A Novel Performance Analysis of the IEEE 802.11 DCF with Hidden Stations

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Abstract

The crucial contribution of the paper is the novel saturated throughput analysis of the IEEE 802.11 Distributed Coordination Function (DCF) in the presence of hidden stations. This approach involves a novel analytical model that is an extension to previous works by other authors which provide Markov chain analysis to IEEE 802.11 DCF. Hidden stations cause most collisions because stations cannot sense each other's transmission and often send packets concurrently, resulting in significant degradation of the network performance. Under the existence of hidden stations, we also propose the previous model with some various assumptions and through a spatial-temporal analysis for saturated condition. The throughput analysis of our model is evaluated by comparision with NS2 simulations and found the model is accurate and suitable for both basic access and request-to-send/clear-to-send (RTS/CTS) access mechanisms.

Keywords: *saturated, IEEE 802.11 DCF, analysis, hidden stations*

1. Introduction

The IEEE 802.11 wireless local area networks (WLAN) have experienced great achievement due to their low cost and simple deployment [1]. DCF is one of the channel-access networks for supporting various wireless networks such as WLAN with an access point and ad hoc. Nevertheless, the random access method unavoidably introduces the hidden stations problem because typical hotspot WLAN access usually include the typical hidden station scenario when the stations beyond the carrier sense range of each other transmit to access point (AP). Hidden stations occur frequently in real-world settings, but the performance impact on the IEEE 802.11 DCF is a significant concern, and it deserves to be researched under diverse assumptions [2].

Since the IEEE proposed the 802.11 protocol for the WLAN, the modeling of the performance of IEEE 802.11 has never failed to fascinate a large number of scholars. Bianchi [3] is the first to originate a model for the saturation throughput of IEEE DCF that merge the exponential backoff mechanism with 2-D Markov chain. Many modified models are proposed to better capture various details of the 802.11 standard. Wu [4] takes the retransmission times into account base on Bianchi's model. Ziouva and Antonakopous [5] propose the model to account for backoff slots being recounted as a consequence of a frozen timer when an consecutive transmission is detected. Ref. [6-10] apply the extra transition state to express the idle state, then put forward a nonsaturated DCF analysis model. In order to simplify the nonempty solving of the queue, these models assume that queue length is very small. Ref. [11,

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12] also propose nonsaturated analysis model respectively, these two models consider the phenomenon which Bianchi ignores. The phenomenon is that only when the channel is idle can the backoff counter descends, yet when the channel is busy it is frozen in nodes backoff procedure. Actually, the phenomenon has been carved by the model proposed in [5], however, this model indicates that the node can send the next data directly without the need to backoff after a successful transmission data procedure that deviates from the standard of IEEE 802.11 DCF to some extent. It's also modeling of nonsaturation condition, Ref. [13, 14] introduce node queue length and the number of packets waiting to be sent on the basis of the 2-D Markov chain, which presented the 3-D Markov chain analysis model respectively. In addition, Ref. [15] utilizes a more complex parallel spatial-temporal Markov chain to analyze the performance of nonsaturated conditions. Ref. [16] regards a heterogeneous network of nonsaturated conditions which are nodes' packet arrival time, data transmission probability and the node collision probability vary from different nodes, and raises the analytical model to analyze throughput, delay and the fairness issue, but this model will require $2n$ (n is the number of nodes) nonlinear equations to solve for different model parameters, and thus the more the number of nodes, the more complex solving is. The above mentioned references are tenable only in the perfect channel without hidden stations.

Meanwhile, many scholars propose several models to represent the hidden station effect on the network performance. Kim and Lim [17] identified the coupling effect when the number of stations is small (less than 8), in which case this conditional collision probability highly depends on the backoff process (number of retransmissions) of other stations. Their model is valid for the special scenario where the contending stations and the hidden stations are partitioned in two different regions, and the number of the contending stations equals the number of hidden stations. Tsertou and Laurenson [18] identify an important phenomenon of the lack of time-synchronization between the hidden stations. That is, the hidden stations do not start decrementing their backoff counters simultaneously after a packet collision (all stations will synchronize after a successful transmission). Kim and Choi [19] study a simple ad hoc network with two transmission pairs, and observe that the packet collisions due to hidden stations tend to occur consecutively. According to [20, 21], the transmission probabilities of a hidden station during two successive slots are not independent. Ref. [22, 23] model the probability that a hidden station will not transmit during the vulnerable period of the successive slots as another parameter. Therefore, the channel access contention of a station with other terminal stations changes the accuracy of modeling [24].

To tackle the challenges, we propose a novel discrete time 3-D Markov system where each slot is a fixed small value taken by backoff Contention Window (CW) counter instead of variable sized slot taken in previous work. The fixed small slot represents the situation that each station may observe different actions on its backoff counter. Then combine with a spatial-temporal analysis. It can generalizes the existing work on the performance modeling of the 802.11 DCF and it is not complex but accurate approximate solution model which reflects the hidden station effect clearly [22].

The rest of this paper is arranged as follows. In Section 2, we briefly introduce the hotspot scenario with hidden stations. In Section 3, we propose a Markov chain based model with equivalent state transition to analyze the average throughput performance of DCF with hidden terminals under saturated conditions. The accuracy of our model is validated by comparing analytical result with that by NS2 in Section 4. Finally, the conclusion is given in Section 5.

2. Hidden Stations Hotspot

A hotspot is a site that offers Internet access over a wireless local area network through the use of a router connected to a link to an Internet service provider. Hotspots may be found in coffee shops and various other public establishments [1]. Figure 1 is an example of the classical hidden station scenarios, where a station, called A, is randomly located within the transmission range of an access point, called H. where both node A and node H are in the communication range of node B. The circle denotes the carrier sense range for simplicity. From the figure we observe that Node H cannot sense the transmission from node A to B. When node H starts a transmission, it may cause collision with A's transmission to B, and therefore node H is called a hidden terminal to node A [25].

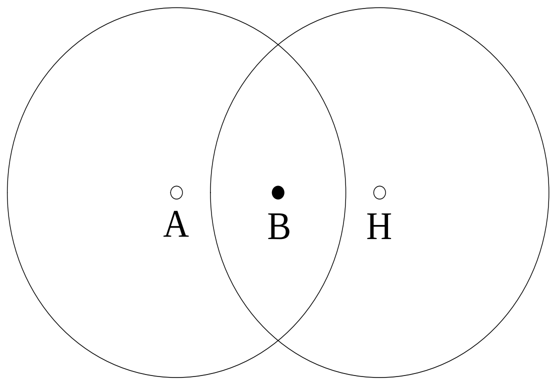

Figure 1. The Classical Hidden Stations Scenario

When the source transmits a data frame to the destination, any station that can sense the transmission from the source and destination, is called a covered station. On the other hand, any station that doesn't sense the transmission from the source but can sense the transmission from the destination is called a hidden station. Consider a wireless network composed of an access point in the center and some mobile stations randomly distributed around it. The transmission in this network can be classified as downstream and upstream traffic: sending a packet from the access point to a station is called the downstream traffic; and sending a packet in the reverse direction is called upstream traffic. There is no hidden station problem in the downstream traffic because all stations can sense the transmission from the access point. However, not all stations can sense the transmission of one another in the upstream traffic so the hidden station problem exists in this condition. In order to study the hidden station effect, we focus on the upstream performance of the network [24].

3. Analytical Model

In the analysis performance, we assume as previously reported [3, 26-28]: (a) the wireless networks operate in an ideal physical environment, i.e., no frame error and the capture effect; (b) each packet collides with constant and independent probability, regardless of the number of collisions already suffered; and (c) fixed number of stations which transmit a packet under saturation conditions.

The analysis includes three parts: (1) A discrete time slot Markov chain is proposed to model the behavior of each station with CW and exponential backoff experiencing hidden terminal effects. By solving the Markov chain, we obtain one formula between transmission probability τ_1 and collision probability p; (2) The analysis of collision probability under hidden terminals results in another formula between τ_1 and p; (3) We solve τ_1 and p to obtain the throughput of both basic and RTS/CTS access [29].

3.1. Markov Chain

In the discrete-time Markov chain, for each station, note that the slot time σ defined in standard for backoff. Three dimensions are used to character its status at time slots t: (1) $s(t)$ is defined as the number of backoff stages; (2) $b(t)$ is the backoff counter; (3) $v(t)$ is the residual time slot during either freezing, transmission or collision. The tri-dimensional process $(s(t),b(t),v(t))$ for the discrete-time Markov chain is shown in Figure 2 Note that $s(t)$=-1 denotes the post-backoff stage after a packet is either transmitted successfully or dropped by retransmission limit [22].

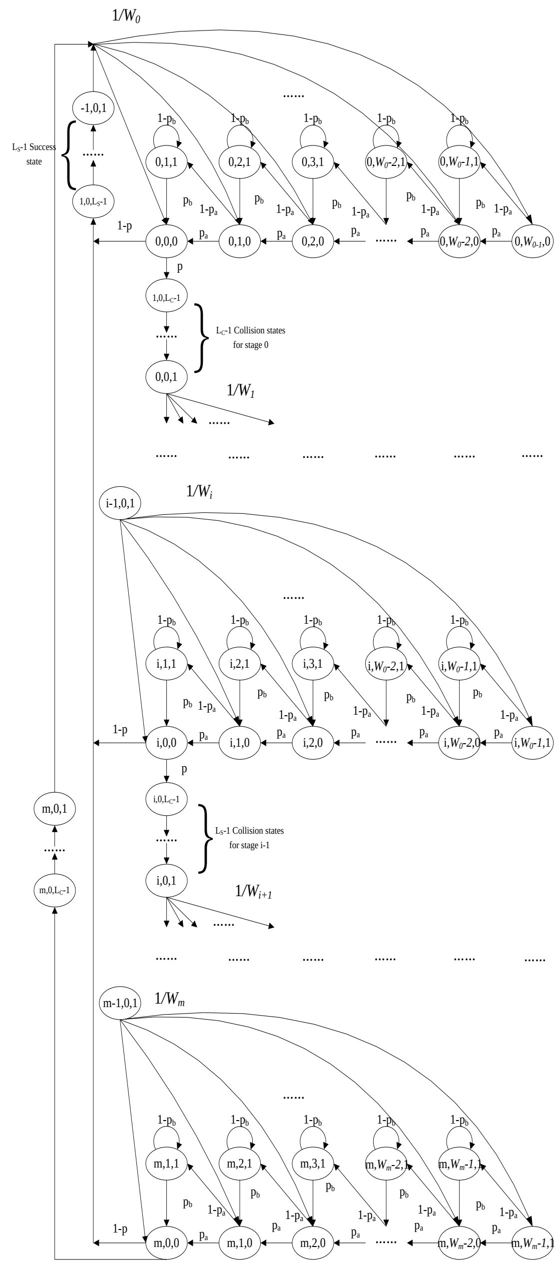

Figure 2. Markov Chain for DCF with Hidden Stations

In the Markov chain, the states with $b(t)>0$ and $v(t)=1$ (marked with solid circle) are actually the equivalent transition states, which represent the state of freezing caused by Carrier Sense (CS) or virtual CS (VCS) and are mathematically equal to the transition states for hidden terminals. The transition probability p_a and p_b are the corresponding mathematically equivalent state transition probabilities. Note that the original states transit at every slot, which is a fixed small value. Here p_a and p_b model the freezing time between subsequent backoff counter between equivalent states. For example, for states (0,0,0), (0,1,0) and (0,1,1), pa determines whether the state transits directly from (0,1,0) to (0,0,0) observing idle, or transits to freezing state (0,1,1) observing busy channel due to the four types of possible carrier sensing. At state (0,1,1), p_b determines the length of the freezing time [22].

For other states with $v(t)>0$, $v(t)$ is used to denote the residual channel busy time slot(s) that will be observed by the station either due to successful transmission or collision.

Based on the IEEE 802.11 standard [1], the size of the contention window, also called backoff window, increases exponentially from the minimum contention window, W_0, to the maximum contention window, W_{max}. It can be represented by

$$W_i = \begin{cases} 2^i W_0 & 0 \le i < m' \\ 2^{m'} W_0 = W_{\max} & i \ge m' \end{cases} \tag{1}$$

where m is the maximum backoff stage and m' is the backoff stage at which the contention window reaches the maximum value W_{max}, and remains at W_{max} after this stage. Without loss of generality, we set $m = m' = 5$ in this paper.

As in paper [3, 4], the key approximation in this model is that the probability p that a transmitted packet collides with others is independent of the state $s(t)$ of the station. In addition, following the saturated concept, we assume that each station transmits in any slot is a stationary probability τ_1. We have $L_S=[T_S/\sigma]$ and $L_C=[T_C/\sigma]$ in the Markov chain, where T_S is the successful transmission time and T_C is the collision time.

The T_S and T_C are the average times the channel is sensed busy because of a successful transmission or a collision, respectively. They are different in the basic and RTS/CTS access methods. For the basic access method, the T_S and T_C can be expressed as:

$$\begin{cases} T_S^{bas} = H + E[P] + \delta + SIFS + ACK + \delta + DIFS \\ T_C^{bas} = H + E[P] + \delta + ACK\_Timeout \end{cases} \tag{2}$$

where H=PHY_Header+MAC_Header. The δ is the propagation delay. The ACK_Timeout=SIFS+ACK +DIFS. For RTS/CTS access method, the T_S and T_C can be expressed as:

$$\begin{cases} T_S^{rts} = RTS + \delta + SIFS + CTS + \delta + SIFS \\ \qquad + H + E[P] + \delta + SIFS + ACK + \delta + DIFS \\ T_C^{rts} = RTS + \delta + CTS\_Timeout \end{cases} \tag{3}$$

where CTS_Timeout=SIFS+CTS+($2\times\sigma$).

We use $P\{i_1,j_1,k_1|i_0,j_0,k_0\}$ to denote the probability $P\{s(t+1)=i_1,b(t+1)=b_1,v(t+1)=k_1|s(t)=i_0,b(t)=b_0,v(t)=k_0\}$ for state transition. Thus, in this Markov chain, the non-null one-step transition probabilities are.

$$
\begin{cases}
P\{i, j-1, 0 \mid i, j, 0\} = p_a & j \in [1, W_i - 1], i \in [0, m] & (4.1) \\
P\{i, j-1, 0 \mid i, j, 1\} = p_b & j \in [1, W_i - 1], i \in [0, m] & (4.2) \\
P\{i, j, 1 \mid i, j, 0\} = 1 - p_a & j \in [1, W_i - 1], i \in [0, m] & (4.3) \\
P\{i, j, 1 \mid i, j, 1\} = 1 - p_b & j \in [1, W_i - 1], i \in [0, m] & (4.4) \\
P\{i, 0, L_C - 1 \mid i, 0, 0\} = p & i \in [0, m] & (4.5) \\
P\{-1, 0, L_S - 1 \mid i, 0, 0\} = 1 - p & i \in [0, m] & (4.6) \\
P\{i, 0, k-1 \mid i, 0, k\} = 1 & k \in [2, L_C - 1], i \in [0, m] & (4.7) \\
P\{-1, 0, k-1 \mid i, 0, k\} = 1 & k \in [2, L_S - 1] & (4.8) \\
P\{0, j, 0 \mid -1, 0, 1\} = 1 / W_0 & j \in [0, W_0 - 1] & (4.9) \\
P\{0, j, 0 \mid m, 0, 1\} = 1 / W_0 & j \in [0, W_0 - 1] & (4.10) \\
P\{i, j, 0 \mid i-1, 0, 1\} = 1 / W_i & j \in [0, W_i], i \in [1, m] & (4.11)
\end{cases}
$$

The meaning of the equations are as follows: 1) (4.1) and (4.2) stand for the decrements of the backoff counter; 2) (4.3) and (4.4) stand for the busy channel state as the (virtual) carrier sensing result; 3) (4.5) and (4.6) stand for the unsuccessful and successful transmission respectively; 4) (4.7) and (4.8) stand for time progress during the transmission; 5) (4.9)-(4.11) stand for the backoff and post-backoff stage. Let $b_{i,k,j}$ be the stationary distribution probability of the Markov chain. First we have,

$$
b_{i,0,0} = b_{0,0,0} p^i \qquad 1 \le i \le m \tag{5}
$$

Since the chain is regular, so for each state, we have

$$
b_{i,j,k} = \begin{cases}
b_{i,0,0} (W_i - j) / W_i & k = 0 \\
(1 - p_a) b_{i,j,0} / p_b & j \in [1, W_i - 1], k = 1 \\
b_{i,0,0} p & i \in [0, m], j = 0 \\
b_{0,0,0} (1 - p^{m+1}) & i = -1
\end{cases} \tag{6}
$$

Therefore, by using the normalization condition for stationary distribution, we have

$$
\begin{aligned}
1 &= \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=0}^{1} b_{i,j,k} + \sum_{i=0}^{m} \sum_{k=0}^{L_c - 1} b_{i,0,k} + \sum_{k=1}^{L_s - 1} b_{-1,0,k} \\
&= \sum_{i=0}^{m} b_{0,0,0} \{ (W_i - 1)[(1 - p_a) p_b^{-1} + 1] / 2 + 1 + p(L_c - 1) \} \\
&\quad + b_{0,0,0} (1 - p^{m+1})(L_s - 1)
\end{aligned} \tag{7}
$$

By substituting (5) (6) into (7), we have,

$$
\begin{aligned}
b_{0,0,0} &= [(1 - p^{m+1})(L_s - 1) + \frac{W}{2} \frac{1 - (2p)^{m+1}}{1 - 2p} \frac{1 + p_b - p_a}{p_b} \\
&\quad + \frac{1 - p^{m+1}}{1 - p} (1 + p(L_c - 1) - \frac{1 + p_b - p_a}{2 p_b})]^{-1}
\end{aligned} \tag{8}
$$

Now the probability τ_1 can be expressed as,

$$\tau_1 = \sum_{i=0}^{m} b_{i,0,0} = \frac{1-p^{m+1}}{1-p} b_{0,0,0} \tag{9}$$

3.2. Collision Probabilities during The Vulnerable Period

The basic access mechanism in IEEE 802.11 is a two-way handshaking method. The hidden stations do not sense the transmission from the source until they receive an ACK. Until then, the channel is considered as idle. If any one of these hidden stations completes its backoff procedure before sensing the ACK, it will send another data frame to the destination, which will collide with the data frame from the existing source. The vulnerable period in hidden stations equals the length of a data frame is shown in Figure 3.

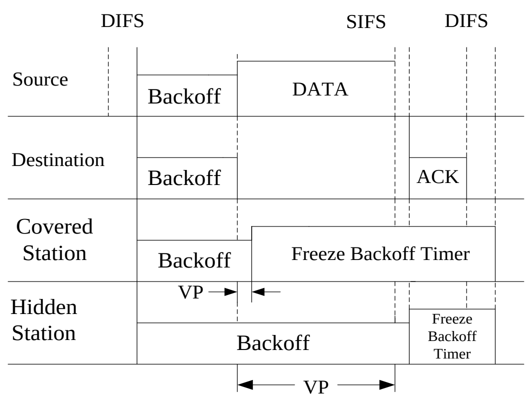

Figure 3. The Vulnerable Period for the Covered and Hidden Stations: The Basic Access Method

The RTS/CTS mechanism (four-way handshaking method) reserves the medium before transmitting a data frame by transmitting a RTS frame as the first frame of any frame exchange sequence and replying a CTS frame after a SIFS period. The hidden station effect on the RTS/CTS access method is shown in Figure 4.

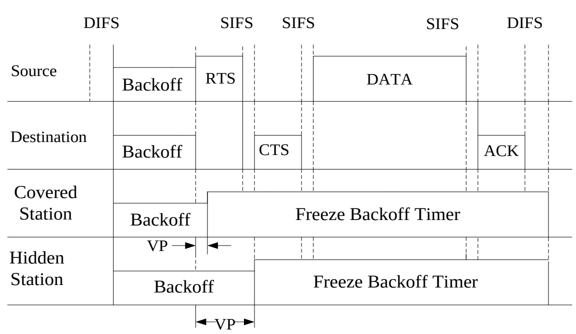

Figure 4. The Vulnerable Period for the Covered and Hidden Stations: The RTS/CTS Access Method

The vulnerable period V for the hidden stations equals the length of the RTS frame plus a SIFS period. Unlike the basic access method, the vulnerable period V for hidden stations in RTS/CTS access method is a fixed length period and is not related to the length of the data frame from the source.

$$\tau_2 = \sum_{i=0}^{m}\sum_{k=0}^{V} b_{i,k,0} =$$

$$\begin{cases} [(V+1)(\frac{1-p^{m+1}}{1-p}) - \frac{V(V+1)}{2W_0}\cdot(\frac{1-(\frac{p}{2})^{m+1}}{1-\frac{p}{2}})]\cdot b_{0,0,0}, & V < W_0 \\ [\frac{1}{2}(\frac{1-p^X}{1-p}) + \frac{W_0}{2}(\frac{1-(2p)^{m+1}}{1-2p}) + (V+1)(\frac{p^X - p^{m+1}}{1-p}) - \frac{V(V+1)}{2W_0}\cdot(\frac{(\frac{p}{2})^X - (\frac{p}{2})^{m+1}}{1-\frac{p}{2}})]\cdot b_{0,0,0}, & W_{X-1} < V < W_X,\ 1 \le X \le m \\ 1, & V > W_m \end{cases} \tag{10}$$

The probability of a successful transmission, P_S is the probability that exactly one station transmits on the channel, conditioned on having at least one station transmit. This probability can also be viewed as the probability of having one of n backlogged stations transmit and none of the covered stations transmit in the same time slot, as well as having none of the hidden stations transmit in the vulnerable period. Then, the probability of a successful transmission is

$$P_S = \frac{n\tau_1(1-\tau_1)^{n_C-1}(1-\tau_2)^{n_H}}{P_{tr}} \tag{11}$$

The normalized system throughput S can be represented as:

$$S = \frac{P_S P_{tr} E[P]}{(1-P_{tr})\sigma + P_S P_{tr} T_S + (1-P_S)P_{tr} T_C} \tag{12}$$

where the E[P] is the average packet length and r is the duration of an empty backoff slot. The T_S and T_C are the average times the channel is sensed busy because of a successful transmission or a collision, respectively. They are different in the basic vs. RTS/CTS access methods.

The derivation of the formulae of p_a and p_b have been elaborated in [22] and the formula of τ_2 is given in the equation (10). By analysing the derivation in [22], the equation (8) is approximatively equivalent to the equation (13).

$$b_{0,0,0} = [\frac{16(1-64p^6)}{1-2p} + \frac{1-p^6}{2(1-p)}]^{-1} \tag{13}$$

We can solve the nonlinear relevant equations to obtain τ_1 and τ_2 by a numerical method. Then we can obtain the value of the normalized system throughput.

4. Model Evaluation

We compare the results of our analytical model with an NS2 simulation. All the parameters used in the analytical model and the NS2 simulation are summarized in Table 1. In order to focus on the hidden station effect and reduce the capture effect on the throughput, we use a ring topology in our analytical model and NS2 simulation. For example, this topology is composed of one access point located in the center of a ring and 14 stations uniformly distributed on the ring. The capture effect can be ignored because of equal distance from the access point to all stations. The transmission range and carrier sensing ranges are set at 597 meters. In this study, we vary the ring diameter, defined as d, to obtain different number of hidden stations in the 15-station network: (a) d=540 meters—each station can sense all the packets from the other 14 stations, so there is no hidden stations and there are 15 covered stations; (b) d=600 meters—only 1 station is hidden and the other 14 are covered; (c) d=630 meters—3 hidden stations and 12 covered stations; (d) d=680 meters—5 hidden stations and 10 covered ones [30].

Table 1. System Parameters

Transmission Rate	2 Mbps
Packet Payload	250 Bytes
MAC header	224 bits
PHY header	192 bits
RTS	160 bits + PHY header
CTS	112 bits + PHY header
ACK	112 bits + PHY header
DIFS	50 μs
SIFS	10 μs
Slot Time (σ)	20 μs
Propagation Delay (δ)	1μs
CW_0	32
CW_{max}	1024
Basic Rate	1Mbps

In next section, we further study the hidden station effect on the performance of the 802.11 DCF in a saturation condition by adjusting parameters. We set the initial value of these parameters and further analysis as follows: (i) the number of stations in the ring topology is 5, 10, 15, 20, 25, 30, 35 and 40 respectively; (ii) we consider the some various number of the hidden stations such as 0, 1, 3, 5 on the designed different number of stations; (iii) the throughput of our analytical model is very close to the simulation results on the different number of stations conditions by NS2 in both the basic and RTS/CTS access method. Our study can be summarized as follows [31].

We compare the numerical results with simulations. In the following figures. Each point for a simulation result shows the average of 20 simulation runs with different seeds and the statistics for each run are collected in an interval of 200 seconds. The simulation results in Figure 5 and Figure 6 show the accuracy of our model in both the basic and RTS/CTS cases.

As shown in Figure 5 and Figure 6 Comparing the saturated throughput of the basic and RTS/CTS access methods, the throughput calculated by our analytical model is very close to the simulation by NS2 in the saturation condition. As the number of the hidden station increases, the saturated throughput decreases. In the basic access method, the saturated throughput decreases about 50%, 75% and 86% in the ring-topology case with 1, 3, 5 hidden stations, respectively. In this saturation region, the RTS/CTS access method also outperforms the basic access method. In the scenario with no hidden stations, the saturated throughput in the basic access method is higher than that in RTS/CTS access method about 27%. In contrast, the saturated throughput in RTS/CTS access method is higher than that in the basic access method about 30%, 110% and 220% in the ring-topology case with 1, 3 and 5 hidden station, respectively. We observe that the total throughput is almost determined by the number of hidden stations to each station, rather than the number of whole stations, which is dominant factor for throughput with no hidden terminals. Meanwhile, we also can see that the basic access method is much more sensitive to the hidden station effect. The network saturated throughput decreases 50% because of just one hidden station and loses about 75% and 85% of throughput in the presence of 3 and 5 hidden stations in the basic access method, respectively. On the other hand, RTS/CTS access method is more robust to the hidden-station effect. It only loses about 10%, 20% and 30% of throughput in the presence of 1, 3 and 5 hidden stations, respectively [32].

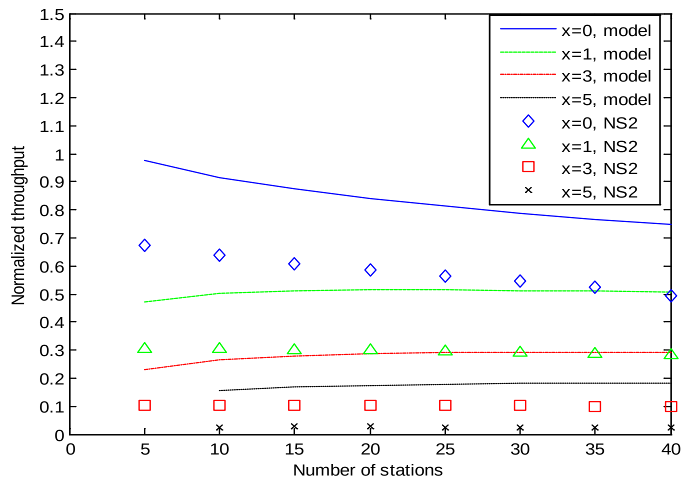

Figure 5. Throughput Versus Number of Stations: Basic Access Method

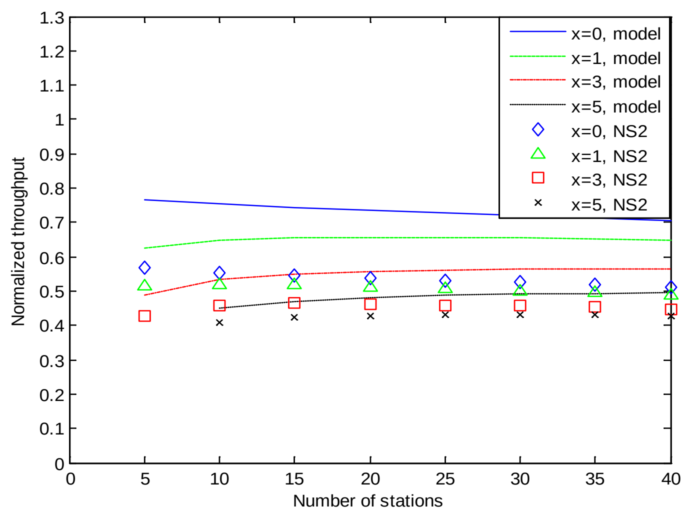

Figure 6. Throughput versus Number of Stations: Rts/Cts Access Method

5. Conclusion

In this paper, we derived an analytical model to compute the non-saturation and saturated throughput of the IEEE 802.11 DCF in the presence of hidden stations for both the basic and RTS/CTS access methods. The proposed model is in good agreement with NS2 simulations in most condition and, thus, can be used to estimate the network throughput. The existing models can be considered as special cases of our model, with zero hidden stations. We intend to continue further our analysis and to simulate such environments to help in the understanding of IEEE 802.11 behavior.

Acknowledgements

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