An Analytical Model with Improved Accuracy of IEEE 802.11 Protocol Under Unsaturated Conditions

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Abstract

In this work the authors present an analytical model that — compared to previously published work — more accurately captures the delay of IEEE 802.11 protocol under low, medium, and near-saturation load conditions. A Markov chain is used to keep track of the instantaneous number of (active) nodes that have a frame to transmit. The number of active nodes varies over time and is a function of various parameters, including the frame individual maximum retransmission count.

One advantage of the proposed analytical model is its ability to estimate the IEEE 802.11 protocol latency and delivery ratio in the presence of quality of service (QoS) classes, each class being defined by a specific maximum retransmission count. Such QoS classes can be adopted to support real time applications for which both latency and delivery ratio must be closely monitored for satisfactory operation. The analytical estimation of these performance parameters may offer useful feedback to admission control schemes.

Keywords: 802.11 protocol, analytical model, markov chain

1. Introduction

The use of IEEE 802.11 based wireless local area networks is growing everyday and is finding its place in many homes, offices, as well as hotspots. The interested reader is referred to [1, 4] for the specific operations of the IEEE 802.11 protocol. The attractive feature of this protocol is its ability to provide low cost wireless Internet connectivity. As a result, an increasing number of services is widely operated over IEEE 802.11. Many of these services, e.g., voice, video, have strict QoS requirements in terms of delay and/or jitter, while they have a more relaxed requirement on the frame delivery rate, i.e., contained frame losses do not significantly affect the service quality. In order to provide different classes of QoS to these services, i.e., IEEE 802.11e [2] was drafted. IEEE 802.11e provides up to 4 classes by allocating 4 different transmit queues where each queue is characterized by distinct backoff parameters (minimum contention window (CW_MIN), maximum contention window (CW_MAX)) and the arbitration inter frame space $(AIFS)$. Both (CW_MIN) and (CW_MAX) determine the back off counter value for each frame transmission and the $AIFS$ specifies the time for which a node has to sense the channel as idle before starting to decrement its backoff counter.

An alternate method to provide multiple QoS classes of traffic is obtained by varying the maximum number of transmission attempts $(RETRYLIMIT)$ that a data link layer frame may undergo as a result of transmission errors, either due to collisions or frame errors induced by the wireless channel. Each class of traffic is assigned a unique $RETRYLIMIT$ value. This QoS method is applicable to services that are delay sensitive, but do not require 100 % frame delivery. Studies have shown that a lower $RETRYLIMIT$

value increases frame loss but helps decrease jitter, whereas a higher $RETRYLIMIT$ value decreases frame loss but increases jitter [8]. Also, it has been shown that varying the $RETRYLIMIT$ value provides an effective way to trade frame delivery ratio for delay requirements [3, 5, 9, 14, 15]. It should be noted that even within the same service, frames might be marked with different QoS requirements and therefore assigned a different classes (in this case, a different $RETRYLIMIT$ value) [13]. For instance, various $RETRYLIMIT$ values can be assigned to distinct frames of a voice application based on the importance of the frame's carried information. This technique is shown to be effective in improving perceived voice quality over the wireless channel [7].

Owing to their practical importance, it becomes necessary to come up with accurate analytical models that can estimate the protocol performance, especially the frame delivery ratio and latency (*service time*). A number of analytical models for the IEEE 802.11 protocol with homogeneous $RETRYLIMIT$ can be found in the literature. The model presented in [4] captures the IEEE 802.11 protocol throughput under heavy load (saturated) condition. The extension of [4] to account for error prone channels with multiple transmission rates is discussed in [12]. A Markov chain based approach to model unsaturated low load conditions is proposed in [6] for both single and multi-hop networks. Models accounting for the hidden terminal problem and addressing multi-hop 802.11 networks are proposed in [11]. An alternate way to estimating frame service time and throughput under unsaturated load conditions is presented in [10]. The derivation of this model — called *user centric model* — is based on the assumption that the set of active nodes does not change while a frame is being serviced. Due to this assumption, the model is accurate at low load, i.e., the number of active nodes changes slowly over time. At medium and high load the number of active nodes may change frequently, causing the model to be less accurate as already noted in [10]. There is no existing model in the literature that can capture the effect of heterogeneous $RETRYLIMIT$ values in the same network.

The objective of this work is twofold. First, an accurate analytical model for medium and near saturation load condition is derived taking into account the fact that the number of active nodes may change while a frame is under service. The changing size of the set of active nodes over time is modeled using a Markov chain that tracks the number of active nodes. Hence, the assumption made in the user centric model in [10] that the set of active nodes does not change while a frame is under service is removed. For each state of the Markov chain, the service time, throughput and frame delivery ratio are-derived, and the overall performance metrics are obtained as weighted averages across all states. Note that the service time of a frame includes the time spent in decrementing the backoff counter, waiting for the transmission from other active nodes to complete and the time spent in failed and successful transmission attempts. Second, the model is generalized to account for multiple classes of service, each class being assigned a unique $RETRYLIMIT$ value. To do so, the state of the Markov chain is redefined to track the number of active nodes, sorted by the class of their respective frame under transmission. In other words, for each class, a counter is used to indicate the number of active nodes that are attempting to transmit frames in that class.

The presented analytical model is validated against an extensive simulation effort. The model accuracy has the potential to offer useful estimation of the IEEE 802.11 protocol latency and delivery ratio in the presence of Quality of Service (QoS) classes, each class being defined by a specific $RETRYLIMIT$ value. Such QoS classes can be adopted to support real time applications (voice and video to name two well known examples) for which both latency and delivery ratio must be closely monitored for satisfactory operation.

2. Analytical Model for Unsaturated Load

The analytical model is described in three subsections. First, the $RETRYLIMIT = \infty$ constraint of previously published models is removed, to account for finite and realistic values of this parameter. Second, the case of homogeneous retry limit (single frame class) is derived, in which all frames are assigned the same $RETRYLIMIT$ value. Third, the model is extended to account for two frame classes, each class with a unique $RETRYLIMIT$ value. The extension of the model to account for three or more frame classes from the two class model is straightforward.

The following assumptions are made:

- There are n stationary nodes sharing a common channel and are within the transmission range of each other (no hidden terminals).
- All nodes are subject to the same signal to noise ratio.
- Frames arrive to each node according to a Poisson process with rate λ.
- At most one frame can be stored at the source for transmission at any time.
- All nodes transmit with the same data rate.

The status of each node is modeled using the two states shown in Figure 1. In state $idle$, the node is not active and waits for the arrival of a newly generated frame. Upon generation of a frame, the node enters state $active$ and begins the transmission procedure. T_s indicates the average frame service time, which is a function of the number of active nodes in the network, the $RETRYLIMIT$ values chosen for the active nodes, etc. The offered load, defined as the arrival rate of frames that are generated when the node is in state $idle$, is then

$$\Lambda = \frac{\lambda}{1 + \lambda T_s}.$$

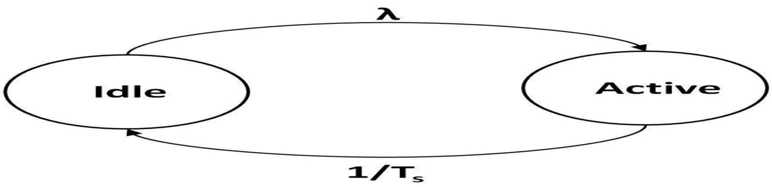

Figure 1

Node State.

2.1 Relaxation of the $RETRYLIMIT = \infty$ Constraint

Computation of saturated (all nodes are always active) service time was first presented in [10]. The analysis in [10] is limited to the case of infinite retry attempts and does not model the case where a frame can be dropped after reaching its $RETRYLIMIT$. In this section, the computation of saturated service time accounting for finite $RETRYLIMIT$ is derived from the models in [4, 12]. In [4, 12] an embedded Markov chain whose states are represented by virtual time slots is used to model a saturated node. The virtual slots represent the current backoff stage and backoff counter value of a node. The duration for which a node will stay in a particular state depends on the channel, which can either be idle or experience a transmission from one or more of the nodes. Using the fact that the nodes will transmit when their backoff counter reaches zero, the transmission probability of a node is determined.

These models however assume that a node makes an infinite number of attempts i.e., $RETRYLIMIT = \infty$. Such an assumption holds well, when each node makes a large number of retry limits. In order to study the effect of varying $RETRYLIMIT$ on the performance of the network, the equations derived in these models are re-derived relaxing the assumption of infinite number of attempts.

By accounting for finite retry limit and applying the procedure as in [4, 12], the probability of a node to transmit in a slot can be found to be

$$\tau_i = \frac{2(1-2p_i)(1-p_i^{m+1})}{W(1-2p)^{m+1}(1-p)+(1-2p)(1-p^{m+1})}$$

for $m \leq L$ and

$$\tau_i = \frac{2(1-2p_i)(1-p_i^{L+1})}{W(1-2p)^{L+1}(1-p)+(1-2p)(1-p^{L+1})} \cdot \frac{1}{(1-2p)p(2^L W+1)(p^L-p^m)} \quad (1)$$

for $m > L$.

where m is the $RETRYLIMIT$ and L is the maximum backoff stage, the attempt at which the contention window equals CW_MAX. p_i represents the probability with which the transmission from a node fails. The derivation for other metrics like the average slot duration Δ and saturation throughput $(Throughput_{saturation})$ is similar to the work done in [4, 12].

The derivation is shown here for the sake of completeness. The probability of a transmission failure for a node i given the node attempts for a transmission is given by

$$P_i = 1 - \left(\prod_{j=0, j \neq i}^{N} (1 - \tau_j) \right) (1 - (P_{dfe})_i)(1 - (P_{afe})_i) \tag{2}$$

where $(P_{dfe})_i$ and $(P_{afe})_i$ are the data frame error and acknowledgement frame error for the node i. The probability of transmission in a given slot is given by

$$P_{tr} = 1 - \prod_{i=0}^{N} (1 - \tau_i) \tag{3}$$

where N is the number of nodes in the network. The probability of no collision at node i is given by

$$(P_{nc})_i = \prod_{j=0, j \neq i}^{N} (1 - \tau_j). \tag{4}$$

The probability of a successful transmission given a transmission takes place in a slot, is given by,

$$P_s = \frac{\sum_{i=0}^{N} \tau_i (P_{nc})_i (1 - (P_{dfe})_i)(1 - (P_{afe})_i)}{P_{tr}}. \tag{5}$$

The probability of collision given a transmission takes place is given by

$$P_c = 1 - \frac{\sum_{i=0}^{N} \tau_i (P_{nc})_i}{P_{tr}}. \tag{6}$$

The probability that a transmission failed due to a data frame error alone given only one transmission takes place, is given by

$$P_{dfe} P_{tr} = \sum_{i=0}^{N} \tau_i (P_{nc})_i (P_{dfe})_i. \tag{7}$$

The probability that a transmission failed due to a acknowledgement frame error alone given only one transmission takes place, is given by

$$P_{afe}P_{tr} = \sum_{i=0}^{N} \tau_i (P_{nc})_i (1 - (P_{dfe})_i)(P_{afe})_i. \quad (8)$$

The average slot duration is given by

$$\Delta = (1 - P_{tr})\sigma + P_s P_{tr} T_{suc} + P_c P_{tr} T_{col} + P_{dfe} P_{tr} T_{suc} + P_{afe} P_{tr} T_{col}. \quad (9)$$

where, T_{suc} and T_{col} are the average successful and collision time seen by a slot. The saturated throughput of the network is given by

$$S = \frac{P_s P_{tr} Payload}{\Delta} \quad (10)$$

where $Payload$, is the average payload information transmitted in a frame.

Now, $\frac{1}{\tau_i}$ represents the average number of slots that elapses between two transmissions from a node i. Such slots include the backoff slots and the slots where transmission from other nodes in the network were observed by the node before it got access to the channel. Using the number of slots required to transmit once, the average time taken by a node i to transmit once is given by

$$\text{Average time for one transmission} = \Upsilon_i \Delta. \quad (11)$$

Hence, for a node whose maximum retry limit is m, the average number of attempts made by a node i for servicing a frame is given by

$$\Upsilon_i = \sum_{k=0}^{m} p_i^k. \quad (12)$$

using this, the service time of a node i, including all the attempts that were made by the node to transmit the frame, is given by

$$T_s^i = \frac{1}{\tau i} \Upsilon_i \Delta. \tag{13}$$

2.2 Homogeneous $RETRYLIMIT$: One Frame Class

Based on the arrival rate and saturated service time the network with nodes that have no queue and use a single $RETRYLIMIT$ under unsaturated conditions can be modeled using an one-dimensional Markov chain as shown in Figure 2. The state of the Markov chain represents the number of active nodes at a given time. The term T_s^i in the figure represents the saturated service time when there are i saturated nodes in the network. As shown in the figure, the rate at which the number of active users increase by one is equal to the rate at which a frame arrives at one of the nodes and the rate at which the number of active nodes decreases by one depends on the rate at which one the nodes completes service.

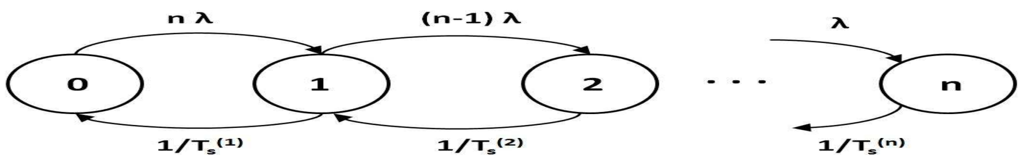

Figure 2

One Dimensional Markov Chain representing one frame class.

Let π_i represent the probability of state i, that is the probability of i nodes being active. Using, global balance equations, the steady state probability of a state i can be written as

$$p_i = \frac{\prod_{k=1}^{i}(n-k+1)\lambda^k}{i!} \cdot \left(\prod_{k=1}^{i} T_s^i\right)\pi_0 \tag{14}$$

for $i = 1, 2, \ldots n$. Since, all π_i can be expressed in terms of $\pi 0$. Applying this and using the fact that sum of all probabilities equals one, the steady state probabilities of π_i for $i = 0, 1, 2, \ldots n$ can be found. Then the net arrival rate that is accepted by the system is given by

$$\Lambda = \sum_{i=0}^{n}(n-i)\lambda\pi_i \tag{15}$$

The average number of nodes in the network is given by,

$$N = \sum_{i=0}^{n} i\pi_i. \tag{16}$$

Using, Little's Theorem, the average service time for a node is given by,

$$\bar{T_s} = \frac{N}{\Lambda}. \tag{17}$$

It can be noted that the service time can also be written as,

$$\bar{T_s} = \frac{\sum_{i=0}^{n} T_s^i \pi_i}{1-\pi_0}. \tag{18}$$

Since all the nodes are assumed to have a homogeneous Poisson arrival of frames and have the same $RETRYLIMIT$, the service time of all nodes will be equal assuming similar SNR conditions. The unsaturated throughput for the network is given by,

$$\hat{S} = \sum_{i=0}^{N} S(i)\pi_i. \tag{19}$$

where, $S(i)$ is the saturated throughput considering i active nodes. Note, that the unsaturated throughput of a node may be less than the net arrival rate, Λ as some of the frames may be dropped after reaching its maximum retry limit. The probability of success for a frame under unsaturated condition is given by

$$P_s = \frac{\hat{S}}{\Lambda}. \tag{20}$$

It should be noted, that this equation is valid for our proposed model, as the model provides an equivalent network that is either unsaturated or at near saturation condition. The delivery ratio of a frame, i.e., the probability with which a frame is successfully transmitted in one of the attempts is given by,

$$\eta = 1 - (1 - P_s)^m \tag{21}$$

where m is the $RETRYLIMIT$.

2.3 Heterogeneous $RETRYLIMIT$: Two Frame Classes

The homogeneous $RETRYLIMIT$ model can be extended to handle the multiple retry limit case by accounting for the type of frame under service in the states of the Markov chain apart from the number of active nodes. Consider two classes of service, type 1 and type 2, differentiated based on the $RETRYLIMIT$ values given by $R1$ and $R2$ respectively. The network can be modeled using a two dimensional Markov chain as shown in Figure 3. The state (i, j) of the Markov chain, represents the state at which there are i nodes servicing a type 1 frame and j nodes servicing a type 2 frame. The following is a list of notations used.

- q is the probability with which a given arrival belongs to type 1.
- q' is the probability with which a given arrival belongs to type 2.
- $T_1^{i,j}$ is the saturated service time for a user of type 1 when i nodes transmit with a $RETRYLIMIT$ value of $R1$ and j nodes transmit with a $RETRYLIMIT$ value of $R2$.
- $T_2^{i,j}$ is the saturated service time for a user of type 2 when i saturated nodes transmit with a $RETRYLIMIT$ value of $R1$ and j saturated nodes transmit with a $RETRYLIMIT$ value of $R2$.
- $\theta(i,j)$ is the probability of finding i nodes serving a type 1 frame and j nodes serving a type 2 frame.
- $S(i,j)$ is the saturated network throughput when i saturated nodes transmit with a $RETRYLIMIT$ value of $R1$ and j saturated nodes transmit with a $RETRYLIMIT$ value of $R2$.

As shown in the Figure 3, the rate at which a node becomes active for servicing a frame of type i is equal to rate at which an arrival of type i occurs at an idle node. Similarly, the rate at which the number of users servicing a frame of type i decreases by one is equal to the rate at which one of the nodes servicing the frame of type i completes service.

Let A represent the state transition matrix corresponding to the given Markov chain. Let $\hat{\theta}$ represent the state vector that gives the probability of being in each state. Clearly, at steady state, $\hat{\theta}$ and A satisfies the condition

$$\hat{S} - A * \hat{S} = \hat{\epsilon} \tag{22}$$

where $\hat{\epsilon}$ represent a small enough value. The equation 22 can be solved using numerical methods and by accounting for the fact that the sum of probabilities equals one, to get the state probabilities. The average number of active nodes is given by

$$N = \sum_{i=0}^{n} \sum_{j=0}^{j=n-i} (i+j)\theta(i,j) \tag{23}$$

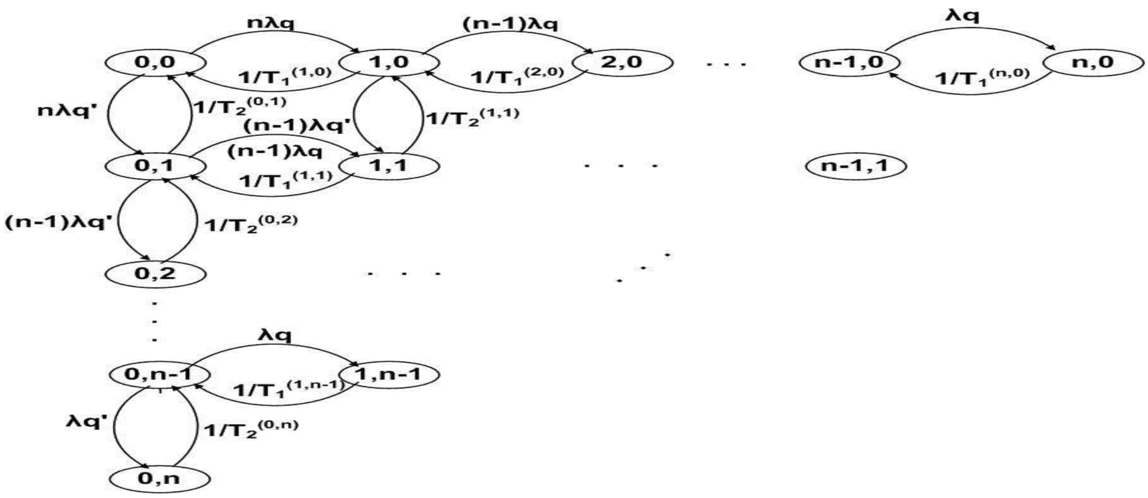

Figure 3

Markov chain representing the network with two frame classes.

where, n is the total number of nodes. The fraction of traffic that is accepted for service is given by

$$\Lambda = \sum_{i=0}^{n} \sum_{j=0}^{j=n-i} (n-(i+j))\lambda\theta(i,j). \tag{24}$$

Using, Little's theorem, the average service time of a node is given by

$$T_s = \frac{N}{\Lambda}. \tag{25}$$

Note that using the presented model, the service time, throughput and delivery ratio of an IEEE 802.11 network under unsaturated load conditions can be estimated. The next section presents a numerical validation of the model when using either one or two frame classes.

3. Results

The proposed model is validated against simulation results and the homogeneous $RETRY-LIMIT$ model is compared against the user centric model proposed in [10].The results are obtained considering an IEEE 802.11b protocol.All simulations are carried out using a custom built C++ event-driven simulator that has been validated against an analytical model [12]. The simulation parameters used are shown in Table 1. The acknowledgment (ACK) frame is always sent at the lowest data rate which is 1 Mbps.

Table 1

Parameter values used in simulation

Path Loss Exponent β = 4	Fading is Flat Rayleigh
Average Transmitter Power = 100 mW	PHY Header = 192 bits
SIFS = 10 μs	Vulnerable Period = 20 μs
DIFS = 50 μs	Slot Time = 20 μs
MAC ACK = 14 bytes	CWmin = 63 slots
CWmax = 1023 slots	MAC Header = 34 bytes

First, a network with 5 nodes and an ideal channel, i.e., no frame errors is considered. The data transmission rate is fixed to be 1 Mbps and the frame size is fixed to 50 bytes. Figure 4 shows the average service time across the net accepted traffic per user. Results are presented for simulations (no queue and with queue), proposed analytical model and for the user centric model proposed in [10]. The x-axis represents the net accepted traffic. The simulation results correspond to the fraction of arrival rate that is not dropped (net accepted arrival rate). The service time obtained through simulation when there is no queue matches the case where there is an infinite queue as expected. At low load conditions, both the proposed analytical model and the ”user centric” model can be observed to closely match the service time obtained through simulations. However, as the load increases (causing the system to reach near saturated conditions), the proposed model is observed to capture the service time more accurately. This further corraborates the observation made in [10] that the user centric model holds good only for low load conditions.

The corresponding throughput against arrival rate plot shown in Figure 5. Once the network reaches saturation, the user centric model boils down to the saturated IEEE 802.11 model and hence it’s results matches the simulations at such conditions.

Next, the effect of channel quality on service time of a frame is considered. Five nodes generating frames of size 500 bytes at the rate of 100 frames per second (2 Mbps of traffic) is considered. The data rate is fixed to be 11 Mbps. Figure 6 shows the plot of average service time against SNR. The analytical model is evaluated for various values of λ till Λ becomes equal to 2 Mbps to get the required service time and throughput. As the SNR decreases, the channel capacity also decrease causing the network to approach saturation. This causes the service time to increase with the decrease in signal to noise ratio. The proposed model is again observed to match the simulation values more closely at near saturation conditions compared to the user centric model.

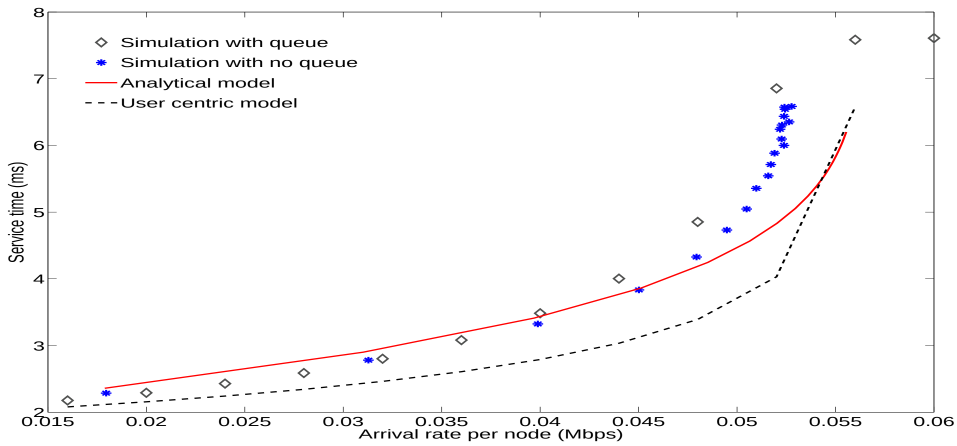

Figure 4

Average service time Vs. arrival rate, one frame class.

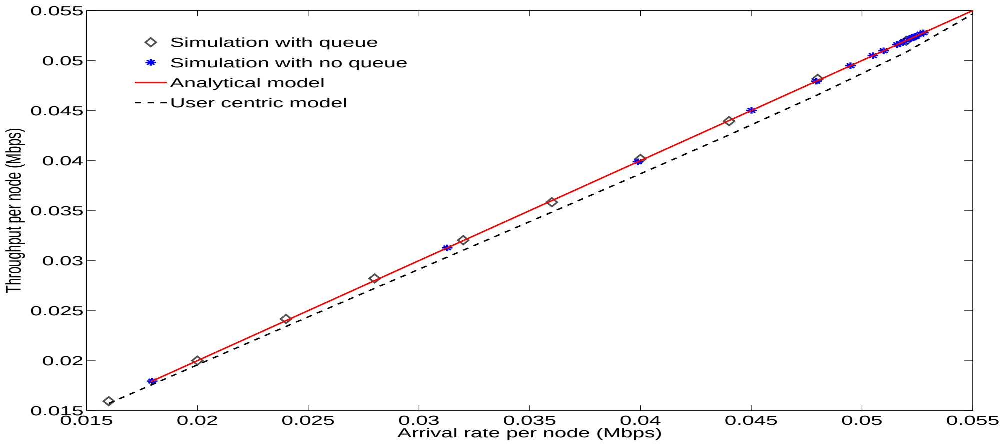

Figure 5

Throughput Vs. arrival rate, one frame class.

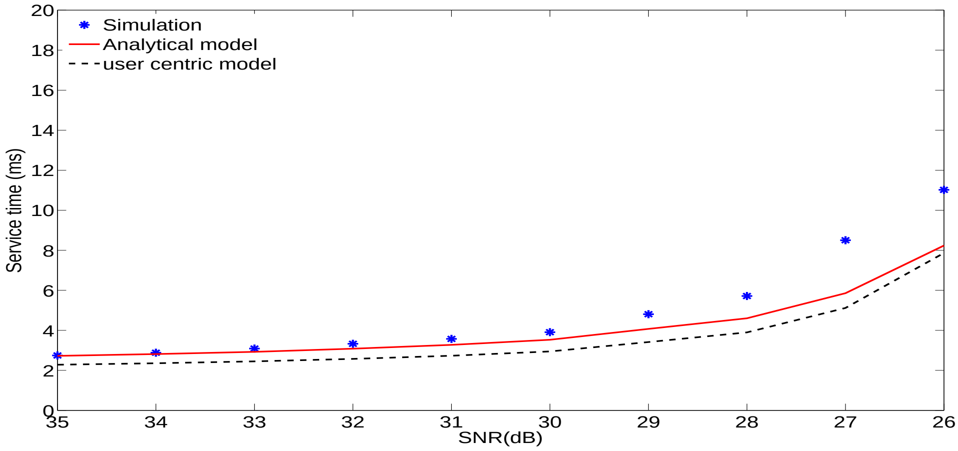

Figure 6

Average service time Vs. SNR, one frame class.

From these results, it can be observed that the proposed model provides a more accurate model owing to its ability to also take into account the change of the set of active users while servicing a frame.

The results for heterogeneous $RETRYLIMIT$ is presented next. In these results only the proposed model and simulation results are shown, as the user centric model does not account for the presence of different retry limits. Nodes are assumed to service two types of frames each with a different $RETRYLIMIT$. The class of frames that receive a higher value of $RETRYLIMIT$ is said to be of higher priority and that with lower value of $RETRYLIMIT$ is said to be of lower priority.

The average service time across arrival rate considering a network with five active nodes with retry limits 4 and 2 are shown in Figure 7. All nodes transmit data at the rate of 1 Mbps. The probability with which an incoming arrival belongs to that of the higher priority is set to be 0.4. The graph shows the service time for the case when there is no frame error and for the case where there can be frame error due to a channel whose signal to noise ratio is 10 dB. The service time for the node at 10 dB is higher than that of the case where there is no frame error as expected. It can be observed that the analytical model matches the simulation results closely. The plot showing the service time of the Analytical Model stops at a point indicating that this is the load at which the maximum service time will be reached which is corroborated by the simulation plot. This is because the saturation is reached at this point as shown in Figure 10. This shows the ability of the model to identify the maximum load that can be handled without reaching saturation and hence prove its application for admission control schemes.

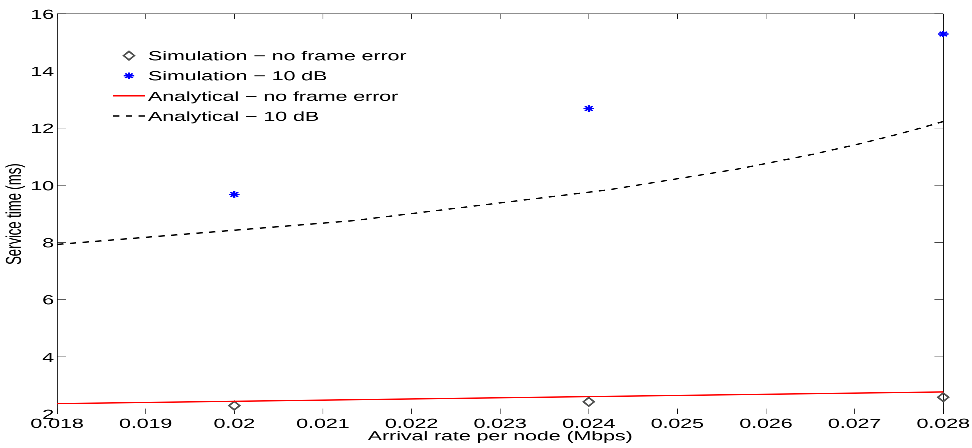

Figure 7

Average service time Vs. arrival rate, two frame classes.

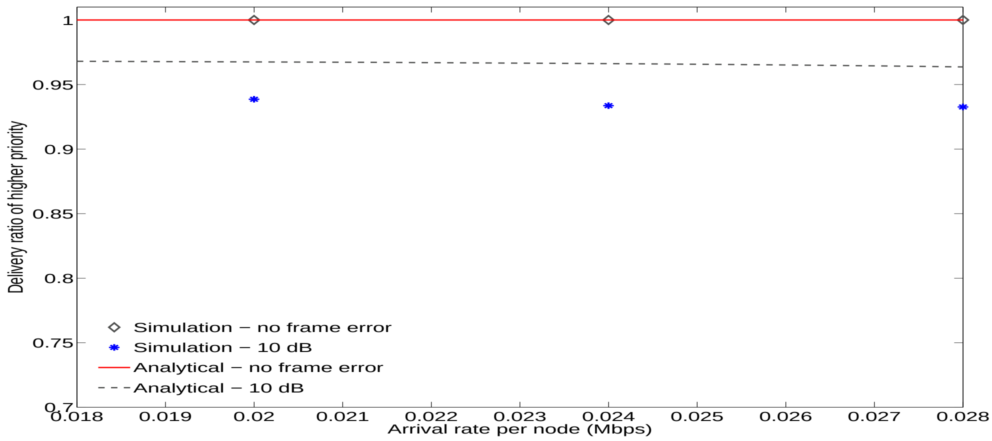

Figure 8

Delivery ratio of higher priority Vs. arrival rate, two frame classes.

The delivery ratio of both the classes is shown in Figure 8 and Figure 9. When the probability of failure is low, under unsaturated conditions, the delivery ratio is similar for both the frame classes. However, at 10 dB SNR, the delivery ratio of lower priority class can be observed to be much lower than that of the higher priority frames, this is because the node is required to make more attempts at low SNR conditions to overcome the increased frame error probability thereby increasing the chance of dropping a frame after reaching the $RETRYLIMIT$. Again, the analytical model can be seen to capture the steady state results. This fact is corroborated by the simulation plots which yields the same value for any further increase in accepted traffic.

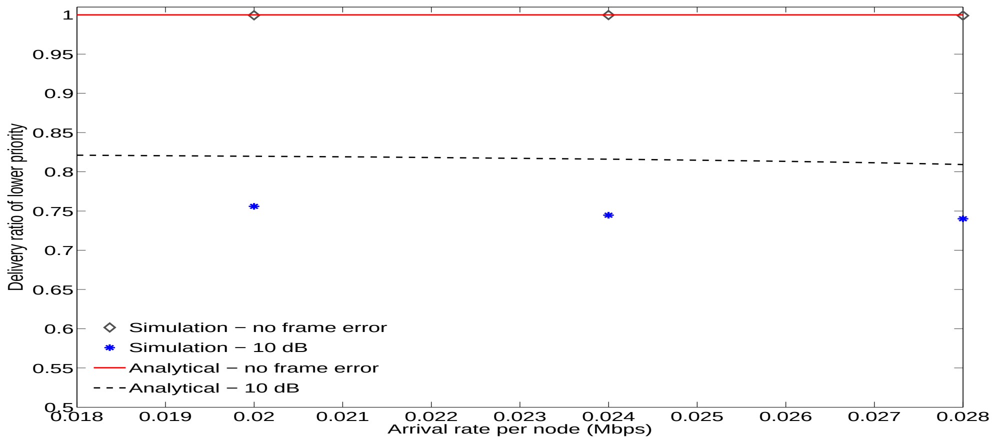

Figure 9

Delivery ratio of lower priority Vs. arrival rate, two frame classes.

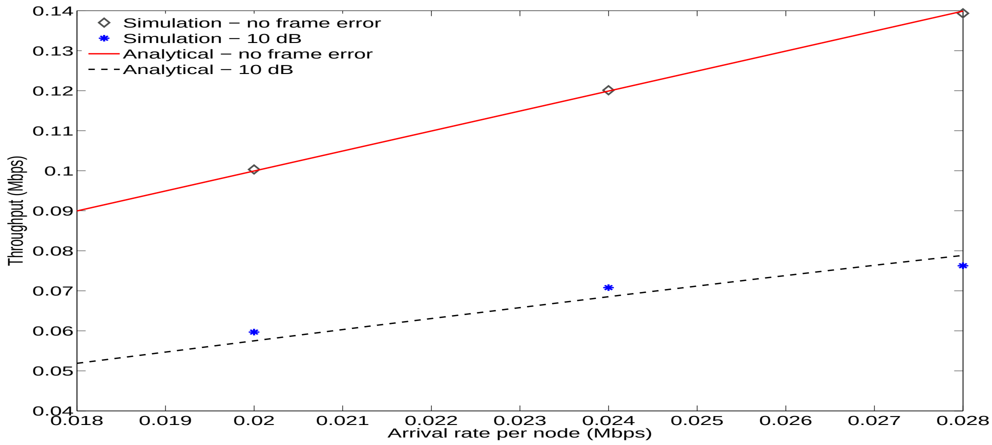

Figure 10

Throughput Vs. arrival rate, two frame classes.

Next, the effect of channel conditions on the frame error is considered. Five nodes generating traffic at the rate of 0.4 Mbps each with $q = 0.4$ is considered. The data rate used by the nodes is fixed to 11 Mbps. Simulation results showing the average service time across received SNR for different values of retry limit are shown in Figure 11. The values of the different retry limits used are indicated within parentheses. It can be observed that the (6,1) retry limit pair enables a node to operate at lower SNR when compared to (4,2). This is because, the (6,1) case on an average makes lesser number of attempts to transmit a frame. Hence the delivery ratio of (6,1) is lower than that of the (4,2) as shown in Figure 12 and Figure 13.

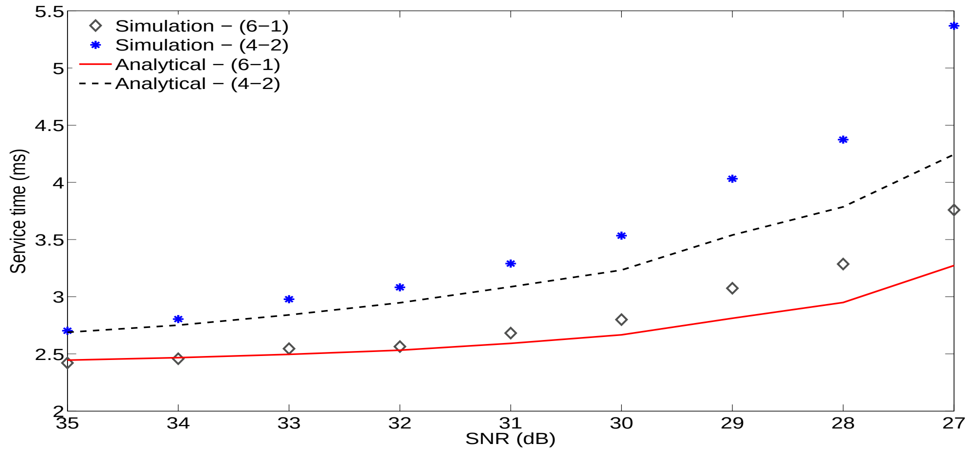

Figure 11

Average service time Vs. SNR, two frame classes.

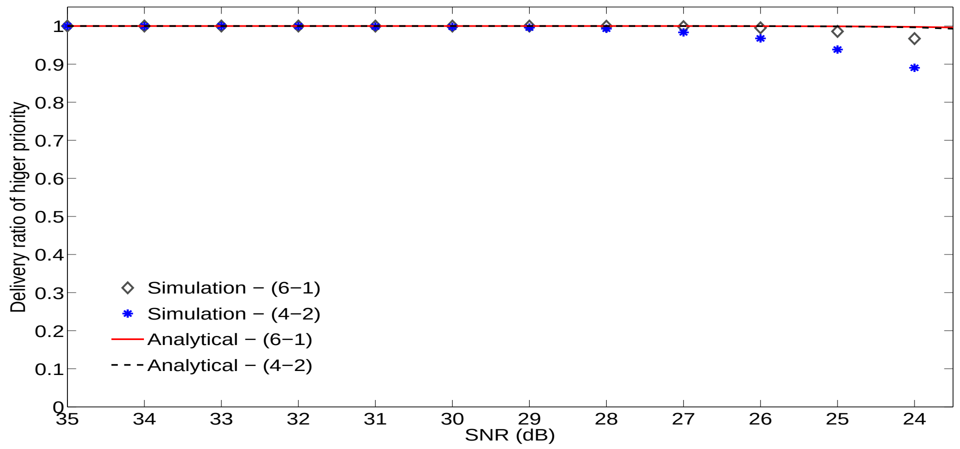

Figure 12

Delivery ratio of higher priority Vs. SNR, two frame classes.

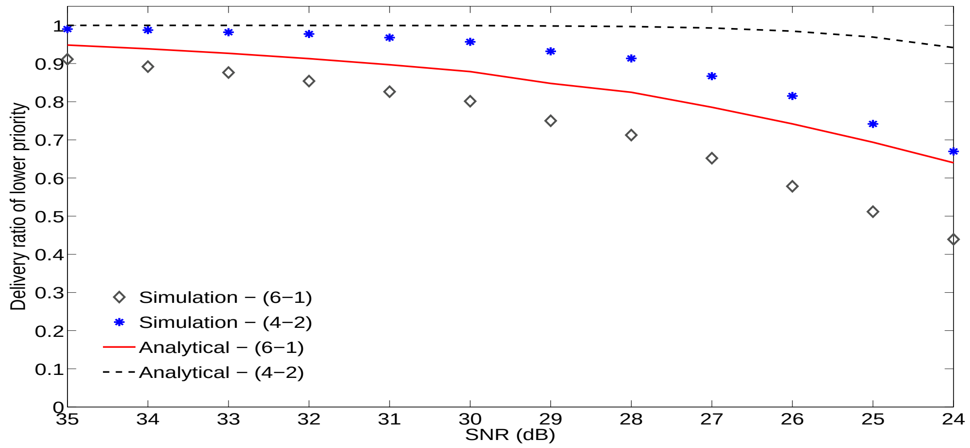

Figure 13

Delivery ratio of lower priority a SNR, two frame classes.

4. Conclusion

An analytical model that captures the performance of IEEE 802.11 in unsaturated conditions was presented and validated against simulation results.Its extension to model a technique that provides different QoS by varying the $RETRYLIMIT$ was also discussed. The presented model can be extended to account for other types of heterogeneous node behaviour, like the presence of multiple transmission rates and different signal to noise ratio values. The ability of the model to capture the maximum load after which saturation occurs was demonstrated. This framework may find its application in admission control strategies and determining optimal network parameters to adequately support delay sensitive applications, like voice and video.

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