Throughput Analysis of the IEEE 802.11 Power Save Mode in Single Hop Ad hoc Networks

Pravati Swain, Sandip Chakraborty, Sukumar Nandi and Purandar Bhaduri
Department of Computer Science and Engineering
Indian Institute of Technology Guwahati, India 781039
Email: {pravati, c.sandip, sukumar, pbhaduri}@iitg.ernet.in

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***Abstract*— In the IEEE 802.11 Power Save Mode (PSM) specified for Independent Basic Service Set (IBSS), time is divided into beacon intervals. At the beginning of each beacon interval, each station in the power save mode periodically wakes up for a duration called announcement traffic indication message (ATIM) window. The stations that have successfully transmitted ATIM frame within the ATIM window will compete to transmit data frame in the rest of the beacon interval. The transmission of an ATIM frame depends on the CSMA/CA mechanism specified in the IEEE 802.11 DCF. The probability of a successful transmission of an ATIM frame has a great impact on the performance of IBSS in power save mode. This paper presents an analytical model to calculate the throughput using the success probability of an ATIM frame transmission in ATIM window of fixed size. The simulation results validate the accuracy of this analytical analysis.**

***keywords* – IEEE 802.11 standards, power save mode, ATIM frame, Markov chain, throughput analysis.**

I. Introduction

IEEE 802.11 MAC for wireless LANs is the most used medium access protocol. It defines two methods for channel access, the mandatory Distributed Coordination Function (DCF) and the optional Point Coordinate Function (PCF). DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA) scheme. CSMA/CA uses a binary exponential backoff (BEB) [1] algorithm to avoid collision in the network. A station may proceed to transmit frames if the medium is sensed idle for an interval larger than DIFS (Distributed Interframe Space) period, otherwise it defers the transmission until the medium is idle more than the DIFS period. Then the station generates a backoff time given by:

$$\textit{Backoff time} = Random() \times \textit{Slot time}.$$

The random value is uniformly distributed over $[0, CW-1]$, where $CW_{\min}+1 \leq CW \leq CW_{\max}+1$, i.e., $CW_{\min}$ and $CW_{\max}$ are the minimum and maximum contention window sizes, respectively. These values are fixed by the physical layer. The backoff counter is decreased as long as the channel is sensed idle and frozen when the channel is sensed busy. After each unsuccessful transmission CW is doubled up to $CW_{\max}+1 = 2^m(CW_{\min}+1)$. The constant m is called maximum backoff stage. For a successful transmission the CW is reset to $CW_{\min}$.

Analytical models have been proposed for the performance analysis of the IEEE 802.11 DCF. Bianchi [2] presents a discrete time Markov model of the IEEE 802.11 DCF with ideal channel conditions. The paper [3] presents a modified version of the Bianchi model, which introduces a fixed retry limit. A number of papers [4], [5], [6], [7], [8] have built upon the original Bianchi model for handling error prone channels, non-ideal transmission channels and capture effect. All these theoretical models are derived for IEEE 802.11 DCF in data frame transmission.

In the IEEE 802.11 power save mode (PSM) for IBSS, time is divided into beacon intervals and each beacon interval divided into two parts, ATIM window and DATA window. In the IEEE 802.11 power save mode for DCF, at the beginning of each beacon interval, each node must stay awake for a fixed interval called the ATIM window. The ATIM window is used to announce any frame pending for stations in power save mode. When a station successfully transmits an ATIM frame within the ATIM window, it can compete to transmit the data frame in the corresponding DATA window. In wireless networks energy resources are considered valuable. Wireless devices usually depend on batteries. The design of "energy efficient" and "energy aware" protocols for wireless networks becomes an important research area. Several MAC protocols have been designed for wireless LANs to minimize the power consumption. The paper [9] introduced a MAC protocol to improve power save in wireless LANs which dynamically chooses an adaptable ATIM window size and different nodes use different ATIM window sizes. The paper [10] proposed a carrier sensing window which is shorter than the ATIM window. However to the best of our knowledge no one has modeled the performance of IEEE 802.11 power save mode in IBSS using ATIM frame transmission. This paper presents a discrete time Markov model to calculate the probability that an ATIM frame is trans-

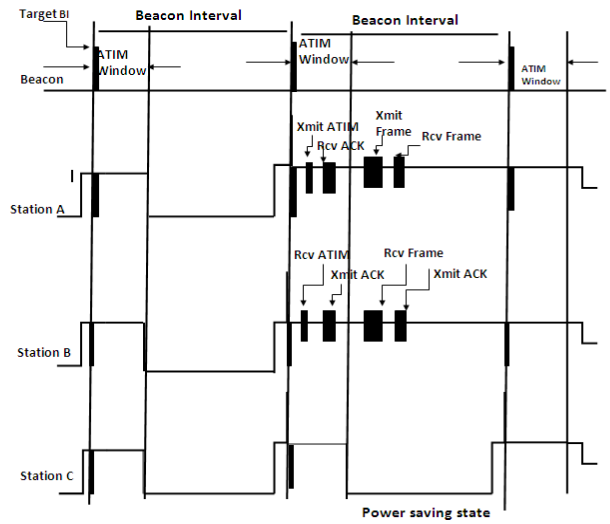

Fig. 1. Power save mode in IBSS [1]

mitted successfully. The throughput of the IEEE 802.11 PSM is then calculated using the ATIM frame success probability. The simulation tool *NS-2* [11] is used to validate the model.

The plan of the paper is as follows. In Section II we first present a brief overview of the IEEE 802.11 PSM. We propose a theoretical model in section III to calculate the throughput using the probability that an ATIM frame is transmitted successfully. Section IV validates the correctness of this model by using simulation. Finally Section V presents the conclusions.

II. The IEEE 802.11 DCF in Power Save Mode

In the IEEE 802.11 PSM there are two different power modes, *power on* and *power save*. In power on or active mode a station transmits or receives frames at any time. We assume nodes are synchronized through a beacon message. Those stations in power save mode wake up periodically to listen to the beacon message and stay awake for an ATIM window period. The transmitter buffers all the broadcast/multicast or unicast frames to the stations in power save mode and announces them in the ATIM window through an ATIM frame. During the ATIM window the control packets are exchanged by the stations to determine whether to go for power save mode or stay awake after the end of the ATIM window for data transmission. The algorithm for the transmission of an ATIM frame is according to CSMA/CA DCF specified in the IEEE 802.11 [1]. For an unicast frame, when a station receives an ATIM frame within the ATIM window, it sends an acknowledgement and stays awake up to the end of the next ATIM window. If no acknowledgement is received the ATIM frame will be retransmitted using the conventional DCF access procedure. If a station is unable to transmit an ATIM frame during the ATIM window, e.g., due to contention, the data frame is buffered and an attempt is made to transmit the ATIM frame during the next ATIM window. If a station does not receive or transmit an ATIM frame during an ATIM window, it may enter the *power save* state at the end of the ATIM window. An ATIM frame or an ATIM-ACK can be transmitted or received only within the ATIM window. A station may discard frames buffered for later transmission to power saving stations if the frame has been buffered for an excessive amount of time. In the IEEE 802.11 standard [1] neither the retry limit nor when to discard the data frame has been specified. As the ATIM window size is very small, the retry limit of seven is not appropriate for ATIM frame transmission. The paper [9] presented a power saving mechanism and has defined the retry limit of three for an ATIM frame transmission and assumed rebuffering of the data frame for at most two beacon intervals.

The power save mode is illustrated through an example. In Fig. 1 station A announces a frame destined for station B by transmitting an ATIM frame during the ATIM window. Station B sends ATIM-ACK to the station A and remains awake for the rest of the beacon interval. Station C goes to *power save* state at the end of the ATIM window, thus saving energy.

III. Modeling and Analysis

A. Network model assumptions

To model and analyze the ATIM packet transmission, we have made the following assumptions. We consider n number of stations. We assume a saturation condition, in which each station has packets to transmit at all times. We have assumed an ATIM window of fixed size. The channel is ideal, i.e., there is no hidden terminal and capture [12]. When a station has a data frame in the buffer to transmit it generates an ATIM frame. There is no broadcasting of ATIM frames, only unicasting transmission. If station A successfully transmits an ATIM frame to station B in a beacon interval (BI), then it cannot transmit another ATIM frame to station B in the same beacon interval.

Before every ATIM frame transmission, the station sets the value of CW to $CW_{\min}+1$. For each unsuccessful transmission the CW is doubled up to $CW_{\max}+1$ and for a successful transmission, the value CW is reset to $CW_{\min}+1$. When station A transmits an ATIM frame to station B, the ATIM frame may collide with another ATIM frame sent by another station. In this case the station will retransmit the ATIM frame. The retry limit for an ATIM frame is three within one beacon interval. If ATIM-ACK is not received after three transmissions in one beacon interval, then the data frame is rebuffered for another try in the next beacon interval. An attempt will be made to transmit the ATIM frame for a total of three times. A rebuffered packet can stay in the buffer for at most two beacon intervals. After three beacon intervals if the ATIM frame is not successfully transmitted then the packet is dropped. This algorithm is derived from the idea proposed in [9]. Algorithms 1 and 2 describe the ATIM frame transmission and reception. In algorithm 1 the variable $BeaconNum$ represents the number of beacon intervals.

Algorithm 1 To transmit an ATIM frame

```
1:  BeaconNum ← 2
2:  CW ← CW_min + 1
3:  W ← random integer from an uniform distribution
    over the interval [0, CW − 1]
4:  while W > 0 do
5:     if Channel == Idle then
6:        W ← W − 1
7:     end if
8:  end while
9:  Transmit ATIM frame.
10: if ATIM-ACK is not received after ATIM-ACK time
    out then
11:    CW ← 2 × CW
12:    if CW ≤ CW_max + 1 then
13:       GOTO 3
14:    else
15:       BeaconNum ← BeaconNum − 1
16:       if BeaconNum ≥ 0 then
17:          GOTO 2
18:       else
19:          DROP the ATIM frame.
20:       end if
21:    end if
22: else
23:    Success
24: end if
```

Algorithm 2 ATIM frame receiver

```
1: if ATIM frame is received then
2:    Send ATIM-ACK.
3: end if
```

B. System Model

Consider the stochastic process $(s(t), b(t), a(t))$ representing the backoff stage $s(t)$, backoff counter $b(t)$ and backoff layer $a(t)$ (the beacon interval number) at time t. Since we have a discrete model of time, the beginning of two consecutive slots will differ by one time unit. The backoff counter is decremented at the beginning of each slot time. The backoff stage represents the retry number to transmits an ATIM frame within one beacon interval and the backoff layer represents the number of beacon intervals used to successfully transmits an ATIM frame. We have modeled this three dimensional process $(s(t), b(t), a(t))$ with a discrete time Markov chain depicted in Fig. 2, where

$$P\{i_1, k_1, a_1 | i_0, k_0, a_0\} = P\{s(t+1) = i_1, b(t+1) = k_1, \\ a(t+1) = a_1 | s(t) = i_0, b(t) = k_0, a(t) = a_0\}.$$

Assume that p is the conditional collision probability, which is constant for a fixed number of stations and independent of the number of retransmissions. This is the probability p that a frame collides. Consider the probability q that the ATIM window ends in the current slot. This is also independent of the number of frame retransmissions. The non null one-step transition probabilities of the Markov chain in Fig. 2 are presented in the equations (1) in Fig. 3.

The first equation indicates that at the beginning of each slot within an ATIM window, the backoff counter is decremented with probability $(1-q)$. The second equation indicates that at any backoff stage and for any backoff counter value if the ATIM window ends, the protocol tries to retransmit the ATIM frame with backoff stage 0 in the next ATIM window. The third equation indicates successful transmission. The fourth equation indicates either successful transmission or an attempt to starts a new ATIM frame transmission. The fifth equation shows that there is collision at the last try within a beacon interval, so one more attempt will be made to send the frame in the next beacon interval with backoff stage 0. The sixth equation shows that within an ATIM window, if there is unsuccessful transmission at backoff stage i, the stage will be increased to $i+1$. The seventh equation shows an unsuccessful transmission, when there is end of ATIM window at the third beacon interval (indicated by $a(t) = 0$) with probability q.

C. Model Analysis

Let $b_{i,k,a}$ be the stationary distribution of the above Markov chain, i.e.,

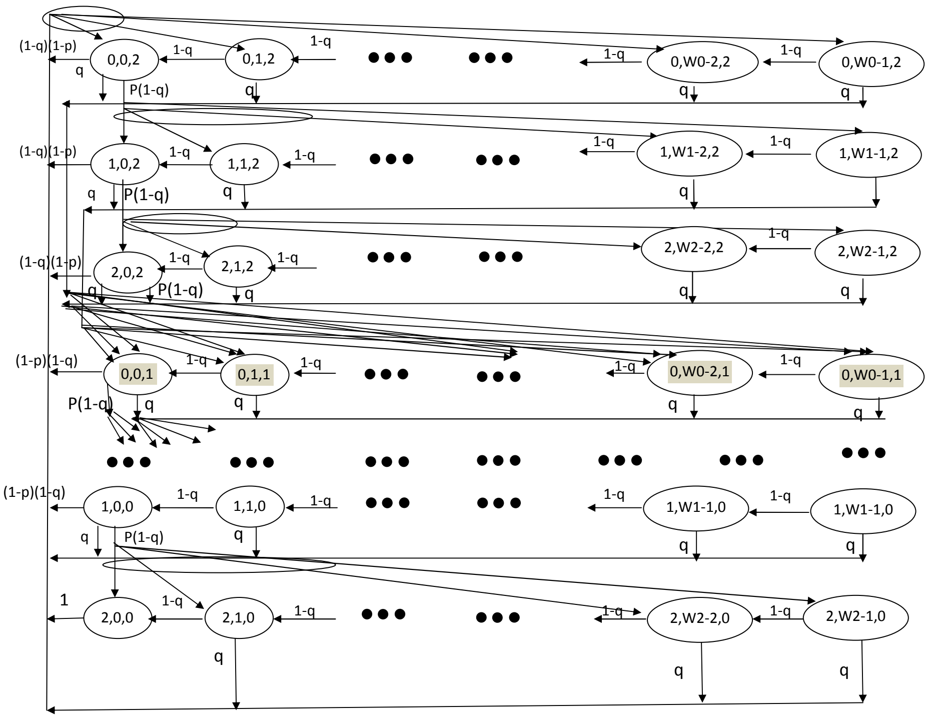

Fig. 2. Markov Model for ATIM frame transmission

$$
\begin{cases}
(I) & P\{i,k,a|i,k+1,a\} = 1-q, & i\in[0,2], k\in[0,W_i-1], a\in[0,2];\\
(II) & P\{0,k,a-1|i,k',a\} = q, & i\in[0,2], k\in[1,W_0-1], a\in[1,2], k'\in[0,W_i-1];\\
(III) & P\{0,k,2|i,0,a\} = (1-p)\times(1-q), & i\in[0,2], k\in[0,W_0-1], a\in[0,2],\\
 & & if\ \ a=0, i\neq 2;\\
(IV) & P\{0,k,2|2,0,0\} = 1, & k\in[0,W_0-1];\\
(V) & P\{0,k,a-1|2,0,a\} = p\times(1-q), & k\in[0,W_0-1], a\in[1,2];\\
(VI) & P\{i+1,k,a|i,0,a\} = p\times(1-q), & i\in[0,1], k\in[0,W_i-1], a\in[0,2];\\
(VII) & P\{0,k,2|i,k',0\} = q, & i\in[0,2]k\in[0,W_0-1], k'\in[1,W_i-1];
\end{cases}
\tag{1}
$$

Fig. 3.

$$
\begin{aligned}
b_{i,k,a} &= \lim_{t\to\infty} P\{s(t)=i, b(t)=k, a(t)=a\},\\
&\quad i\in[0,2], k\in[0,W_i-1], a\in[0,2]
\end{aligned}
$$

To obtain the stationary distribution $b_{i,k,a}$, we solve the balance equations:

$$
\begin{aligned}
b_{i,0,a} &= p(1-q)b_{i-1,0,a} \quad 0<i\leq 2\\
b_{0,0,a} &= p(1-q)b_{2,0,a} \qquad a\in[1,2]
\end{aligned}
\tag{2}
$$

$$
b_{i,0,a} = p(1-q)^i b_{0,0,a} \quad 0<i\leq 2 \tag{3}
$$

From equation (3), the stationary distribution is given by equation (4) in Fig. 4, where

$$
\begin{aligned}
M &= (1-q)(1-p)\sum_{i=0}^{2}\sum_{a=1}^{2} b_{i,0,a} + b_{2,0,0} +\\
&\quad (1-p)(1-p)\sum_{i=0}^{1} b_{i,0,0} + q\sum_{i=0}^{1}\sum_{k=0}^{W_i-1} b_{i,k,0}
\end{aligned}
$$

and

$$
N = p(1-q)b_{2,0,a+1} + \sum_{i=0}^{2}\sum_{k=0}^{W_i-1} b_{i,k,a+1}.
$$

Using equation (3), equation (4) can be simplified to

$$b_{i,k,a} = \begin{cases} M, & i=0, k=W_0-1, a=2; \\ M \times \sum_{k=0}^{W_0-(k+1)} (1-q)^k, & i=0, k \in [0, W_0-2], a=2; \\ N, & i=0, k=W_0-1, a \in [0,1]; \\ N \times \sum_{k=0}^{W_0-(k+1)} (1-q)^k, & i=0, k \in [0, W_0-2], a \in [0,1]; \\ \frac{p(1-q)}{W_i} \times \sum_{l=0}^{W_i-(k+1)} (1-q)^l b_{i-1,0,a}, & i \in [1,2], k \in [0, W_i-1], \\ & a \in [0,2] \end{cases} \quad (4)$$

Fig. 4.

$$b_{i,k,a} = \frac{1}{W_i} \sum_{l=0}^{W_i-1-k} (1-q)^l b_{i,0,a} \quad (5)$$
$$0 < i < 2, k \in [0, W_i-1], a \in [0,2].$$

Using the normalization condition for a stationary distribution, the simplified result is as follows:

$$1 = \sum_{i=0}^{2} \sum_{k=0}^{W_i-1} \sum_{a=0}^{2} b_{i,k,a} \quad (6)$$
$$= \sum_{i=0}^{2} \sum_{k=0}^{W_i-1} \sum_{a=0}^{2} \frac{1}{W_i} b_{i,0,a} \sum_{l=0}^{W_i-1-k} (1-q)^l. \quad (7)$$

After some calculation, using equation (5) and (6) we simplify $\sum_{a=0}^{2} b_{0,0,a}$ as a function of the conditional collision probability p, the probability q that ATIM window ends and $CW_{\min}$, the minimum contention window size. We calculate the the probability q using the uniform distribution on the number of ATIM frames that can be successfully transmitted within an ATIM window.

Let τ be the probability that a station transmits in a randomly chosen slot time. This can be obtained as,

$$\tau = \sum_{i=0}^{2} \sum_{a=0}^{2} b_{i,0,a} \quad (8)$$
$$= \sum_{i=0}^{2} \sum_{a=0}^{2} p(1-q)^i b_{0,0,a} \quad (9)$$

As usual the relation between τ and p is

$$p = 1-(1-\tau)^{(n-1)}. \quad (10)$$

A collision in the channel occurs when at least one of the remaining stations transmit. Let P_{tr} be the probability that there is at least one ATIM frame transmission in the considered slot time. The probability P_{as} that an ATIM frame transmission is successful is given by

$$P_{tr} = 1-(1-\tau)^n \quad (11)$$
$$P_{as} = \frac{n\tau(1-\tau)^{(n-1)}}{P_{tr}}. \quad (12)$$

This probability value P_{as} gives a gross overview of the number of stations that remain active in the data window if there are n number of stations in the IEEE 802.11 PSM. The total energy saved can be calculated using the probability P_{as}. Similarly the probability P_{as} can be used to calculate the throughput, as it is the probability that a station will stay in power on model in the data window for the data transmission.

D. Throughput Analysis

The fraction of time the channel is used to successfully transmit payload bits is called the system throughput [2]. Let S denote the normalized system throughput. In the IEEE 802.11 power save mode, when a station successfully transmits an ATIM frame within the ATIM window, it competes to transmit the data frame in the corresponding DATA window. For simplicity we assume that if a station successfully transmits an ATIM frame within the ATIM window then eventually it can successfully transmit data frames in the DATA window. We calculate the throughput using the probability value P_{as} as follows.

$$S = \frac{E[\textit{payload information transmitted in a slot time}]}{E[\textit{length of a slot time}]}$$
$$= \frac{P_{as} P_{tr} E[p]}{(1-P_{tr})\sigma + P_{as} P_{tr} T_s + (1-P_{as}) P_{tr} T_c}.$$

$E[P]$ is the average packet payload size (in terms of time unit, e.g., μs). We assume all packets have the same size, so $E[p] = P$. T_s and T_c are the average time the channel is sensed busy because of a successful transmission or a collision respectively, and σ is the empty slot time. Let $H = PHY_{\text{hdr}} + MAC_{\text{hdr}}$ be the packet header and δ the propagation delay. Then

$$T_s = \textit{DIFS} + H + E[P] + \delta + \textit{SIFS} + ACK + \delta$$
$$T_c = \textit{DIFS} + H + E[P] + \textit{SIFS} + ACK.$$

IV. Model validation

For validating our model, we used the simulation tool *NS-2* [11]. The simulation area is chosen such that all stations are within one single hop distance, i.e., the received signal strength is always detectable. We assume the ATIM window period is 20 percent of the beacon interval. We present the throughput for the basic access in IEEE 802.11 DCF in power save mode under the Direct Sequence Spread Spectrum (DSSS) physical layer [1]. The system parameters used in the calculation are listed in Table I.

For a fixed number of stations, we run 10 simulations with different random seed values. The symbol +

TABLE I

PARAMETERS USED IN THE CALCULATION

Payload of data packet	1024 bytes
Data	1024 bytes + MAC header + PHY header
ACK	14 bytes + PHY header
PHY header	$192\mu s$
MAC header	28 bytes
Basic rate	1Mbps
Data rate	2Mbps
Slot time	$20\mu s$
SIFS	$10\mu s$
DIFS	$50\mu s$

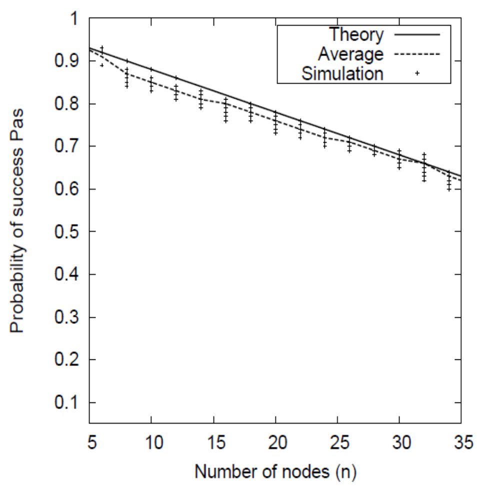

Fig. 5. Probability of Success of an ATIM frame

represents the result of each simulation. Fig. 5 displays the probability of successful transmission of an ATIM frame against the number of nodes. In Fig. 5 the solid line represents the results calculated using the Markov model and the dotted line represents the average value of all 10 simulations for each node. The figure shows that the theoretical and simulation results are close. Fig. 6 presents the throughput against number of nodes. Again the theoretical results match the simulation results. It can be noted that the throughput obtained from our model is marginally less than the one obtained from Bianchi's model due to the the ATIM window overhead of IEEE 802.11 PSM.

V. CONCLUSION

This paper presents an analytical model based on a Markov chain for the transmission of an ATIM frame of the IEEE 802.11 DCF in power save mode. We use the success probability of an ATIM frame to calculate the throughput of the IEEE 802.11 DCF in power save mode. The theoretical results are almost similar to the simulation results in terms of probability of success and normalized throughput.

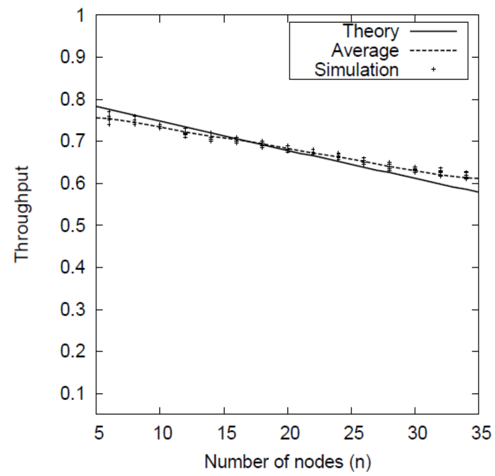

Fig. 6. Throughput of 802.11 PSM with different node size

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