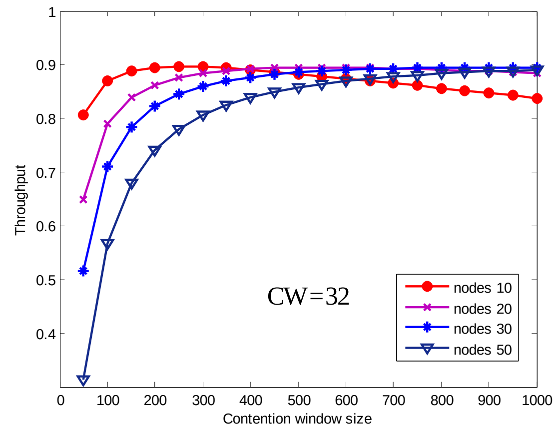

Fig 12: Saturation throughput with contention window for various nodes

In Fig.13, the behavior of CSMA/CA protocol for various data rates using both the algorithms is observed. The throughput decreases as the channel data rate increases in both cases. This is because the frame transmission time decreases as the channel data rate increases and the duration of DIFS, SIFS and slot time are independent on data rate results in throughput degradation.

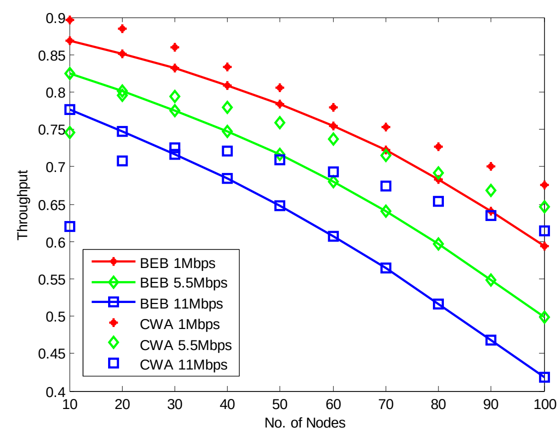

Fig 13: Saturation throughput with contention window for various nodes

6. CONCLUSIONS

In this paper, the analysis of Throughput and Energy Efficiency of IEEE 802.11 DCF based on Markov chain is carried out using CWA and BEB algorithms. The analysis shows that the transmission of large data payloads is more advantageous from the standpoint of energy consumption under saturation conditions. According to the results, the number of contending nodes, the backoff stage and the size of the contention window strongly affect the throughput. When the number of nodes is less than 30, CWA performs better. The throughput is maximum when the contention window size is 300 but the energy efficiency decreases. By properly selecting the size of the contention window, the CWA gives better throughput and energy efficiency compared to existing backoff algorithm.

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